

# **Bureau of Ocean Energy Management Resource Evaluation of Critical and Hard Offshore Mineral Programmatic Reference (RE- CHOMPR)**

**Version: FINAL, October 24, 2023**

**U.S. Department of the Interior  
Bureau of Ocean Energy Management  
Headquarters, Sterling, VA**



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## List of Abbreviations and Acronyms

<b>Abbreviation/Acronym</b>	<b>Term</b>
2D	two dimensional
3D	three dimensional
\$	U.S. Dollars
dmtu	dry metric ton unit of contained manganese
°C	degrees Celsius
%	percent
Al <sub>2</sub> O <sub>3</sub>	alumina
APTIM	Aptim Federal Services, LLC
ATO	antimony trioxide
AUV	Autonomous Underwater Vehicle(s)
BOEM	Bureau of Ocean Energy Management
CCD	carbonate compensation depth
CCZ	Clarion-Clipperton Zone
CFR	Code of Federal Regulations
CHOMPR	Critical and Hard Offshore Mineral Programmatic Reference
cm	centimeter(s)
CM	critical mineral(s)
Co	cobalt
COMEX	Commodity Exchange
CIF	Cost, Insurance, and Freight
CPC	Circum-Pacific Council for Energy and Mineral Resources
CRC	cobalt-rich ferromanganese crust(s)
CSA	CSA Ocean Sciences Inc.
Cu	copper
ddp	delivery duty paid
DOI	Department of the Interior
EEZ	Exclusive Economic Zone
Energy Act	United States Energy Act of 2020
EO	Executive Order
eSMS	extinct sulfide deposits
ETF	exchange-traded funds
EU	European Union
EV	electric vehicle
Fe-Mn	ferromanganese
FOB	Free on Board
FR	Federal Register
FTE	full-time employees
G	gram
GLORIA	Geological Long-Range Inclined Asdic
GSR	Global Sea Mineral Resources
HMS	heavy mineral sands
HREE	heavy REE
HREY	high heavy rare earth elements plus yttrium
ISA	International Seabed Authority
km	kilometer(s)
Kt	thousand tons
ky	thousand years
LAB	lead-acid batteries
LBMA	London Bullion Market Association

LIB	lithium-ion batteries
LME	London Metal Exchange
LREE	light REE
m	meter(s)
mm	millimeter(s)
MMS	Minerals Management Service
Mn	manganese
MoU	Memorandum of Understanding
Mt	metric ton
My	million years
Ni	nickel
NMC	nickel-manganese-cobalt
NOAA	National Oceanographic and Atmospheric Administration
OCS	Outer Continental Shelf
OMZ	Oxygen Minimum Zone
Pamco	Pacific Metals Company LTD
PCZ	prime crust zone
PDF	portable document format
PGM	platinum group metal
PMN	polymetallic nodule
ppm	parts per million
RE-CHOMPR	Resource Evaluation of Critical and Hard Offshore Mineral Programmatic Reference
REE	rare earth elements
REO	rare earth oxide
REY	rare earth elements plus yttrium
ROV	remote-operated vehicle
SHFE	Shanghai Futures Exchange
SME	Subject Matter Expert
SMS	seafloor massive sulfides
T	ton
Ti	titanium
TREE	total rare earth elements
UK	United Kingdom
U.S.	United States
USGS	U.S. Geological Survey
VMS	volcanogenic massive sulfides
wt.-%	weight percentage

# 1 Introduction and Objectives

The Bureau of Ocean Energy Management (BOEM), Marine Minerals Program, within the Department of the Interior (DOI) is responsible for the stewardship of non-energy minerals on the Outer Continental Shelf (OCS), including critical minerals (CMs) (e.g., 87 Federal Register [FR] 10381, 2022 Final List of Critical Minerals). The adequate supply of domestic sources of CMs is necessary for United States (U.S.) economic prosperity and national security, highlighted by a series of Executive Orders (EOs) issued in recent years, including EO 14017 on “America’s Supply Chains” (February 24, 2021), EO 13953 on “Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries” (September 30, 2020), and EO 13817 on “A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals” (December 20, 2017). BOEM’s mission includes oversight of exploration and leasing of sand and gravel for use in coastal restoration and beach nourishment projects, as well as exploration, leasing, and development of strategic, critical, and other hard minerals.

The U.S. is lagging other developed nations in domestic critical mineral planning and investments. A series of recent EOs, referenced in the introduction, recognize this issue and direct federal agencies to take actions to bolster development of domestic critical mineral resources. BOEM has received inquiries about BOEM regulations governing CM leasing and the types of environmental information needed to support such decisions on the OCS. Considering potential impending requests to develop OCS critical mineral resources, BOEM needs a Critical and Hard Offshore Mineral Programmatic Reference (CHOMPR) focused on marine critical mineral activities within U.S. federal water jurisdiction.

Over the past 65 years, industry has occasionally indicated interest in developing U.S. OCS critical minerals, yet BOEM and its predecessor agencies have not issued a competitive lease for such minerals. The Minerals Management Service (MMS) completed two Environmental Impact Statements in 1990 (MMS 90-0009 and MMS 90-0029) for a gold sale in Norton Sound in 1991, and a cobalt crust sale offshore Hawaii and Johnston Island. No bids were received by the sale dates, so the lease sales were cancelled. Internationally, but still under U.S. jurisdiction, Lockheed Martin has continuously held and performed assessments of polymetallic nodules (PMNs) in the eastern Pacific Clarion-Clipperton Zone (CCZ) under a Deep Seabed Hard Mineral Resources Act (30 U.S.C. §§ 1441 et seq., June 28, 1980) National Oceanographic and Atmospheric Administration (NOAA) exploration license since 1984.

In recent years, several other countries have shown increasing interest in offshore critical minerals. For example, the Norwegian government has completed successful marine mineral exploratory expeditions within the Norwegian Exclusive Economic Zone (EEZ) and has initiated an opening process for mineral activity on the Norwegian continental shelf, including the development of a strategic impact assessment. In 2020, Japan’s Ministry of Economy, Trade, and Industry conducted a successful excavation test of a cobalt-rich crust on the seabed of Japan’s EEZ.

The objective of this Assessment is to focus on exploration, characterization, and exploitation of critical minerals, including the unique and complex extraction technologies used in mining, transport, and refining. The Resource Evaluation of Critical and Hard Offshore Mineral Programmatic Reference (RE-CHOMPR) will assist Subject Matter Expert’s (SMEs) review and evaluate requests to conduct deep sea CM activities such as proposed prospecting, leasing, and operational activities regulated by 30 Code of Federal Regulations (CFR) 580, 30 CFR 581, and 30 CFR 582. Specific objectives include:

- Identify, consolidate, and summarize existing governmental, industry, academic, and non-governmental information, regulations, and best practices needed to evaluate the technical feasibility, benefits, and costs of potential competitive leasing and development associated with CM activities.
- Investigate deposits of interest include PMNs, cobalt-rich ferromanganese crusts, seafloor massive sulfides (SMS). Deposits of phosphorites and heavy mineral sands are also of interest.

The project covers multiple deposits of interest, but the bulk (greater than 80 percent [%] of the effort is concentrated on PMNs.

## **2 Existing Data Synthesis and Review of OCS Minerals; Minerals Use; and Associated Physical, Environmental, and Archeological Data**

### **2.1 Existing Information Review**

#### **2.1.1 Methods**

The Aptim Federal Services, LLC (APTIM) Team reviewed the relevant literature including peer-reviewed publications, gray literature, trade journals, and freely available processed data relevant to the BOEM scenario for offshore CM resource evaluation.

The APTIM Team used its Library Services capacity for this review under the direction of CSA Ocean Sciences Inc.'s (CSA's) Director of Library Services. The multi-faceted process briefly described below quickly resulted in a comprehensive listing of relevant documents, the basis for development of a database necessary for a review of existing data, information, or studies regarding CM resources. Identification of relevant source material was based on a search of numerous bibliographic and library sources. An extensive search for all relevant scientific and technical information was conducted using five major sources, described below:

- Proquest Dialog (<https://dialog.proquest.com/professional/commandline>).
- OCLC WorldCat (<http://www.oclc.org/us/en/worldcat/default.htm>).
- Internet search engines to locate relevant websites such as conference proceedings and archives (e.g., <https://www.google.com>, <https://www.bing.com>, <https://search.yahoo.com>).
- Digital Repositories, including industry-related sites and web-wide open term searches.
- Key scientific publishers such as Elsevier and Wiley.

Databases searched included those listed below, including the respective periods for their holdings and in consideration of temporal relevancy of the data. Given the accumulative nature of distribution maps, references, and summaries, and the non-linear evolution of CM activities, the search included publications from the past 60+ years. The search scope was constrained to focus on relevant sources that included:

- Marine minerals geology and geochemistry, oceanographic studies.
- Oceanographic research cruises, initial scientific reports, and resultant literature.
- Marine mineral data compilations, databases, and maps.
- Acoustic and electromagnetic deep water survey capabilities of industry in the 800-meter (m) to 6,000-m water depth, with focus on autonomous surface and submarine vehicles such as autonomous underwater vehicles (AUVs), remote-operated vehicles (ROVs), and advanced environmental measuring and monitoring kit.
- Marine engineering, naval architecture, ocean, and underwater technology.
- Abstracts in new technology and engineering.
- Mechanical and transportation engineering abstracts.
- U.S. Geological Survey (USGS) mineral and geochemical databases (USGS 2023a; 2023b).

Finally, in concert with the Team's SMEs, internet search engines were used to find specific journal articles, relevant websites, and the digital document repositories, which served as excellent sources of gray literature and conference papers, including web-wide key word searches and maintained sites. While

appearing less sophisticated than Proquest Dialog and OCLC WorldCat that were used in the search process, this approach was highly productive, especially with the leadership of CSA's Director of Library Services in communication with the SMEs. SMEs also used the literature libraries that they have assembled over the years and knowledge of current researchers in marine minerals to help find, rank, and filter relevant literature and databases. SMEs had full access to journals from key scientific publishers e.g., Elsevier.

Following review, all selected and remaining citations were entered into EndNote bibliographic management software. Portable document format (PDF) references were then attached to the citations. A bibliography was then exported from the bibliographic software to create the references list at the end of this document.

### **2.1.2 Findings**

Minerals are defined as naturally occurring inorganic elements or compounds having an orderly internal structure and characteristic chemical composition, crystal form, and physical properties (USGS 2023b). All rock types and constituent minerals are products of dynamic earth processes: the creation and burial of seafloor and the movement, collision, and weathering of the continents. Each mineral has its own history of heat, pressure, transport, and chemical and physical weathering. Weathered minerals can be transported as bedload sediments or can be dissolved in streams, rivers, groundwater, and oceans. Dissolved minerals can be heated, cooled, change chemical properties, and can precipitate back to solid form. Life forms: land, air, and marine- also metabolize minerals and can provide catalysts for fixation of important mineral precipitates especially some discussed in this report.

Secure sources of CMs are essential to support the energy transition and specifically, to support the electrification of the transportation sector, battery storage, and continued fast development of renewable resources such as wind and solar. In 2017, the USGS issued a report on the CM resources of the U.S. with an emphasis on prospects for future supply (Schulz et al. 2017). The report began by noting the rapid growth in minerals used in high technology such as computers and circuit chips. In the 1980s, there were 12 'high technology' elements on the periodic table, 16 elements in the 1990s, and 60 elements in the 2000s. The report also mentioned the possibility of a deep-sea supply of certain minerals, namely manganese and cobalt.

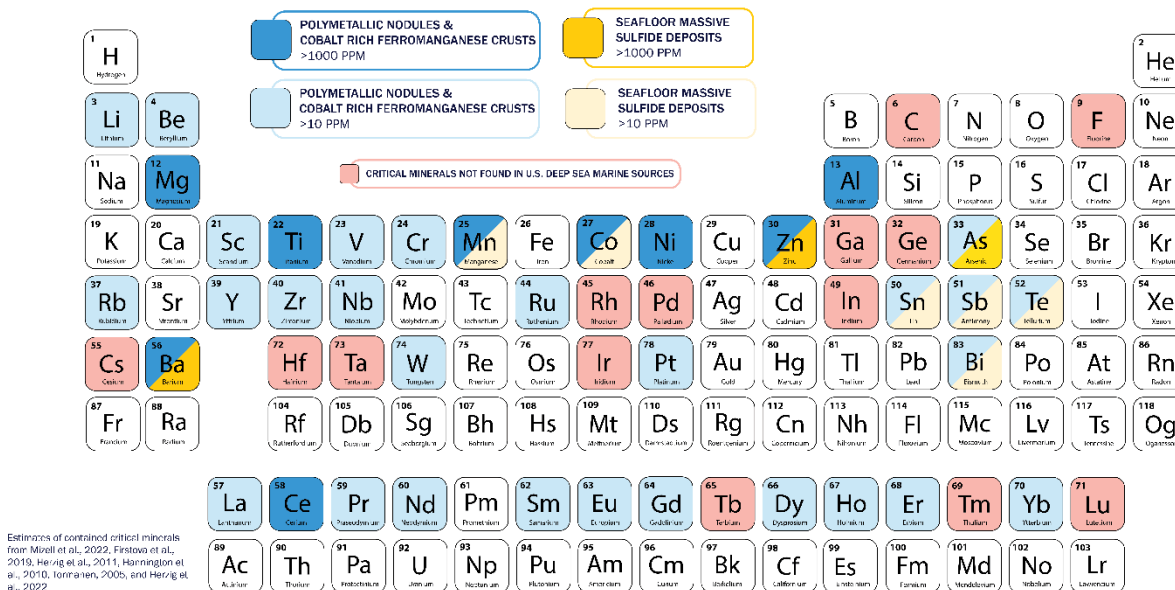
The U.S. government periodically reassesses CMs needed. The current assessment emphasizes domestic CM and material supply chains to support the clean energy transition and the decarbonizing of the energy, manufacturing, and transportation economies (U.S. Department of Energy 2023). The U.S. Energy Act of 2020 (Energy Act) defines a *critical mineral* as a 'non-fuel mineral or mineral material that is essential to the economic or national security of the U.S., and which has a supply chain vulnerable to disruption.' According to the Energy Act, CMs are also characterized as 'serving an essential function in the manufacturing of a product, the absence of which would have significant consequences for the economy or national security' (USGS 2022). Currently, there are 50 CMs defined by the Energy Act.

This report describes potential offshore CM resources in the U.S. OCS and EEZ including the Pacific Islands OCS and EEZ. These CM resources encompass both deep sea mineral deposits and nearshore deposits. Globally, very little offshore mining has been done to date and those few instances involve nearshore beach sands containing gold. But governments have offered license areas for heavy mineral sands (e.g., New Zealand, Namibia, South Africa) and discussions for mining offshore phosphorites are ongoing between companies and regulators in Mexico and New Zealand. However, the most significant development is the culmination of decades of resource assessment of deep-sea minerals, mostly in international waters, leading to possible production within three to five years. Some of these areas and the resources that have been found are analogous in geologic setting to relatively un-or-underexplored areas of the U.S. OCS and EEZ, in particular the U.S. Pacific Island OCS and EEZ.

Seafloor minerals in international waters are regulated by the International Seabed Authority (ISA), an autonomous international organization established under the United Nations Convention on the Law of the Sea. Other nations such as the Cook Islands and Norway have deep sea minerals in their EEZ and Extended Continental Shelf and have been developing regulatory frameworks for exploration and exploitation. One of the purposes of this report, in part, is to provide a guide to the possible distribution of offshore CM and associated economically important minerals that are found in these deposits in the U.S. OCS and EEZ.

Thirty-six of the 50 CM are found in deep sea mineral deposits. Significant sources of CM, especially nickel (Ni), cobalt (Co), zinc (Zn), titanium (Ti), aluminum (Al), manganese (Mn), magnesium (Mg), barium (Ba), and cerium (Ce) are found in deep sea PMNs and cobalt-rich ferromanganese crusts (CRCs) (Figure 1).

## U.S. CRITICAL MINERALS FROM DEEP SEA MARINE SOURCES



**Figure 1. U.S. Critical Minerals Found in Deep Sea Mineral Deposits (U.S. CM are Colored)**

Pursuant to Section 7002 of the Energy Act the Secretary of the Interior, acting through the Director of the USGS, published in 2021 within the **Federal Register** a draft list (86 FR 62199) and in 2022 (87 FR 10381) a subsequent final list of 50 mineral commodities for inclusion on the Interior Department’s list of CMs and the methodology USGS used to create the list. The 2022 final list of CMs from the USGS (2022), shown on Figure 1, includes the following:

- [Aluminum](#) Al, used in almost all sectors of the economy.
- [Antimony](#), Sb, used in lead-acid batteries and flame retardants.
- [Arsenic](#), As, used in semi-conductors.
- [Barite](#), BaSO<sub>4</sub>, used in hydrocarbon production. CM element is Ba.
- [Beryllium](#), Be, used as an alloying agent in aerospace and defense industries.
- Bismuth, Bi, used in medical and atomic research.
- Cerium, Ce, used in catalytic converters, ceramics, glass, metallurgy, and polishing compounds.

- Cesium, Cs, used in research and development.
- Chromium, Cr used primarily in stainless steel and other alloys.
- Cobalt, Co, used in rechargeable batteries and superalloys.
- Dysprosium, Dy, used in permanent magnets, data storage devices, and lasers.
- Erbium, Er, used in fiber optics, optical amplifiers, lasers, and glass colorants.
- Europium, Eu, used in phosphors and nuclear control rods.
- Fluorspar, (CaF<sub>2</sub>) used in the manufacture of aluminum, cement, steel, gasoline, and fluorine chemicals. CM element is F.
- Gadolinium, Gd, used in medical imaging, permanent magnets, and steelmaking.
- Gallium, Ga, used for integrated circuits and optical devices like light emitting diodes.
- Germanium, Ge, used for fiber optics and night vision applications.
- Graphite, C, used for lubricants, batteries, and fuel cells.
- Hafnium, Hf, used for nuclear control rods, alloys, and high-temperature ceramics.
- Holmium, Ho, used in permanent magnets, nuclear control rods, and lasers.
- Indium, In, used in liquid crystal display screens.
- Iridium, Ir, used as coating of anodes for electrochemical processes and as a chemical catalyst.
- Lanthanum, La, used to produce catalysts, ceramics, glass, polishing compounds, metallurgy, and batteries.
- Lithium, Li, used for rechargeable batteries.
- Lutetium, Lu, used in scintillators for medical imaging, electronics, and some cancer therapies.
- Magnesium, Mg, used as an alloy and for reducing metals.
- Manganese, Mn, used in steelmaking and batteries.
- Neodymium, Nd, used in permanent magnets, rubber catalysts, and in medical and industrial lasers.
- Nickel, Ni, used to make stainless steel, superalloys, and rechargeable batteries.
- Niobium, Nb, used mostly in steel and superalloys.
- Palladium, Pd, used in catalytic converters and as a catalyst agent.
- Platinum, Pt, used in catalytic converters.
- Praseodymium, Pr, used in permanent magnets, batteries, aerospace alloys, ceramics, and colorants.
- Rhodium, Rh, used in catalytic converters, electrical components, and as a catalyst.
- Rubidium, Rb, used for research and development in electronics.
- Ruthenium, Ru, used as catalysts, as well as electrical contacts and chip resistors in computers.
- Samarium, Sm, used in permanent magnets, as an absorber in nuclear reactors, and in cancer treatments.
- Scandium, Sc, used for alloys, ceramics, and fuel cells.
- Tantalum, Ta, used in electronic components, mostly capacitors and in superalloys.
- Tellurium, Te, used in solar cells, thermoelectric devices, and as alloying additive.
- Terbium, Tb, used in permanent magnets, fiber optics, lasers, and solid-state devices.
- Thulium, Tm, used in various metal alloys and in lasers.
- Tin, Sn, used as protective coatings and alloys for steel.
- Titanium, Ti, used as a white pigment or metal alloys.
- Tungsten, W, primarily used to make wear-resistant metals.
- Vanadium, V, primarily used as alloying agent for iron and steel.
- Ytterbium, Yb, used for catalysts, scintillometers, lasers, and metallurgy.
- Yttrium, Y, used for ceramic, catalysts, lasers, metallurgy, and phosphors.
- Zinc, Zn, primarily used in metallurgy to produce galvanized steel.
- Zirconium, Zr used in high-temperature ceramics and corrosion-resistant alloys.



The 2022 list of CM will be updated periodically to represent or reflect current data on supply, demand, concentration of production, and current policy priorities USGS (2022).

The amount of CM in the U.S. OCS and EEZ may be significant. The U.S. Pacific OCS and EEZ overlap or share geologic and oceanographic similarities to large known quantities of CM in international waters and in other Pacific Island EEZs. The best studied deep sea mineral resources are the PMN deposits in the Pacific CCZ that centers along the 12° North latitude and extends 4,800 kilometers (km) between the U.S. Kingman Island and Palmyra Atoll EEZ and Clipperton Island (France). The CCZ has been extensively sampled since the 1970s (Adamczyk et al. 2023). Today, it is estimated that approximately 44 million metric tons of cobalt, a CM needed for electric vehicle batteries and electric grid battery storage, are contained in PMN in the CCZ. This far exceeds both the 7 million metric ton global terrestrial reserves and the 13 million metric ton global terrestrial reserve base (including currently subeconomic deposits) of cobalt. Similarly, the estimated 274 million metric tons of nickel in the CCZ greatly exceeds the 89 million tons global terrestrial reserves and the 150 million metric tons reserve base of this important CM also required for electric vehicle (EV) batteries and energy storage (Hein et al. 2013). PMNs were also found off the U.S. eastern seaboard in the Atlantic OCS off the Carolina coast in the 1960s but are less studied than the CCZ PMN. They contain a similar suite of metals but are more enriched in cobalt and less so in nickel.

CRC studied in the Pacific in an area known as Prime Crust Zone (PCZ) are even more enriched in cobalt and rare-earth elements plus Yttrium (REY) CM. Fifty million metric tons of cobalt are estimated to be in the PCZ CRC and the PCZ CRC are also strongly enriched in the CM manganese, argon, yttrium, tellurium, and thorium (Hein et al. 2013).

Parts of the Hawaii OCS, Guam OCS, and Northern Mariana Island OCS and the entirety of Jarvis Island EEZ, Kingman Reef and Palmyra Island EEZ, Johnston Atoll EEZ, and Wake Island EEZ lie within the PCZ. These areas are underexplored for CRC and are likely to contain significant CM resources (Hein et al. 1987). CRC on seamounts off southern California contain a similar suite of metals but are less enriched in cobalt and Ni.

The potential CM resource in SMS is not well known. Analysis of SMS deposits have shown that they could be a significant source of the CMs zinc, arsenic, and barium.

### **2.1.2.1 Nearshore Minerals**

Nearshore minerals occur within soft sediments along continental margins in water depths less than 500 feet and generally adjacent to terrestrial mineral deposits. Nearshore minerals can include titanium, tin, platinum, gold, silver, heavy mineral sands, phosphorites, rare earth elements (REE), and others (BOEM 2023). REE are a group of seventeen chemical elements that include yttrium and the 15 lanthanide elements (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium). REE are all metals with similar properties and are often found together in geologic deposits (King 2023). Nearshore minerals discussed in this report are heavy mineral sands (HMS) and phosphorites.

#### **2.1.2.1.1 Heavy-Mineral Sands and Phosphorites**

HMS are sedimentary deposits of dense mineral grains that accumulate within unconsolidated sediments (sand, silt, and clays) typically in coastal environments where they locally form concentrations of economically important minerals known as ‘heavy minerals.’ CMs such as titanium, zirconium, and aluminum are found in common heavy mineral sand grains such as ilmenite, rutile, zircon, and sillimanite as well as REY (Ce, La, Nd, Th, and Y) in monazite.

HMS are formed by both physical and mechanical concentration of bedrock minerals that are freed by weathering. The process begins within terrestrial environments where igneous, metamorphic, and

sedimentary rocks erode and contribute sand, silt, clay, and heavy minerals to stream and river drainages and ultimately to coastal areas, such as deltas, beach face, barrier islands, tidal lagoons, and into the nearshore environment.

This concentration into “placer deposits” occurs because their hydraulic response is different from low density mineral grains (Dillon 1984).

HMS deposits in coastal environments are significant in the global mineral economy. Some economic deposits can contain less than 1% heavy-mineral content, but composite grades are typically more than 2% and locally can exceed 10% (Van Gosen et al. 2014). Estimates of HMS resources from deposits within a single district can exceed more than 1,000 metric ton (Mt) of ore (total sand bodies) and can be vast in size, ranging from several kilometers to as much as tens of kilometers in length (Van Gosen et al. 2014).

Heavy minerals commonly found in HMS deposits are listed below (Van Gosen et al. 2014).

Heavy Minerals (specific density greater than 2.9 grams per cubic centimeter).

- Hematite,  $\text{Fe}_2\text{O}_3$
- Magnetite,  $\text{Fe}_3\text{O}_4$
- Pyrite,  $\text{FeS}_2$
- Pyrolusite,  $\text{MnO}_2$
- Monazite,  $(\text{Ce,La,Nd,Th})\text{PO}_4$
- Ilmenite,  $\text{FeTiO}_3$
- Zircon,  $\text{ZrSiO}_4$
- Xenotime,  $\text{YPO}_4$
- Goethite,  $\text{FeO}(\text{OH})$
- Rutile,  $\text{TiO}_2$
- Corundum, also referred to as alumina,  $\text{Al}_2\text{O}_3$
- Leucoxene, alterations of Fe-Ti oxides
- Staurolite,  $(\text{Fe,Mg})_2\text{Al}_9\text{Si}_4\text{O}_{23}(\text{OH})$
- Limonite,  $(\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O})$
- Spinel,  $\text{MgAl}_2\text{O}_4$
- Sphene,  $\text{CaTiSiO}_5$
- Epidote,  $(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$
- Garnets,  $(\text{Ca,Mg,Fe,Mn})_3(\text{Al,Fe,Cr,V})_2(\text{SiO}_4)_3$
- Kyanite,  $\text{Al}_2\text{SiO}_5$
- Sillimanite,  $\text{Al}_2\text{SiO}_5$
- Andalusite,  $\text{Al}_2\text{SiO}_5$
- Tourmaline, borosilicates including schorl,  $\text{NaFe}^{2+}_3\text{Al}_6(\text{Si}_6\text{O}_{18})(\text{BO}_3)_3(\text{OH})_3(\text{OH})$
- Amphibole, group of silicate minerals including tremolite,  $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

The key HMS with CM are ilmenite, rutile, leucoxene, sphene that are titanium bearing; monazite and xenotime that are REY bearing; zircon containing zirconium; and kyanite, sillimanite, and andalusite that are aluminum bearing. Garnet grains can be a source of the CMs manganese, aluminum, chromium, or relative.

Phosphorite, also called phosphate rock, is defined as phosphate-rich sedimentary rock in nodular or compact masses. Phosphates in phosphorite may be derived from a variety of sources, including marine invertebrates that secrete shells of calcium phosphate, and the bones and excrement of vertebrates, as well as high organic productivity produced by nutrient and phosphate-rich upwelled water (Boggs Jr. 2009; Manheim et al. 1982; Parrish 1982; Sheldon 1981; USGS 2022). Phosphorites occur within hard

substrates along continental shelves and slopes of the Atlantic and Pacific continental margins and on seamounts in water depths between 0.8 to 3.2 km where deep-water upwelling occurs under areas of high biological productivity (BOEM 2023).

Phosphorite minerals include phosphorous and REE (possibly uranium). REY are known to concentrate in marine phosphorite deposits during their formation. A study by Hein et al. (2016) documented that marine phosphorites sampled on the continental margin had low total REY contents and high heavy REY (HREY) complements, as compared to phosphorites sampled from seamounts that had higher individual REY contents and very high HREY complement. Hein et al. (2016) deduced that the predominant causes of higher concentrations and larger HREY complements in seamount phosphorites as compared to continental margin phosphorites is their relative geological time of formation, changes in seawater REY concentrations over time, water depth of formation, differences in organic carbon content in the depositional environments and its role in the development of diagenetic zones in the sediment, and possibly the concurrent precipitation of ferromanganese (Fe-Mn) oxides with the seamount phosphorites. Fe-Mn crusts and nodules are another potential resource for REY. Seamount phosphorites often occur in the same places as the Fe-Mn crusts on seamounts.

The U.S. has well-developed world-class phosphate mines and undeveloped phosphate deposits on shore, especially in Florida where phosphates have been continuously mined in the state since the 1880s. These deposits likely extend offshore but have not been fully delineated. Large offshore phosphorite deposits are also associated with CRC on the Blake Plateau that extends from North Carolina and along the east coast of Florida. Phosphate deposits are also known offshore southern California, in the Hawaii OCS, the U.S. Pacific Island OCS, and EEZ.

Globally, offshore phosphorite resources have been delineated and mining has been proposed in the Gulf of California (Mexico), Chatham Rise (New Zealand), and along the continental margin south of Walvis Bay (Namibia), but none of the projects has been sanctioned by regulators to date.

### **2.1.2.2 Polymetallic Nodules**

PMNs (also referred to as manganese nodules) are spherical precipitates of manganese, iron oxides, and other metals (e.g., nickel, cobalt, copper, and zinc) that form around a core material, such as a shell fragment and very slowly build up around the nucleus in layers (Hein and Petersen 2013; USGS 2022). Typically, PMNs are 2 centimeters (cm) to 15 cm diameter concretions on the deep abyssal seafloor in the world's oceans. Although composed principally of manganese and iron hydroxides, they contain nickel, copper and cobalt along with traces of lithium, zirconium, molybdenum and various REE (Cuyvers et al. 2018). Though found in all of the earth's oceans, PMNs are especially concentrated in the north and south-central Pacific Ocean and the Central Indian Ocean (Cronan 1992).

In the Pacific setting, PMNs sit upon or within the upper 10 cm of calcareous and silicious oozes or very soft red clays on the abyssal plains at water depths between 3 and 6 km at most occurrences. The average depth of the known nodule-rich areas are similar in the Pacific and Indian Oceans, but are nearly 700 m to 3800 m shallower in the Atlantic Ocean (McKelvey 1986). Nodules on the Blake Plateau are found at 800 m water depth. Nodules occur within all ocean basins but are most abundant in the central Pacific. PMNs, where present, can provide hard substrate for meio and macro fauna.

There are several types of Fe-Mn concretions. Some are diagenetically related to Fe-Mn crusts and phosphorite deposits. Others can form on hydrothermal systems along mid-ocean ridges. Early literature tended to group these Fe-Mn concretions together with PMN. Today's literature treats Fe-Mn pellets and nodules associated with phosphorite deposits and Fe-Mn crusts as different than PMN deposits owing to important differences in how they form and variations in their chemical composition. For PMN, two processes form PMNs, hydrogenetic nodules accrete metals directly from seawater and diagenetic nodules

that accrete metals from enriched pore waters (Cronan 2019). Many PMNs have both components—a smooth hydrogenetic top and a rough or bulbous diagenetic base.

Controls on PMN formations include:

- Slow pelagic sedimentation outside the reach of terrigenous turbiditic sedimentation.
- Adjacent to areas of marine productivity and at or below the carbonate compensation depth.
- Bottom currents and local micro topography.
- Semi-constant conditions over millions of years for nodules to grow.

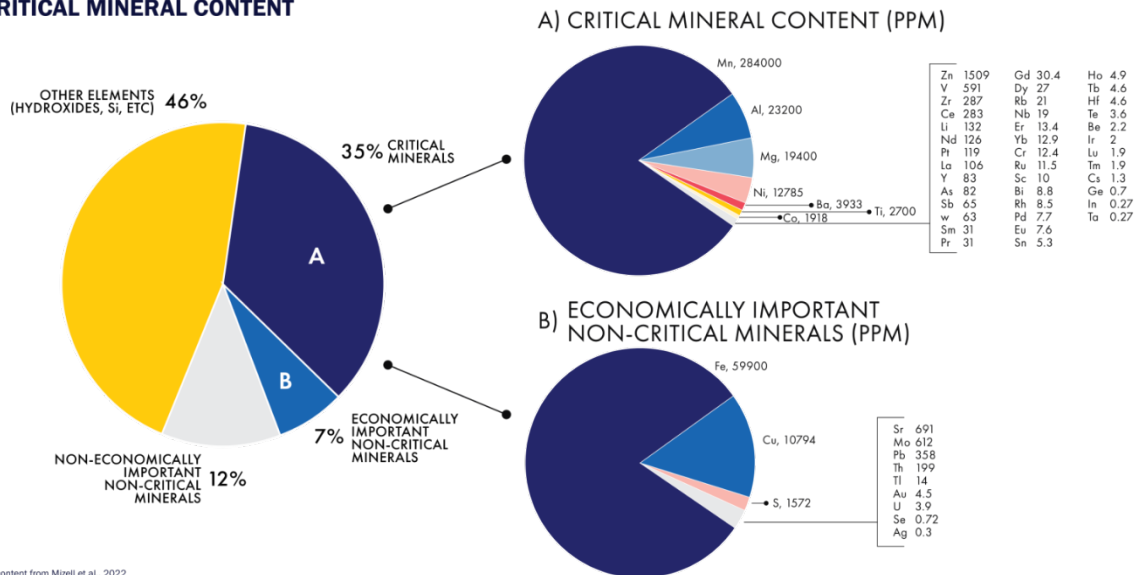
The main control on PMN formation is that they are found in areas with exceptionally low rates of geologic sedimentation because nodules accrete at a rate in the range of 2 to 10 millimeter per million years with hydrogenetic nodules growing slower than diagenetic nodules (Verlaan and Cronan 2022). Age dating of nodules and sedimentation rates, where nodules are present, suggests sedimentation rates less than 10 cm per thousand years approximates the boundary condition for nodules to accrete. Sedimentation any greater than 10 cm per thousand years would bury the potential nucleation material (Hein and Petersen 2013; Verlaan and Cronan 2022). Even high rates of in situ sedimentation beneath areas of high productivity constrain PMN formation. This end member ultra-low sedimentation rate boundary condition for nodule formation precludes, of course, any areas reached by turbiditic sedimentation from the continental margins from producing PMNs.

The most concentrated PMN deposits are regionally adjacent to, but not directly under, areas of high marine productivity. In situ pelagic sedimentation in areas of high productivity lowers the carbonate compensation depth (CCD). If the CCD intersects the seafloor, calcareous organic material may accumulate too rapidly to allow for nodule growth. Nodules that do form in these conditions tend to be enriched in Mn and depleted in nickel and copper because the biogeochemical processes that fix nickel and copper are overwhelmed. Both hydrogenetic and diagenetic nodules grow around a hard nucleus, a rock fragment or biological hard material such as shark teeth or bone. Diagenetic nodules tend to be enriched in nickel and copper facilitated by biomaterials (fecal pellets and biofilms) associated with marine productivity. Diagenetic nodules, in general, are most abundant and larger at or just below the CCD in areas of moderate in-situ and transported sedimentation associated with marine productivity. Hydrogenetic nodules accreting from colloidal manganese in seawater are, in general, found below the CCD in areas of lower marine productivity. Hydrogenetic nodules tend to be enriched in cobalt and depleted in copper and nickel (Mizell 2022; Verlaan and Cronan 2022).

PMNs are enriched in critical minerals and economically important non-critical minerals. Metal content from CCZ nodules give the best estimate of what the metal content may be for PMN from unexplored areas of the U.S. Pacific Island OCS and EEZ. Thirty-five percent (35%) of the composite CCZ PMN metal content are critical minerals such as manganese, nickel, cobalt and REY. Seven percent (7%) of the same composite CCZ PMN comprise economically important noncritical minerals such as copper and iron (Figure 2).

# CLARION-CLIPPERTON ZONE (CCZ)

## POLYMETALLIC NODULE CRITICAL MINERAL CONTENT



Metal content from Mizell et al., 2022

**Figure 2. Critical Mineral and Economically Important Non-Critical Mineral Content of CCZ PMN**

The greatest concentrations of metal-rich nodules occur in the CCZ, an area south of Hawaii that extends 4,800 km from Kingman Reef, Palmyra Island EEZ (U.S.) to Clipperton Island (France) off the western coast of Mexico.

Nodules are also concentrated in the Peru Basin and in the Penrhyn Basin near the Cook Islands, and at abyssal depths in the Indian and Atlantic oceans (Cronan 1975; Hein and Petersen 2013). The abundance of nodules and, therefore, the quantities of associated metals are moderately well known for the CCZ, the Central Indian Ocean Basin and the Cook Islands EEZ, but poorly known for other areas of the global ocean (Petersen et al. 2017). The U.S. Pacific Island OCS and EEZ, for instance, which is closest and shares conditions favorable for PMN formation is under explored.

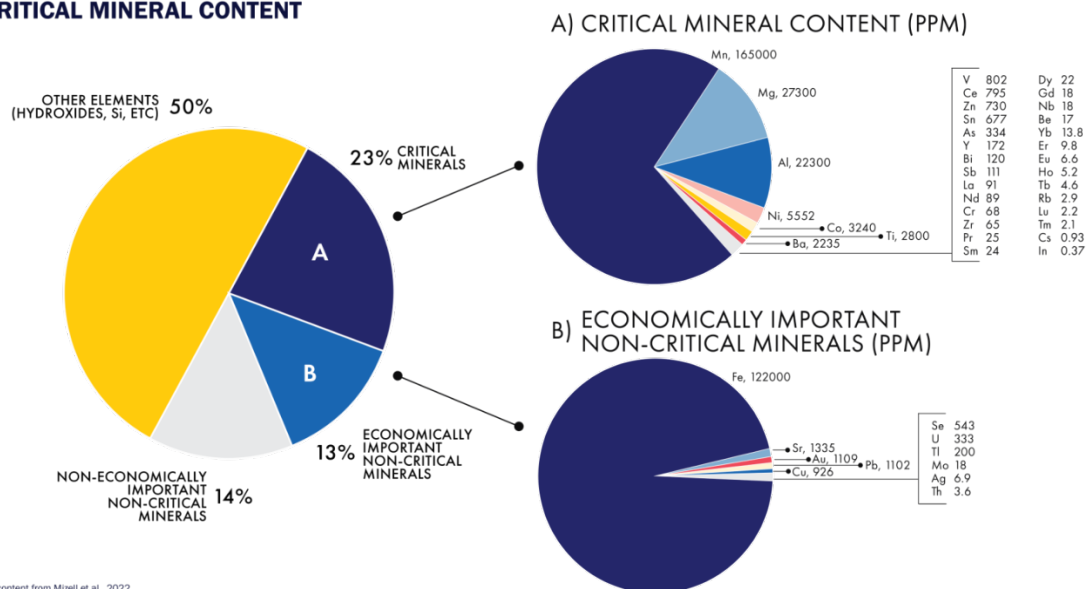
Generally, Pacific Ocean nodules have the higher average manganese, nickel, and copper contents, and Atlantic Ocean nodules have the highest average cobalt and iron content (McKelvey 1986; Mizell 2022). The metal ratios also differ considerably. Metal ratios of manganese-iron are much lower in Atlantic and Indian Ocean nodules than those in the Pacific, and the copper-nickel ratio in Atlantic nodules is also appreciably lower than ratios in the Pacific and Indian Ocean. The moderate negative correlation between manganese and iron in Pacific nodules is much weaker in Indian Ocean samples and is nearly absent in Atlantic nodules. The strong positive correlation between nickel and copper and the negative correlation between combined nickel and copper and iron found in the Pacific nodules are weaker in Atlantic and Indian nodules (McKelvey 1986). A latitudinal relation for manganese and combined nickel and copper has been documented, with an increase in these metals toward the equator, but decreasing rather abruptly in the zone extending a few degrees north and south of the equator (McKelvey 1986).

Blake Plateau PMN are also enriched in critical minerals such as nickel, cobalt, and REY. Critical metals comprise 23% of the bulk chemistry of Blake Plateau PMN. Economically important non-critical metals such as manganese, gold, and copper comprise 13% of the bulk chemistry (Figure 3).

# BLAKE PLATEAU

## POLYMETALLIC NODULE

### CRITICAL MINERAL CONTENT



**Figure 3. Critical Mineral and Economically Important Non-Critical Mineral Content of Blake Plateau PMN**

Selected metal constituents in Blake Plateau PMNs when compared to Pacific abyssal manganese nodules are presented in **Table 1**.

**Table 1. Comparative Values of Selected Metal Constituents in Blake Plateau Nodules with Pacific Nodules (values in weight %) (Flanagan and Gottfried 1980; Manheim et al. 1982; McKelvey 1986)**

Element	Values (weight %) Blake Plateau	Values (weight %) Pacific
Manganese	16.3	29.14
Iron	11.10	5.78
Nickel	0.62	1.34
Copper	0.10	1.15
Cobalt	0.33	0.22
Calcium	11.90	2.19
Silicon	2.00	6.50
Titanium	0.20	0.30
Zinc	0.045	0.16
Lead	0.092	0.055
Molybdenum	0.036	0.076
Vanadium	0.058	0.052
Cerium	0.072	0.029
Arsenic	0.046	0.0039

Manganese and iron are the principal metals in PMNs and the iron/manganese ratio is controlled by the ratio of hydrogenetic/diagenetic input and whether the sediments involved in diagenesis are oxic, i.e.,

containing measurable amounts of oxygen. The metals of greatest economic interest in PMNs include nickel, copper, cobalt, and manganese. In addition, there are traces of other valuable metals such as molybdenum, REEs, and lithium that have industrial importance in many high-tech and green-tech applications and can be recovered as by-products (Hein and Petersen 2013).

Many land-based mines are extracting REEs as the primary ore, whereas REEs in the nodule and crust deposits would be extracted as a byproduct of focus metals, such as manganese, nickel, copper, and cobalt (Hein et al. 2013).

Given the conditions for PMN formation, the most favorable areas in U.S. Federal waters are in the Pacific, U.S. Federal waters around Hawaii, the Alaska OCS, and U.S. Pacific Islands OCS and EEZ. To various degrees, seafloor samples have been collected to document the potential for, and distribution of, PMNs in these more favorable regions. Seafloor samples that could document the presence and distribution of PMNs in regions that are less favorable for the formation of PMNs are lacking, except in areas with extensive sampling for other purposes such as seafloor sampling in support of oil and gas development in the Gulf of Mexico OCS.

### **2.1.2.3 Cobalt-Rich Ferromanganese Crusts**

Cobalt-rich ferromanganese crusts, also known as CRCs, are two-dimensional deposits forming pavements on rock outcrops on seamounts and ridges at water depths of 400-7,000 m. The thickest and most metal-rich crusts occur at depths of about 800 to 2,500 m. Located in the western and central Pacific Ocean, as well as the south and northeast Atlantic Ocean, they primarily consist of manganese-oxides and amorphous iron-oxyhydroxides. Marine iron-manganese or polymetallic crust deposits are hydroxide/oxide deposits of cobalt-rich iron/manganese (ferromanganese) formed by direct precipitation of minerals from seawater (hydrogenetic precipitation) onto hard substrates on seamounts, ridges, and plateaus as pavements and coatings on rocks at depths ranging from 400-7,000 m and can reach a thickness of 25 cm in areas that are kept sediment-free for millions of years (Cuyvers et al. 2018; Glasby et al. 2010; Hein et al. 2013; Koschinsky and Hein 2017; USGS 2022).

In approximate order of decreasing abundance, substrate rocks for ferromanganese crust deposits include volcanic breccia, hyaloclastite, basalt, phosphorite, limestone, volcanoclastic sandstone, mudstone, and chert (Aplin 1984; Aplin and Cronan 1985; Craig et al. 1982; Halbach et al. 1982; Hein et al. 1985; Koski et al. 1985; Schwab et al. 1985). The type of substrate depends on the part of the edifice that is sampled and the geographic location (Hein et al. 1987).

Like PMNs, iron-manganese crusts contain high concentrations of iron and manganese hydroxides, cobalt, copper and nickel, along with trace concentrations of other metals and REEs (Cuyvers et al. 2018). Many metals contained within CRCs are critical to the U.S. economy and national security, cobalt and platinum being two prominent examples of said metals.

CRCs are present within the U.S. OCS and EEZ and within the EEZ of other nations and in international waters, especially in the Pacific. CRCs are most extensive within the central and western Pacific, and crusts are thickest in the northwest Pacific where the seamounts are old (Jurassic age), the oldest in the global ocean. Atlantic and Indian Ocean seamounts and ridges have less iron-manganese crusts than the Pacific because there are fewer seamounts and sediment-free ridges (Hein et al. 2013).

Polymetallic crusts are similar to hydrogenetic PMNs in that they are both iron manganese oxyhydroxide that can concentrate cobalt, nickel, platinum, and manganese within the crusts. The crusts, like hydrogenetic nodules, accrete and grow extremely slowly from contact with dissolved metals and colloids in seawater. The crusts are thin- ranging from a patina to up to 80 millimeters (mm) with those over 40 mm thick being of interest for potential resource delineation. Crusts form on hard substrates that are swept clean of sediments such as on volcanic ridges, spreading centers, or of most interest, seamounts;

especially, those on older seafloor where many old mid-plate volcanic edifices have accumulated ferromanganese crusts for nearly 70 million years (Nielsen et al. 2009).

What initiates precipitation of the first molecular layer from seawater onto hard substrate is unclear, although once the process of precipitation begins it becomes autocatalytic, a process in which the given compound serves as a catalyst of its own synthesis (Hein et al. 1987).

For growth to occur over the long periods of time required, very low sedimentation away from the reach of terrestrial input and even low pelagic sedimentation is required. Bottom currents that can bring metal fixing nutrients and metals in solution in these ultra-low sedimentation regimes also favor crust formation.

Thicker crust formation on the sides of seamounts correlates with the Oxygen Minimum Zone (OMZ) because low oxygen waters contain more dissolved manganese. Oxygen rich waters are colder and deeper, but warmer surficial waters are oxygenated by contact with the atmosphere and enhanced by wind and wave action. Transects across ocean basins will show ocean wide OMZ between 800 and 1,200 meters. While conditions favoring polymetallic crust growth plot in low productivity areas, the OMZ is enhanced by bacterial processes consuming oxygen in response to primary productivity layers. This OMZ is controlled primarily by atmospheric interfaces, by ocean temperature, and then by ocean current interaction, which also creates chemical conditions that favors the cobalt-rich ferromanganese crusts to accrete.

Areas with many seamounts on older seafloor, such as in the west central Pacific, are favored for crust development, especially where the seamounts have intersected present and paleo OMZ. This area is called prime crust zone.

Northwest equatorial Pacific crusts in the prime crust zone also typically have the highest concentrations of rare metals (Hein et al. 2013; U.S. Congress and Office of Technology Assessment 1987). Iron-manganese crusts can also form in regions within and near continental margins, such as continental shelves, slopes, banks, and plateaus where sedimentation rates are higher, which is the case for Gulf of Alaska Seamounts and the Chukchi Borderland on the Alaska OCS and in the OCS off southern California (Conrad et al. 2017; Gartman et al. 2022).

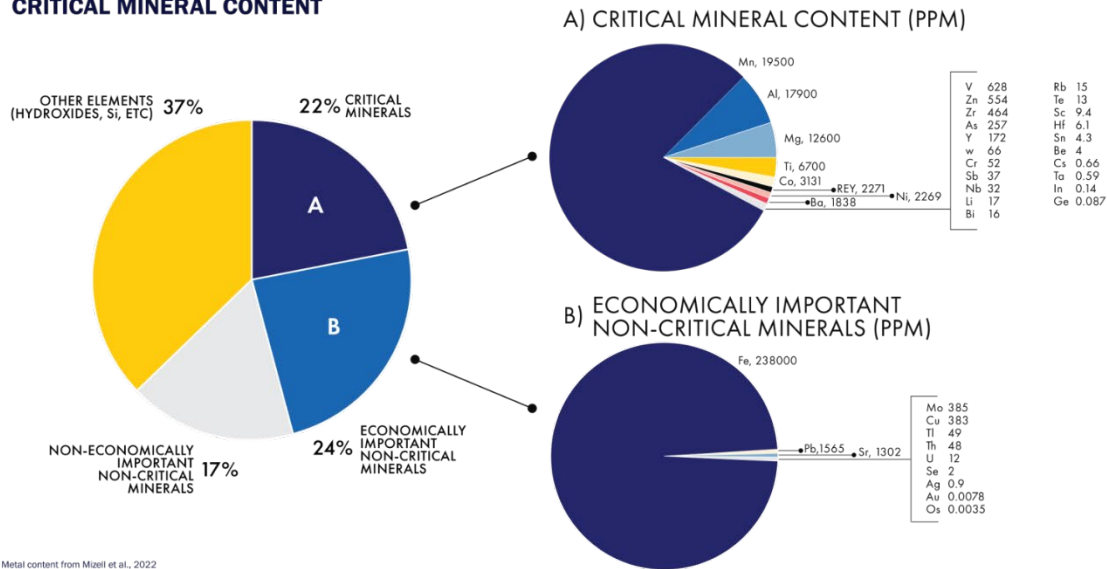
CRCs are known to be present in the Atlantic OCS, Pacific OCS, Hawaii OCS, and Pacific Island OCS and EEZ. Mineral sampling has been supported by USGS and others off southern California and in the prime crust zone in the west-central Pacific. The bulk chemistry of California margin CRC contains 22% CM- namely manganese, aluminum, magnesium, titanium, cobalt, REY, nickel, and barium. Economically important non-critical minerals contained are iron, lead, molybdenum, and copper (Figure 4).



# CALIFORNIA MARGIN

## COBALT RICH FERROMANGANESE CRUST

### CRITICAL MINERAL CONTENT

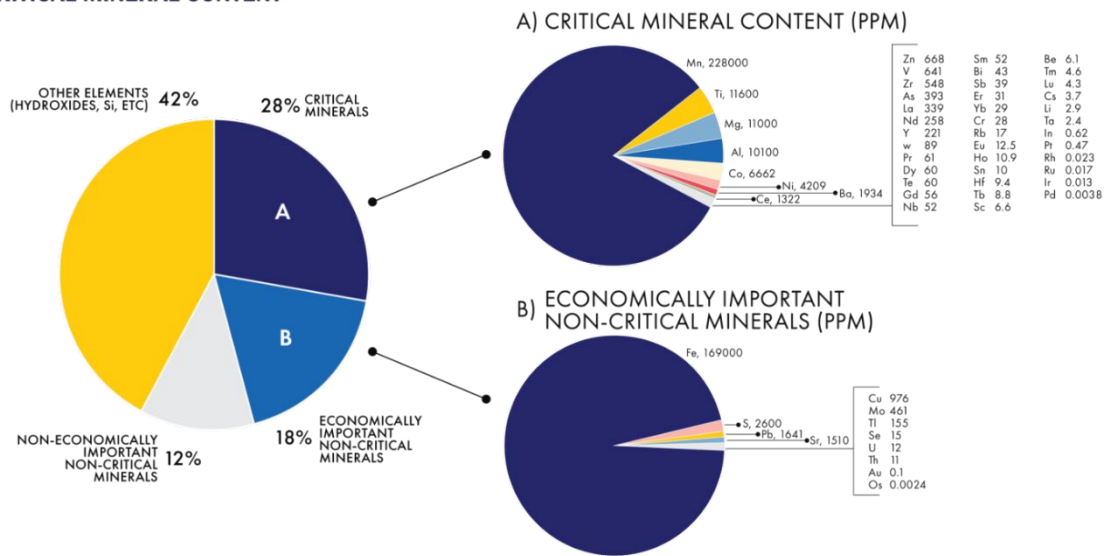


**Figure 4. CM and Economically Important Non-Critical Minerals in California Margin CRC**

The CRC in the prime crust zone in the west-central Pacific are diagenetically related to CRCs that have been sampled in the U.S. Pacific Island OCS and EEZ. The bulk chemistry of prime crust zone CRC samples contain 28% CM consisting of manganese, titanium, magnesium, aluminum, cobalt, nickel, and REY. Economically important non-critical minerals comprise 18% of the bulk samples of prime crust zone CRC including iron, molybdenum, lead, and copper (Figure 5).

# PRIME CRUST ZONE

## CRITICAL MINERAL CONTENT



**Figure 5. CM and Economically Important Non-Critical Minerals in Prime Crust Zone CRC**

#### 2.1.2.4 Seafloor Massive Sulfides and Related Hydrothermal Deposits

SMS deposits, also known as black smoker deposits, are deposits of metal-bearing minerals with high base metal and sulfide content that form on and below the seabed as a consequence of the interaction of seawater with a heat source below the seafloor (hydrothermal circulation), mainly at volcanically active oceanic spreading centers and along volcanic arcs (Boschen et al. 2013; Hannington et al. 2005; Petersen et al. 2017; USGS 2022). SMS are the only metal-bearing deposits of (current) commercial significance that form at active plate boundaries (Cuyvers et al. 2018).

At seafloor spreading centers, hot magma rises through fractures to generate new ocean floor from the cooled magma. SMS form when cold seawater percolates down through the seafloor. Cracks and fissures form when the molten magma cools to brittle basalt upon contact with the cold seawater. Seawater will penetrate through these cracks into the newly formed crust. The penetrating seawater will heat to temperatures greater than 400 degrees Celsius (°C), become acidic, and have low redox potential. The heated seawater becomes acidic and corrosive in this process, which leaches iron, manganese, copper, zinc and gold, and silver among other species from the oceanic basement. The greatly heated fluids with metals in solution becomes buoyant and rise along the major and minor fissures where they contact cold seawater and rapidly cool upon contact to precipitate metals that can no longer be held in solution and form massive sulfides on the seafloor and within the underlying stockwork (Boschen et al. 2013; Kleiv and Thornhill 2022; Rahn 2019).

A portion of the minerals may precipitate to form chimneys and mounds; however, most minerals are transported as plumes and deposited as particulate debris (Cuyvers et al. 2018). High concentrations of copper, zinc, lead, gold, and silver can form in the sulfide minerals formed at spreading centers (Bischoff et al. 1983).

Deep-sea vents are primarily concentrated along Earth's mid-oceanic ridge systems in the Pacific, Atlantic, Arctic, and Indian oceans (60% of SMS). Twenty-five percent are located in back-arc basins with the remaining 15% believed to be submarine volcanic arcs and intraplate volcanic settings (Miller et al. 2018). Hydrothermal vents that can produce SMS deposits are found at 1,000–4,000 m depth and are characterized by temperatures up to 400° C and high acidity (pH 2–3).

Of all deep marine mineral deposits, only SMS deposits have a major direct corollary economic mineral deposit type on land in the volcanogenic massive sulfides (VMS) deposit. VMS deposits comprise some of the most important historical economic mineral deposits such as Rio Tinto in the Iberian pyrite belt, and Rammelsberg in Germany that were first mined in the Bronze Age and Middle Ages, respectively. Only after geologists adopted plate tectonic theory and its implications did they understand that those important historic mineral deposits and other 19<sup>th</sup> and 20<sup>th</sup> century discoveries, such as Kidd Creek in Canada and Besshi and Kuroko in Japan, must have originated on the seafloor. The discovery of Atlantis Deep active submerged ore forming system in the diverging rift system in the Red Sea, 1965, and of black smokers at seafloor spreading centers in 1980, showed the present-day mechanism for massive sulfide deposition and a fuller understanding of how these deposits form.

It is important to note that in contrast to PMNs and cobalt-enriched iron-manganese crusts that are surficial two-dimensional resources, SMS deposits are a three-dimensional resource. Most research into SMS deposits have taken chimney samples and near surface sediments for mineral characterization. Very few deposits have been drilled and cored through the ~ 20-70 m interval subsurface to characterize the mineralized stockwork that is likely to be associated SMS deposits of economic exploration interest.

The composition of SMS deposits varies in accordance with the physicochemical conditions of the water and the nature of the underlying rocks from which the metals are leached. Deposits generally contain around 8% zinc, with a noted increase in concentrations at ridge axes and back-arc basins. Silver and gold are also found within SMS. Back-arc settings favor the inclusion of silver and gold; proximity to land and

the associated supply of sediments increase lead and arsenic concentrations (Fouquet 2012). Deposits with high concentrations of copper, gold and cobalt have also been identified at the Northern Equatorial Mid-Atlantic Ridge (Cherkashov et al. 2010).

According to Petersen et al. (2017), most SMS deposits that are presently known are small, three-dimensional bodies, much smaller than corollary VMS deposits on land that are actively mined. Only a few SMS deposits, however, have been drilled and cored through their stockwork. Most sampling of SMS deposits have been surficial within the upper 1 or 2 m, or by sampling SMS chimneys with an ROV.

However, some deposits contain metals such as copper, zinc, gold, and silver, which are of economic interest. Other trace elements that are important for a variety of industry uses, such as bismuth, gallium, germanium, iridium, and tellurium can be enriched at certain SMS sites and may be considered as possible by-products (Firstova et al. 2019; Monecke et al. 2016). Reliable global resource estimates for SMS deposits are not possible, as it is not presently known how much of the metal that is released by high-temperature fluid convection over a given length of a ridge axis and over a specific geological time frame is actually deposited as massive sulfides (Petersen et al. 2017). However, there is evidence from recent seafloor surveys that large, but inactive or extinct sulfide deposits (eSMS) occur away from the ridge axis where long-lasting fluid flows along stable fault systems allow for the accumulation of massive sulfides over large time spans, and that large eSMS deposits can be found in a strip of a few tens of kilometers away from mid-ocean ridges at only a few meters below a sediment or lava carapace (McCaig et al. 2007). Overall, knowledge about the regional and local spatial controls of sulfide deposition is currently still lacking.

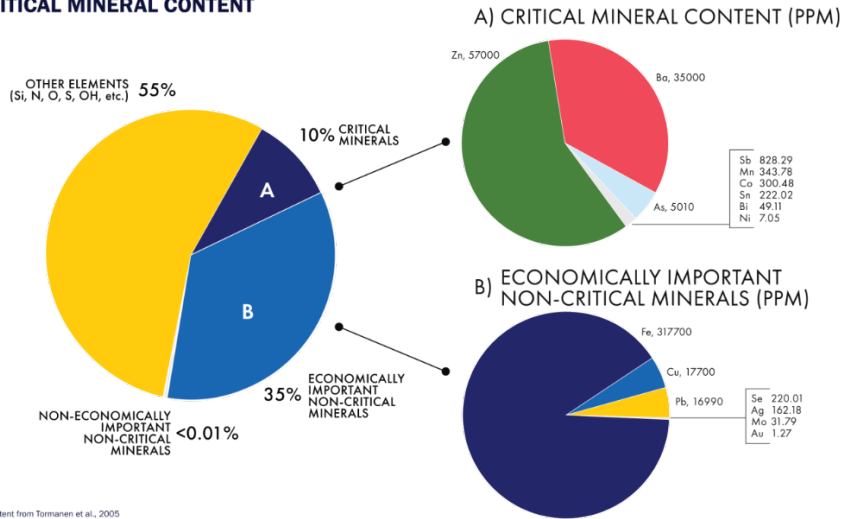
Nevertheless, several regions have been identified as being favorable for the development of commercially attractive SMS deposits. They include Middle Valley Site of the Juan de Fuca Ridge, where an estimated 15 million tons of ore deposits can be found, making it one of the largest sulfide deposits known (Fouquet 2012), the western Pacific, with its numerous back-arc basins, and the slow-spreading Mid-Atlantic Ridge (Fan et al. 2021). These regions have been explored intensively for their mining potential. The mid-ocean ridges in the Indian Ocean are characterized by slow and ultra-slow spreading, which makes them another potential site for commercially significant quantities of SMS deposits. The Red Sea has also been considered an area of particular interest due to a slow-spreading tectonic setting in which metal-bearing muds are deposited directly on the seafloor. It is one of the most important hydrothermal deposit sites known and contains millions of tons of ores with commercially significant quantities of zinc, copper and silver (Cuyvers et al. 2018). SMS deposits along the Arctic Mid Ocean Ridge in the extended continental shelf of Norway are attracting exploration interest. A number of junior mining companies have recently formed in Norway to secure exploration contracts.

In the U.S., an area of promising SMS deposition is in the Escanaba Trough in the Pacific OCS off Oregon and Northern California. Bulk chemistry of samples indicates a 10% CM component consisting primarily of zinc, barium, and arsenic, with traces of antimony, manganese, cobalt, and tin (Figure 6). Economically important non-critical minerals found in Escanaba Trough bulk chemistry samples are iron, copper, lead, selenium, silver, molybdenum, and gold. Several researchers analyzing Escanaba Trough deposits have focuses on the genesis of electrum (gold/silver) and gold deposits (Törmänen 2005).

# ESCANABA TROUGH

## SEAFLOOR MASSIVE SULFIDE (SMS) DEPOSIT

### CRITICAL MINERAL CONTENT



Metal content from Tormanen et al., 2005

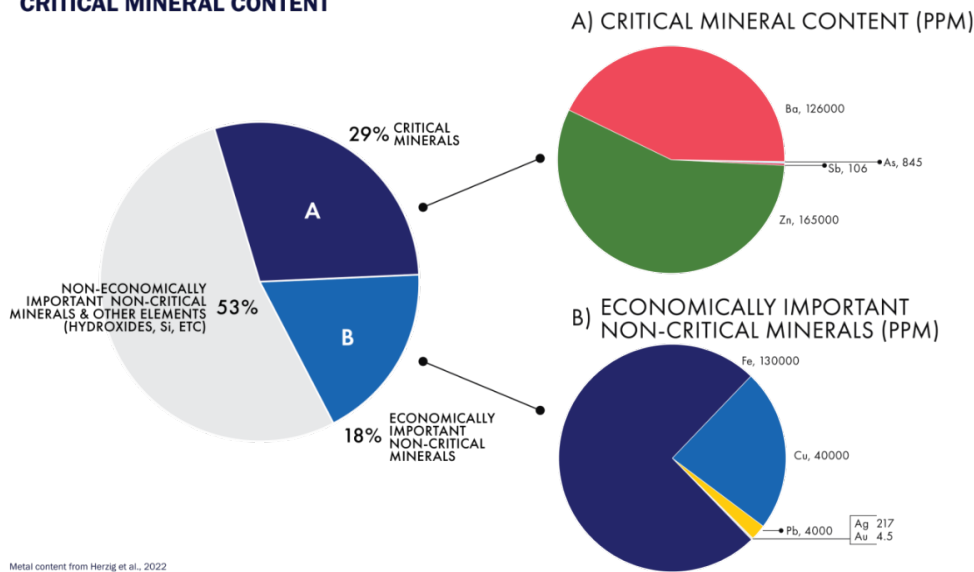
**Figure 6. CM and Economically Important Non-Critical Minerals in Escanaba Trough SMS**

The Guam and Northern Mariana Islands OCS is prospective for SMS deposits that may correlate to Kuroko and Besshi type VMS mineralization. CM in bulk samples from Guam and Northern Mariana Islands type SMS deposits are principally zinc and barium with arsenic and antimony (Figure 7). Economically important non-critical minerals contained in Guam-Northern Mariana Islands OCS are iron, copper, lead, silver, and gold (Herzig et al. 2002).

# GUAM AND NORTHERN MARINA ISLANDS

## SULFIDE MASSIVE SEAFLOOR (SMS) DEPOSIT

### CRITICAL MINERAL CONTENT



Metal content from Herzig et al., 2022

**Figure 7. CM and Economically Important Non-Critical Minerals in the Guam and Northern Mariana Island OCS SMS**

## **2.1.3 Review of Known Offshore CM Resources and Associated Economic Non-Critical Mineral Resources in U.S. Federal Waters**

### **2.1.3.1 Polymetallic Nodules**

#### **2.1.3.1.1 Location of Resources**

Figures 8 through 15, and 27 show permissive areas for PMN formation. Permissive, for the purposes of this report, indicates that the bio-geological conditions are favorable for PMN presence or PMN have been sampled. The basis for assessing the permissive areas is discussed by OCS and EEZ.

#### **2.1.3.1.2 Atlantic OCS**

Polymetallic nodules are closely associated with a large semi-contiguous area of phosphorite, phosphate manganese pavement, and ferromanganese crusts in the northern portion of the Blake Plateau on the U.S. continental margin. Polymetallic nodules in the Blake Plateau differ from Pacific nodules in that they are found at water depths of 250 to 1,000 m (Manheim et al. 1980) instead of 4,000 m and deeper in the Pacific. Bedform ripples from the southern part of the Blake Plateau indicate the Gulf Stream flows 20 to 30 cm per second (Hollister 1973) and faster bringing metal bearing colloids and phosphate saturated waters across the sea bottom. Bottom sediments are well sorted as the result of persistent strong currents. In the northern part of the Blake Plateau where phosphorite, pavements, and nodules are found is a non-depositional to erosional surface, gravel consisting of phosphorite nodules, ferromanganese nodule, and coral fragments that characterize the central Blake Plateau (Hollister 1973; Steson 1961). Sections cut through Blake Plateau nodules show that they grow around lag gravels of Oligocene-Miocene phosphorites. Nodules and crusts from the area show that they are manganese impregnated phosphorites (Manheim et al. 1980). The main nodule fields overlie hard phosphorite pavements (Commeau et al. 1984). During the early commercial activity around PMNs, Deep Sea Ventures tested a nodule collection system on the Blake Plateau before deploying their system to the CCZ in the Pacific (Dettweiler, personal communication).

Oceanographic conditions for phosphorite deposition are the primary drivers of the phosphorite and ferromanganese crusts in the Blake Ridge area.

The combined OCS of Puerto Rico and the U.S. Virgin Islands is 399,190 km<sup>2</sup>. The Circum-Pacific Council for Energy and Mineral Resources (CPC) mineral maps show 23 coring sites within the Puerto Rico and U.S. Virgin Islands OCS, two of which recovered PMNs. Of nine bottom photograph stations within the OCS, two documented nodules. The two cores that recovered nodules and the bottom photographs that documented nodules are on the Puerto Rico Ridge. Nodule abundance in one bottom photograph was less than 1%. The other bottom photograph showed a nodules abundance of 10% to 25%. A 1% nodule abundance contour encircles these locations (CPC 1984). Three nodules were recovered from a single core approximately 360 km north-northeast of the Puerto Rico OCS. Two nodules were surface nodules, and one was categorized as buried (73 cm). Metal content was similar with an average cobalt content of 0.39%, copper of 0.15%, and zinc of 0.06%. Nickel was not analyzed (Smith et al. 1968).

The Dutkiewicz model for PMN occurrence, which is trained on conditions that are thought to produce Pacific PMNs, estimates a 0 to 25% probability of nodule occurrence in the Atlantic OCS (Dutkiewicz et al. 2020) with higher probabilities seaward of the Atlantic OCS, for example, along the New England Seamount where PMNs have been recovered.

The Blake Plateau of the southeastern U.S. EEZ contains one of the largest single deposits of manganese nodules and ferromanganese pavement with deposits of nodules and extensive and continuous pavements of manganese-phosphorite (also see Section 2.2.2) (Buchannon 1995). Most nodules of the Blake Plateau

have nuclei of phosphorite, although some have manganese crusts as nuclei. Surrounding the nuclei are lenses of aragonite or high-magnesium calcite (Manheim et al. 1982). Like other Atlantic nodules, those found on the Blake Plateau generally have higher relative iron concentrations than Pacific nodules (particularly the CCZ) (Hobbs III 1991; Manheim et al. 1982).

#### **2.1.3.1.2.1 Gulf of Mexico OCS**

The Gulf of Mexico OCS is likely not prospective for PMNs, primarily because the sedimentation rate is too high. Extensive seismic surveys for basin studies and for oil and gas exploration show tens of kilometers of sediment infill since the basin opened in the Jurassic. Average sedimentation rates in the central deep water Gulf of Mexico are 1,200 cm/thousand years (ky) (Flemings 2021), which is 120 times the maximum sedimentation rate (less than 10 cm/ky) needed to allow for PMN growth. The Gulf of Mexico OCS is arguably the most studied offshore shelf and deep water seafloor because of survey and support activities performed for the oil and gas industry. The very-high resolution surveys for site characterization are performed in the vicinity of the oil and gas drilling or development activity. Fields of PMNs have not been found to date in these local site investigations. Nor have comprehensive systematic seafloor surveying and sampling programs encountered PMN fields. Beginning in 2015, a three-year modern multibeam and geochemical survey was acquired over the entire Mexican and U.S. sectors of the Gulf of Mexico. The purpose of the survey was to find hydrocarbon seeps and to take geochemical cores (Decker et al. 2022). High backscatter features, that in general indicate harder and rougher sea bottom were targeted and the core barrels were navigated to these locations. Approximately 800,000 km<sup>2</sup> of seafloor was mapped, and 1,500 cores were taken. No PMNs were recovered (Orange and Gharib, 2023). However, Texas A&M researchers dredged apparent ferromanganese crusts at various parts of the deepwater Gulf of Mexico and, in particular, from the Eastern Gulf of Mexico at 3,200 m water depth. Fragments of the crust were indurated with sediment and epifaunal organisms and bottom photographs from the area confirmed the crust was at the sediment water interface (Petuegnat et al. 1972).

#### **2.1.3.1.2.2 Navassa Island EEZ**

The EEZ around Navassa Island, between Jamaica and Haiti, is 13,900 km<sup>2</sup>. Two coring locations are shown within, or near adjacent to, the Navassa Island EEZ. Neither recovered PMNs. None of the four bottom photograph stations within, or near adjacent to, the Navassa Island EEZ indicated PMNs (CPC 1984).

#### **2.1.3.1.2.3 Pacific OCS**

The Pacific OCS extends off Washington, Oregon, California, and Hawaii. The geologic setting of the continental OCS off Washington, Oregon, and California is different from the mid-Pacific volcanic islands comprising the OCS around Hawaii and this difference has implications for the formation and presence of PMNs.

#### **2.1.3.1.2.3.1 U.S. Pacific Continental OCS**

The U.S. Pacific Continental OCS is a seismically active continental margin with transform fault movement from Baja California through central California and plate subduction beneath northern California, Oregon, and Washington. Polymetallic nodules have been found off the Pacific Continental OCS, but no extensive fields are known. The Pacific Continental OCS is probably the best studied of the of the U.S. OCS with extensive marine research by institutions (Scripps, Monterey Bay Aquarium Research Institute, Oregon State University, among others) and the U.S. Navy.

The main reason PMNs are not abundant in the continental Pacific OCS is that the sedimentation rates along the Washington, Oregon, and Northern California continental margin are too high towards the coast where the seafloor is older. Other contributing factors that suppress PMN formation are low bottom water oxygen concentration.

Sample patterns bear this out. Of 95 sediment cores compiled for the CPC project in the OCS between the Canadian border and the Gorda Escarpment none recovered nodules. Of the 10 bottom photograph stations in this same part of the OCS none showed any nodules (CPC 1984).

Nodules have been found in the southern part of the continental Pacific OCS during research surveys. Dredge hauls on the Santa Lucia Escarpment recovered nodules (and cobalt-rich ferromanganese crusts) from estimated water depths of 2,100-2,700 m on old seafloor (~19 million years [My]) offshore southern California. Ellipsoidal nodules 3 to 15 cm in diameter with large mudstone nuclei and spheroidal nodules 4 to 10 cm in diameter were sampled. Both had smooth textures (Gibbs et al. 1993). The sampling methods did not allow for calculation of abundances or relative distribution. Cobalt content in the nodule samples ranged from 0.17 to 0.29% (Gibbs et al. 1993). Nodules from the Santa Lucia Escarpment are enriched in nickel (0.44%) and the cobalt content is 0.21%. The nodules plot as hydrogenetic on a Fe-Mn-(Co+Ni+Cu) x 10 ternary diagram. Growth rates ranged from 2.5 to 8.1 mm/My (Conrad et al. 2017).

### **2.1.3.1.2.3.2 Hawaii OCS**

The Hawaii OCS is more favorable for PMNs, but nodules are much less abundant than in adjacent areas outside the Hawaii OCS. Ferro-manganese nodules are also found at relatively shallow depths in the Hawaiian Archipelago, principally along three prominent terrace levels (400 to 800 m, 1,200 to 1,600 m, and 2,400 m) where dredge sampling and sea bottom photography indicates widespread crusts and pavements, but also include nodules. Small PMNs are common in some areas typically 1 to 2 cm in diameter that had local abundance adjacent to rock outcrops (Craig et al. 1982). Of 134 sediment cores compiled for the CPC project from around the main Hawaiian Islands only 3 recovered nodules. Of the 17 bottom photograph stations, none showed any nodules. Nodule abundance does increase along the OCS boundary to the northeast and southwest of the main Hawaiian Islands ramping from 1% to 10% in both directions. A similar pattern holds for samples taken NW of the main Hawaiian Island from Nishoa Island to Pearl and Hermes Reef. Of 49 sediment cores taken in this portion of the OCS only one recovered nodules. Of 11 bottom photographs, two showed nodule abundance less than 1% and three showed nodule abundance of 25% to 50% (CPC 1984).

### **2.1.3.1.2.3.3 Alaska OCS**

In Alaskan OCS waters, data suggest that ferromanganese mineralization in the Chukchi Borderland likely occurs as concomitant crusts and nodules, although the abundance and distribution of nodules in this region may not be comparable to abyssal plain settings. The areal extent of shallow ferromanganese deposits in the Alaska OCS remains unknown. Manganese nodules have not been recovered from any of the Alaska offshore regions, though oceanographic and geologic criteria suggest that the Canada Basin meets some, but not all, of the prospective criteria for the formation of abyssal-plain-type manganese nodules (Gartman et al. 2022). Full-sized (i.e., macronodules, defined as nodules larger than approximately one centimeter diameter) have not been recovered from the Canada Basin in the Beaufort Sea; however, micronodules have been found in cores collected from the central Canada Basin (Clark et al. 1980). Micronodules are often found concomitant with macronodules in other regions of the global ocean. Areas prospective for manganese nodules are at water depths of 3,800 m or deeper, where the Canada Basin Abyssal Plain is deepest, flattest, and undergoes the lowest sedimentation rates.

Seabed samples compiled by the CPC covering the Alaska OCS reported one PMN sample out of 64 sediment cores and 9 bottom photos within the Alaska OCS in the Gulf of Alaska, North Pacific, Shumagin Bank, and Bristol Bay (CPC 1984). The nodule sample was on the south side of the Aleutian Thrust south of the Islands of the Four Mountains. A review of tens of thousands of marine samples in the Alaska OCS by Gartman et al. (2022) did not identify any nodules. However, geologic and oceanographic data suggest that the Canada Basin in the Arctic Ocean is prospective for abyssal type PMNs (Gartman et al. 2022). The Dutkiewicz model for PMN occurrence places a 40% to 80% probability for nodules to occur on the Alaska Plain within the Alaska OCS south of Kodiak Island (Dutkiewicz et al. 2020).

Dredge samples from four research cruises in the Chukchi Borderland area of the Canada Basin did yield ferromanganese crusts and a few nodules (Hein et al. 2017). Nodules were recovered at 2 of the 10 sites that recovered crusts. The size of the nodules is not noted. Seven nodules were analyzed. The nodules were anomalous for very high iron/manganese ratios and high concentrations of scandium (Hein et al. 2017).

### 2.1.3.1.2.4 U.S. Pacific Islands OCS and EEZ

#### 2.1.3.1.2.4.1 American Samoa

The OCS of American Samoa is 390,000 km<sup>2</sup>. It borders on the EEZ of Tokelau to the north, Samoa to the west, Niue to the south, and Cook Islands to the east (Figure 8). Broadly, American Samoa falls within or is adjacent to favorable areas for PMNs and the prime crust zone. The Cook Islands EEZ is well documented to contain high abundance of cobalt-rich hydrogenetic PMNs. As of 2005 the OCS of American Samoa was largely unexplored for PMNs. Conditions are favorable for PMNs to be present. Pelagic in situ sedimentation rates are thought to be less than 5 mm/ky (Hein et al. 2005). At least twelve sediment samples are known at this time and six of these had PMNs. The abundances were reported as low to medium. To the western side of the American Samoa OCS on the boundary with the Cook Islands EEZ, nine samples with PMNs are reported but it is unclear how many of those came from the American Samoan OCS.

The mineral resources compilation map (CPC 1996) shows approximately 22 core location with no nodules reported, 11 core location that recovered nodules, and 11 seabed photographic stations with no nodules in the American Samoan OCS. A 1% PMN contour plots east and southeast of Rose Island within the OCS. A ramp from 10% to 25% abundance is at the southeast OCS boundary. Six bottom sample stations in the American Samoan portion of this area reported nodules.

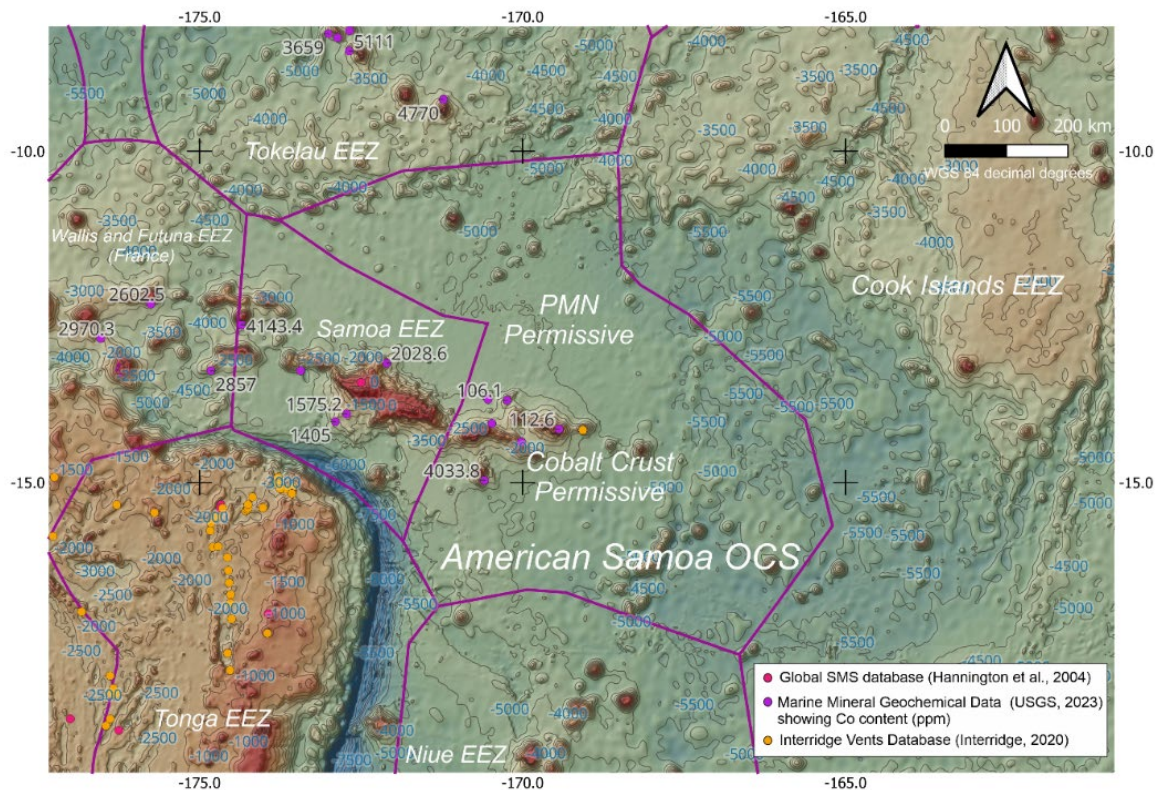


Figure 8. PMN and CRC Permissive Areas in the American Samoa OCS



### 2.1.3.1.2.4.2 Baker Reef and Howland Island

The Baker Reef and Howland Island EEZ is approximately 425,700 km<sup>2</sup>. Polymetallic nodules are likely to occur on the abyssal plains in the Baker Reef-Howland Island EEZ (Figure 9). In-situ (pelagic) sedimentation rates of less than 10 mm per thousand years measured in the area are favorable for nodule formation and growth of diagenetic nodules with very high copper and nickel content if similar to nearby nodules collected and analyzed by Japanese researchers (Hein et al. 2005). Of approximately 21 sampling locations, 4 reported nodules. One of four bottom photographs showed 1% to 10% abundance. The other three bottom photographs did not indicate nodules at those locations. A 1% abundance contour intersects the western perimeter of the Baker Reef- Howland Island EEZ. Another 1% contour is wholly within the Baker Reef- Howland Island EEZ (CPC 1999).

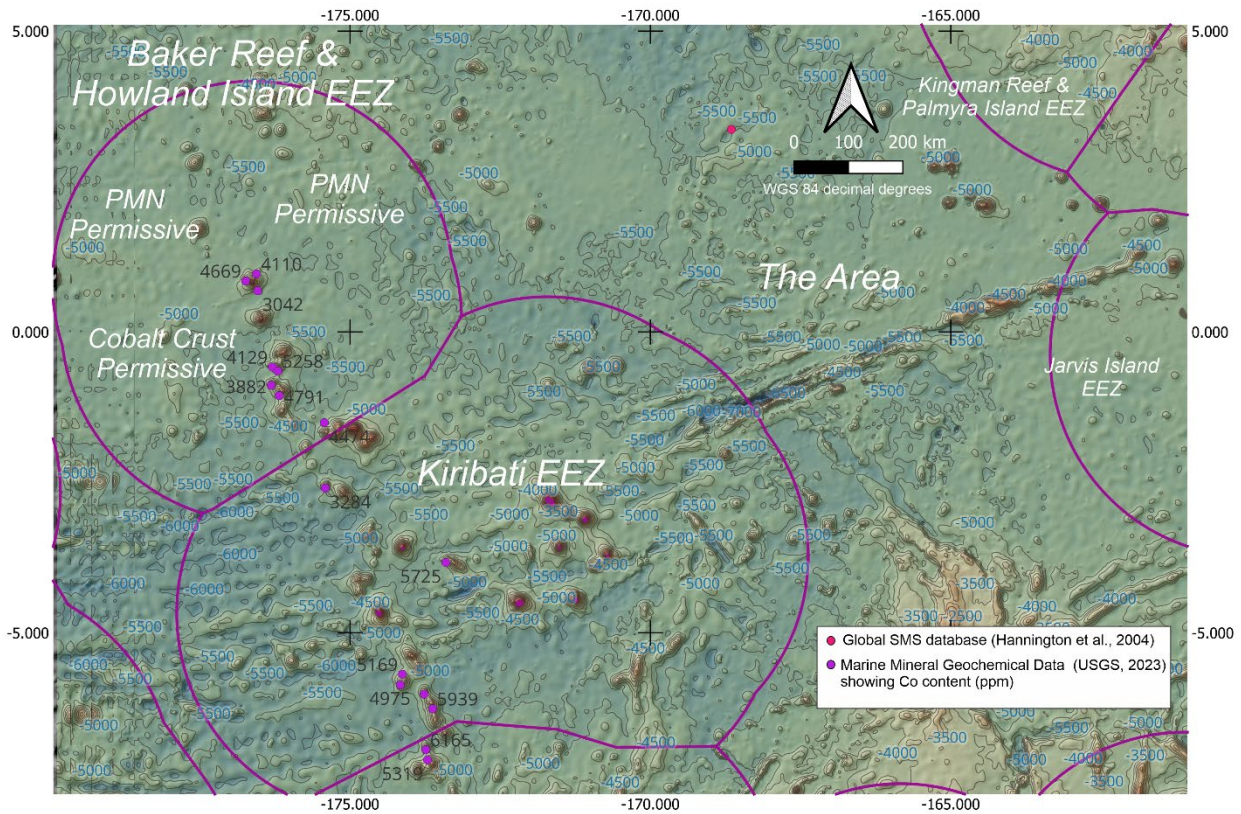
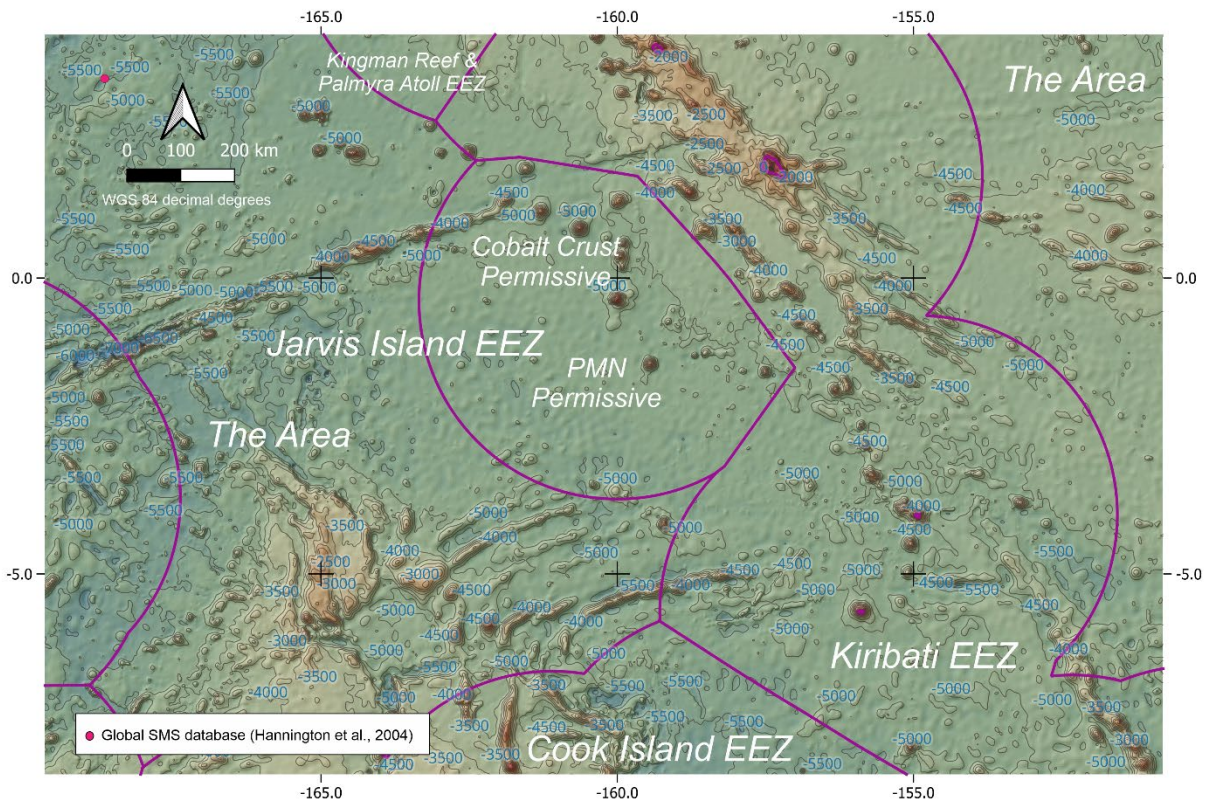


Figure 9. PMN and CRC permissive areas in the Baker Reef and Howland Island EEZ

### 2.1.3.1.2.4.3 Jarvis Island

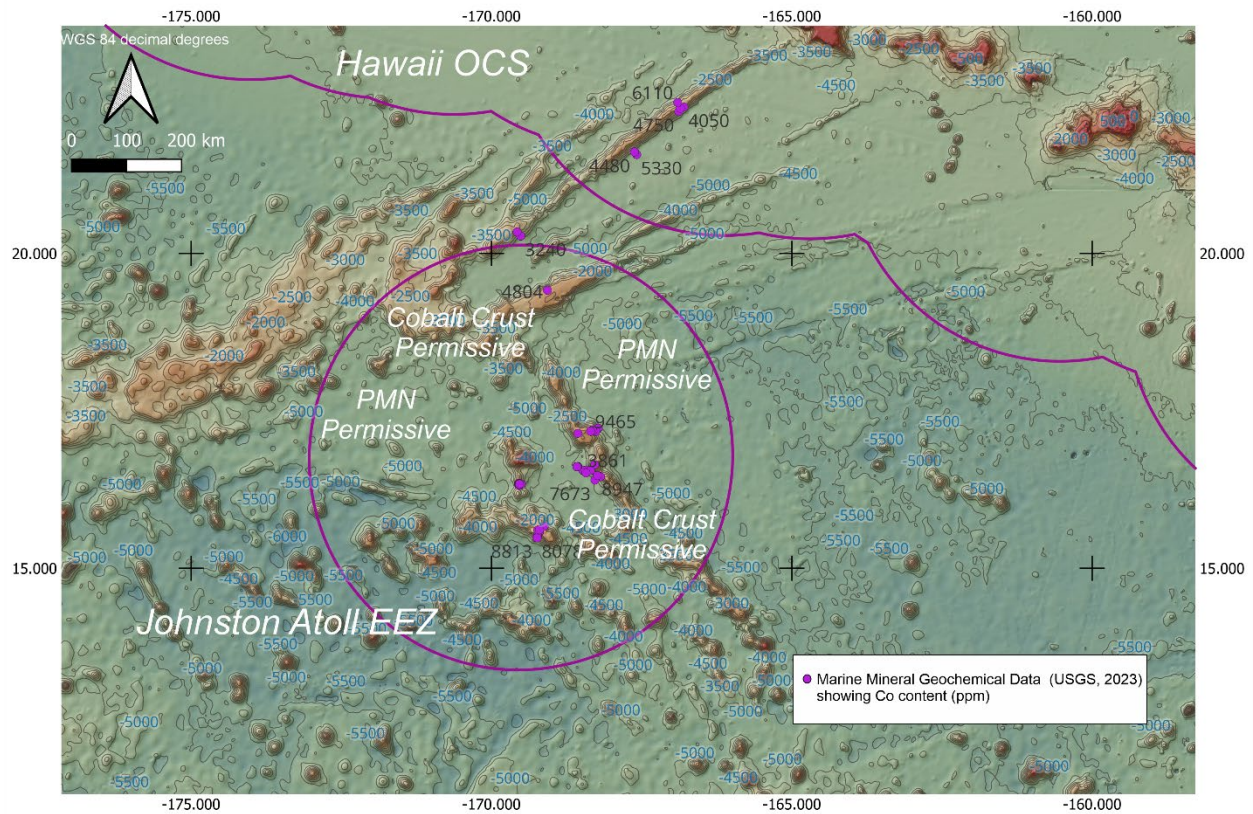
The Jarvis Island EEZ is 323,100 km<sup>2</sup> (Figure 10). A 1% PMN contour intersects the Jarvis Island EEZ to the southeast. Of 16 sampling stations within or adjacent to the Jarvis Island EEZ, 8 recovered nodules with one station reporting geochemistry of greater than 18% nickel plus copper (CPC 1996; 1999) but the Jarvis Island EEZ is thought to be prospective for nodules based on cruises by British and Japanese researchers (Hein et al. 2005).



**Figure 10. PMN and CRC permissive areas in the Jarvis Island EEZ**

#### **2.1.3.1.2.4.4 Johnston Atoll**

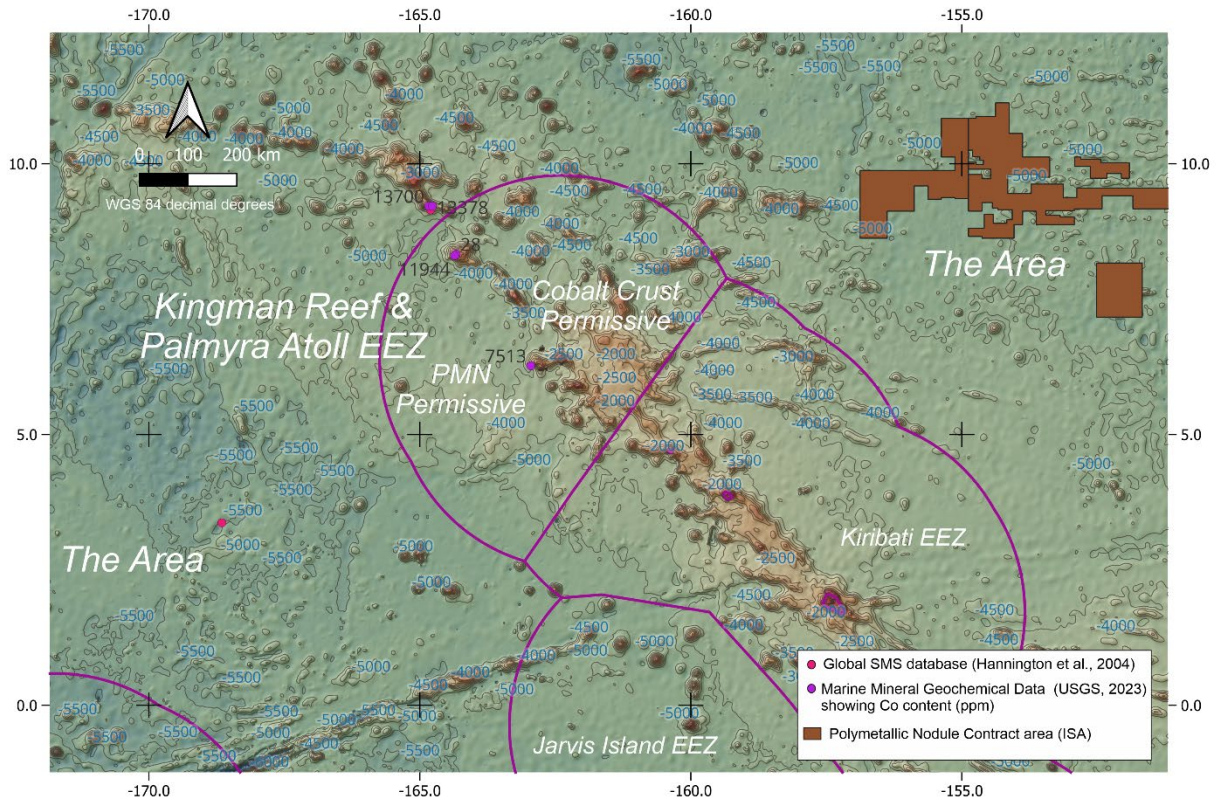
The Johnston Atoll EEZ is approximately 449,300 km<sup>2</sup> (Figure 11). A ramp in PMN abundance contours from 1%, 10%, 25%, to 50% begins about 30 km south of Johnston Island reaching 50% (the highest in this map series) at the southern EEZ boundary. Another contour ramp rises from 1% to 10% abundance to the east. A 1% contour encompasses much of the areas to the north and west of Johnston Island EEZ. Two bottom camera stations show 25% to 50% abundance to the south and east. A series of bottom camera stations show greater than 50% PMN abundance just outside the southern EEZ boundary (CPC 1999). Hein et al. (2005) characterizes the area as promising for nodules but not much work has been done. Geological Long-Range Inclined Asdic (GLORIA) side scan images suggest that there may be areas on the abyssal plains in between the seamounts where nodules may be extensive. Mineral grades are not known (Hein et al. 2005).



**Figure 11. PMN and CRC permissive areas in the Johnston Atoll EEZ**

#### **2.1.3.1.2.4.5 Kingman Reef and Palmyra Atoll**

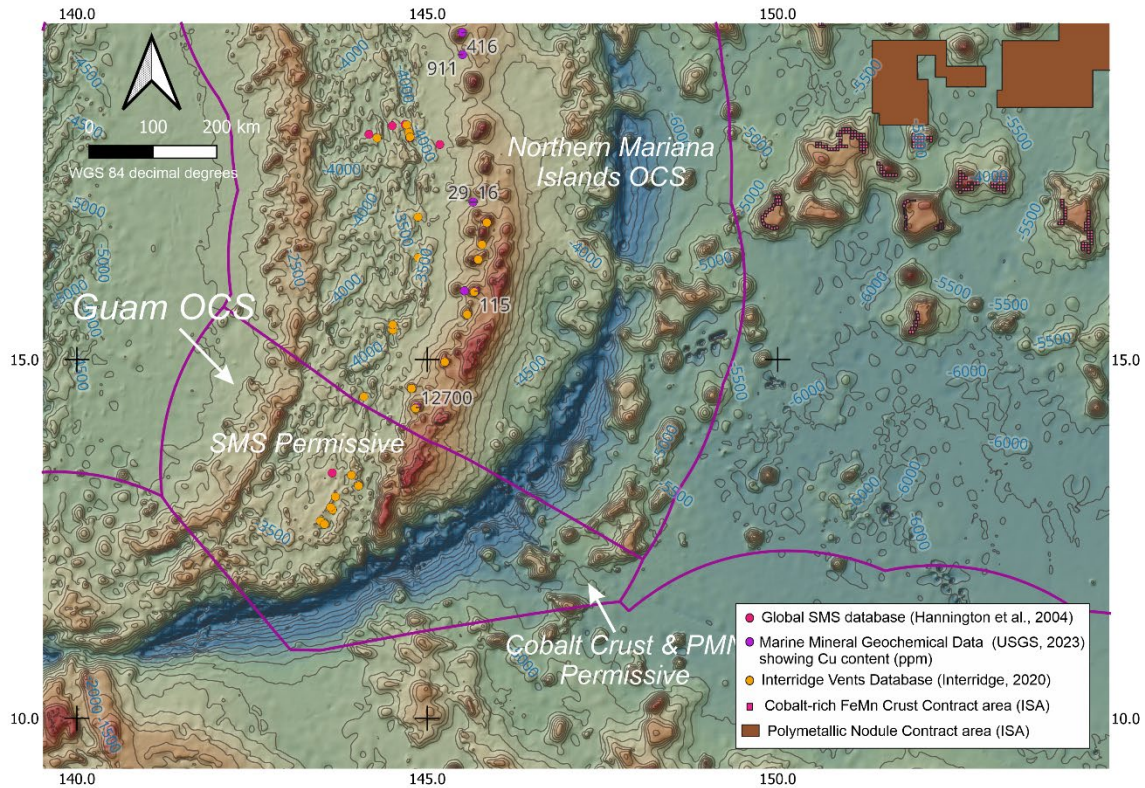
The Kingman Reef and Palmyra Atoll EEZ are approximately 411,600 km<sup>2</sup> (Figure 12). Polymetallic nodules occur on the plain west of Kingman Reef and Palmyra Atoll (Hein et al. 2005) even though core locations on the compilation map in this area did not identify nodules (CPC 1999). The setting should be favorable for nodules. A vast span of ISA contract areas for PMNs, where nodules are abundant begins 700 km to the east. The sedimentation rate is low. Grades and abundances are not known. GLORIA side scan sonar data suggest that nodules may be extensive on the abyssal plains within the Kingman Reef and Palmyra Atoll EEZ (Hein et al. 2005).



**Figure 12. PMN and CRC permissive areas in the Kingman Reef and Palmyra Atoll EEZ**

### 2.1.3.1.2.4.6 Guam

The Guam OCS is 218,000 km<sup>2</sup> (Figure 13). Hein reports that some bottom photographs on the abyssal plains east and west of Guam indicate nodules but the abundance appears to be low (Hein et al. 2005). The CPC mineral maps draw a 1% PMN contour in the western part of the Guam OCS in the western Mariana Basin based on five cores and/or bottom photograph stations from the area. Some areas of the Guam OCS are not conducive for PMNs. One of the twenty core locations on the back-arc spreading center recovered nodules. Another 1% contour is east-southeast of Guam based in part, on two bottom camera surveys showing 1% to 10% nodule cover (CPC 1999).



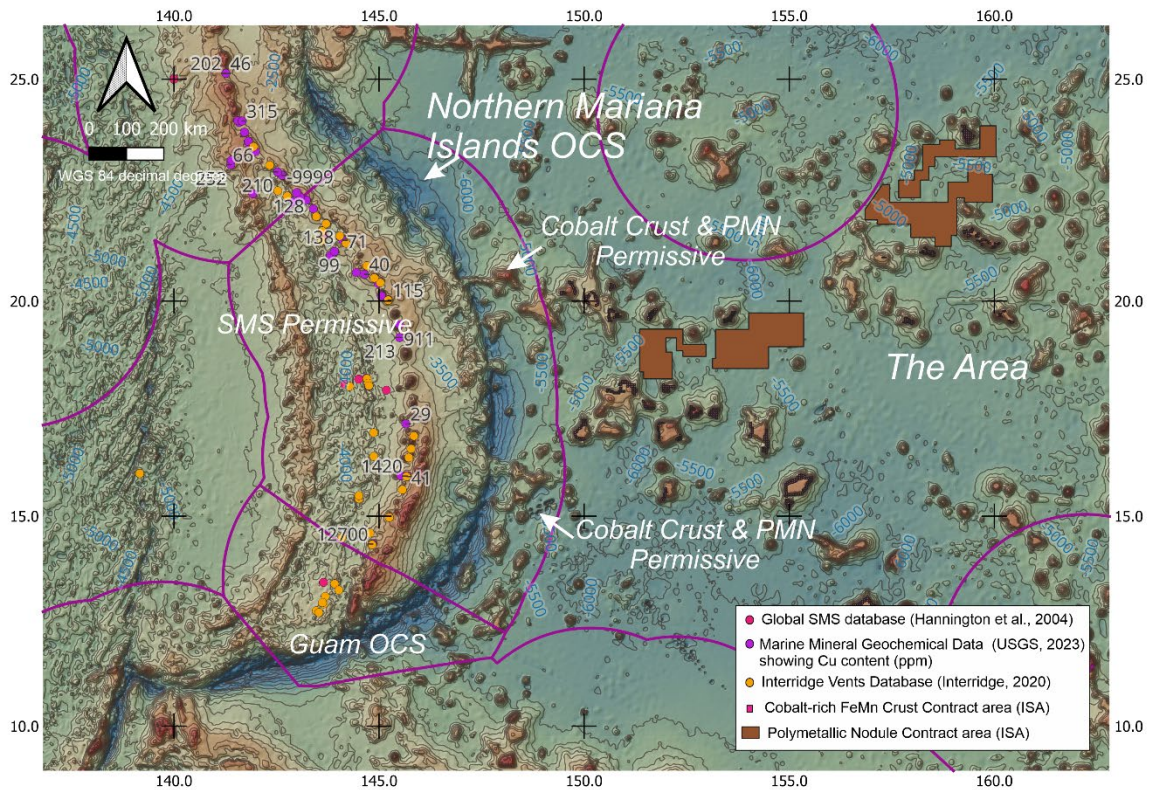
**Figure 13. SMS, PMN, and CRC permissive areas in the Guam OCS**

#### 2.1.3.1.2.4.7 Midway Atoll

The Midway Atoll EEZ is approximately 348,000 km<sup>2</sup>. Polymetallic nodules are present in the Midway Atoll EEZ but little work on abundance or grade has been done (Hein et al. 2005). Nodules were recovered at 8 of 20 sampling locations within the Midway Atoll EEZ. Three bottom photo locations showed high abundance in the southwest portion of the EEZ, and one showed no nodules in the central EEZ. The perimeter of the Midway Atoll EEZ intersects with the 1% abundance contour. The 10% abundance contour is just beyond the EEZ boundary to the north-northeast (CPC 1999).

#### 2.1.3.1.2.4.8 Northern Mariana Islands

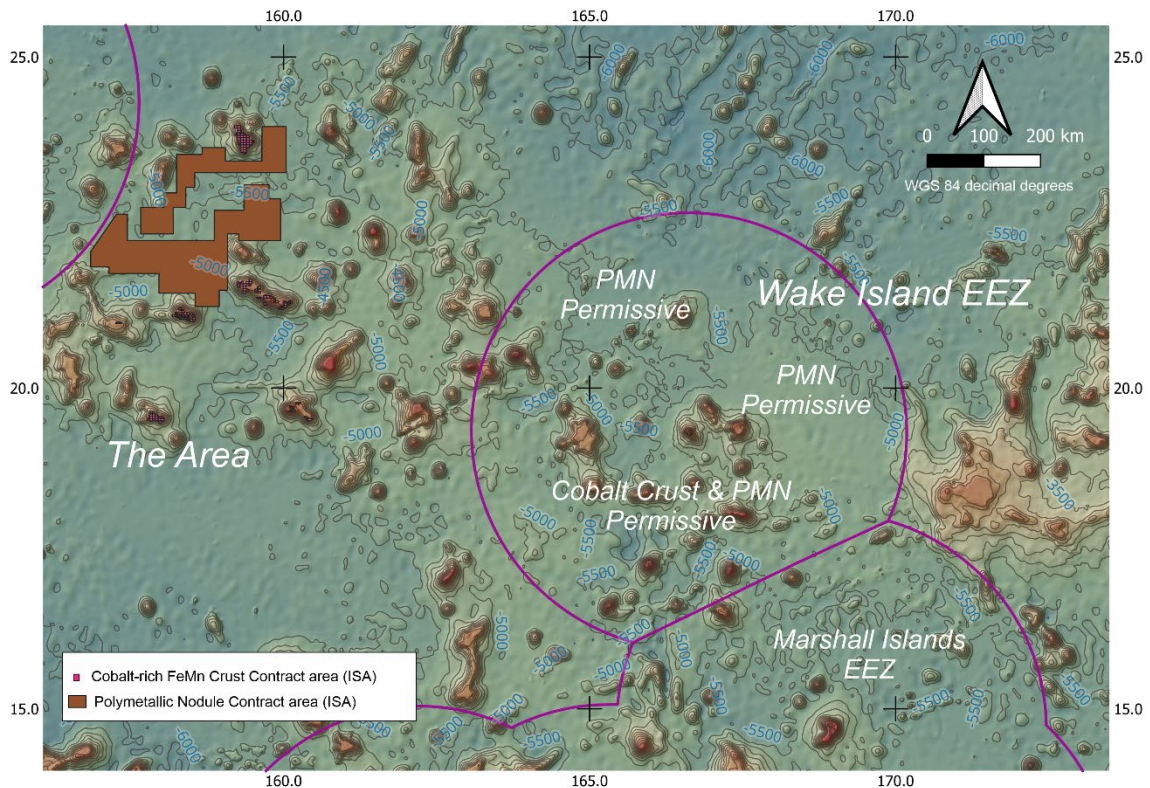
The Northern Mariana Islands OCS is approximately 758,121 km<sup>2</sup> (Figure 14). Polymetallic nodules are, in general, not favored over most of the Northern Mariana Islands OCS because of the high sedimentation rates in the fore-arc and back-arc settings associated with volcanic activity. The most favorable areas for nodules will be on the old ocean crust east of the Mariana trench. Polymetallic nodules have been photographed and recovered, however. A 1% PMN contour extends northeast, east, and south of Saipan. Of seven bottom photographs, six showed nodules ranging from less than 10% to greater than 50% abundance. The back-arc basin is relatively well sampled with over 60 sediment cores. Of these, seven recovered nodules. Of nine bottom photograph sites in the back-arc, four showed nodules ranging in abundance from less than 10% to 25% to 50%. The high abundances intersect the 1% contour for nodule abundances on the western perimeter of the Northern Mariana Islands OCS (CPC 1999).



**Figure 14. SMS, PMN, and CRC permissive areas in the Northern Mariana Island OCS**

#### **2.1.3.1.2.4.9 Wake Island**

The Wake Island EEZ is approximately 406,300 km<sup>2</sup> (Figure 15). Polymetallic nodules are likely to be extensive in the Wake Island EEZ, but the grade and distribution is poorly known (Hein et al. 2005). Most of the Wake Island EEZ falls within the 10% and 25% PMN abundance contours (CPC 1999). Two bottom photograph stations showed greater than 25% nodule abundance. In October 2019, Beijing Pioneer Hi-Tech Development Company (China) received large PMN contract areas from the International Seabed Authority 450 km to the NW of the Midway Island EEZ.



**Figure 15. PMN and CRC permissive areas in the Wake Island EEZ**

### 2.1.3.1.3 Mineral Content and Ore Grade

The table below (Table 4) shows the typical mineral content based on samples taken within five key PMN deposit resources. Manganese is by far the largest in terms of percentage of the total nodule in each case (17 to 34 by weight), followed by iron (6 to 16) and silicon (5 to 8). There is a moderate degree of similarity between the nodules found in different locations: Western Pacific and Cook Islands nodules are significantly lower in manganese and higher in iron than those in the other areas, they also have lower nickel and copper content but greater cobalt and REE content. The elements of interest for economic extraction can be grouped as follows:

- Nickel, copper, cobalt, and manganese: these are generally the focus of companies and governmental agencies investigating nodule extraction. The grades of nickel and copper are comparable with terrestrial deposits such as the polymetallic sulfide ores found in Canada and Russia, and the grade of cobalt is higher than the majority of terrestrial Cu-cobalt and nickel-cobalt co-product mines in operation. The large proportion of manganese present means that it would be a key by-product from nodule processing and a potentially important contributor to the economics of nodule extraction and processing.
- Other base or alloy metals such as zinc, titanium, vanadium, molybdenum, and lead.
- Rare earth and other transition metals such as strontium, yttrium, zirconium, lanthanum, cerium, and neodymium.
- Other elements that are less likely to provide significant economic value such as iron, magnesium, aluminum, sulfur, calcium, potassium, sodium, phosphorus, and barium.

**Table 2.**  
**Estimated Mineral Content of Polymetallic Nodules in Key Locations (est. wt. %)**

Estimated content of all resources	CCZ	Peru Basin	Western Pacific	Cook Islands	Indian Ocean
Nickel	1.28	1.30	0.49	0.38	1.10
Cobalt	0.19	0.05	0.47	0.38	0.12
Copper	1.08	0.60	0.25	0.23	1.04
Manganese	28.40	34.20	20.80	16.90	24.50
Total Rare Earths	0.08	0.04	0.22	0.17	0.11
Titanium	0.27	0.16	1.60	1.28	0.45
Molybdenum	0.06	0.05	0.04	0.03	0.06
Vanadium	0.06	0.04	0.06	0.05	0.05
Iron	5.99	6.12	15.70	16.20	7.24
Strontium	0.07	0.07	0.11	0.09	0.09
Potassium	0.98	0.81	0.61	0.90	1.00
Zinc	0.15	0.18	0.06	0.05	0.12
Phosphorus	0.16	0.15	0.33	0.34	0.15
Barium	0.39	0.32	0.15	0.12	0.17
Lead	0.04	0.01	0.11	0.10	0.11
Sulfur	0.16	0.00	0.00	0.18	0.00
Tungsten	0.01	0.01	0.01	0.00	0.00
Silicon	6.10	4.82	7.51	7.03	8.10
Aluminum	2.32	1.50	2.64	3.42	2.26
Sodium	2.16	2.65	1.45	1.76	1.42
Magnesium	1.94	1.71	1.33	1.42	1.51
Calcium	1.68	1.82	1.84	1.99	1.71
Chlorine	0.68	0.50	0.00	0.42	0.00
Other Minerals	0.09	0.10	0.13	0.13	0.18
Loss on ignition	15.70	16.20	24.90	27.70	24.90
Water	20.40	9.42	9.42	12.70	16.78
Unknown	9.57	17.17	9.77	6.04	6.83

Source: CRU Group, adapted from (Sharma 2022)

Figure 16 provides an estimate of the share of the gross value of the economically valuable minerals in PMNs for the different locations. This is based on 2022 average prices using a variety of price indices and benchmarks. Generally, the pricing is based on the final metal price for each element; in reality variable levels of cost would be involved in processing each element into pure metallic form.

Note that minerals such as silicon, aluminum, and magnesium (which are present in the nodule in the form of their oxides) have been excluded from the value contribution. While all of these minerals are extracted commercially from terrestrial deposits, the grade of commercial terrestrial deposits is much higher than the nodules, and the extraction of the raw materials is generally low-cost large scale open pit mines. Typically, quartz mined for silicon metal production contains more than 99 silicon dioxide, bauxite for aluminum is 15 to 25 aluminum content, ore from which magnesium can be extracted contains 24 to 30 manganese, and less than 1 alumina, silica, and iron oxide; on this basis, PMNs would not be a suitable raw material for production of the corresponding metals. The processing of PMNs is likely to include a smelting step in which these minerals would be removed in the slag. Therefore, in the value



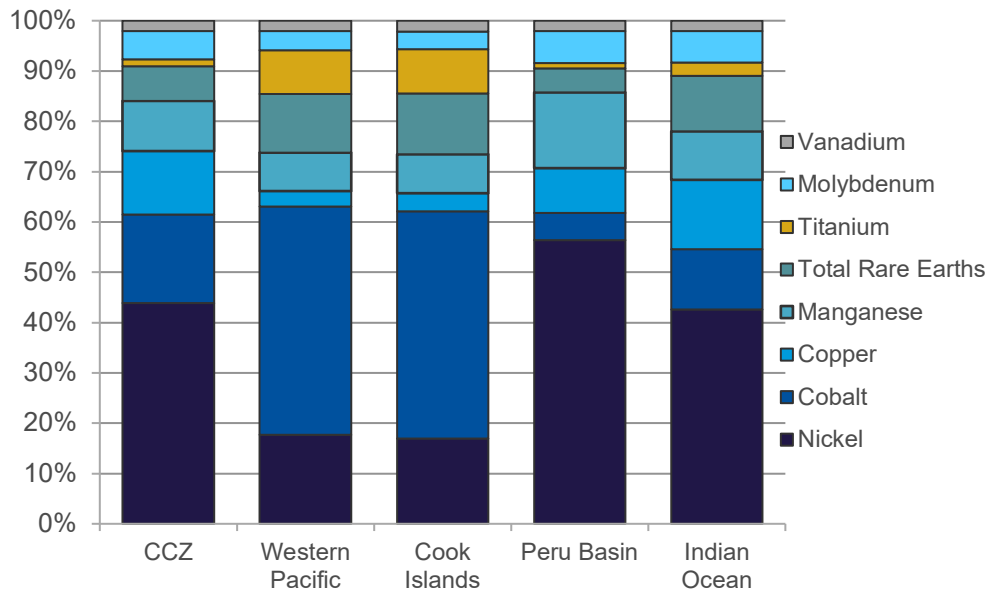
estimate below, these minerals are treated as impurities that are unlikely to be extracted from PMNs, though it is possible that some value could be extracted as a by-product.

Across the various PMN resources there is variation between the value share of each of the economically valuable minerals, based on 2022 price levels. Nickel is the main contributor to value for CCZ, Peru Basin and Indian Ocean nodules, whereas cobalt is the most valuable component of Western Pacific and Cook Islands nodules. In all cases, the combined value of nickel and cobalt is approximately 60 of the total. Manganese, copper, and REE account for a further 20 to 30. Titanium accounts for 10% of the value share for Western Pacific and Cook Islands nodules; in reality this may not be economically recoverable. The terrestrial ilmenite that can be used as the raw material for titanium production typically contains 25 to 40% titanium, far higher than the level present in nodules.

### 2.1.3.1.4 Comparison to Terrestrial Deposits

#### 2.1.3.1.4.1 Mineral Content and Grade

Table 5 compares the typical recoverable metal content of PMNs against other terrestrial sources of the same metals, focusing on those that contribute the most to nodule value: nickel, cobalt, copper and manganese. Polymetallic nodules are unlike other terrestrial deposits in terms of their metal content; no terrestrial deposits contain these elements in similar proportions. The closest comparisons are polymetallic nickel-cobalt-copper sulfide ores, such as those found in Canada and Russia, which contain comparable levels of nickel, copper and cobalt. However, these do not contain manganese; nickel laterite ores such as those found in Indonesia contain comparable nickel and cobalt levels to nodules, but negligible copper content and a low level of manganese.



DATA: CRU, (Sharma 2022).

**Figure 16. Polymetallic Nodules Estimated Gross Value Share by Resource Location**

Seabed deposits are polymetallic with several minerals contributing significantly to the value of the deposit.

**Table 3.**  
**Typical Recoverable Metal Content in Polymetallic Nodules and Terrestrial Deposits**

Material	Ni	Co	Cu	Mn	Polymetallic
Polymetallic nodules (CCZ, typical)	1.0-1.5%	0.1-0.2%	1.10%	28-31%	Yes
Nickel-Copper-Cobalt sulfide ore	0.5-3.0%	~0.05%	2.20%	0	Yes
Nickel laterite ore (saprolite layer)	1.4-1.8%	0	0	0	No
Nickel laterite ore (limonite layer)	1.0-1.1%	0.05-0.20%	0	~0.8%	Yes
Copper sulfide ores	0	0	0.5-1.5%	0	Yes
African Copperbelt copper-cobalt ores	0	0.0-1.5%	1.0-4.0%	0	Yes
Copper oxide ore	0	0	0.4-0.5%	0	No
Manganese ore (oxide)	0	0	0	40-44%	No
Manganese ore (carbonate)	0	0	0	36-39%	No

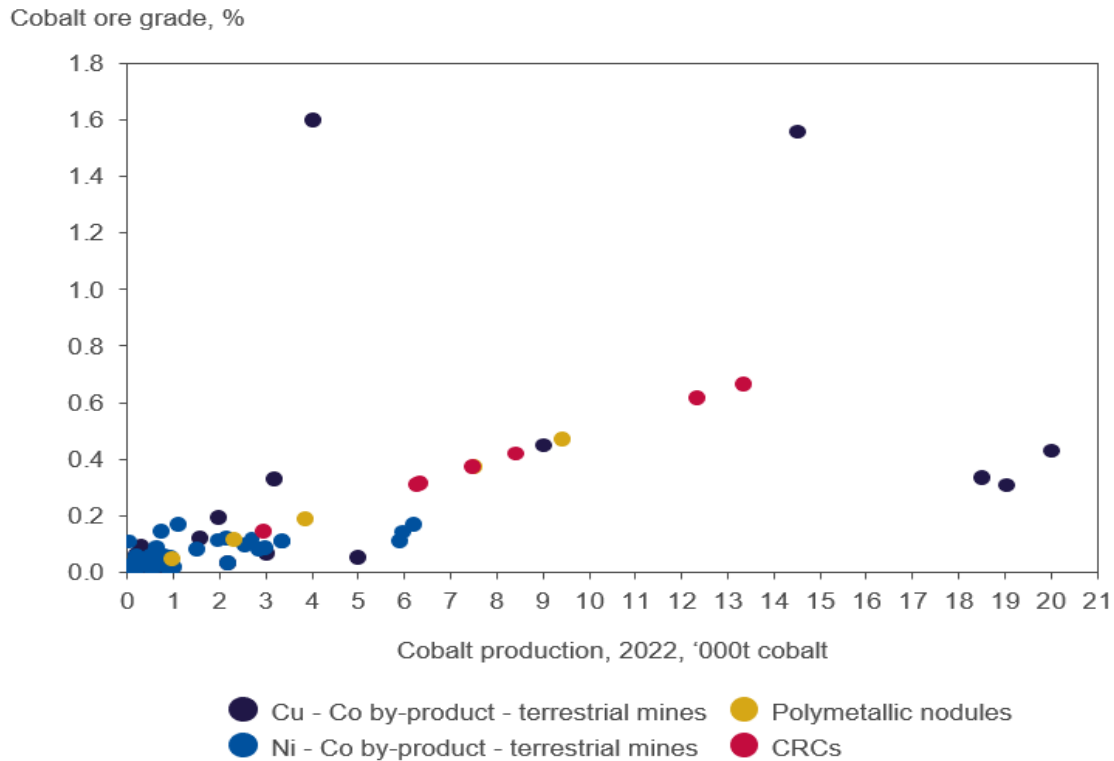
Source: CRU

Terrestrial base metal deposits are also often polymetallic: commercially extracted terrestrial copper deposits may include lead, zinc, precious metals, platinum group metals (PGMs) and cobalt. Within nickel deposits, typical by-products include PGMs, precious metals, copper, and cobalt. Manganese is extracted from dedicated mines, with no by-products.

The following sections provide comparisons of nodule potential mineral grades and scale against terrestrial deposits for valuable minerals. Ore grades are defined as the concentration of an element of interest in a potentially minable deposit. Ore grades may be expressed as a percentage, parts per million, or parts per billion.

#### **2.1.3.1.4.2 Cobalt**

Commercially extracted terrestrial nickel-cobalt operations have cobalt ore grades lower than 0.3% cobalt. Copper-cobalt operations having higher ore grades, reaching as high as 1.6% cobalt at a limited number of mines. Comparatively, PMNs from the Cook Islands and the Western Pacific would sit near the highest cobalt content when compared to terrestrial mines and provides significant economic upside. The CCZ, Indian Ocean and Peru Basin nodule deposits have cobalt content reported in the range of 0.1-0.25% cobalt, comparable with the content of most terrestrial cobalt-extracting operations.

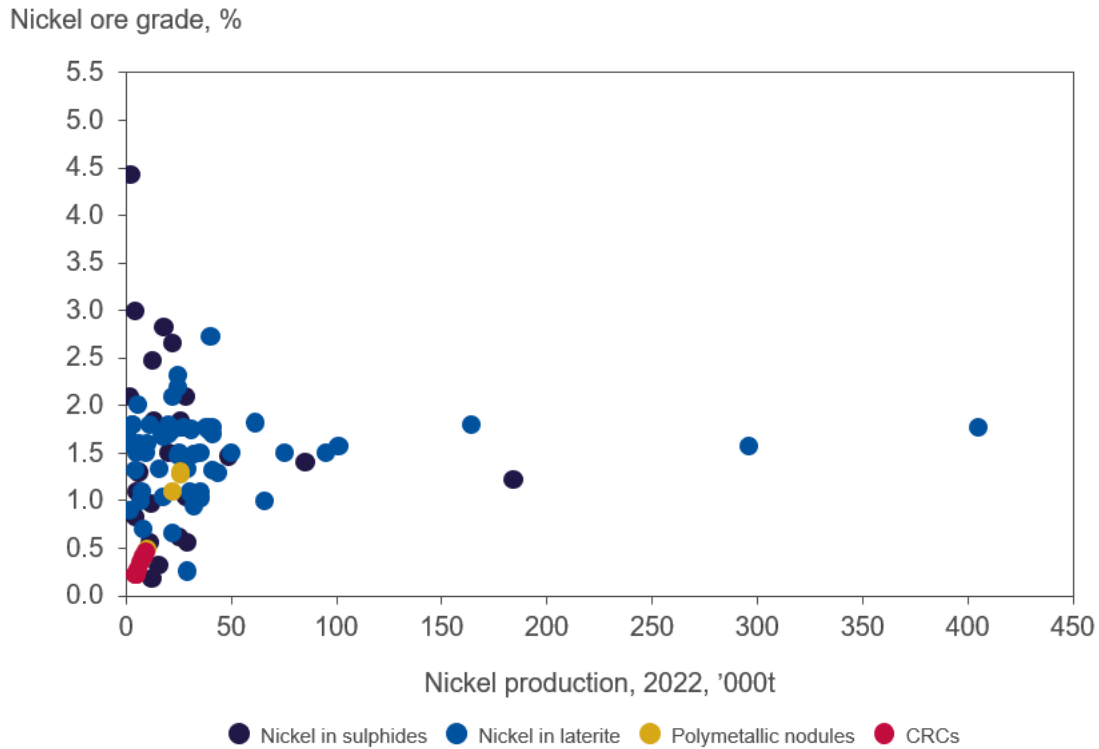


DATA: CRU, (Sharma 2022). Each dot represents the run of mine grades of individual operating Cu-Co or Ni-Co mines for the offshore deposits, we have assumed a production capacity of 2.0 Mt/y gross weight of nodule extraction [derived from (Sharma 2018)] to allow for the different deposits to be compared with similar terrestrial mines in terms of both scale and grade. In practice, deep sea mineral extraction could be significantly larger or smaller than this level.

**Figure 17. Comparison of Cobalt Grade in Terrestrial and Undersea Deposit Types**

### 2.1.3.1.4.3 Nickel

Nickel ore grades at terrestrial mines can vary widely depending on deposit geology. Commercially extracted laterite deposits typically have nickel content of between 0.9 to 2.0% nickel; sulfide operations can vary more widely, in some cases reaching as high as 4.5% nickel. Polymetallic nodules have comparable nickel content to many commercially operating nickel mines, with a range of ore grades of 0.4% nickel and 1.3% nickel.

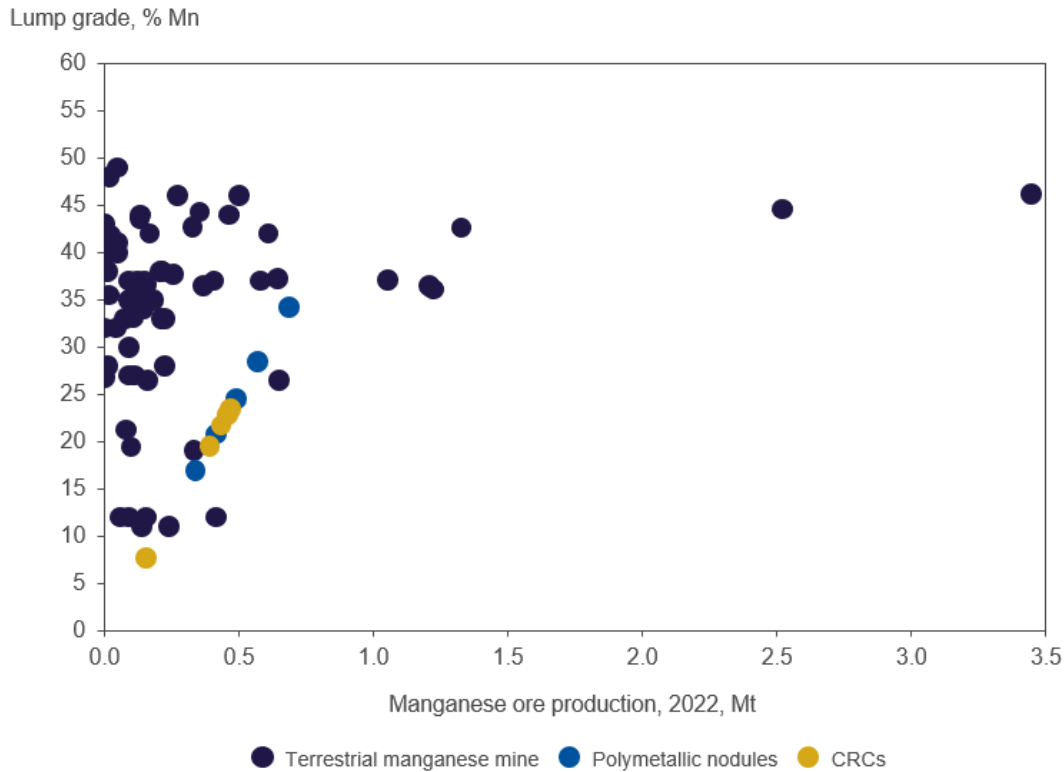


DATA: CRU, (Sharma 2022).

**Figure 18. Comparison of Nickel Ore Grades Compared to Undersea Deposit Types**

#### 2.1.3.1.4.4 Manganese

Although it forms one of the largest components within PMNs and CRCs, the manganese content of these offshore deposits is lower than the observed manganese lump grade for terrestrial operations. Most terrestrial mines have lump grades between 35% to 50% manganese, while the estimated manganese content of PMNs sits between 17% to 35% manganese depending on deposit location. Terrestrial manganese deposits of lower manganese content between 10% to 20% are typically carbonate ores, whose suitability for leaching rather than smelting leads to their more common use in specialty manganese product production instead of ferroalloys. The chart shows that at a 2 Mt/yr operating rate, the extraction of PMNs would be larger than nearly all terrestrially operating manganese mines.

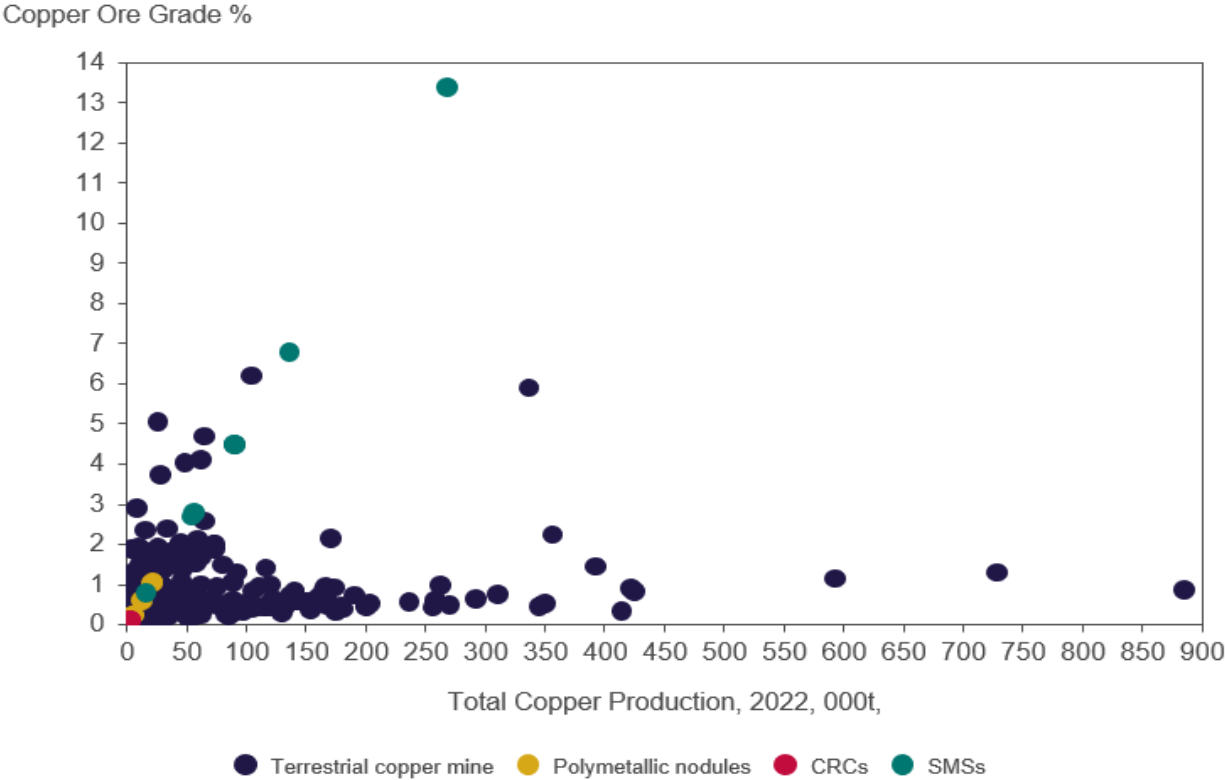


DATA: CRU, (Sharma 2022).

**Figure 19. Comparison of Terrestrial Manganese Mining Operations Underwater Extraction**

#### 2.1.3.1.4.5 Copper

Copper content shows larger variance between different offshore deposit types. It forms 0% to 1% of PMNs, but some seafloor massive sulfides have reported copper content of 13%. Terrestrial deposits also show a significant degree of variance in copper grade; most deposits have copper run of mine grades between 0.5% to 2.0% copper, with a small number of operations having grades from 3% up to 6%.



DATA: CRU, (Sharma 2022).

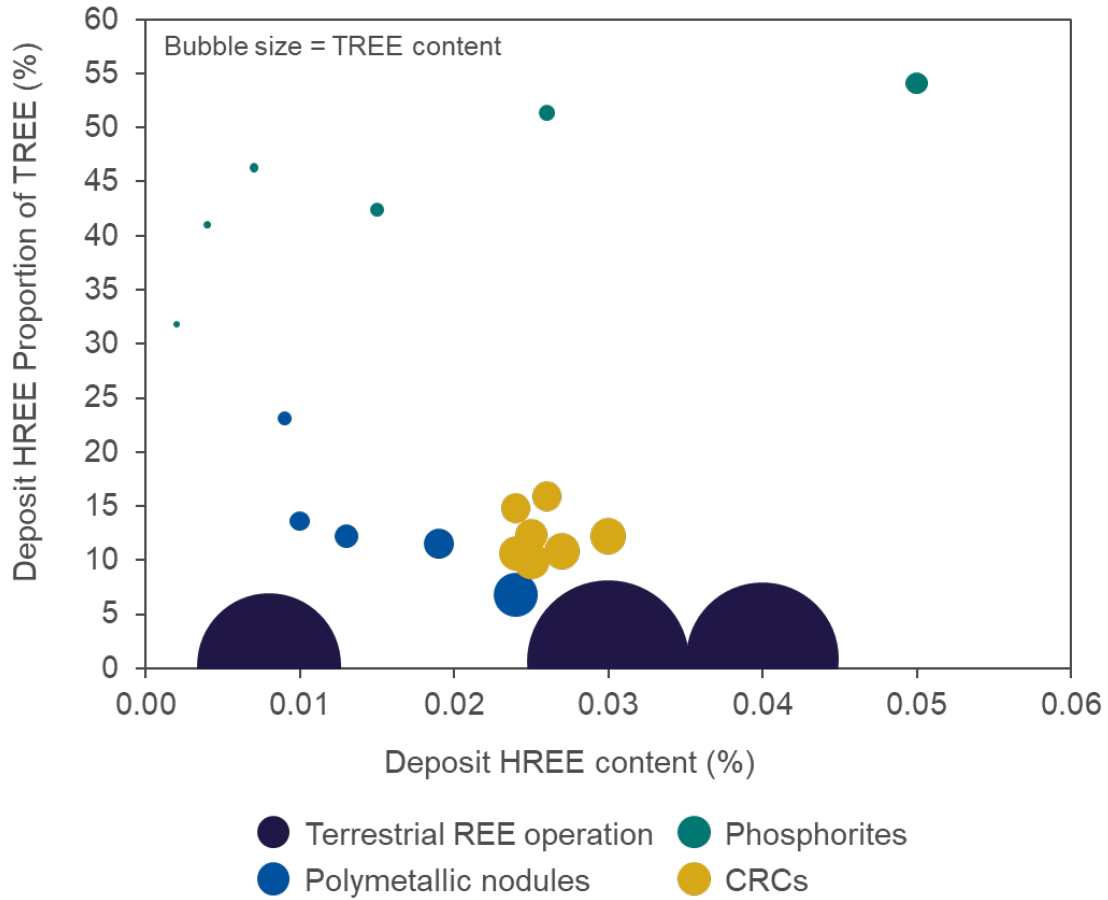
**Figure 20. Comparison of Terrestrial Copper Mining Operations and Underwater Extraction**

**2.1.3.1.4.6 Rare Earth Elements**

Terrestrial REE deposits vary both in their overall rare earth content, but also the composition of the individual elements. Within the U.S., the only Rare Earth operation is Mountain Pass in California, which has a total REEs contained of 4%. Sample operations in Australia and China have REE content of 4% to 5%, respectively. In the commercially extracted deposits shown in the table below, 97% to 99% of the REE content is light rare earth elements (LREE).

While overall REE content in offshore deposits is lower than terrestrial operations—PMNs total REE content ranges from 0.11% to 0.35%—the proportion of that content consisting of more valuable and critical heavy REEs (HREE) is significantly higher. Phosphorites have HREE proportions of total REE content of 30% to 55%; CRCs and nodules are on average 12% and 13%, respectively. In contrast, terrestrial deposits contain an average HREE content of 0.57%, a fraction of their undersea counterparts. Some phosphorites (leached seamount type) are reported to contain a greater HREE content than terrestrial deposits, despite far lower overall REE content.

The chart below shows the HREE content of different onshore and offshore deposit types against the HREE percent of total REE content, as well as demonstrating the overall REE content.



**Figure 21. Comparison of grade and size of terrestrial vs. undersea REE deposits**

Table 4 compares the content of the 15 REEs within several existing REE operations and the known PMNs and CRCs and phosphorites:

**Table 4. Comparison of REE Deposit Content of Terrestrial REE Operations Versus Polymetallic Nodules (REE % contained)**

Element	Mt. Pass (USA) Existing operations	Mt. Weld (Australia) Existing operations	Typical China Existing operations	CCZ Polymetallic nodules	Indian Ocean Polymetallic nodules	Western Pacific Polymetallic nodules	Cook Islands Polymetallic nodules	Peru Basin Polymetallic nodules
Lanthanum	1.3480	1.0800	1.2170	0.0110	0.0130	0.0620	0.0173	0.0070
Cerium	1.9070	2.0540	2.4480	0.0280	0.0540	0.0620	0.0991	0.0110
Praseodymium	0.1710	0.2270	0.2870	0.0030	0.0030	0.0230	0.0041	0.0010
Neodymium	0.4930	0.8250	0.9150	0.0130	0.0140	0.1500	0.0160	0.0060
Samarium	0.0420	0.1120	0.0470	0.0030	0.0030	0.0050	0.0035	0.0010
Europium	0.0070	0.0240	0.0100	0.0010	0.0010	0.0200	0.0009	0.0000
Gadolinium	0.0110	0.0500	0.0360	0.0030	0.0030	0.0040	0.0036	0.0020
Terbium	0.0010	0.0040	0.0040	0.0000	0.0010	0.0010	0.0006	0.0000
Dysprosium	0.0040	0.0110	0.0030	0.0030	0.0030	0.0050	0.0035	0.0020
Holmium	0	0.0020	0	0.0000	0.0000	0.0040	0.0007	0.0000
Erbium	0	0.0030	0.0260	0.0010	0.0010	0.0160	0.0019	0.0010
Thulium	0	0.0010	0	0.0000	0.0000	0.0010	0.0003	0.0000
Ytterbium	0	0.0020	0	0.0010	0.0010	0.0020	0.0020	0.0010
Lutetium	0.0002	0	0	0.0002	0.0002	0.0004	0.0003	0.0000
Yttrium	0.0080	0.0320	0.0040	0.0080	0.0110	0.0010	0.0141	0.0070
Total	3.992	4.427	4.997	0.075	0.108	0.356	0.168	0.039

Element (REE content by type)	Mt. Pass (USA) Existing operations (REE content by type)	Mt. Weld (Australia) Existing operations (REE content by type)	Typical China Existing operations (REE content by type)	CCZ Polymetallic nodules (REE content by type)	Indian Ocean Polymetallic nodules (REE content by type)	Western Pacific Polymetallic nodules (REE content by type)	Cook Islands Polymetallic nodules (REE content by type)	Peru Basin Polymetallic nodules (REE content by type)
LREE	3.961	4.298	4.914	0.058	0.087	0.302	0.140	0.026
MREE	0.0230	0.0890	0.0530	0.0070	0.0080	0.0300	0.0086	0.0040
HREE	0.008	0.040	0.030	0.010	0.013	0.024	0.019	0.009
Total	3.992	4.427	4.997	0.075	0.108	0.356	0.168	0.039



<b>Element (REE proportions by type)</b>	<b>Mt. Pass (USA) Existing operations (REE proportions by type)</b>	<b>Mt. Weld (Australia) Existing operations (REE proportions by type)</b>	<b>Typical China Existing operations (REE proportions by type)</b>	<b>CCZ Polymetallic nodules (REE proportions by type)</b>	<b>Indian Ocean Polymetallic nodules (REE proportions by type)</b>	<b>Western Pacific Polymetallic nodules (REE proportions by type)</b>	<b>Cook Islands Polymetallic nodules (REE proportions by type)</b>	<b>Peru Basin Polymetallic nodules (REE proportions by type)</b>
LREE	99.2	97.1	98.3	77.1	80.4	84.7	83.4	66.7
MREE	0.6	2.0	1.1	9.3	7.4	8.4	5.1	10.3
HREE	0.2	0.9	0.6	13.6	12.2	6.8	11.5	23.1
Total	100	100	100	100	100	100	100	100

**Table 5. CRC Rare Earth Element Deposit Content (REE % contained)**

Element (cobalt-rich ferromanganese crusts)	Atlantic Ocean (cobalt-rich ferromanganese crusts)	Indian Ocean (cobalt-rich ferromanganese crusts)	PCZ (cobalt-rich ferromanganese crusts)	North Pacific non-PCZ (cobalt-rich ferromanganese crusts)	South Pacific (cobalt-rich ferromanganese crusts)	CCM (cobalt-rich ferromanganese crusts)	Arctic Ocean (cobalt-rich ferromanganese crusts)
Lanthanum	0.0283	0.0260	0.0339	0.0320	0.0204	0.0270	0.0152
Cerium	0.1532	0.1033	0.1322	0.1360	0.0818	0.1260	0.0867
Praseodymium	0.0064	0.0053	0.0061	0.0061	0.0041	0.0060	0.0043
Neodymium	0.0252	0.0230	0.0258	0.0275	0.0184	0.0250	0.0172
Samarium	0.0055	0.0048	0.0052	0.0057	0.0038	0.0050	0.0044
Europium	0.0012	0.0011	0.0013	0.0014	0.0018	0.0010	0.0011
Gadolinium	0.0058	0.0052	0.0056	0.0066	0.0044	0.0060	0.0048
Terbium	0.0009	0.0008	0.0009	0.0010	0.0006	0.0010	0.0008
Dysprosium	0.0048	0.0047	0.0060	0.0056	0.0041	0.0050	0.0045
Holmium	0.0010	0.0009	0.0011	0.0011	0.0009	0.0010	0.0009
Erbium	0.0028	0.0025	0.0031	0.0031	0.0027	0.0030	0.0025
Thulium	0.0004	0.0004	0.0005	0.0004	0.0004	0.0000	0.0004
Ytterbium	0.0024	0.0023	0.0029	0.0028	0.0022	0.0030	0.0023
Lutetium	0.0004	0.0004	0.0004	0.0004	0.0003	0.0000	0.0004
Yttrium	0.0184	0.0180	0.0221	0.0190	0.0177	0.0170	0.0197
Total	0.257	0.199	0.247	0.249	0.163	0.226	0.165

Element (REE content by type)	Atlantic Ocean (REE content by type)	Indian Ocean (REE content by type)	PCZ (REE content by type)	North Pacific non-PCZ (REE content by type)	South Pacific (REE content by type)	CCM (REE content by type)	Arctic Ocean (REE content by type)
LREE	0.219	0.162	0.203	0.207	0.129	0.189	0.128
MREE	0.0127	0.0118	0.0138	0.0146	0.0109	0.0130	0.0112
HREE	0.025	0.025	0.030	0.027	0.024	0.024	0.026
Total	0.257	0.199	0.247	0.249	0.163	0.226	0.165

<b>Element (REE proportions by type)</b>	<b>Atlantic Ocean (REE proportions by type)</b>	<b>Indian Ocean (REE proportions by type)</b>	<b>PCZ (REE proportions by type)</b>	<b>North Pacific non-PCZ (REE proportions by type)</b>	<b>South Pacific (REE proportions by type)</b>	<b>CCM (REE proportions by type)</b>	<b>Arctic Ocean (REE proportions by type)</b>
LREE	85.2	81.7	82.2	83.4	78.6	83.6	77.4
MREE	4.9	5.9	5.6	5.9	6.6	5.8	6.8
HREE	9.9	12.3	12.2	10.8	14.8	10.6	15.9
Total	100	100	100	100	100	100	100

**Table 6. Phosphorites Rare Earth Element Deposit Content (REE % contained)**

Element (Phosphorites)	California Borderland (Phosphorites)	Blake Plateau (Phosphorites)	Peru Margin (Phosphorites)	Chatham Rise (Phosphorites)	Unleached Seamount (Phosphorites)	Leached Seamount (Phosphorites)
Lanthanum	0.0024	0.0071	0.0010	0.0023	0.0102	0.0180
Cerium	0.0019	0.0036	0.0018	0.0016	0.0015	0.0029
Praseodymium	0.0004	0.0011	0.0002	0.0003	0.0014	0.0023
Neodymium	0.0017	0.0048	0.0009	0.0012	0.0061	0.0102
Samarium	0.0003	0.0009	0.0002	0.0002	0.0012	0.0020
Europium	0.0001	0.0002	0.0000	0.0000	0.0003	0.0005
Gadolinium	0.0005	0.0013	0.0002	0.0003	0.0018	0.0032
Terbium	0.0001	0.0002	0.0000	0.0000	0.0002	0.0005
Dysprosium	0.0005	0.0012	0.0002	0.0003	0.0017	0.0031
Holmium	0.0001	0.0003	0.0000	0.0001	0.0004	0.0008
Erbium	0.0004	0.0008	0.0001	0.0002	0.0013	0.0025
Thulium	0.0000	0.0001	0.0000	0.0000	0.0002	0.0004
Ytterbium	0.0003	0.0007	0.0001	0.0002	0.0013	0.0022
Lutetium	0.0000	0.0001	0.0000	0.0000	0.0002	0.0004
Yttrium	0.0060	0.0130	0.0019	0.0038	0.0224	0.0441
Total	0.015	0.035	0.007	0.011	0.050	0.093

Element (REE content by type)	California Borderland (REE content by type)	Blake Plateau (REE content by type)	Peru Margin (REE content by type)	Chatham Rise (REE content by type)	Unleached Seamount (REE content by type)	Leached Seamount (REE content by type)
LREE	0.007	0.018	0.004	0.006	0.020	0.035
MREE	0.0012	0.0029	0.0004	0.0006	0.0040	0.0073
HREE	0.007	0.015	0.002	0.004	0.026	0.050
Total	0.015	0.035	0.007	0.011	0.050	0.093

<b>Element (REE proportions by type)</b>	<b>California Borderland (REE proportions by type)</b>	<b>Blake Plateau (REE proportions by type)</b>	<b>Peru Margin (REE proportions by type)</b>	<b>Chatham Rise (REE proportions by type)</b>	<b>Unleached Seamount (REE proportions by type)</b>	<b>Leached Seamount (REE proportions by type)</b>
LREE	45.6	49.4	62.1	53.3	40.6	38.0
MREE	8.2	8.2	6.1	5.7	8.0	7.8
HREE	46.3	42.4	31.8	41.0	51.4	54.1
Total	100	100	100	100	100	100

Source: CRU, (Sharma 2022), (Hein et al. 2016)

#### 2.1.3.1.4.7 Zinc

Lead, zinc, gold, and silver only contribute significantly to overall offshore deposit value within SMS. SMS deposits have zinc grades that are in most cases higher than most terrestrial zinc mines. Most zinc is mined at terrestrial deposits containing 2 to 8 zinc, whereas SMS deposits (excluding sediment-hosted mid-ocean ridges) have reported zinc grades between 7 to 20 zinc.

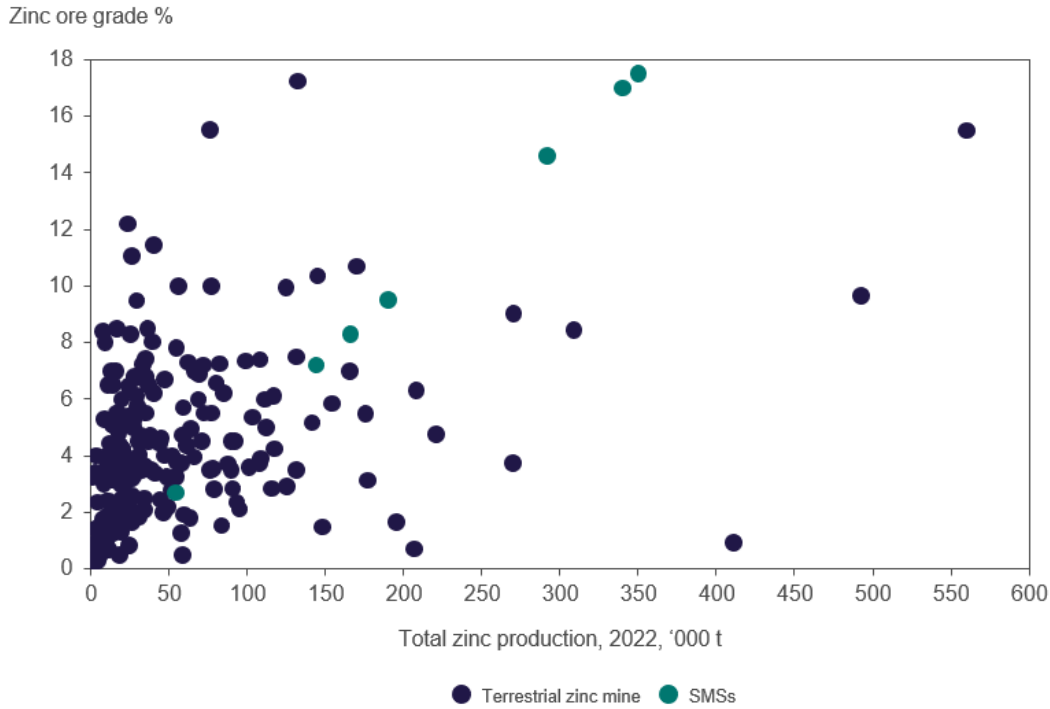
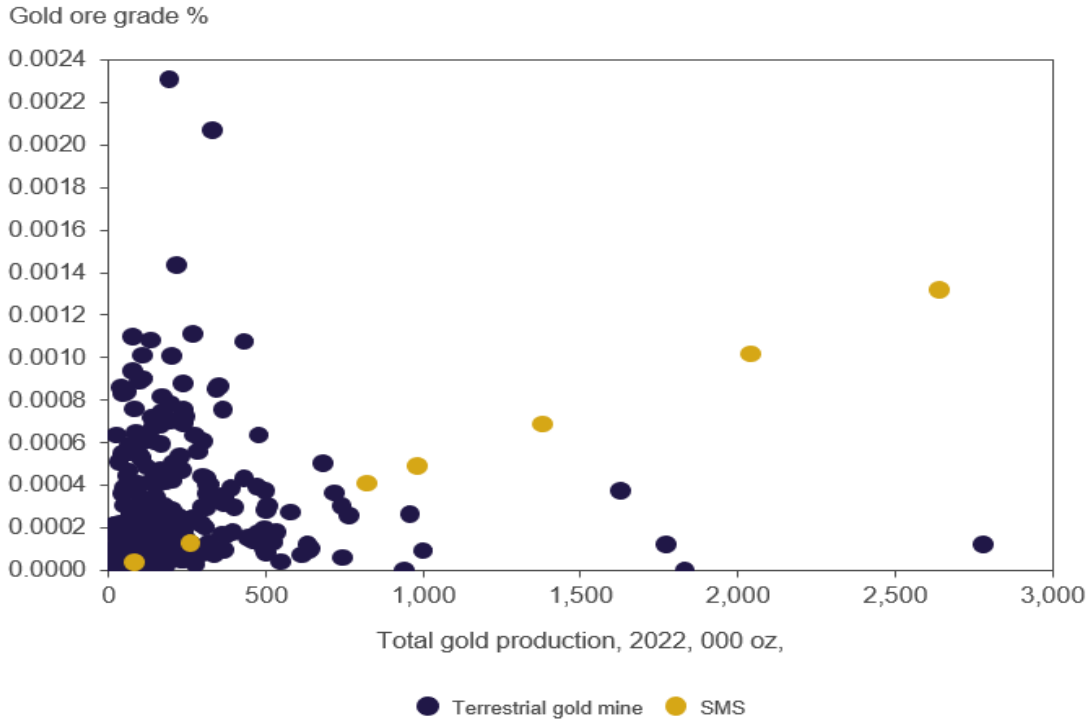


Figure 22. Terrestrial Deposit Zinc Ore Grades Compared to Seafloor Massive Sulfides

#### 2.1.3.1.4.8 Gold

While gold is not listed on the USGS critical minerals list, within the SMS deposits it represents a significant share of the total value—as high as 40% of deposit value in some cases using 2022 average prices. Gold content in SMS deposits is between 4 to 14 grams/ton in most deposit types, which is comparable with many gold-producing terrestrial deposits.

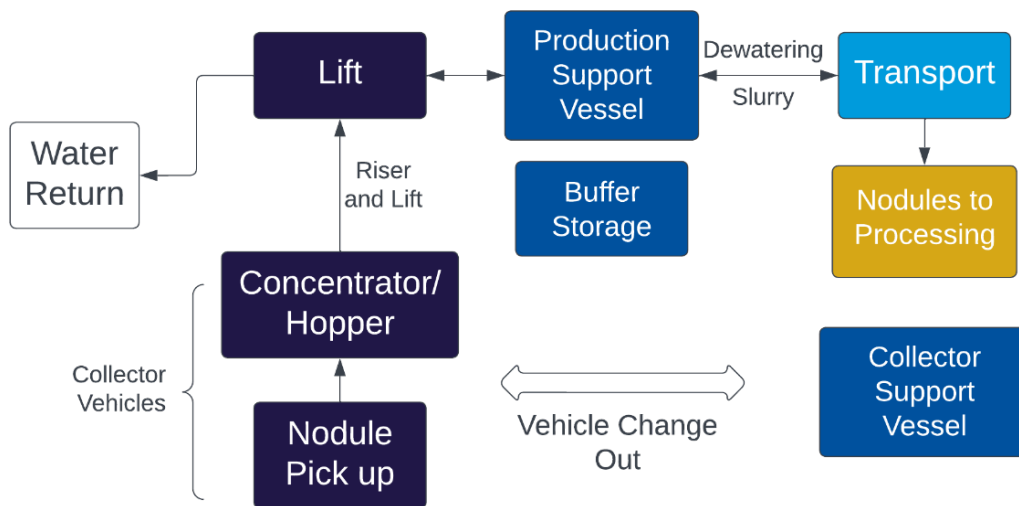


**Figure 23. Terrestrial Deposit Gold Ore Grades Compared to Seafloor Massive Sulfides**

### 2.1.3.1.5 Extraction and Exploitation Methodologies

#### 2.1.3.1.5.1 Extraction

The extraction of PMNs is profoundly different than that of terrestrial mineral deposits. Nodules are found on the seabed or partially buried to a few centimeters. Nodules are collected by collector vehicles using a precision hydraulic lift, which would remove sediment and water through hoses to a riser that in turn would lift the nodules to a vessel on the surface. Nodules would be transferred to transport ships for transferring to shore.



Source: The Metals Company

**Figure 24. Possible Polymetallic Nodule Extraction Flowsheet**

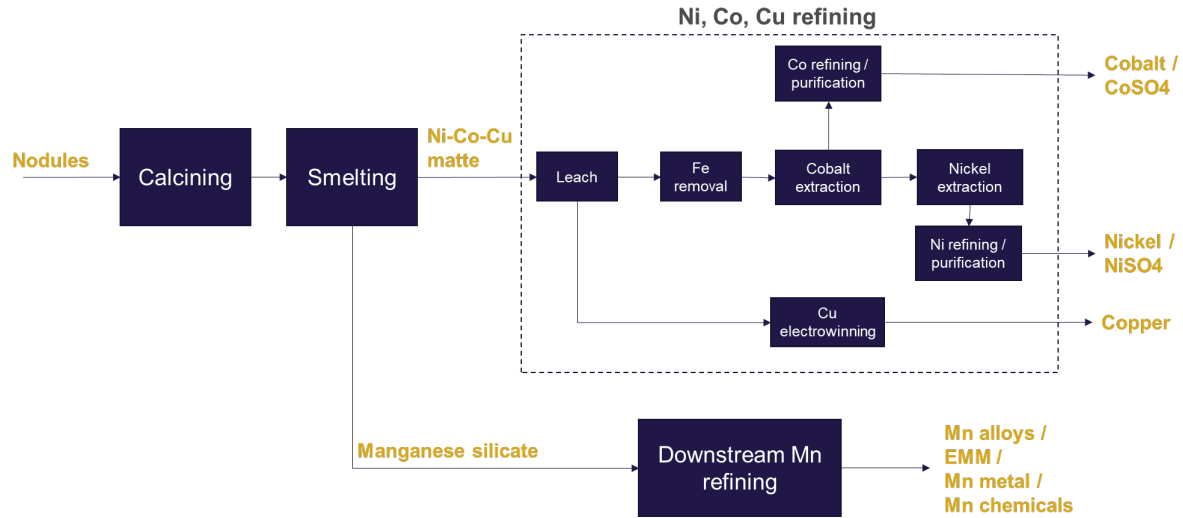
The nodule collection process involves no rock cutting, digging, drilling, and blasting. The majority of terrestrial ores—including copper and nickel sulfides, manganese ores, and nickel laterites—are extracted using either open pit or underground mining methods. Open pit mining, in contrast, involves the removal of overburden using heavy equipment such as bulldozers and excavators, followed by the drilling, blasting, and removal of the ore using haul trucks or conveyor belts.

### 2.1.3.1.5.2 Processing

Processing of nodules would most likely occur onshore, using existing technologies and similar methods to traditional processing routes for polymetallic raw materials. Different developers are considering different processing options, but the majority generally involve calcining and smelting to produce a nickel-copper-cobalt matte product and a manganese silicate by-product. The matte would be hydrometallurgically refined through various leaching and solvent extraction steps to remove impurities and separate the valuable metals into individual products. This refining may or may not be directly integrated with the smelting step. Recovery rates are predicted to be 95% for nickel, 77% for cobalt, 86% for copper and 99% for manganese (to the silicate; further manganese losses would occur in processing to a final product). Terrestrial polymetallic ores, including copper and nickel sulfides, are usually beneficiated using grinding and flotation methods to produce a concentrate before smelting occurs. For PMNs, calcining in a rotary kiln would replace this step.

The unique nature of the PMNs could mean that a specific onshore processing plant would need to be constructed, or possibly an existing facility could be repurposed. The availability of spare polymetallic smelting and refining capacity that could recover all metal streams is limited. The processing would generate a manganese silicate by-product. This would have similar specifications to terrestrial manganese ore and could therefore be processed into a variety of finished manganese products, but its value is unproven.





Source: CRU

**Figure 25. Possible Nodule Processing Flowsheet and Potential Routes to Market**

### 2.1.3.1.6 Synthesis – Polymetallic Nodules

PMN deposits are likely present in unexplored areas in the U.S. Pacific OCS and EEZ including the American Samoa OCS, Baker Reef and Howland Island EEZ, Jarvis Island EEZ, Johnston Atoll EEZ, Kingman Reef and Howland Island EEZ, Guam OCS, Northern Mariana Islands OCS, and Wake Island EEZ. Each of these areas contain conditions favorable for the presence of PMN, especially those that are geographically adjacent to the PMN abundance trends generally indicated by current PMN exploration contract areas in international waters that are supported by resource exploration campaigns. Kingman Reef and Palmyra Atoll EEZ, Northern Mariana Island OCS, and Wake Island EEZ are U.S. jurisdictions that are geographically near proximal to current PMN exploration contract area in international waters. A similar rationale can be made for Jarvis Island EEZ, which is geographically proximal to the explored nodule rich areas in the Cook Island EEZ.

Being geographically proximal to known high abundances of PMN does not mean that PMN will be similarly abundant in the geographically proximal areas. The Hawaiian Islands OCS, for instance, is geographically proximal to the rich nodule zones of the CCZ and is arguably the best explored area of the U.S. Pacific jurisdictions, PMN are present but not as abundant as in the geographically proximal CCZ. However, each of these areas in the U.S. Pacific warrants dedicated exploration efforts to assess the resource potential.

The known PMN areas in the Atlantic OCS off of the Blake Plateau also warrant renewed exploration efforts. These nodules have different origins as compared to Pacific Island OCS and EEZ nodules. The Atlantic OCS nodules are associated with continental margin phosphorite deposition. Blake Plateau PMN have a similar bulk CM by weight as CCZ PMN but are more enriched in cobalt and less enriched in nickel.

Less prospective for PMN are areas within the Alaska OCS, the OCS off Washington, Oregon, and California, Puerto Rico and U.S. Virgin Island OCS, and Gulf of Mexico OCS.

PMN companies and governmental agencies looking at marine minerals see PMN as being attractive for the production of nickel, cobalt, manganese, copper, and as sources for REY.

The grade of PMN deposits compare favorably to economic terrestrial deposits of nickel, cobalt, and copper. Other economic products from the processing sequence, such as manganese, are lower grade, but PMN production, if established and sustained, would overwhelm terrestrial production.

The mineral processing sequence proposed for PMN involves both pyrometallurgic and hydrometallurgic processes. In the pyrometallurgic process, nodules are heated to produce calcine that is then smelted to produce alloy and manganese silicate. Iron slag is separated from the alloy to produce a matte. The hydrometallurgic process separates the metals in the matte to nickel sulfate, cobalt sulfate, copper cathode, and ammonium sulfate (TMC 2023).

### **2.1.3.2 Cobalt-rich Ferromanganese Crusts**

#### **2.1.3.2.1 Location of Resources**

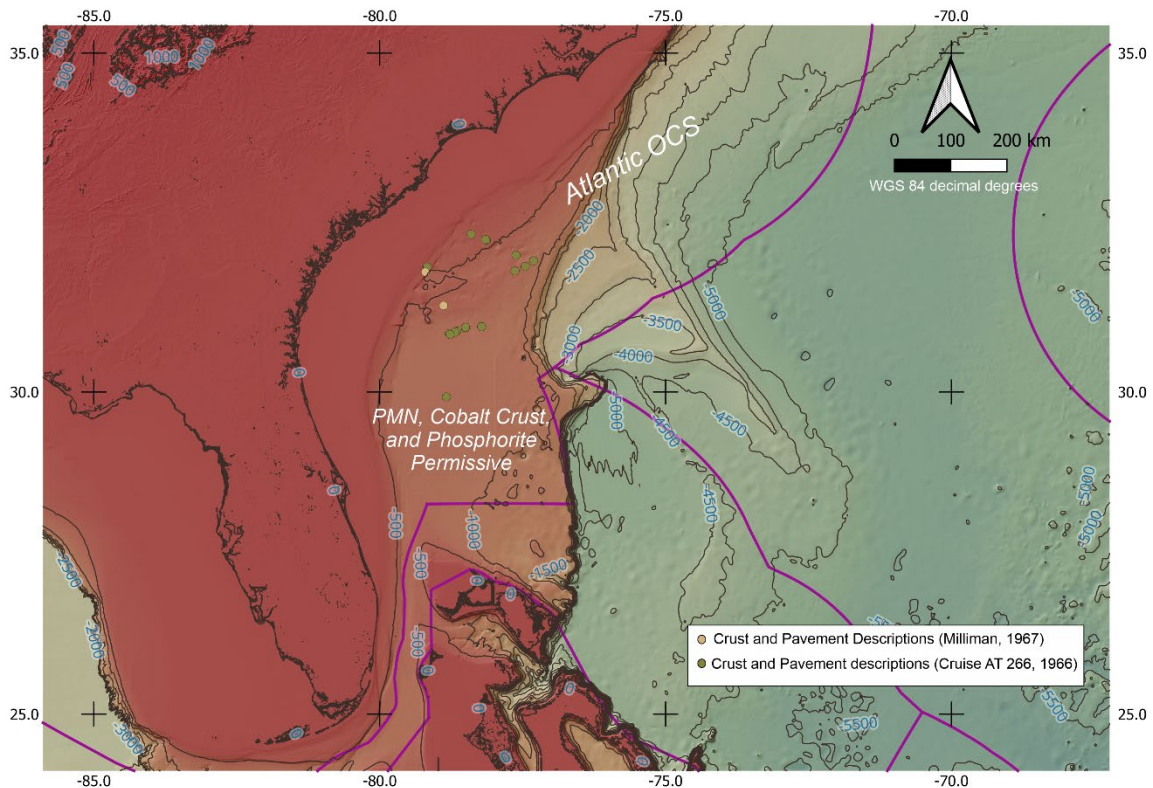
Figures 8 through 15, 26 and 27 show permissive areas for CRC formation. Permissive, for the purposes of this report, indicates that the bio-geological conditions are favorable for CRC presence or CRC have been sampled. The basis for assessing the permissive areas is discussed by OCS and EEZ.

##### **2.1.3.2.1.1 Atlantic OCS**

Ferromanganese crusts are closely associated with a large semi-contiguous area of phosphorite, phosphate manganese pavement, and PMNs in the northern portion of the Blake Plateau (Hollister 1973). A large ferromanganese pavement, 150 km by 80 km, 150 km southeast of Charleston, South Carolina is shown by Manheim et al. (1980) based on interpretation of geophysical, dredge, and coring data acquired by Woods Hole in the 1960s. A reinvestigation by the USGS in 1982 determined that the entire current-swept portion of the Blake Plateau is underlain by hard phosphorite pavement. Ferromanganese impregnation of phosphorite pavements constitutes the main form of ferromanganese crusts. Cobalt content in the crusts (0.32%) (Commeau et al. 1984) is less than the cobalt content in Pacific crusts.

The New England Seamounts, a chain that extends 1,400 km from the continental slope off Massachusetts to the Bermuda Rise, are known to have thick cobalt-rich ferromanganese crusts on their flanks and crests. Four of the seamounts are within the Atlantic OCS (Bear, Physalia, Mytilus, and Retriever). These are covered to varying degrees by glacial gravels and cobbles that may obscure underlying crust (Commeau et al. 1984). All four of these seamounts are within (and helped define) the Northeast Canyons and Seamounts Marine National Monument (NOAA 2016).

An area that could be favorable for cobalt-rich ferromanganese crusts in the Puerto Rico and U.S. Virgin Island OCS is on Puerto Rico Ridge where the nodules have been found, but no cobalt-rich ferromanganese crusts are indicated in this area on the CPC minerals map (CPC 1984). Currents and upwelling could favor cobalt-rich ferromanganese crusts on the flanks of the islands, but no crusts are reported.



**Figure 26. PMN, CRC, and Phosphorite Permissive Areas in the Atlantic OCS**

### 2.1.3.2.1.2 Gulf of Mexico OCS

The Gulf of Mexico OCS is generally not prospective for cobalt-rich ferromanganese crusts primarily because the sedimentation rate is too high and the sediments too mobile by buoyant salt deformation. Extensive seismic surveys for basin studies and for oil and gas exploration show tens of kilometers of sediment infill since the basin opened in the Jurassic. Average sedimentation rates in the central deep water Gulf of Mexico are 1,200 cm/ky (Flemings 2021). The Gulf of Mexico OCS is arguably the most studied offshore shelf and deep water seafloor because of survey and support activities performed for the oil and gas industry. Very-high resolution surveys for site characterization are performed in the vicinity of the oil and gas drilling or development activity. Extensive ferromanganese pavements or crusts have not been found to date in these local site investigations. Nor have comprehensive systematic seafloor surveying and sampling programs encountered PMN fields. Beginning in 2015, a three-year modern multibeam and geochemical survey was performed over the entire Mexican and U.S. sectors of the Gulf of Mexico. The purpose of the survey was to find hydrocarbon seeps and to take geochemical cores (Decker et al. 2022). Approximately 800,000 km<sup>2</sup> of seafloor was mapped and 1,500 cores were taken. No ferromanganese crusts were recovered (Orange and Gharib, 2023).

### 2.1.3.2.1.3 Navassa Island EEZ

Currents and upwelling could favor precipitation of ferromanganese crusts on the flanks of Navassa Island, but none are reported.

#### **2.1.3.2.1.4 Pacific OCS**

##### **2.1.3.2.1.4.1 U.S. Continental Pacific OCS**

Cobalt-rich ferromanganese crusts are generally not found in the subduction zone area from the Canadian border to Gorda Escarpment but are present in the southern part of the continental U.S. Pacific OCS. The main reasons why they are not favored to form in the northern part of the OCS is because of the high sedimentation rate within this portion of the OCS, and because the sedimentation rate increases where the seafloor is older as it moves toward the subduction zone. Bottom water oxygen levels are low (Dutkiewicz et al. 2020) as a function of terrigenous sediment input in the northern section of the OCS. No cobalt-rich iron-manganese crusts are indicated in this portion of the OCS on the CPC project minerals compilation (CPC 1984).

The USGS supported cobalt-rich ferromanganese crust sampling cruises in the late 1980s assembled data on the resource in the OCS off central and southern California. Co-rich iron-manganese crusts are widespread on seamounts and ridges (Conrad et al. 2017; Gibbs et al. 1993; Hein et al. 1987; Hein et al. 2010). Crust thickness ranged widely from a less than 0.1 mm patina to 84 mm. Crusts over 30 mm thick are found on Guide and Taney seamounts off San Francisco, on Davidson Seamount off central California, and San Juan, San Marcos, Hoss, Adam, and Little Joe Seamounts, and the Patton Escarpment off southern California. The geologic and oceanographic conditions are low sedimentation rates on old seafloor seaward of the San Andreas transform fault, upwelling and high primary productivity, and a well-developed oxygen minimum zone (Conrad et al. 2017; Dutkiewicz et al. 2020).

The cobalt- rich iron-manganese crusts off central and southern California are 50% more enriched in cobalt relative to CCZ PMNs but approximately half (47%) of the mean cobalt composition in the Prime Crust Zone in the central and western Pacific that includes U.S. Territorial OCS and EEZ. The cobalt-rich iron-manganese crusts off California have similar cobalt grades as crusts from the Atlantic and Indian Oceans (Conrad et al. 2017). For nickel, the cobalt- rich iron-manganese crusts off California is about half as enriched (53%) than nickel in crusts in the Prime Crust Zone but is comparable to nickel in crusts from the Atlantic and Indian Oceans (Conrad et al. 2017).

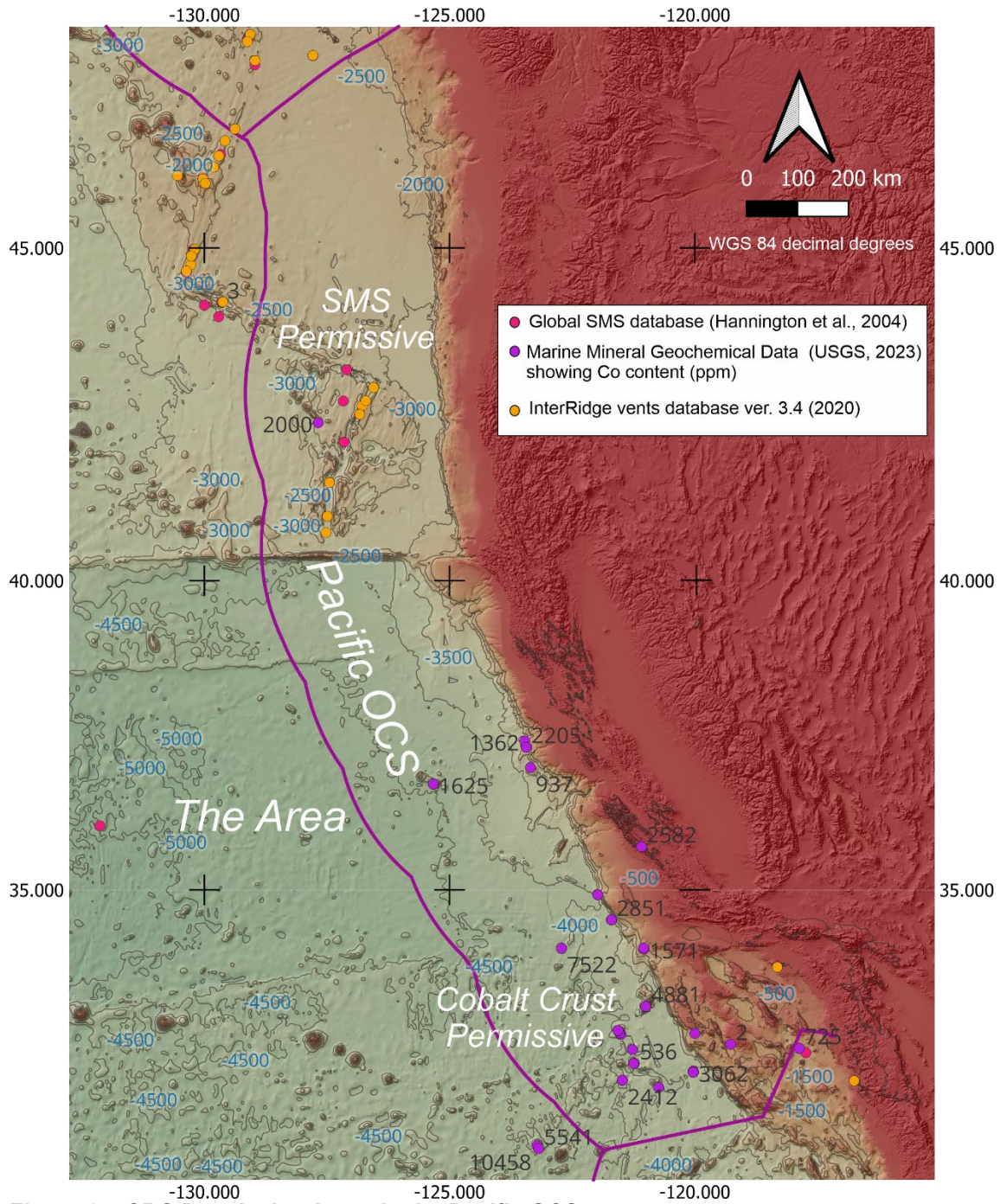


Figure 27. CRC Permissive Areas in the Pacific OCS

#### 2.1.3.2.1.4.2 Hawaii OCS

Evidence for extensive ferromanganese crusts within 200 nautical miles of the main Hawaiian Islands and the Hawaiian Islands archipelago was assembled and published from the 1950s through the 1970s. Interest in these ferromanganese crusts was heightened when it became understood that the crusts had four to five times the cobalt content typical of CCZ nodules (Glasby and Andrews 1977). A compilation of the findings is presented by Craig et al. (1982). Co-rich ferromanganese crusts are widespread as pavements on deep terraces resulting from growth and subsidence cycles along the archipelago. Cobalt enriched crusts thicken with age because they have had more time to grow and so are thinner in the main Hawaiian Islands and, in general, thicken towards Hermes Reef northwest on the archipelago. But thickness of the crust varies widely within this overall trend. The two main deep terraces are Lualualei (370-560 meters water depth) and Waho (900-1,200 meters water depth) where large areas are swept free of sediment. The Waho terraces and sediment free slopes and ridge crests are at the optimal depth for cobalt-crust growth where currents interact with topography and the oxygen minimum zone.

Thirteen priority prospects both within and outside of the Papahānaumokuākea Marine National Monument have been mapped, of which 10 have crusts greater than 3 centimeters thickness and 24 other confirmed crust locations (Morgan 2017). Some of these locations may be coincident with some of the USGS database sample sites (Adamczyk et al. 2023). Approximately 40 rings around the islands and seamount crests have optimum water depth for cobalt-rich ferromanganese crusts (Morgan 2017). Average chemical composition of crusts on-axis from Hawaii to Midway Island indicated 0.91% cobalt, 0.45% nickel, and 1.05% copper. Off-axis geochemical results were 0.60% cobalt, 0.37% nickel, and 0.10% copper (Hein et al. 1987). Cobalt content of the crusts sampled on the ridge (Necker Ridge) extending southwest from Necker Island ranges from 0.4 to 1.2% (Adamczyk et al. 2023).

#### 2.1.3.2.1.4.3 Alaska OCS

The compositions of iron-manganese crusts in and close to continental margins of Alaska are generally less enriched in metals of economic interest (e.g., cobalt, nickel) than open-ocean crusts and are typically considered less prospective, economically, as is attributed to faster growth rates and greater inputs of iron (Conrad et al. 2017; Hein et al. 2016). On average, bulk ferromanganese crusts from the Gulf of Alaska seamounts have higher concentrations of manganese and nickel than the average composition of crusts from the PCZ in the Northwest Pacific Ocean, while iron and zinc concentrations are similar, and cobalt and copper concentrations are lower (**Table 5a**) (Koski 1988).

**Table 7a. Chemical Composition of Ferromanganese Minerals from Alaska Regions of the U.S. Exclusive Economic Zone, compared to Fe-Mn Crusts from the Prime Crust Zone (PCZ) in the Northwest Pacific Ocean by Weight Percentage (Koski 1988)**

Element	Chukchi Borderland (wt.%)	Gulf of Alaska (wt. %)	PCZ (wt. %)
Iron	19.9	23.3	16.9
Manganese	7.7	12.7	22.8
Silica	11.1	0	4.1
Aluminum	6.3	0	1.0
Calcium	1.2	0	4.0
Magnesium	1.7	0	1.1
Sodium	1.6	0	1.6
Potassium	1.1	0	0.5
Titanium	0.4	0	1.2
Phosphorous	0.5	0	1.0

**Table 7b. Chemical Composition of Ferromanganese Minerals from Alaska Regions of the U.S. Exclusive Economic Zone, Compared to Fe-Mn Crusts from the Prime Crust Zone (PCZ) in the Northwest Pacific Ocean by Parts per Billion (Koski 1988)**

Element	Chukchi Borderland (ppb)	Gulf of Alaska (ppb)	PCZ (ppb)
Silver	<0.3	0	0.1
Arsenic	559.0	0	393.0
Barium	451.0	0	1,934.0
Beryllium	5.8	0	6.1
Bismuth	3.9	0	43.0
Cadmium	3.5	0	3.6
Chlorine	>12,694.0	0	9.100
Cobalt	1,452.0	4,300.0	6,662.0
Chromium	43.0	0	28.0
Cesium	3.0	0	3.7
Copper	643.0	520.0	976.0
Gallium	13.0	0	18.0
Germanium	0.7	0	0
Hafnium	10.0	0	9.4
Mercury	<54.0	0	9.3

**Table 7c. Chemical composition of ferromanganese minerals from Alaska regions of the U.S. Exclusive Economic Zone, compared to Fe-Mn crusts from the Prime Crust Zone (PCZ) in the Northwest Pacific Ocean by Parts per Million (Koski 1988)**

Element	Chukchi Borderland (ppm)	Gulf of Alaska (ppm)	PCZ (ppm)
Indium	0.3	0	0.6
Lithium	89.0	0	2.9
Molybdenum	209.0	0	461.0
Niobium	39.0	0	52.0
Nickel	2,289.0	4,000.0	4,209.0
Lead	233.0	0	1,641.0
Rubidium	47.0	0	17.0
Sulfur	2,693.0	0	2,600.0
Antimony	48.0	0	39.0
Scandium	47.0	0	6.6
Selenium	<0.6	0	15.0
Tin	8.4	0	10.0
Strontium	476.0	0	1,510.0
Tantalum	0.8	0	2.4
Tellurium	16.0	0	60.0
Thorium	62.0	29.2	11.0
Thallium	83.0	0	155.0
Uranium	11.0	15.9	12.0
Vanadium	936.0	0	641.0
Tungsten	49.0	0	89.0
Zinc	341.0	660.0	668.0
Zirconium	428.0	0	548.0
Lanthanum	150.0	259.0	339.0
Cerium	849.0	1,801.0	1,322.0
Praseodymium	42.2	0	61.0
Neodymium	170.0	263.0	258.0
Samarium	42.6	59.3	52.0
Europium	10.8	13.1	12.5
Gadolinium	47.0	61.0	56.0
Terbium	7.8	9.1	8.8
Dysprosium	44.6	54.0	60.0
Yttrium	192.0	0	221.0
Holmium	9.0	0	10.9
Erbium	24.2	0	30.9
Thulium	3.7	4.7	4.6
Ytterbium	22.7	28.3	29.0
Lutetium	3.6	4.4	4.3



The mineral map compiled by the CPC does not show any cobalt-rich ferromanganese crusts in the Alaska OCS. One ferromanganese crust sample is outside of the Alaska OCS on Guide Ridge in the vicinity of Parker Seamount in the seamount province of the Gulf of Alaska (CPC 1984). The USGS geochemical database includes five bulk crust samples from two sites in the seamount province with cobalt content of 0.35% in one sample (Adamczyk et al. 2023). The samples are characterized as lower in cobalt than crusts found at lower latitudes (Gartman et al. 2022; Koski 1988). Since the mineral resource research on the Gulf of Alaska seamounts in 1979, modern surveys have focused on biological instead of mineral studies (Gartman et al. 2022). Dredge samples from four research cruises in the Chukchi Borderland area of the Canada Basin did yield ferromanganese crusts and a few nodules (Hein et al. 2017). Ten sampling sites recovered ferromanganese crusts. The crusts ranged in thickness from 0.6 centimeters to 8.6 centimeters. The crusts were enriched in scandium (Hein et al. 2017).

### **2.1.3.2.1.5 U.S. Pacific Islands OCS and EEZ**

#### **2.1.3.2.1.5.1 American Samoa**

The American Samoa OCS is largely unexplored for Cobalt-rich ferromanganese crusts (Hein et al. 2005). Sampling from a seamount on the boundary between Samoa and American Samoa indicates cobalt content less than 0.5%. There are 34 seamounts in the American Samoa OCS (Kim and Wessel 2011; Kim and Wessel 2023). These seamounts should be prospective for hydrothermal manganese and cobalt-rich ferromanganese crust. The USGS geochemical database catalogs four bulk crust and two hydrothermal manganese samples. Three bulk crust samples are enriched in cobalt 0.4%, 0.36%, and 0.24%, respectively (USGS 2023a).

#### **2.1.3.2.1.5.2 Baker Reef and Howland Island**

There are 33 seamounts in the Baker Reef-Howland Island EEZ (Kim and Wessel 2011; Kim and Wessel 2023). Cobalt-enriched crusts have been sampled within the Baker Reef-Howland Island EEZ. German researchers dredged samples from Titov seamount southeast of Baker Reef. High cobalt content (mean 0.97% and max 1.3%) were associated with these samples (Hein et al. 2005). Three bulk samples from Howland Island show cobalt content ranging from 0.3% to 0.41%, nickel content ranging from 0.29% to 0.43%. Five bulk crust samples from the eight seamounts south of Baker Reef including Winslow Reef on the southeast boundary line report cobalt content between 0.4% and 0.5%, nickel content 0.25% and 0.37%, and copper content between 0.12% and 0.19% respectively (USGS 2023b).

#### **2.1.3.2.1.5.3 Jarvis Island**

The Jarvis Island EEZ contains 22 seamounts (Kim and Wessel 2011; Kim and Wessel 2023) and a ridge that is in the northern part of the EEZ that are favorable settings for cobalt-rich ferromanganese crusts, but very little resource work has been done. Cobalt-rich ferromanganese crusts have not been systematically explored in the Jarvis Island EEZ. Samples collected in the 1960s from 5080 meters had a relatively high nickel (0.77%) and copper (0.54%) giving a nickel + copper of 1.31% (Hein et al. 2005).

#### **2.1.3.2.1.5.4 Johnston Atoll**

There are over 75 seamounts in the Johnston Atoll EEZ (Kim and Wessel 2011; Kim and Wessel 2023). Cobalt-rich ferromanganese crusts have been relatively well-studied on Johnston Atoll (Hein et al. 2005). 130 bulk crust samples from the Johnston Atoll EEZ in the USGS geochemical database are enriched in cobalt with most samples elevated above 0.5%, many samples ranging from 0.7% to 0.9% cobalt, and several with 1.3% cobalt. Nickel grades range from 0.4% to 1.4%. (USGS 2023b).

Morgan maps 11 priority prospects and 7 other confirmed crust locations. Some of these locations may be coincident with some of the USGS database sample sites (Adamczyk et al. 2023), Morgan also highlights approximately 30 additional locations that have optimum water depth for cobalt-rich ferromanganese crusts (Morgan 2017).

#### **2.1.3.2.1.5.5 Kingman Reef and Palmyra Atoll**

Cobalt-rich crusts from SP Lee Guyot and several unnamed seamounts have been sampled by USGS and German researchers. Thirty-four samples have been analyzed including some just outside the EEZ boundary and these have high cobalt concentrations with an average of 1.2% and a maximum of 2.5% (Hein et al. 2005). There are over 50 seamounts in the Kingman Reef and Palmyra Atoll EEZ (Kim and Wessel 2011; Kim and Wessel 2023). The crusts that have been sampled so far are thin because of relatively high bio-productivity. There may be areas with thicker crusts in the EEZ. Three sampling locations are shown on the CPC maps with cobalt content exceeding 1.5% for two locations and 1% to 1.5% for one location. The USGS geochemical database shows three samples—two bulk crust and one phosphorite deposit. The phosphorite sample is enriched in cobalt. The Kingman Reef and Palmyra Atoll is prospective for high grades and tonnage (Hein et al. 2005).

#### **2.1.3.2.1.5.6 Guam**

Cobalt-rich ferromanganese crusts are likely to be present in the Guam OCS (Hein et al. 2005). There are 11 seamounts east of the Marianna Trench (Kim and Wessel 2011; Kim and Wessel 2023) that are on old seafloor where conditions should support thick cobalt-rich ferromanganese crusts. Many ISA contracts in the prime crust zone are 700 km to the NE of the Guam OCS. Data from similarly situated seamounts suggest that crust in this area are likely to be thick and have high concentrations of cobalt, nickel, and platinum. Possible intermediate resource for cobalt, titanium, cerium, nickel, and REY. Nineteen additional seamounts are on the fore-arc volcanic arc, and back arc. These younger seamounts are less likely to have accumulated crusts but may host SMS (See Section 3.1.3.2.6.6).

#### **2.1.3.2.1.5.7 Midway Atoll**

Cobalt-enriched ferromanganese crusts have been studied in the Hawaiian Islands and Midway Atoll. The Midway Atoll EEZ contains approximately 30 seamounts (Kim and Wessel 2011; Kim and Wessel 2023). In general, the studies show high content in cobalt and titanium, moderate content in nickel, and low platinum but only a few samples have been collected from the Midway Atoll EEZ (Hein et al. 2005). Four of six bulk crust samples show greater than 1.5% cobalt content in the northwest part of the Midway Atoll EEZ (CPC 1999).

#### **2.1.3.2.1.5.8 Northern Mariana Islands**

A similar setting to Guam, thick, cobalt-rich ferromanganese crusts should be present on seamounts that are on old seafloor east of the Mariana Trench, but the distribution and grade are poorly known (Hein et al. 2005). There are approximately 40 seamounts in the Northern Mariana Islands OCS that are east of the Mariana Trench. The USGS geochemical database show 20 locations that are along the volcanic arc. As expected for samples in this geological setting, cobalt is low except for one bulk sample location with 0.8% cobalt content in the northern part of the volcanic arc within the OCS. There are no samples in the USGS geochemical database for the seamounts east of the Mariana Trench that would be in the prime crust zone (USGS 2023a). ISA contract areas for cobalt-rich ferromanganese crusts are as close as 43 km to seamounts in the Northern Mariana Islands OCS.

#### **2.1.3.2.1.5.9 Wake Island**

There are 36 seamounts within or on the boundary of the Wake Island EEZ (Kim and Wessel 2011; Kim and Wessel 2023). The Wake Island EEZ is within the prime crust area. No studies of Wake Island cobalt-rich ferromanganese crusts had been done as of 2005 and no samples from the Wake Island EEZ are in the USGS geochemical database (USGS 2023a). ISA contracted areas for cobalt-rich ferromanganese crusts, however, are as close as 300 km from the Wake Island EEZ. “All data indicate that thick crusts rich in cobalt, nickel, and platinum should occur on seamounts within the Wake EEZ”

(Hein et al. 2005). Cobalt content normalized to a hygroscopic moisture and substrate-free basis. [%Co= Co (51.23)/ (Fe+Mn)] (Manheim and Lane-Bostwick 1989).

#### 2.1.3.2.2 Mineral Content and Ore Grade

Iron-manganese crusts contain three CM in abundance, manganese, cobalt, and platinum. In addition, nickel, lead, thallium, and cerium are significantly enriched in crust deposits. In comparison, abyssal nodules are enriched in copper, nickel, and cobalt in that order, but cobalt is 3 to 6 times more abundant in crusts than in abyssal nodules or in ores mined on land. Mineralogy of cobalt-rich iron-manganese crusts (Hein et al. 1987) are shown below:

- **Dominant:** vernadite ( $\delta$ -Mn O<sub>2</sub>), goethite (FeOOH · x H<sub>2</sub>O)
- **Rarely Dominant:** todorokite, carbonate fluorapatite
- **Commonly Present:** quartz, plagioclase, carbonate fluorapatite, calcite, goethite, amorphous aluminosilicate
- **Less Commonly Present:** barite, clinoptilolite, smectite, phillipsite, natrojarosite, pyroxene, chlorite, manjiroite, k-feldspar
- **Presence Uncertain:** manganosite, manganese-calcite, maghemite, hematite

Iron and manganese occur in subequal amounts in iron-manganese crusts, with manganese generally higher in open-ocean environments in the Pacific and iron generally somewhat higher in Atlantic and Indian Ocean crusts and in continental margin crusts around the Pacific. Traditionally, cobalt and secondarily nickel have been the metals of greatest economic interest in iron-manganese crusts, and mean concentrations for large areas of the global ocean range from 0.30% to 0.67% and 0.23% to 0.46%, respectively. Smaller areas that would compose a 20-year mine site (Hein et al. 2013) could average about 0.8% cobalt and 0.5% nickel. Another metal of great interest to the photovoltaic solar cell industry is tellurium, which globally averages about 50 parts per million (ppm) in crusts, with a maximum value of 205 ppm (Hein et al. 2013).

Studies have described interelement correlations in crusts. Cobalt is commonly enriched in the outer layers of crusts, whereas platinum is enriched in the inner layers. Cobalt, platinum, lead, nickel, cerium, arsenic, molybdenum, cadmium, and zinc concentrations are positively correlated with manganese content, whereas copper and beryllium are positively correlated with iron (Aplin 1984; Aplin and Cronan 1985; Glasby and Andrews 1977; Halbach 1984; Halbach et al. 1982; Hein et al. 1985). In addition to these interelement correlations, correlations exist between various elements and depth of water as well as latitude. Of the elements that increase in abundance in crusts with increasing depth of water, copper and iron show the strongest correlations; other elements that show a positive correlation are beryllium, potassium, cerium, aluminum, titanium, silicon, and barium. Elements that correlate negatively with depth of water (decrease with depth) are manganese, cobalt, nickel, lead, molybdenum, cadmium, arsenic, and strontium (Aplin and Cronan 1985; Barnes 1967; Hein et al. 1985).

CRCs with sufficient mineral content to be commercially of interest occur between 800 and 2,500 meters on seamounts (that cover an estimated area of ~17.2 million km<sup>2</sup> or 4.7% of the global ocean floor) and occupy ~10% of these seamounts. CRC contract areas awarded by the ISA in international waters are 20 km<sup>2</sup>, which is notably smaller than the standard contract size they issue for SMS or PMNs. Furthermore, since phosphorite substrate rock and CRCs occur together, CRC mining technology could in theory be used to exploit both deposit types. This approach would provide two potential multi-component ore deposits in one mining operation, one with P and REE co-products and one with focus metals (cobalt, nickel, and manganese) and by-products (e.g., molybdenum, REE, and tellurium).

The ferromanganese crusts from Hein and others (2017) range in thickness from 6 to 86 millimeters, with an average thickness of 43 millimeters. The chemical compositions determined from ferromanganese crusts from the Chukchi Borderland indicate that crusts there might not have the same economic potential,

in terms of metal content, as crusts elsewhere in the global oceans, unless markets for more rare and critical metals such as Scandium evolve (Gartman et al. 2022).

In comparison to continental crusts, CRCs are believed to be more strongly enriched in many rare and critical metals, such as platinum, cobalt, bismuth, tellurium, niobium, and REEs. An example of this is found in the prime crust zone, which boasts CRCs with higher tonnages of manganese, nickel, molybdenum, argon, bismuth, yttrium, tellurium, and thallium. CRCs have the notable feature of high concentrations of cobalt, with an average of 0.14% to 0.97% and 0.19% to 0.74% depending on the source distance and oceanic region. High cobalt concentration does come at the cost of copper and nickel content, which is higher in PMNs.

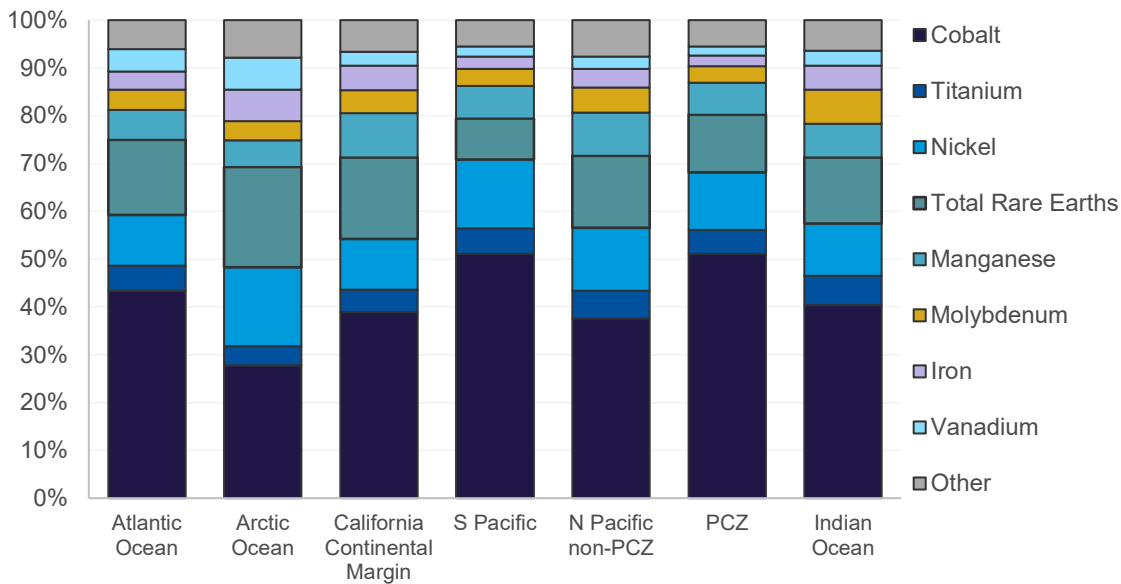
Geographically, cobalt, nickel, and platinum content are generally highest in crusts from the central and northwest Pacific and lowest in crusts from along the spreading centers in the southeast Pacific, the continental margins, and along the volcanic arcs of the west Pacific. Conversely, cobalt and nickel contents are low for crusts from the Atlantic and Indian Oceans. For this reason, the northwest equatorial Pacific has been deemed the ideal zone for crust exploration as crusts there typically have the highest concentrations of rare metals (Hein et al. 2013).

As depicted in the table below, the exact mineral composition of a CRC deposit varies by location. Iron and manganese form the largest proportion of the mineral content across all regions, each accounting for 15% to 25% of the elemental content, followed by silicon and calcium.

**Table 8.**  
**Mineral Composition of CRCs Across Various Ocean Zones, Dry Wt. %**

Mineral	Atlantic Ocean	Indian Ocean	PCZ	North Pacific (non-PCZ)	South Pacific	California Continental Margin	Arctic Ocean
Cobalt	0.4	0.3	0.7	0.4	0.6	0.3	0.1
Titanium	0.9	0.9	1.2	1.0	1.1	0.7	0.4
Total Rare Earths	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Nickel	0.3	0.2	0.4	0.3	0.5	0.2	0.2
Molybdenum	0.0	0.1	0.0	0.1	0.0	0.0	0.0
Manganese	15.9	14.5	22.8	23.4	21.7	19.5	7.7
Iron	21.1	22.7	16.9	22.5	18.1	23.8	19.8
Vanadium	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Strontium	0.1	0.1	0.2	0.2	0.1	0.1	0.0
Phosphorus	0.7	0.4	1.0	1.0	0.8	0.6	0.5
Copper	0.1	0.1	0.1	0.1	0.1	0.0	0.1
Potassium	0.5	0.6	0.6	0.8	0.6	0.9	1.1
Lead	0.1	0.1	0.2	0.1	0.1	0.2	0.0
Zinc	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Barium	0.2	0.1	0.2	0.2	0.2	0.2	0.0
Sulfur	0.3	0.1	0.3	0.2	0.2	0.0	0.3
Tungsten	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Loss on ignition	26.8	27.3	32.0	25.3	18.5	16.4	23.0
Water	11.8	1.0	8.0	6.9	10.2	9.4	9.6
Silicon	4.6	6.8	4.1	5.9	4.8	10.8	11.0
Calcium	4.2	1.3	4.0	2.5	3.5	2.3	1.2

Mineral	Atlantic Ocean	Indian Ocean	PCZ	North Pacific (non-PCZ)	South Pacific	California Continental Margin	Arctic Ocean
Aluminum	1.9	1.8	1.0	1.8	1.3	1.8	6.3
Magnesium	1.5	2.2	1.1	1.4	1.3	1.3	1.7
Sodium	1.3	1.6	1.6	2.0	1.5	2.0	1.6
Chlorine	0.8	1.0	0.9	1.1	1.1	0.7	1.3
CO2	4.4	0.0	0.7	0.7	0.8	0.4	0.0
Other elements	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Unspecified	1.5	16.3	1.6	1.7	12.4	8.1	13.5



SOURCE: CRU

Figure 28. CRC Value Share Compared Across Oceanic Zones

### 2.1.3.2.3 Comparison to Terrestrial Resources

Mineral content of deposits in the prime crust zone compared with those that are part of global terrestrial reserves can be found in underlying table. CRCs in the Pacific crust zone have significantly more thallium (1,700 times), tellurium (10 times more), thorium, cobalt, and yttrium than the entire terrestrial reserve base (Hein et al. 2013).

Table 9. Prime Crust Zone Versus Terrestrial Reserves Mineral Content, Mt

Mineral	Prime Crust Zone (Mt)	Global Terrestrial Reserves (Mt)
Mn	1714	630
Cu	7.4	690
Ti	88	414
Ni	32	80
Vn	4.8	14
Mo	3.5	10
Li	0.02	13

Mineral	Prime Crust Zone (Mt)	Global Terrestrial Reserves (Mt)
Co	50	7.5
Tu	0.67	3.1
Nb	0.4	3
As	2.9	1
Th	0.09	1.2
Bi	0.32	0.3
Y	1.7	0.5
Te	0.45	0.02
Th	1.2	0.0004
Rare Earth Oxide (REO [total])	16	110
Total	NA	7,533

As per Table 9, global oceanic cobalt resources are also nearly five times greater than terrestrial resources, with the prime crust zone itself containing double the volume of terrestrial resources. While deposit grade is dependent on geography, the grade range between oceanic and terrestrial deposits is quite similar, with only Morocco offering higher grade resources than oceanic deposits (Cailteux et al. 2005; Dehaine et al. 2021; Dewaele et al. 2006; Hitzman et al. 2017; Kalenga and Balyahamwabo 2020; Mambwe et al. 2022; Mizell 2022; Shengo et al. 2019; USGS 2022).

**Table 10.**  
**Prime Crust Zone Versus Terrestrial Reserves and Resources, Mt**

Mineral	Terrestrial Geography	Grade	Terrestrial Reserves	Oceanic Zone	Grade	Resource
Cobalt	Central African Copperbelt (DRC & Zambia)	0.246% - 1.1%	4-8 Mt of Co	Global	0.14–0.97%	Resources >120Mt (crust + nodules)
Cobalt	Cuba	0.18%	0.5 Mt	Global	0.14–0.97%	50 Mt
Cobalt	Russia	0.06%	0.25 Mt	PCZ	0.14–0.97%	>120Mt (crust + nodules)
Cobalt	Australia	0.014-0.21%	1.4 Mt	Global	0.14–0.97%	>120Mt (crust + nodules)
Cobalt	U.S.	0.01-0.12%	0.069 Mt	Global	0.14–0.97%	>120Mt (crust + nodules)
Cobalt	Canada	0.02-0.66%	0.22 Mt	Global	0.14–0.97%	>120Mt (crust + nodules)
Cobalt	Morocco	1%-1.5%	0.013 Mt	Global	0.14–0.97%	>120Mt (crust + nodules)
Cobalt	Global	0.04-0.22%	Reserves 7.6 Mt Resources 25-34 Mt	Global	0.14–0.97%	>120Mt (crust + nodules)

#### 2.1.3.2.4 Extraction

While both types of deposits are expected to utilize a seabed resource collector (mining unit), lifting system, and support vessels, the differences between mining terrestrial and CRC deposits are extensive and stretch across all stages of the mining process. In the prospecting stage, terrestrial mining utilizes common mapping and analysis tools such as satellites, meanwhile, crust exploration requires more specific techniques such as hull mounted followed by AUV multibeam echosounder, side scan sonar, high

resolution sub-bottom profilers, camera payloads, and sampling systems. The exploration stage is also unsurprisingly more technically challenging, owing to the need to extract seamount cores from far below the surface. However, a benefit of the nature of CRCs is that they eliminate the need for development processes like vegetation removal that a terrestrial site would require. In contrast to surface and pit mining, the proposed seabed minerals mining operations are based on a concept of a mining unit, ore unit, ROV and mining support vessel (Hein et al. 2013; Herzig et al. 2002). The latest breakthrough development of the proposed technology was conducted as late as 2020 and was based on improving the reactions of the cutter head based on changing seafloor topography as it excavates and dredges (Orita et al. 2022).

**Table 11.**  
**Terrestrial Versus Crust Comparative Resource Extraction Process**

Label	Mining Process Factors	Terrestrial	CRC mining
Prospecting	Locating	Satellite imagery, aerial mapping, surface mapping, structural analysis, seismic analysis	Mapping and sizing seamounts using hull mounted and/or AUV multibeam echosounder, side scan sonar, sub-bottom profiling systems, and camera. Rapid-drop crust sampling for grade.
Exploration	Sample drilling	Drilling conducted using conventional equipment for surveying and sampling conducted; prefeasibility study—determination of mining method	Dredging/coring of the seamount, bottom video + photography, water column sampling.
Exploration	Exploratory shaft digging	Drilling conducted using conventional equipment for surveying and sampling conducted; prefeasibility study—determination of mining method	Large, well equipped sea vessel with bottom acoustic beacons, if necessary,
Development	Shaft expansion for trial	Vegetation and over burden removal, plant construction equipment, support infrastructure	Environmental zoning and monitoring.
Exploitation	Full Extraction operations/Production	Conducted with large extraction equipment; blasting, drilling, dredging, collecting	Next generation hover AUV/ROV imaging working with new design low impact cutter/crusher/fracture technology combined with hopper and lift system to mining vessel.
Exploitation	Processing	Onsite minerals processing, tailings disposal	Transport from ships to shore.

### **2.1.3.2.5 Processing**

In terms of processing, terrestrial mining entails processing the minerals onshore or on-site, meanwhile, CRC processing can either be pyrometallurgical or hydrometallurgical. Due to the inefficient economics of offshore processing, processing of the collected CRC ores will be onshore. When onshore, the ore would need to be crushed and milled to a fine (more than 80% particle size less than 75 micrometers). At this point, the same processing techniques proposed for PMNs are transferable to CRC mineral extraction (hydrometallurgical methods such as floatation or jigging), which are expected to produce yields of 77%,

mineral purity of 86% and recoveries of up to 93%. Alternatively, sulfuric acid leaching in the presence of carbon can also be used with CRCs and has seen average leaching ratios of nickel and cobalt as high as 98.6% and 91.6%, respectively. Hydrometallurgical processing, as it is already high moisture based, could be used to recover cobalt and nickel, coupled with reductive leaching using carbon as the reducing agent, which is illustrated in Figure 30. This would be less detrimental than using ammonia to leach cobalt and nickel.

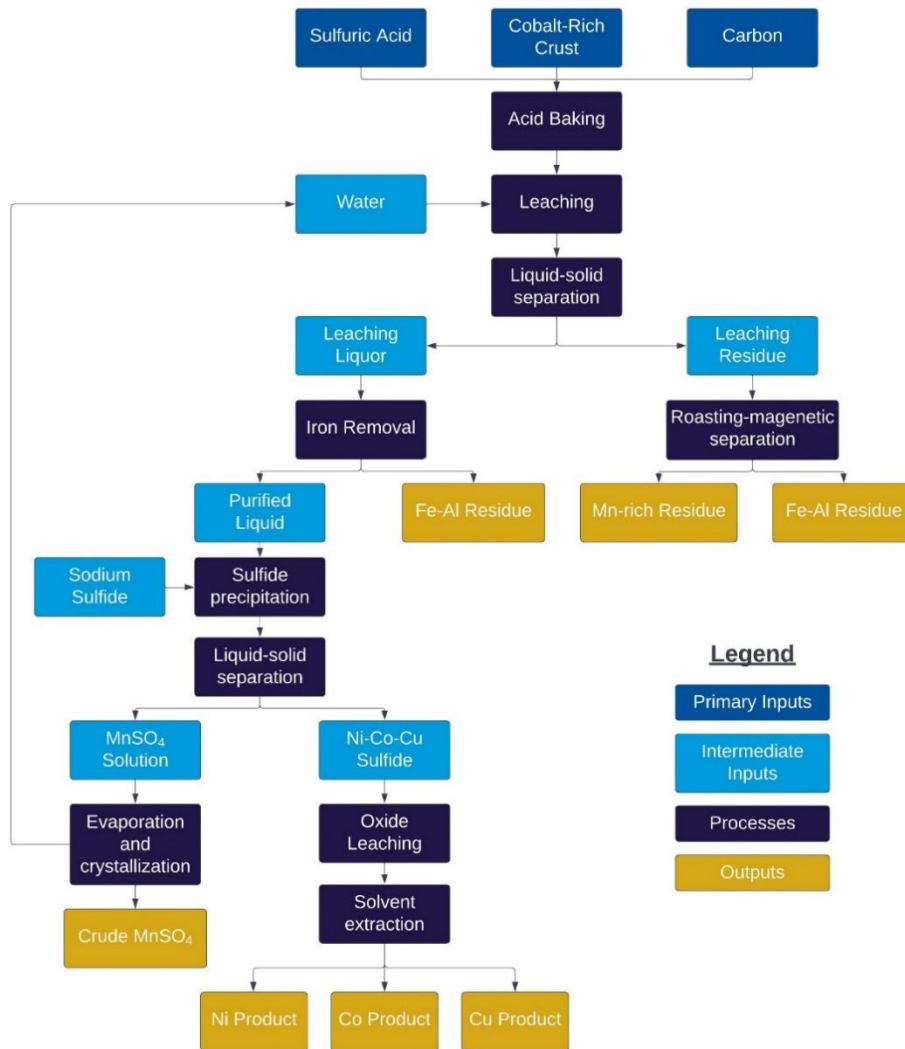


Figure 29. Proposed CRC Processing Method (Li et al. 2022)

### 2.1.3.2.6 Synthesis- Cobalt-rich Ferromanganese Crusts

The U.S. OCS and EEZ are endowed with several types of CRC deposits. On the Blake Plateau, CRCs are coincident with cobalt rich PMN and phosphorite deposits. Seamounts in the OCS off southern California are characterized by CRC that are less enriched in cobalt than PCZ CRC but are more enriched in nickel. All of the U.S. Pacific Island OCS and EEZ are prospective for CRC. Some areas such as Wake Island EEZ and Guam and Northern Mariana Islands OCS lie entirely (Wake Island) or in part in the PCZ but are underexplored. Cobalt crust contract areas have been issued to entities by the ISA that are geographically adjacent to U.S. OCS or EEZ. Hawaii OCS and Johnston Atoll EEZ are both prospective for CRC based on cumulative research and sampling by researchers supported by USGS and others.



The bulk chemistry of CRC samples in the U.S. OCS and EEZ are enriched in desirable CM such as cobalt, nickel, and REY. Other CM present in samples are manganese, aluminum, magnesium, titanium, barium. Economically important non-critical minerals found or prospective in U.S. OCS and EEZ CRC deposits are copper, molybdenum, lead, and iron.

Cobalt and nickel have been the metals of greatest economic interest in CRC because of expected demand for electric vehicles and grid battery storage. Mean concentrations are large areas of the global ocean ranges from 0.3% to 0.47% for cobalt and 0.23% to 0.46% for nickel. High-grade areas with a 20-year mining run could grade on average 0.8% cobalt and 0.5% nickel. Tellurium, of great interest in the manufacture of solar photovoltaic cells, averages 50 ppm with maximum values of 205 ppm in some CRC. Tellurium averages 60 ppm in PCZ CRC that are thought to be most representative of U.S. Pacific Island OCS and EEZ CRC (Mizell 2022).

Cobalt in the PCZ is estimated to be 3.8 times the total terrestrial global reserve base. The U.S. OCS and EEZ cobalt reserves that lie within the PCZ are expected to be large but lack comprehensive resource surveys. CRCs in the Pacific crust zone have significantly more Thallium (1,700 times), Tellurium (10 times more), thorium, and yttrium than the entire terrestrial reserve base (Hein et al. 2013). Thallium, tellurium, thorium, and yttrium reserves in the U.S. OCS and EEZ are expected to be large.

CRC mineral processing should, in general, be able to follow the processing sequence developed for PMN because of the similarities in the raw mineral material and the suite of contained economic metals. Current mineral processing for PMN involve both pyrometallurgical and hydrometallurgical methods to produce cobalt, nickel, copper.

Compared to PMN that have similar polymetallic metal content as CRC even though less enriched in cobalt, PMN is much easier to mine with successful pilot production from the CCZ. The difficulty in mining CRCs lies in the fact that the crusts are attached to rock substrates, and for successful crust mining, the crust recovery process needs to minimize attached substrate to avoid diluting the ore grade and the additional engineering and environmental problems with sediment production. At the same time, minable crusts are thin. Crusts targeted for mining should be at least 40 millimeters thick. At present it is thought that mining systems for CRCs should be capable of mining at least 1 million metric tons of ore per year. As such, mining CRCs is not technologically feasible at present, but technology is developing. However, there are several proposed mineral processing methods including water jet stripping of crusts from the rock substrate or vibration fragmentation, where the mining/collecting unit could contain an additional fragmentation step to prepare the ore for vertical transport as slurry. Countries such as Brazil, China, and Russia have signed CRC exploration contracts in international waters through the ISA of about 3 by 103 square kilometers each, with the assumption that technological advancement in this area will allow for future CRC mining.

### **2.1.3.3 Seafloor Massive Sulfides**

#### **2.1.3.3.1 Location of Resources**

Figures 13, 14 and 27 show permissive areas for SMS formation. Permissive, for the purposes of this report, indicates that the bio-geological conditions are favorable for SMS presence or SMS have been sampled. The basis for assessing the permissive areas is discussed by OCS and EEZ.

##### **2.1.3.3.1.1 Atlantic OCS**

Neither the continental Atlantic OCS, nor the Puerto Rico or U.S. Virgin Islands OCS are prospective for SMS deposits but could host hydrothermal manganese associated with New England seamounts and the Caribbean seamounts and islands.

#### **2.1.3.3.1.1.2 Gulf of Mexico OCS**

The Gulf of Mexico OCS is not prospective for SMS deposits. Any hydrothermal systems that formed during the rifting phase of the Gulf of Mexico in the Jurassic are too deeply buried.

#### **2.1.3.3.1.1.3 Navassa Island EEZ**

The Navassa Island EEZ are thought to be prospective for SMS deposits but could host hydrothermal manganese.

#### **2.1.3.3.1.1.4 Pacific OCS**

##### **2.1.3.3.1.1.4.1 U.S. Continental Pacific OCS**

Seafloor massive sulfide deposits are present at the Gorda Ridge, a slow spreading, sediment covered, mid ocean ridge located approximately 250 kilometers offshore northern California. Massive sulfide deposits on ledges, chimneys, and mounds that are found on the margins of sediment hills in the Escanaba Trough. Escanaba Trough is a slow spreading segment of the Gorda Ridge. Escanaba Trough is defined by high ridges on both sides of the trough that are 10 to 15 kilometers apart. The sediment blanket in the trough is as thick as 900 meters (Törmänen and Koski 2006). Most spreading centers are sediment free, but sedimented spreading centers have the potential to better capture metal precipitates than hydrothermal fluids that vent directly to the ocean where they are dispersed by settling and currents. Sediment hosted SMS deposits are enriched in lead, arsenic, antimony, silver, mercury and tin relative to massive sulfides from other seafloor spreading centers. Barite encrustations in the Escanaba Trough SMS sediments are enriched in zinc, lead, silver, and gold. High gold content, to 10.1 ppm with an average of 1.4 ppm are found in samples from the sediment covered seafloor within the Escanaba Trough. The gold is primary precipitation from the hydrothermal fluids and as secondary aggregate colloids formed through weathering and oxidation (Törmänen and Koski 2006).

USGS conducted new surveys in the Escanaba Trough in 2022 using the JASON submersible and electromagnetic tools in the Sentry AUV (NOAA 2022). SMS deposits were photographed and sampled using a sediment corer. Electromagnetic surveys (magnetic and self-potential) that can detect deeper alteration were also conducted along with multibeam, sub-bottom profiler, and geochemical sensors (pH redox, conductivity, and temperature). Results from this survey are still in publication but initial results were favorable with possible detection of buried anomalies and venting structures confirmed with the ROV.

Follow-on surveys using a surface drillship or seafloor drill to take cores from the electromagnetic targets showing hydrothermal alteration will be needed to define the SMS resource and distribution in the Gorda Ridge system.

##### **2.1.3.3.1.1.4.2 Hawaii OCS**

The Hawaii OCS is not thought to be prospective for SMS deposits but could host hydrothermal manganese such as is described for Johnston Atoll and other volcanic islands (Hein et al. 2005).

##### **2.1.3.3.1.1.4.3 Alaska OCS**

Hydrothermal activity is known along the Aleutian islands (Hannington et al. 2004). The only entry in the Alaska OCS in the InterRidge vents database (2020) describes a scuba diver who reported data from a nearshore 30° C hydrothermal vent in the western Aleutian Islands. Volcanism in the Aleutian arc could form volcanic massive sulfide deposits, such as those found on land that originated at the seafloor. Gartman et al. (2022) note 24 active volcanoes in the Aleutian Island chain. The western part of the volcanic arc may host submarine hydrothermal systems but no submarine hydrothermal activity has been identified to date (Gartman et al. 2022).

The Aleutian Arc is prospective for hydrothermal minerals, as active volcanic arcs host hydrothermal activity and associated mineralization throughout the global ocean. The Aleutian Arc extends from the Gulf of Alaska to the Kamchatka Peninsula in the Russian Far East and separates the Pacific Ocean from the Bering Sea (Gartman et al. 2022). The potential for hydrothermal activity and associated active seafloor mineralization in the region may be associated with the extensional intra-arc/summit basins that occur between emergent volcanic islands, with basins forming as grabens associated with block rotation (Geist et al. 1988). There is also the possibility of hydrothermal minerals that are not associated with active hydrothermal vents in this setting (Gartman et al. 2022).

### **2.1.3.3.1.1.5 U.S. Pacific Islands OCS and EEZ**

#### **2.1.3.3.1.1.5.1 American Samoa**

Vailulu'u seamount likely hosts hydrothermal manganese deposits with potential for nickel, molybdenum, and chromium (Hein et al. 2005) in the American Samoa OCS. Vailulu'u seamount is active, the plume was first discovered in 2000 and documented from the Pisces AUV in 2005. No samples are recorded in the database. The seamount and surroundings have the potential for SMS deposits of gold, silver, copper, lead, and zinc.

#### **2.1.3.3.1.1.5.2 Baker Reef and Howland Island**

The Baker Reef and Howland Island EEZ is not thought to be prospective for SMS deposits but could host hydrothermal manganese (Hein et al. 2005).

#### **2.1.3.3.1.1.5.3 Jarvis Island**

The Jarvis Island EEZ is not thought to be prospective for SMS deposits but could host hydrothermal manganese (Hein et al. 2005).

#### **2.1.3.3.1.1.5.4 Johnston Atoll**

The Johnston Atoll EEZ is not thought to be prospective for SMS deposits but could host hydrothermal manganese (Hein et al. 2005)

#### **2.1.3.3.1.1.5.5 Kingman Reef and Palmyra Atoll**

The Kingman Reef and Palmyra Atoll EEZ is not thought to be prospective for SMS deposits but could host hydrothermal manganese (Hein et al. 2005).

#### **2.1.3.3.1.1.5.6 Guam**

Guam, situated on the southern end of the Mariana Islands volcanic arc and its surroundings- the arc and the back-arc are volcanically active. The central part of the Guam OCS is prospective for SMS deposits that may be analogous to Kuroku-type VMS mineralization. Eight active hydrothermal systems have been identified by various researchers in the Guam OCS (Hannington et al. 2004; InterRidge 2020). Geochemical results from Alvin dives on the Mariana Arc show average gold content at 715 parts per billion (ppb), silver at 169 ppm, copper at 1%, and zinc at 9.1% (Hannington et al. 2004). Geochemical analyses of massive sulfide chimneys in the Guam EEZ show concentrations of gold ranging from 148 to 3,160 ppb, silver ranging from 2 to 243 ppm, copper ranging from 0.15% to 2.24%, and zinc ranging from 0.03% to 9.08% (Kakegawa et al. 2008).

#### **2.1.3.3.1.1.5.7 Midway Atoll**

The Midway Atoll EEZ is not thought to be prospective for SMS deposits but could host hydrothermal manganese (Hein et al. 2005).

#### **2.1.3.3.1.1.5.8 Northern Mariana Islands**

Northern Mariana Islands, situated on the main of the Mariana Islands volcanic arc and its surroundings- the arc and the back-arc are volcanically active. The central and western part of the Northern Mariana Islands OCS is prospective for SMS deposits. Thirty-two active hydrothermal systems have been identified by various researchers in the Northern Mariana Islands OCS (Hannington et al. 2004;

InterRidge 2020). Geochemical results from Alvin dives on the Mariana Arc show average gold content at 715 ppb, silver at 169 ppm, copper at 1%, and zinc at 9.1% (Hannington et al. 2004). The USGS geochemical database reports analyses from 44 samples in the Northern Mariana Islands. Only one site was elevated in copper (1.27%), but notably many of the samples are enriched in titanium with most sample reporting titanium content higher than 0.35% with some samples reporting content higher than 1% titanium (USGS 2023a).

### 2.1.3.3.1.1.5.9 Wake Island

The Wake Island EEZ is not thought to be prospective for SMS deposits but could host hydrothermal manganese (Hein et al. 2005).

### 2.1.3.3.2 Mineral Content and Ore Grade

SMS deposits can contain critical minerals including cobalt, arsenic, platinum, and zinc. They also tend to be rich in base other base metals like iron copper and lead as well as other elements such as gold, silver, and molybdenum (Krasnov et al. 1995). The exact chemical and mineralogical composition of a SMS deposit will depend on the tectonic setting and the nature and extent of the hydrothermal activity of the deposit sampled.

The SMS mineral property that has come closest to development is the Solwara prospect offshore Papua New Guinea that was being developed by Nautilus Minerals. They reported an indicated resource of 1.03 million tons consisting of 7.2% copper, 5 grams per ton (g/t) gold, 23 g/t silver, and 0.4% zinc and an inferred resource of 1.54 million tons consisting of 8.1% copper, 6.4 g/t gold, 34 g/t silver, and 0.9% zinc (Golder Associates 2012).

SMS prospecting is starting in the Norwegian EEZ through several junior mining companies in anticipation of the imminent final regulatory rules that will allow the issuance of exploration and development licenses by the Norwegian Petroleum Directorate. Grade and tonnage of these prospects is still immature.

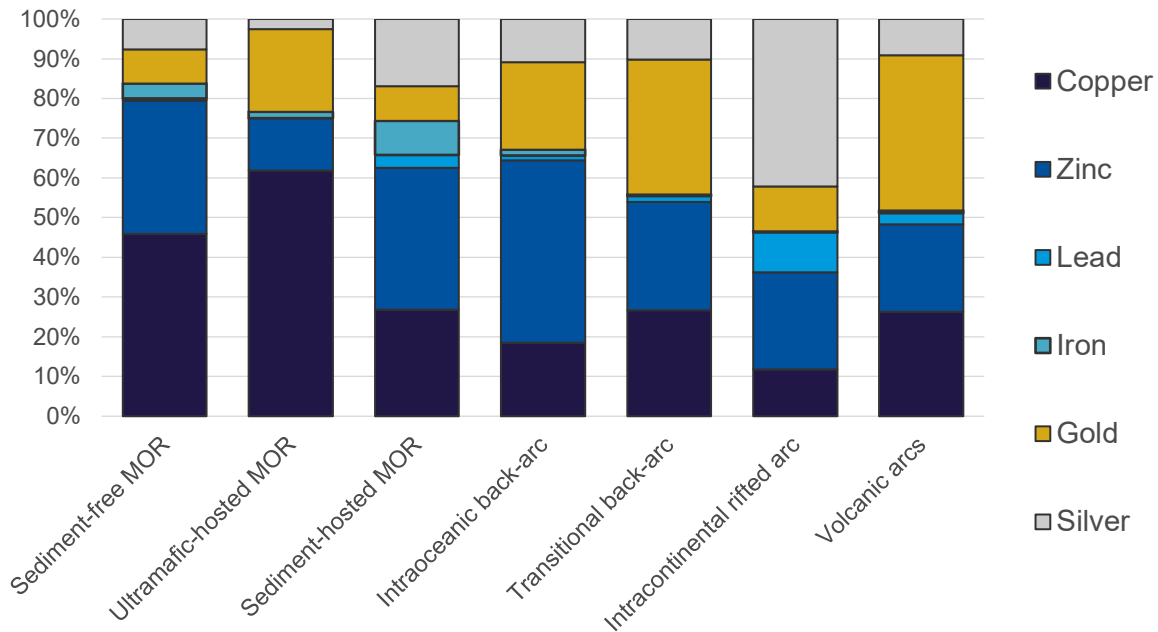
Ore grades can vary greatly between deposits located in different settings. The table below shows the minerals most commonly (or abundantly) found in SMS deposits in the form of pyrite ( $\text{FeS}_2$ ), pyrrhotite ( $\text{Fe}_{1-x}\text{S}$ ), chalcopyrite ( $\text{CuFeS}_2$ ), sphalerite ( $[\text{Zn,Fe}]\text{S}$ ) and galena ( $\text{PbS}$ ). Mid-ocean ridge SMS deposits usually contain the highest copper concentrations, back-arc basins are associated with high zinc and silver concentrations and transitional back-arc and volcanic arc settings contain the highest gold concentrations, averaging between 3-30 ppm (Herzig et al. 2002; Rahn 2019).

**Table 12.**  
**Bulk Chemical Composition of Seafloor Polymetallic Sulfides**

Element	Intra-oceanic Back-Arc Ridges	Inter-continental Back-Arc Ridges	Mid-Ocean Ridges (MOR)	Sediment-free MOR	Ultramafic-hosted MOR	Sediment-hosted MOR	Volcanic arcs
Pb (wt.%)	0.4	11.8	0.1	0.2	<0.1	0.4	2.0
Fe	13.0	6.2	26.4	27	24.8	18.6	9.2
Zn	16.5	20.2	8.5	8.3	7.2	2.7	9.5
Cu	4.0	3.3	4.8	4.5	13.4	0.8	4.5
Ba	12.6	7.2	1.8	0	0	0	0
As (ppm)	845	17,500	235	0	0	0	0
Sb	106	6,710	46	0	0	0	0

Element	Intra-oceanic Back-Arc Ridges	Inter-continental Back-Arc Ridges	Mid-Ocean Ridges (MOR)	Sediment-free MOR	Ultramafic-hosted MOR	Sediment-hosted MOR	Volcanic arcs
Ag	217	2,304	113	94	69	64	197
Au	4.5	3.1	1.2	1.3	6.9	0.4	10.2

Figure 30 shows the value share that minerals contained in SMS contribute to the mined ore. In most settings, zinc and copper contribute the bulk of the value, with gold and silver adding a significant portion in some cases.



**Figure 30. Relative Value Shares of Metals Contained in SMS Deposits, 2022 Average Prices**

### 2.1.3.3.3 Comparison Against Terrestrial Resources

SMS can differ from terrestrial deposits in their mineral composition, often containing higher grades, especially in copper content (Miller et al. 2018). Zinc, gold, and silver grades that are also typically much greater than those in land-based volcanogenic massive sulfides (Hein et al. 2013). A comparison of the size of SMS deposits with terrestrial ores shows that extremely large VMS deposits such as Kidd Creek in Canada (135 million tons) or Neves Corvo in Portugal (262 million tons) so far have not been discovered at the modern seafloor (Herzig et al. 2002). Mineral composition of surficial samples from submarine hydrothermal deposits from Myojin Knoll and Suiyo Seamount; however, appear to be close analogues to the Kuroko VMS deposit (Glasby et al. 2008) and are analogous to potential SMS deposits in the Guam and Northern Mariana Islands OCS. The Escanaba Trough SMS deposits in the U.S. Pacific OCS are analogous in setting to the large Windy Craggy VMS deposits in British Columbia (Canada), which contain over 430 million metric tons of copper (1.44%), gold (0.22 g/t), silver (4.0 g/t), cobalt (0.066%), and zinc (0.25%) (Koski and Mosier 2012). Very few SMS deposits have been drilled and cored from surface through the stockworks, so comparisons of SMS deposits to relatively smaller VMS analogs is still not established. Sampling is often biased to chimneys and other easily accessible samples. SMS systems that are blanketed, i.e. not precipitating minerals to the water column to be dispersed by currents that could be larger, have not been representatively sampled.

Key differences between SMS and terrestrial sulfide deposits exist in the mining process, from prospecting to exploitation as shown in the table below. The high-pressure environment drastically changes the type of equipment required as it needs to be highly corrosion resistant and able to be operated from the surface.

#### 2.1.3.3.4 Extraction

In contrast to PMN and CRC deposits which are surficial two-dimensional deposits, SMS deposits are three-dimensional with important mineralization in the stockworks. Mining methods are still being developed for SMS mining. Nautilus opted to develop three subsurface mining machines consisting of an auxiliary cutter that would prepare the ground for a bulk cutter that would excavate material into stockpiles that would be collected by the collecting machine. These were built by Soil Machine Dynamics and tested but never deployed for mining operations at the Solwara property in PNG (Soil Machine Dynamics 2023). Other concepts by Bauer Maschinen emphasize vertical versus the horizontal extraction used in the Nautilus/Soil Machine Dynamics approach. The technology that best controls sediment plumes will have a technological and environmental advantage. Established submersible pump or airlift systems will bring the crushed slurry through a riser to the mining surface vessel. Bulk carriers will transport the mined material to shore where it can be transported to a mineral processing center.

**Table 13.**  
**Process Comparison of Terrestrial and SMS Mining**

Label	Mining Process Factors	Terrestrial	SMS mining
Prospecting	Locating	Satellite imagery, aerial mapping, surface mapping, structural analysis etc. seismic methods.	Water chemistry Tow-yo surveys, hull mounted multibeam echosounders. AUV surveys with redox, nephelometer, temperature, pH sensors. AUV or deep tow electromagnetic surveys.
Exploration	Sample drilling	Drilling conducted using conventional equipment for surveying and sampling conducted; prefeasibility study – determination of mining method.	Drilling and coring using geotechnical drilling vessel or seafloor drills to establish resource potential.
Exploration	Exploratory shaft digging	Drilling conducted using conventional equipment for surveying and sampling conducted; prefeasibility study – determination of mining method.	Core drilling
Development	Shaft expansion for trial	Vegetation and over burden removal, plant construction equipment, support infrastructure.	Environmental baseline and monitoring program.
Exploitation	Full Extraction operations/Production	Conducted with large extraction equipment; Blasting, drilling, dredging, collecting.	Conducted with smaller portable equipment relative to terrestrial conventions. Combination of technology from previous designs for Crust and nodule mining, including modified technology from terrestrial coal and ocean diamond mining methods. Drive body (ROV) Ore Crusher (coal/diamond cutter attached to flexible drill) Ore Lifter + dewatering.

Label	Mining Process Factors	Terrestrial	SMS mining
Exploitation	Processing	Onsite minerals processing, tailings disposal.	Vessel support for further processing and transport to shore.

Source: (Herzig et al. 2002)

### 2.1.3.3.5 Processing

Flowsheets are specific to the mined deposits but processing of SMS ores do not appear to diverge significantly from existing processing of polymetallic sulfides. Ball mill index values indicate low to medium resistance to comminution for SMS deposits. Common sulfide flotation methods are indicated to perform well. So conventional grinding and flotation should produce copper concentrates with high recovery. Gold is refractory—being associated with pyrite. Gold recoveries of 70% into pyrite concentrates from copper flotation. Gold can be extracted from pyrite concentrates through conventional technologies of roasting/cyanidation or by pressure oxidation/cyanidation. Copper concentrates are expected to be ‘clean’ and not present problems by custom copper smelters. Zinc may be extracted by reverse flotation (Golder Associates 2012).

### 2.1.3.3.6 Synthesis Seafloor Massive Sulfides

Escanaba Trough on the Gorda Ridge seafloor spreading center in the Pacific OCS off northern California hosts SMS deposits. Because of its proximity to the continental margin and its steep geomorphology, the Escanaba Trough receives sediment by ocean currents and turbiditic flows, which blankets some metalliferous vent sites concentrating mineralization, increasing the potential for richer SMS deposits. The closest VMS analog to Escanaba Trough is the Windy Craggy mineralization on the west coast of Canada—one of the largest known copper, gold, and cobalt deposits.

Kuroko type mineralization is anticipated to be present in Guam and Northern Mariana Islands OCS SMS deposits. Eight active hydrothermal systems have been identified in the Guam OCS. Geochemical results from staffed submersible dives and sample analysis show enrichment in zinc, copper, silver, and gold. Thirty-two active hydrothermal systems have been identified in the Northern Mariana Islands OCS. Staffed submersible dives and sample analysis from the Northern Mariana Islands OCS show enrichment in zinc, copper, silver, gold, and titanium.

In the Pacific OCS off California and Oregon, Escanaba Trough deposits contain in bulk sample 10% CM including zinc, barium, arsenic, antimony, manganese, cobalt, and tin. Economically important non-critical minerals in Escanaba Trough make up 35% of bulk samples comprised of iron, copper, lead, selenium, silver, molybdenum, and gold (Morton et al. 1990).

In the Guam and Northern Mariana Islands OCS SMS deposits contain in bulk sample 29% CM including zinc, barium, arsenic, and antimony. Economically important non-critical minerals found in Guam and Northern Mariana Islands OCS SMS make up 18% of bulk samples comprised of iron, copper, lead, silver, and gold.

Hydrothermal manganese could be prospective on the flanks of any of the volcanic seamounts and islands in the U.S. OCS and EEZ.

Globally, more than 200 sites of hydrothermal mineralization have been documented and so far, approximately 10 of these deposits have sufficient tonnage and grade to be considered for commercial mining. Areas of potential polymetallic-sulfide deposits are estimated to cover 3.2 million km<sup>2</sup> globally, with 58% of the known sulfides in areas beyond national jurisdiction. Junior mining companies have formed explore and acquire SMS mining properties in the Norwegian EEZ, but grades and tonnage have not yet been established. The SMS prospect that moved furthest to development was the Solwara in the EEZ of Papua New Guinea where they disclosed an indicated resource of 1.03 million tons consisting of

7.2% copper, 5 g/t gold, 23 g/t silver, and 0.4% zinc and an inferred resource of 1.54 million tons consisting of 8.1% copper, 6.4 g/t gold, 34 g/t silver, and 0.9% zinc in their public filings. Using Solwara as an example, a mining operation would still need to line up a series of minable prospects even though they can be richer per ton than onshore VMS deposits.

Extraction methods for SMS deposits are still being developed. The submarine cutters and collectors developed for the Solwara mineral property in PNG were smaller marinized versions of existing concepts for onshore surface mining. Other concepts emphasize vertical vs horizontal extraction that may decrease and control sediment plumes.

Processing of SMS ores should be amenable to conventional grinding and flotation pyrometallurgical, and hydrometallurgical processes used in the processing of sulfide ores and present no significant difficulties or technological hurdles to overcome.

#### **2.1.3.4 Shallower Deposits (Phosphorites and Heavy Mineral Sands)**

Figure 26 shows permissive areas for phosphorite formation in the Atlantic OCS. Permissive, for the purposes of this report, indicates that the bio-geological conditions are favorable for phosphorite presence or extensive phosphorites have been sampled. The basis for assessing the permissive areas is discussed by OCS and EEZ. See discussions below for other instances and permissive areas for phosphorites and heavy mineral sands.

##### **2.1.3.4.1 Phosphorites**

Phosphate deposits are found on continental margins and shelves where there is upwelling. The ocean is nearly saturated with phosphate, but cold ocean water holds more phosphate than warm ocean water. At upwelling areas, phosphate precipitates with changing temperature, pH, and other changes. Phytoplankton and other organisms consume the phosphate and help concentrate phosphate in the sediments. Besides phosphate, rare earth elements plus yttrium (REY) are known to concentrate in phosphorites during diagenesis of biogenic calcium carbonate ( $\text{CaCO}_3$ ) to carbonate fluorapatite ( $\text{Ca}_5(\text{PO}_4, \text{CO}_3)_3(\text{F}, \text{O})$ ) (Hein et al. 2016). Most upwelling occurs at points along continental margins where cold deep current collides and mix with warmer currents. Volcanic islands and seamounts can provide conditions for local upwelling and local marine productivity that starts the bio-geochemical cycle that precipitates phosphate from seawater.

It should be noted in this report that the acquisition of many far-flung Pacific Islands in the U.S. Territorial EEZ was the result of the pursuit of phosphate fertilizer and saltpeter for gunpowder-phosphate that had been concentrated by seabirds in the phytoplankton-zooplankton-fish food chain. The American Guano Company and others actively pursued and mined guano in the Pacific and influenced the passage of The Guano Islands Act of 1856 that provided for annexation of any guano deposits found by U. S. citizens that were “not under the lawful jurisdiction of any other government” (48 U.S.C. Ch. 8).

Phosphorites are formed when phosphate materials found in seawater substitute in calcium-rich sediments/precipitates as apatite form hard rock. Geographically, the largest phosphorite concentrations are found in regions along the west coasts of Africa, both coasts of the U.S., New Zealand, and in the central part of the northern Pacific. Other areas of interest for phosphorite exploration are the continental shelves and slopes off western South America, northern Spain, Morocco, Namibia, and South Africa. Within these regions, phosphorites occur in three general oceanic environments: continental margins (shelf, slope, banks, and plateaus), seamounts (especially the old (Cretaceous) seamounts in the northwest Pacific), and lagoon/insular deposits.

Phosphorites can occur in the same areas as CRCs and are mostly of interest for their phosphorus and heavy rare earth element content. Seamount phosphorites occur in the same places as CRC on seamounts and the phosphorites are typically covered with iron-manganese crusts. This makes exploration for



phosphorites challenging as a main product, but beneficial as a by-product of CRC mining. At present, solely sourcing/identifying phosphorite substrate rock beneath iron-manganese crusts require the development of new technology (Hein et al. 2016; Sakellariadou et al. 2022; Yamazaki 2022).

#### **2.1.3.4.2 Heavy Mineral Sands**

Heavy mineral sands are a type of placer deposit. They are also known as: beach placers, black sand deposits, and mineral sands. Placer deposits are heavier than other sands and are resistant to weathering. Placers deposits of interest can include gold, tin, gemstones, and diamonds. To be a placer, the grains need to have weathered from the host rock and be carried and concentrated by water, wind or both. These minerals are usually transported within sediment by stream and river systems to drop inland within riffles, pools, and point bars or are carried further out to the coast within the sediment bedload.

Beach sands contain the most important accumulations of heavy minerals, which are formed when waves deposit sand on beaches where heavier minerals are concentrated, while backwash carries lighter minerals such as quartz back into the sea. Changes in sea level expose older, paleo-shorelines, known as strandlines that can also be a source of heavier mineral sands or in inland dunes where heavy mineral sands can be separated by wind processes.

The main heavy mineral sands that are mined are ilmenite, rutile, monazite, zircon, leucoxene, sillimanite, and garnets. Rutile, ilmenite, and leucoxene are mined for the CM titanium; zircon for the CM zirconium; garnets for CM aluminum, magnesium, or manganese; monazite for the REE CM cerium, lanthanum, neodymium, or thorium. It is common for a heavy mineral sand deposit to contain a combination of the HMS minerals. The HMS sands from various mine sites between Trail Ridge, an inland eolian dune line, and the coast in Florida and Georgia have produced titanium, zirconium, and REE HMS since the 1960 and production is ongoing at the present time. These HMS sands are also present within the barrier islands in the Florida and Georgia coast and likely extend offshore but have not been mined to date. Other large producers are also entirely onshore such as Murray Basin, Australia (Earth Resources 2023). However, some also have offshore component such as Tormin Mineral Sands in South Africa that is not being mined at present. Guaju mine in Paraiba, Brazil has monazite mines within paleo beach dune sands within one kilometer of the present shoreline. These deposits also likely extend offshore. The Indian government has granted offshore licenses along the Kerala coast. The most accessible heavy mineral sands are onshore beach deposits and offshore mining of heavy mineral sands has not been deployed except in a few cases. Wet mining of heavy mineral sands using a dredge, however, is common because of the shallow water table typical of nearshore deposits.

Depending on local present day and paleo coastal geomorphology and longshore drift HMS can be found in the proximal offshore where buried paleo beach sands may present or where wave and current action may concentrate the heavy sand components. Present day beaches and nearshore sands are constantly being reworked, so HMS deposits delineated in one decade may shift towards another location in the next.

#### **2.1.3.4.3 Location of Resources**

##### **2.1.3.4.3.1 Atlantic OCS**

Large phosphate resources are found onshore on the coastal plains of North Carolina, South Carolina, Georgia, and Florida. Florida hosts world class onshore phosphate deposits across the state and these have been mined since their discovery in the 1880s. Some of these resources are known to extend offshore and others are thought to likely extend offshore (Hobbs III 1991).

Offshore phosphate deposits are well known but not delineated from southern Virginia to the tip of Florida. Phosphorites are closely associated with a large semi-contiguous area of ferromanganese crusts discussed in section x of this report, phosphate manganese pavement, and PMNs in the northern portion of the Blake Plateau. (Hollister 1973). A phosphorite pavement on the northwestern half of a large ferromanganese pavement, 150 km southeast of Charleston, SC is shown by Manheim et al. (1980) based

on interpretation of geophysical, dredge, and coring data acquired by Woods Hole in the 1960s. A reinvestigation by the USGS in 1982 determined that the entire current-swept portion of the Blake Plateau from North Carolina in the north to Florida in the south is underlain by hard phosphorite pavement.

The extensive and continuous phosphorite pavements on the Blake Plateau are found in water depths between 500 and 650 meters on outcrops of Eocene-age rocks. Pavements form two types, thin slabs from 2 to 5 cm in thickness that may consist of largely ferromanganese oxides and carbonate veins, and thick slabs exceeding 6 cm in thickness that possess a phosphorite core and accretionary oxide and replaced layers of less than 4 cm in thickness (Manheim et al. 1982).

The shelf off Georgia was established as a major site of occurrence of offshore phosphorite deposits in the late 1980s (Manheim 2007). In southern coastal Georgia drilling has confirmed the extension of the phosphate-rich Hawthorn formation from economic deposits in the same formation in Florida. This phosphate-rich geologic formation extends as least 20 km offshore (Cathcart et al. 1984). Integration of petrographic and chemical analyses with regional geophysics and stratigraphy led to the conclusion that shallow sediments on the Georgia shelf contained potentially economic deposits of phosphate.

Phosphate deposits are found along the Florida platform margin approximately 30 km offshore from Homestead to Ft. Lauderdale (CPC 1984). Unconsolidated phosphatic sediment 25 km by 150 km lies at the continental margin 130 km southeast of the GA FL border (CPC 1984; Manheim et al. 1980).

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific Islands and seamounts through bio geochemical precipitation of phosphate by phytoplankton zooplankton and fish. The Puerto Rico and U.S. Virgin Islands OCS are prospective for phosphate on the island flanks. An offshore phosphate deposit is on the boundary of the U.S. Virgin Island OCS but may plot in the British Virgin Island EEZ (CPC 1984).

Geologists have identified several offshore areas of the U.S. OCS that have potential for hosting heavy mineral placer deposits, although data are still too sparse for compiling resource assessments. One of the most promising areas for titanium (ilmenite, rutile) sands and associated minerals in the region is located between New Jersey and Florida. Heavy-mineral studies on the New Jersey's inner continental shelf showed a range of heavy minerals between 0.36 to 12.8 weight percentage (wt.-%), averaging 3.6. However, heavy mineral studies offshore Maryland suggested that concentrations in that region were low. In Virginia, heavy mineral suites had higher concentrations of heavy minerals and concentrations of minerals of economic value than areas offshore to the south, including North Carolina, Georgia, and Florida (Hobbs III 1991).

Seismic profiling has disclosed many old beach ridges and buried stream channels on the continental shelves of the U.S. OCS. According to Dillon (1984) these sites may host heavy mineral placer deposits and preliminary sampling has suggested that these may be economic in many locations.

The Trail Ridge heavy mineral sand complex is a paleo eolian dune interbedded with peat and fine sand that extends approximately 170 km from Starke, FL to Jessup GA. The Trail Ridge complex has been mined for ilmenite, leucocene, zircon, and staurolite (Van Gosen and Ellefsen 2018) since the 1950s. Drainage from the St. John's, Nassau, St. Mary's and others are conduits to redistribute Trail Ridge complex heavy mineral concentrations to the beaches and offshore. As a consequence, Cumberland Island, Amelia Island, Little Talbot Island, and Ponte Vedra are beach barrier islands enriched in heavy mineral sands. Embayments and lagoonal systems in parallel to Trail Ridge as well as sand bars further offshore that formed when sea level was lowered could preserve heavy mineral sands.

The Puerto Rico and U.S. Virgin Islands OCS may be prospective for heavy mineral sands in beach deposits and offshore on the shelves. Reconnaissance surveys for heavy mineral sands in Puerto Rico found that magnetite and other heavy minerals were concentrated in beach and dune sand deposits near the mouths of rivers (Guillou and Glass 1957). Beach sands on the west coast of Puerto Rico from

Aguadilla to Mayaguez are enriched in magnetite. On the south coast many localized sands are enriched in magnetite, often to concentrations of 20% (Guillou and Glass 1957). The east coast is less prospective but with local rich heavy mineral concentrations. The main heavy mineral is magnetite, but ilmenite is present associated with the magnetite. Chromite occurs in sands on the west coast. Sphene is a minor constituent but is widespread (Guillou and Glass 1957).

#### **2.1.3.4.3.2 Gulf of Mexico OCS**

The CPC mineral maps do not show phosphorite deposits on Florida's Gulf Coast (CPC 1984). Major active phosphate mines, however, are on Florida's Gulf Coast in the St. Petersburg and Tampa area (Mindat.org 2023). These phosphorite deposits almost certainly extend offshore on the Florida platform. The CPC maps do show phosphate deposits on the flanks of the Florida Platform south of Key West (CPC 1984). No phosphate deposits are shown along the Florida Escarpment, but the setting is favorable for phosphorite deposits to be present there.

Promising areas for HMS have been identified in the Gulf of Mexico off Mobile Bay, Apalachicola, and Galveston (Dillon 1984).

Heavy mineral beach sands enriched with ilmenite were found in Mississippi Sound and associated islands. Mississippi Sound extends from the mouth of the Pearl River west to Mobile Bay. A chain of barrier islands, Cat, Ship, Horn, Petit Bois, and Dauphin comprises the Sound's southern limit (Foxworth et al. 1962). Similar to the heavy mineral sands in northeast Florida and southeast Georgia, the heavy mineral beach sands in Mississippi have an Appalachian source (Foxworth et al. 1962; Van Gosen and Ellefsen 2018). Weight percent for individual samples ranged from 0.11% to 95.7% heavy minerals. The 95.7% heavy mineral sample contained 41.6% ilmenite. Average grade in the beach sands is estimated at 2% to 6%. On the Gulf side of the barrier beaches bulk concentrations may average 60% heavy minerals (Foxworth et al. 1962). Concentrations of 1% to 3% have profitably mined in Florida and elsewhere. Barrier islands and coastlines can change rapidly year on year from storm events, erosion, re-deposition and longshore drift. The deposits sampled in the early 1960s would need to be revisited since the distribution and grade will have changed.

The Colorado River drains the Precambrian Llano uplift in central Texas which should carry heavy minerals to the Texas barrier island beach sands near Matagorda, TX. (Hahn et al. 1961) report large inland deposits in the Fall Zone along the watershed but also beach deposits at Matagorda Island. Ilmenite samples from cores ranged from 1.58% to 30.00% based on minus 20 mesh and sink-float sorting (Hahn et al. 1961). Offshore deposits are likely to be present but temporal. It is unknown to the authors whether the large coastal restoration/ beach restoration projects for Galveston since Hurricane Ike (2009) performed any offshore heavy mineral reconnaissance work. If not, it would have been prudent to implement in advance of these types of civil contracts.

The Rio Grande also drains crystalline rocks from the rift system in New Mexico and Big Bend. Hohn et al., did take samples Millacy county along the South Texas coast but ilmenite in these samples were less than 1% (Hahn et al. 1961).

#### **2.1.3.4.3.3 Navassa Island EEZ**

Local upwelling and associated marine productivity can precipitate phosphate at seamounts through bio geochemical precipitation of phosphate by phytoplankton zooplankton and fish. The Navassa Island EEZ is prospective for seamount phosphate and island/lagoonal phosphate. Navassa Island was claimed by the U.S. in 1857 under the Guano Islands Act of 1856. Mining of oolitic phosphorite began in 1865 by the Navassa Phosphate Company of Baltimore. Approximately 450,000 kilograms of phosphate were mined between 1865 and 1898 (Miller et al. 2008).

The Navassa Island EEZ is not thought to be prospective for heavy mineral sands. Although heavy minerals do derive from basalts, the lack of deposits is likely caused by the steep profile of the island and

lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

#### **2.1.3.4.3.4 Pacific OCS**

##### **2.1.3.4.3.4.1 U.S. Continental Pacific OCS**

Phosphorite deposits are an alteration product of ferromanganese crusts and are commonly found together. The CPC project compiled 23 phosphorite deposits on seamounts off southern California and 6 off central California (CPC 1984). Hein et al. (2010) reports phosphorite deposits on Little Joe and Ben Seamounts.

The best prospects for chromite placer deposits, other associated minerals, and perhaps precious metals on the western U.S. OCS are offshore southern Oregon. Heavy mineral sands have been identified on the Washington Oregon shelf and on the coastline of California. Heavy minerals are transitory deposits and can change and redistribute over time in response to ongoing wave and longshore drift processes and episodic storm events. Work done in the 1970s showed 0 to 10% heavy minerals with patches of 10% to 20% and 20% to 30% extending over 450 km along the Washington Oregon shelf (McKelvey 1986). In California heavy mineral sands are reported along Crescent City (McKelvey 1986) and off San Francisco in the Gulf of Farallones (Wong 2001) but no reports of distributions or grades are given.

##### **2.1.3.4.3.4.2 Hawaii OCS**

Phosphorite deposits are an alteration product of ferromanganese crusts and are commonly found together. Crusts are commonly impregnated by phosphorite and calcite. Hein et al. (Hein et al. 1985) reports widespread phosphorite cemented breccia along Necker Ridge. Crusts are often separated by a paper-thin phosphorite layer. Phosphorite breccias of 2% to 4% were also found on Colahan and Abbott Seamounts on the northern end of the Hawaiian archipelago (Hein et al. 1985).

The Hawaii OCS is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

##### **2.1.3.4.3.4.3 Alaska OCS**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of seamounts through biogeochemical precipitation of phosphate by phytoplankton zooplankton and fish. Phosphorite can be an alteration product of ferromanganese crusts. One of the ferromanganese crusts from the Gulf of Alaska seamounts was interlayered with phosphorite (Gartman et al. 2022).

Gold prospectors in Alaska explored for stream placers to identify gold bearing hydrothermally altered amphibolites and schists. Beach sands were also processed for gold. Placer deposits are the most economically important nearshore deposit in Alaska. Nearshore placers have produced 30% of the total placer gold production in Alaska (Gartman et al. 2022). The Lituya Bay area beach sands were mined by Russians before 1867 and afterward by Americans. A 6 km stretch of beach east of Cape Yakataga was mined for gold in the early 1900s. The Lituya and Yakutat beach sands are estimated to have produced up to 3,700 ounces of gold (Reimnitz and Plafker 1976). Shelf sampling in the Yakataga seaward of the gold enriched sands yielded heavy mineral sands concentrations up to 47% (Reimnitz and Plafker 1976). Gartman et al. (2022) report that the Yakataga beach sands are still being actively explored. The sands contain a heavy mineral fraction including zircon, ilmenite, garnet, and epidote-group minerals (Gartman et al. 2022). Reconnaissance surveys of Bristol Bay noted small amounts of titanomagnetite. Ilmenite is reported in sands around Adak Island. Nearshore REE and tin bearing placers are reported on the Seward Peninsula. Platinum group placers are known in the Goodnews Bay region. Onshore/nearshore placers are varied and rich across many settings in Alaska and exploration for offshore deposits has been limited.

### **2.1.3.4.3.5 U.S. Pacific Islands OCS and EEZ**

#### **2.1.3.4.3.5.1 American Samoa**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific Islands and seamounts through bio geochemical precipitation of phosphate by phytoplankton zooplankton and fish. The American Samoa OCS is prospective for seamount phosphate and island/lagoonal phosphate. The seamount phosphate has not been delineated and the distribution and grades are unknown (Exon 1982; Hein et al. 2005).

The American Samoa OCS is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

#### **2.1.3.4.3.5.2 Baker Reef and Howland Island**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through biogeochemical precipitation of phosphate by phytoplankton, zooplankton, and fish. The Baker Reef and Howland Island EEZ is prospective for seamount phosphate and island/lagoonal phosphate. Baker Reef and Howland Island were claimed for the U.S. under The Guano Islands Act by the American Guano Company. Island/lagoonal guano phosphate deposits were mined from 1850 to 1891. Seamount phosphate deposits were dredged by German scientists in 1985 that were locally high-grade and abundant. The seamount phosphate in the EEZ could be widespread but has not been delineated and the distribution and grades are unknown (Hein et al. 2005).

The Baker Reef and Howland Island EEZ is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

#### **2.1.3.4.3.5.3 Jarvis Island**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through bio geochemical precipitation of phosphate by phytoplankton, zooplankton, and fish. The Jarvis Island EEZ is prospective for seamount phosphate and island/lagoonal phosphate. Over 200,000 tons of guano phosphate were mined on Jarvis Island in the last half of the 19<sup>th</sup> century. Jarvis Island became a U.S. possession through The Guano Islands Act of 1856.

The seamount phosphate has not been delineated and the distribution and grades are unknown but could be widespread (Hein et al. 2005).

The Jarvis Island EEZ is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

#### **2.1.3.4.3.5.4 Johnston Atoll**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through biogeochemical precipitation of phosphate by phytoplankton, zooplankton, and fish. The Johnston Atoll EEZ is prospective for seamount phosphate and island/lagoonal phosphate. Guano phosphate was mined from Johnston Atoll in the last half of the 19<sup>th</sup> and early 20<sup>th</sup> centuries. Johnston Atoll was annexed to the U.S. through The Guano Islands Act of 1856 (Hein et al. 2005).

Seamount phosphorite has been sampled by many cruises in conjunction with cobalt-enriched ferromanganese crust field studies. Seamount phosphorite deposits are likely to be widespread but have not been fully delineated. The distribution and grades are not fully known (Hein et al. 2005).

The Johnston Atoll EEZ is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

#### **2.1.3.4.3.5.5 Kingman Reef and Palmyra Atoll**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through biogeochemical precipitation of phosphate by phytoplankton, zooplankton, and fish. The Kingman Reef and Palmyra Atoll EEZ is prospective for seamount phosphate and island/lagoonal phosphate. Kingman Reef was claimed by the U.S. under The Guano Islands Act of 1856. Palmyra Atoll was part of the Kingdom of Hawaii and became a U.S. possession in 1898. The island/lagoonal phosphorite deposits that are likely present on Kingman Reef and Palmyra Atoll were not mined in the 19<sup>th</sup> century and may be extensive. The seamount phosphate could be widespread in the EEZ but has not been delineated and the distribution and grades are unknown (Hein et al. 2005).

The Kingman Reef and Palmyra Atoll EEZ is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

#### **2.1.3.4.3.5.6 Guam**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through biogeochemical precipitation of phosphate by phytoplankton, zooplankton, and fish. The Guam OCS is prospective for seamount phosphate and island/lagoonal phosphate. The seamount phosphate has not been delineated and the distribution and grades are unknown (Hein et al. 2005).

The Guam OCS is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

#### **2.1.3.4.3.5.7 Midway Atoll**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through biogeochemical precipitation of phosphate by phytoplankton, zooplankton, and fish. The Midway Atoll EEZ is prospective for seamount phosphate and island/lagoonal phosphate. Midway Atoll was annexed to the U.S. in 1867 through The Guano Islands Act but was not mined at the time. Island/lagoonal phosphate may be extensive. However, a drilling program in 1965 on Sand Island and in the lagoon did not recover phosphorite. The seamount phosphate has not been delineated and the distribution and grades are unknown (Hein et al. 2005).

The Midway Atoll EEZ is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

### **2.1.3.4.3.5.8 Northern Mariana Islands**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through biogeochemical precipitation of phosphate by phytoplankton zooplankton and fish. The Northern Mariana Islands OCS is prospective for seamount phosphate and island/lagoonal phosphate. Island phosphorite averaging 20% to 26% was mined by the Japanese from Saipan, Rota, Tinian, and Arguijan Islands in the 1930s. Large reserves of 23% phosphate may remain on Rota and Tinian (Hein et al. 2005).

The seamount phosphate has not been delineated and the distribution and grades are unknown (Hein et al. 2005).

The Northern Mariana Islands OCS is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

### **2.1.3.4.3.5.9 Wake Island**

Local upwelling and associated marine productivity can precipitate phosphate on the flanks of Pacific islands and seamounts through bio geochemical precipitation of phosphate by phytoplankton zooplankton and fish. The Wake Island EEZ is prospective for seamount phosphate and island/lagoonal phosphate. No deposits have been delineated or mined but conditions favor their presence. The seamount phosphate has not been delineated and the distribution and grades are unknown (Hein et al. 2005).

The Wake Island EEZ is not thought to be prospective for HMS. Although heavy minerals do derive from basalts, the lack of deposits is likely to the geometry of the steep profile of the islands, lack of a terrigenous shelf, lack of concentrating mechanisms and structures such as longshore transport and catchments, and wave action that tends to disperse heavy grains oceanward.

### **2.1.3.4.4 Mineral Content**

Phosphorites are composed predominantly (>25%) of carbonate fluorapatite, and thus the major elements found in phosphorites are phosphorus, calcium, silicon, aluminum, iron, magnesium, potassium, and calcium. As such, phosphorite deposits are sourced for their phosphate. Seamount phosphorites contain REE and hence are sourced for their high-heavy REE (avg. 60% of the total REE) (Sakellariadou et al. 2022).

The figure below shows the REE grade in phosphorites sourced from different geological settings in the global ocean. In general, the Peru Margin, Chatham Rise, and Blake Plateau phosphorite samples contain the highest non-phosphate components, detrital aluminosilicates, biogenic silica, and biogenic calcite (Hein et al. 2016).

CRCs and nodules have on average much lower heavy REE volumes as a proportion of the total REE content than phosphorites which contain an average of 49% to 60% of heavy REEs. In the case of phosphorites, HREE volumes come at the cost of ore grade. Crusts have total REE grades up to 1%, but more typically 0.20% to 0.40%, while nodules have lower grades, 0.08% for CCZ and 0.17% for Cook Island nodules. Phosphorites have average total REE grades of 161 to 727 ppm which is much lower than crusts and nodules (Hein et al. 2016).

**Table 14. Mineral content of phosphorite deposits (dry wt. %)**

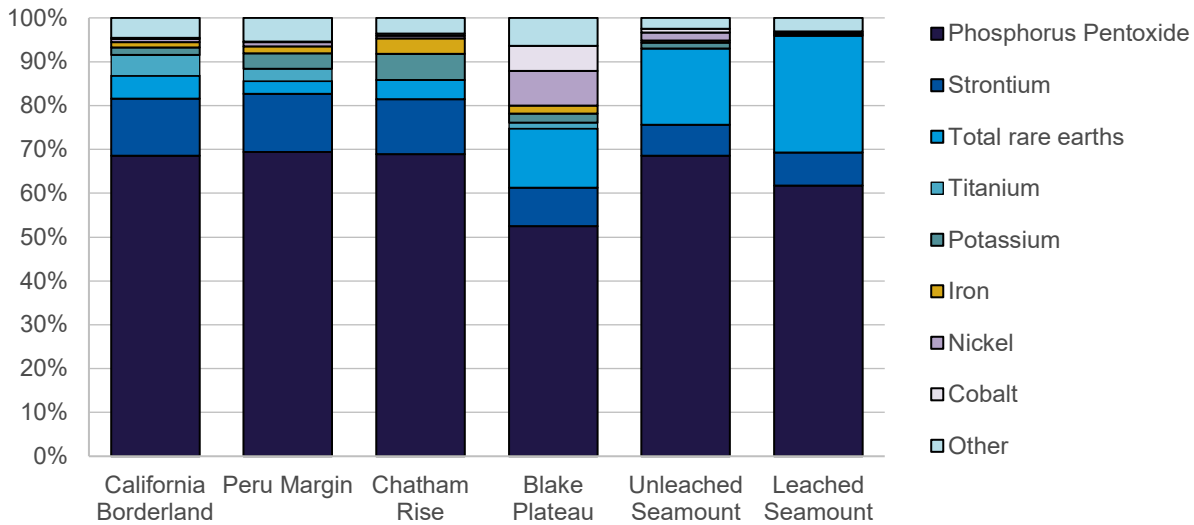
Mineral	California Borderland	Peru Margin	Chatham Rise	Blake Plateau	Unleached Seamount	Leached Seamount
Phosphorus Pentoxide	26.600	22.200	19.200	20.200	29.100	31.000
Total rare earths	0.015	0.007	0.010	0.035	0.050	0.094
Strontium	0.207	0.176	0.145	0.138	0.122	0.156
Barium	0.068	0.014	0.009	0.032	0.048	0.440
Sulfur	1.100	1.400	0.640	0.680	0.680	0.710
Vanadium	0.010	0.006	0.007	0.011	0.003	0.004
Cobalt	0.001	0.000	0.001	0.013	0.002	0.001
Nickel	0.004	0.004	0.003	0.047	0.012	0.002
Iron	1.600	1.720	3.240	2.350	0.660	0.460
Molybdenum	0.001	0.002	0.000	0.002	0.000	0.001
Copper	0.002	0.001	0.001	0.007	0.008	0.004
Lead	0.000	0.001	0.001	0.002	0.001	0.015
Zinc	0.006	0.004	0.003	0.009	0.005	0.008
Manganese	0.008	0.010	0.009	0.911	0.121	0.071
Aluminosilicate	3.940	4.230	7.410	4.040	2.990	2.880
Magnesium	0.710	0.660	0.620	0.650	0.270	0.210
Calcium	30.600	25.200	31.000	31.800	34.700	35.400
Sodium	1.270	1.310	0.700	0.710	0.800	0.660
Potassium	0.410	0.730	1.050	0.510	0.360	0.000
Titanium	0.190	0.090	0.000	0.050	0.000	0.000
Phosphorus	0.000	0.000	0.000	0.000	0.000	0.000
Calcium Phosphide	0.000	0.000	0.000	0.000	0.000	0.000
Sulfur Trioxide	0.000	0.000	0.000	0.000	0.000	0.000
Loss on ignition	11.100	10.600	16.900	16.700	9.140	8.730
Water	4.710	4.490	4.050	3.700	2.220	2.140
Chlorine	0.103	0.183	0.085	0.051	0.121	0.050
Fluorine	2.091	2.216	1.786	2.722	2.577	3.901
Carbon Dioxide	6.310	5.900	5.820	13.000	5.120	6.350
Other Minerals	0.028	0.030	0.025	0.030	0.015	0.012
Unspecified	8.915	18.817	7.284	1.601	10.875	6.702

Data: CRU, adapted from (Hein et al. 2016).

As with other offshore deposit types, location, and mineral content all affect comparability to terrestrial deposits. For a specific example where phosphorites are comparable to terrestrial deposits, most CRC substrates in the Japanese EEZ have been classified as phosphatized limestone and hyaloclastite with 12% to 15% weight phosphorous. The contents of these substrates are like the on-land phosphorous ores that Japan imports from China and Morocco (Hein et al. 2016). However, most phosphorite in the central Californian margin is unevenly distributed and found in deep water, which decreases its economic viability as compared to terrestrial deposits. Phosphorite deposits in waters less than 330 meters have higher mineral concentrations (Mullins and Rasch 1985).

Within the analyzed seabed mineral deposits, phosphorites have by far the largest proportion of deposit value in the form of REEs, which account for up to 27% of the estimated total value based on 2022 prices. The California Borderland and Blake Plateau of particular interest given that these deposits are located within U.S. federal waters off the coast of California and South Carolina, respectively.





**Figure 31. Estimated Mineral Valuation Within Selected Phosphorite Deposits**

#### 2.1.3.4.5 Comparisons to Terrestrial Mining Operations

Looking at terrestrial deposits, in India, monazite reserves are estimated to be about 5 meitnerium, 70 to 75% of which occur in beach placers and the rest in inland and offshore areas. Monazite is an important exploration target for cerium and the associated LREEs and less for HREEs such as terbium (Tb), dysprosium (Dy), and gadolinium (Gd). Bastnäsite (terrestrial) deposits in China and the U.S. constitute the largest percentage of the world’s rare-earth economic resources, while monazite deposits in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the U.S. constitute the second-largest segment (King 2023).

The large onshore phosphate deposits in Florida are extensive Miocene and Pliocene quartz sand, clay, apatite, and calcium carbonate deposits formed in shallow seas within the Hawthorn and Bone Valley formations, respectively. Phosphorus pentoxide (P<sub>2</sub>O<sub>5</sub>) content of 30% to 36% in the phosphorite nodules from these formation with some geographic variance. The Florida phosphate deposits have been mined since the 1880s with typical tonnage of 1.1 million metric tons per km<sup>2</sup> (Cathcart et al. 1952). The Hawthorn Formation extends offshore off Georgia and the Bone Valley Formation likely extends offshore in the Gulf of Mexico OCS (Morrison and Yates 2011).

#### 2.1.3.4.6 Extraction

There has not been any offshore production of phosphorite to date, but there have been system designs and tests. Boskalis, the large global dredging company, has designed a phosphorite mining system for Chatham Rock Phosphate, a company looking to secure environmental permits to begin productions of phosphorite on the Chatham Rise in the EEZ of New Zealand. The phosphorite deposits on Chatham Rise are located off the southern island of New Zealand in water depths of 350 to 450 meters. The production system was designed to mine phosphorite from the 4,726 km<sup>2</sup> mineral property area under license to Chatham Rock Phosphate Ltd. The mining system suspends a drag head and riser from the production vessel. The drag head loosens the soil by a combination of cutting and jetting, mixes the cut material with water, which is pumped up the riser. Separation of phosphorite from other sediment occurs on the production vessel. Sediment is returned at depth via a diffuser (Van Raalte et al. 2013). Offshore phosphate mining systems need to be designed for specific deposits, however, a suspended dredging system such as the Boskalis design for Chatham Rise could be the method that is applicable for other continental margin phosphorite deposit, depending on the extent of cementation or other pavements associated with the deposits.

The same process for separating heavy mineral sand found below the water table applies to nearshore heavy mineral sands. A suction dredge lifts the sand and transports it through a pipe to a preliminary processing station. The processing station will separate HMS from quartz, calcite, feldspar, silts, and clays by magnetic, gravity, electrostatic, and chemical processes. The HMS will be dried and transported for further separation into ilmenite, rutile, zircon, monazite, and others by temperature-controlled magnetic and electrostatic separation and X-ray diffraction (König and Verryn 2021; Patruni et al. 2016).

#### **2.1.3.4.7 Processing**

After separation from sediment rock phosphorite can be quite enriched and if the bulk chemistry does not contain any deleterious elements may require little beneficiation prior to product sale for application as fertilizer or animal supplements. Chatham Rise nodules, for example, grade at 21.5% P<sub>2</sub>O<sub>5</sub>.

Mineral sands deposit mining can require less energy than conventional open pit or underground mining due to their particle structure. Mineral sands can be excavated using wet or dry mining techniques (Van Gosen et al. 2014) (State Government of Victoria 2022). Wet mining involves mechanical dredging of the mineral sands (sifting) from under the surface of a water body. Dry mining uses traditional earth moving equipment such as scrapers, trucks, excavators, and front-end loaders to excavate the mineral sands deposit (State Government of Victoria 2022). Heavy-mineral sands deposits can also be processed utilizing acid leaching mechanisms (Van Gosen et al. 2014). Other proposed concentration techniques include gravity separation by means of spiral concentrators, magnetic separation, high-tension separation, floatation techniques, etc. Gravity separation, specifically, would increase the concentration of the mined sands up to ~90% heavy minerals so that it will be ready for processing and individual separation, thus offering a promising processing technique (Moscoso-Pinto and Kim 2021).

In the example of titanium dioxide (TiO<sub>2</sub>) production, heavy minerals sands are processed from a HMN concentrate. Magnetic separation separates the HMN concentrate into ilmenite + garnet and zircon + rutile. Garnets are separated from ilmenite by gravity separation. Zircon and rutile are separated by temperature controlled electrostatic separation. Both can be homogenized into compositions by X-ray diffraction (König and Verryn 2021). Ilmenite is smelted and reduced with carbon to produce titanium(III) oxide Ti<sub>2</sub>O<sub>3</sub> slag. Magnesium, chromium, vanadium, nickel, manganese, and copper can occur in ilmenite at low concentrations. Ilmenite beneficiated by calcining may release these elements (Van Gosen et al. 2014).

#### **2.1.3.4.8 Synthesis Phosphorites and Heavy Mineral Sands**

In the Atlantic OCS phosphate resources occur from southern Virginia to southern Florida on the Blake Plateau with concentrations documented offshore Georgia, along the Florida platform margin and 130 km southeast of the Georgia-Florida border. The Puerto Rico and U.S. Virgin Islands OCS may also host phosphate deposits on the island flanks and along the boundary of the U.S. Virgin Islands OCS and the British Virgin Island EEZ. In the Gulf of Mexico OCS phosphorite deposits likely extend offshore from the land deposits that are actively mined in the St. Petersburg and Tampa region. In the Pacific OCS phosphorite is an alteration product of Fe-Mn crusts and these are commonly found together in the OCS off southern California. In the Hawaii OCS phosphorite deposits coincident with CRC in the Necker Ridge area and on seamounts in the northern end of the Hawaiian Island chain. Phosphorite may be present in the Alaska OCS coincident with CRC, but few samples support their presence to date. All of the U.S. Pacific Island OCS and EEZ may host phosphorite deposits on island flanks and on seamounts.

CM contained in phosphorite deposits are primarily REE but with coincidence with CRC can also contain cobalt, nickel, barium, and zinc. The economically important minerals are carbonate fluorapatite and phosphate, which are used as fertilizer and animal feed supplements.

The U.S. is a major global producer of phosphate with, at the time, a resource base of 16 billion metric tons in the eastern Coastal Plain phosphate province in Florida and North Carolina (Cathcart et al. 1984).

The same formations extend offshore in the Atlantic OCS off Georgia and likely in the Gulf of Mexico OCS off Tampa Bay. Grades and tonnage are not known but are expected to be large.

Extraction using a cut/jet drag head and lift to a surface vessel, but the systems will vary with water depth.

Processing of phosphorite involves separation from sediment but may require little beneficiation after REY extraction from the produced sediment.

The principal HMS deposits rich in ilmenite, zircon, and monazite is in east central Florida and southeast Georgia where they have been mined since the mid-20<sup>th</sup> century. Barrier islands in this area are enriched in HMS. Transitory nearshore sands bars and buried beach sands are likely to contain HMS but resource sand surveys would need to be undertaken. HMS are also found in beach sands in Mississippi and Texas. Nearshore sands would be dredged, and the heavy fraction would be separated initially by gravity and magnetic methods. Further separation would take place at the processing plant by magnetic and electrostatic methods.

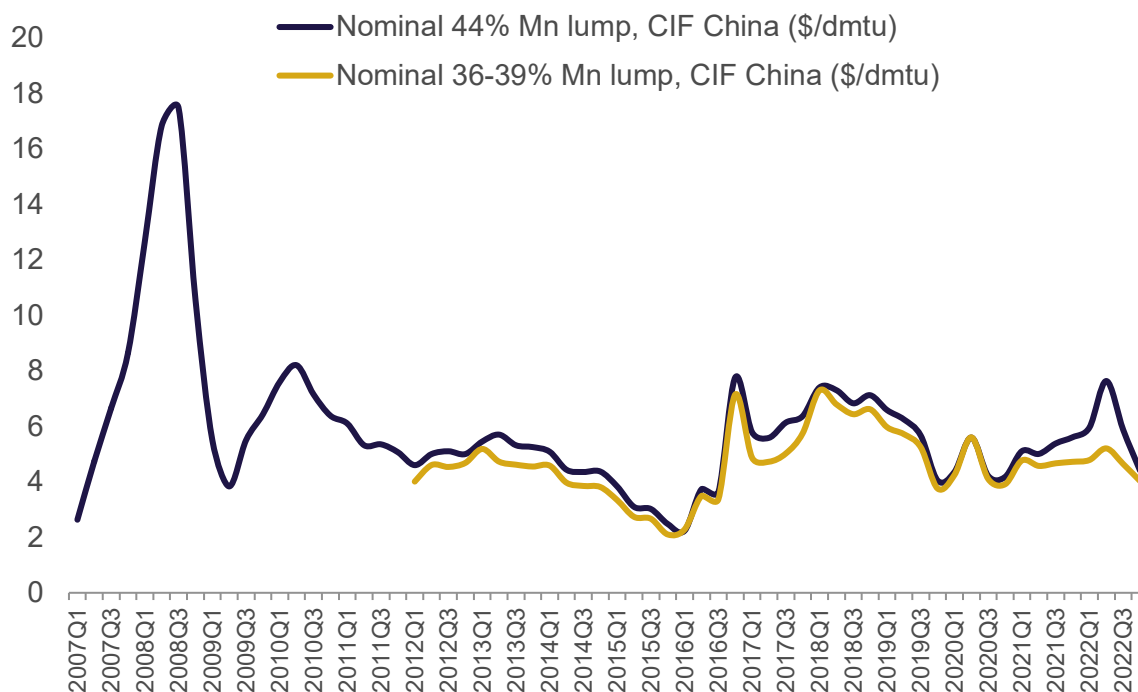
### **3 Recent Commodity Prices and Pricing Mechanisms (CM and Economically Valuable non-CM)**

#### **3.1 Manganese**

Unlike homogenous exchange-traded commodities such as copper and gold, manganese ore is not a standard product with a single value in each market. While for other commodities there is a single, well-defined target product and relatively limited operational flexibility, manganese alloy production has a far greater range of outcomes, including product type, specification, and desired slag characteristics; therefore, there are a larger number of drivers for the value of manganese bearing material.

The most important trade flows of manganese ore are those of semi-carbonate (36% to 39% manganese) ore from South Africa and oxide ore (44%) from South Africa, Australia, and Brazil amongst other exporters. As by far the largest importer of manganese ore, China's import price for medium and high-grade ore are key industry pricing benchmarks for the manganese ore market.

Manganese ore is typically priced in U.S. dollars per dry metric ton unit of contained manganese (\$/dmtu), where a ton unit is defined as 1/100<sup>th</sup> of a ton. A price of \$5/dmtu for a 40% manganese content ore would translate to a price of  $\$5 \times 40\% \times 100 = \$200/\text{ton}$  of ore in dry gross weight terms.



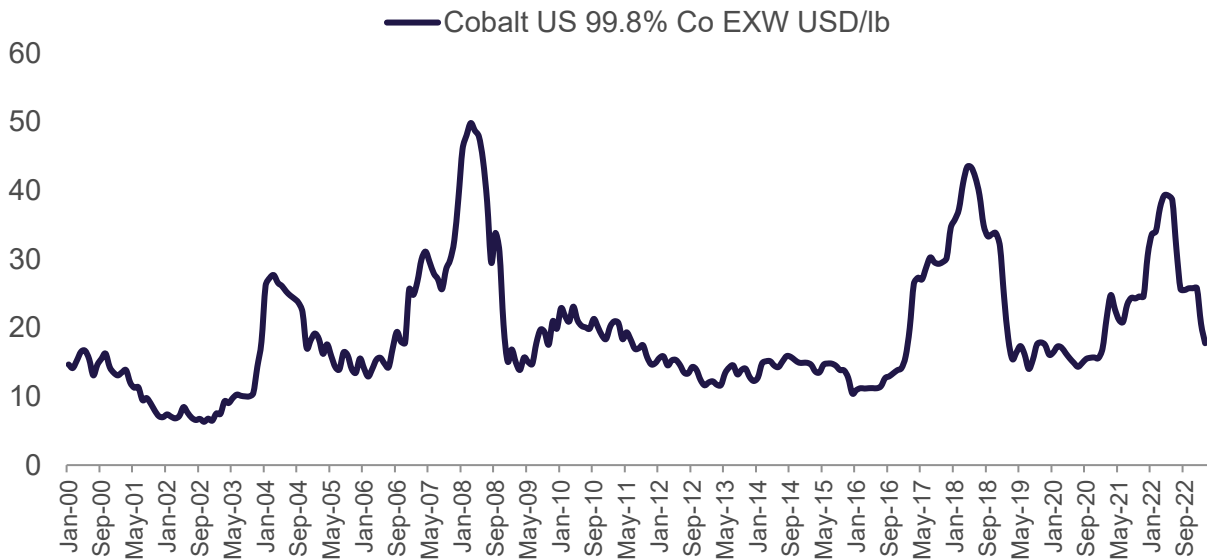
DATA: CRU

**Figure 32. Historical manganese ore prices, quarterly 2007-- 2022, CIF China, \$/dmton**

### 3.2 Cobalt

Cobalt metal prices are reported on exchanges such as the London Metal Exchange (LME), as well as independent price derivation based on regular industry contacts. Cobalt intermediary products, most importantly cobalt hydroxide as this is the typical form of cobalt exported from the DRC, are typically priced as a proportion of a benchmark cobalt metal price.

In addition to cobalt metal, cobalt is often traded in the form of chemicals. Cobalt sulphate is a key component in some lithium-ion batteries for use in electric vehicles, portable electronics and other applications. The price of this chemical closely follows cobalt metal prices because it can be readily converted from cobalt metal by addition of sulfuric acid. Battery grade cobalt sulphate is a value-added product which is not traded at exchanges.



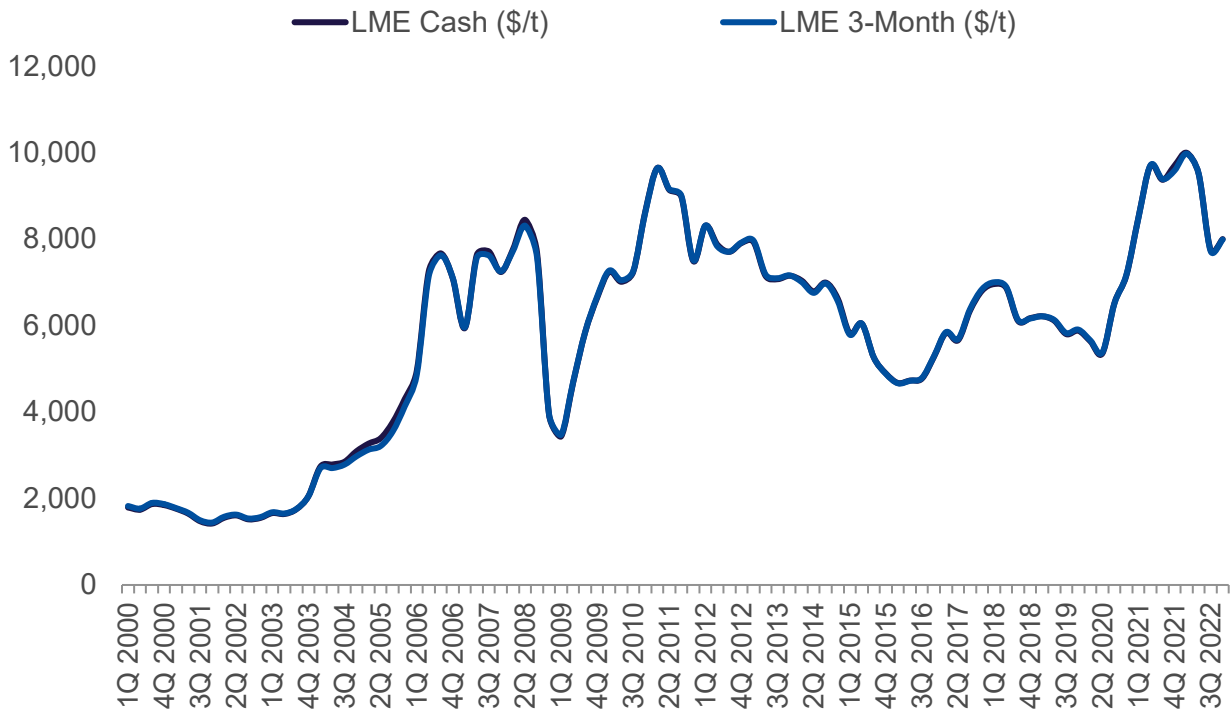
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**Figure 33. Monthly Historical Cobalt Metal Prices, 2000 – February 2023, \$/pound**

### 3.3 Copper

A range of metals, including copper cathode, are traded on the LME, which provides a transparent marketplace for copper pricing. Most of the copper is sold through contracts directly between producers and consumers on the physical market at prices fixed for various periods, but the setting of these prices is heavily influenced by the LME. The LME price refers to copper cathode of a specific purity, import duty unpaid, in LME warehouses around the world. To take physical delivery of duty-paid metal, buyers normally pay an additional charge. The prices of copper raw materials or other forms of copper product are usually related to the LME price. Copper is also traded on the Shanghai Futures Exchange (SHFE) and the Commodity Exchange (COMEX).

Prices within the copper market respond to market fundamentals (supply, demand, and costs) as well as non-fundamental factors (such as the U.S. dollar and investor/fund positioning).

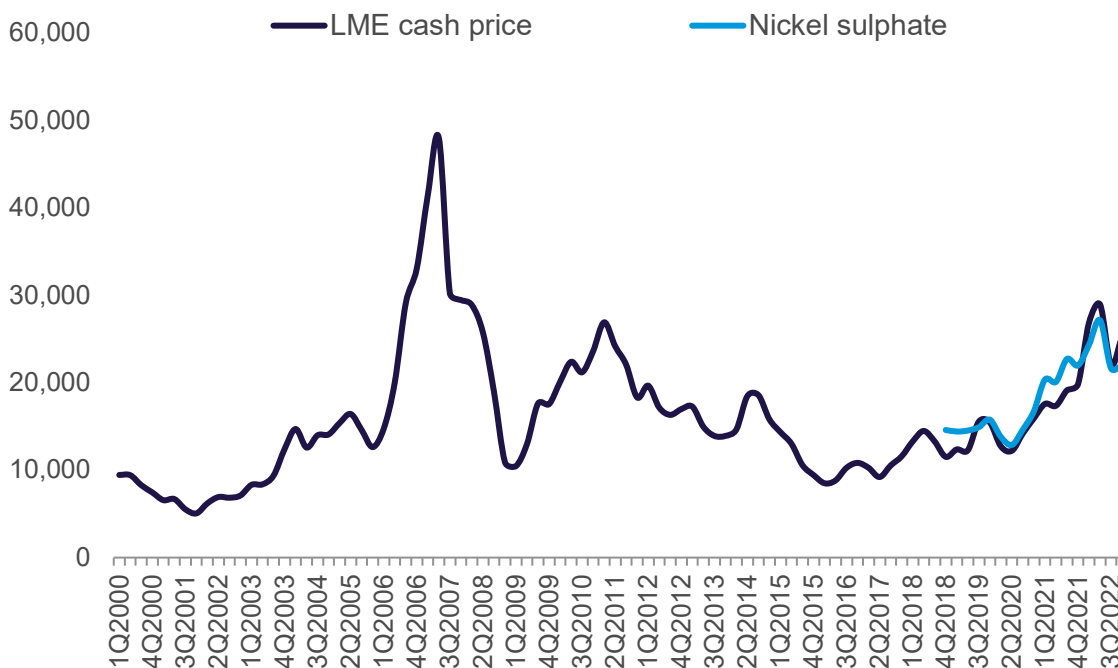


Data: CRU

**Figure 34. LME Cash and 3-month Copper Price, 2000 – 2022 (quarterly), \$/t copper**

### 3.4 Nickel

A range of metals, including nickel cathode, are traded on the LME, which provides a transparent marketplace for nickel pricing. Most of the nickel is sold through contracts directly between producers and consumers on the physical market at prices fixed for various periods, but the setting of these prices is heavily influenced by the LME. The LME price refers to nickel (in the form of cathode, briquettes or pellets) of a specific purity, import duty unpaid, in LME warehouses around the world. To take physical delivery of duty-paid metal, buyers normally pay an additional charge. The prices of other forms of nickel or nickel product are usually related to the LME price. Nickel is also traded on the SHFE.



DATA: CRU

**Figure 35. Historical Nickel and Nickel Sulphate Prices, 2000-- 2022, \$/t contained nickel**

### 3.5 Rare Earth Elements

There is no industry recognized index or commodity exchange guideline for rare earth prices. Typically, Chinese market prices are taken as a reference for negotiations. Prices for chemicals are quoted per kilogram of Rare Earth Oxide (REO or REO equivalent), on a Free on Board (FOB) China basis. There is a huge difference between prices of the most abundant elements (La, Ce, Y), \$1-3/kilogram, and the rarer elements, although all tend to follow a common pattern.

The following factors have driven absolute and relative REO prices:

**The basket problem:** Although deposits and mining regions differ in their REO composition, rare earths are still largely mined as a group globally, and the global ratio is slow in responding to changes in demand for individual elements.

**Chinese market control and politics:** Although the supply—demand balance is an important determinant of prices; this is less so than in other commodities. This is mainly because of China’s dominant position, and the influence of Chinese government policy on the market. This policy is driven by several strategic imperatives, including the need to conserve domestic resources to feed downstream integration into magnet metals, the need to control polluting industries, and the rising importance of REEs as a geopolitical tool. The methods of controlling production include production and export quotas, environmental policy, and the recent consolidation into six main state-owned enterprises.

**Table 15.**  
**Rare Earth Elements Nominal Prices (Global Annual Average Prices), 2018 – 2022, \$/kg REO**

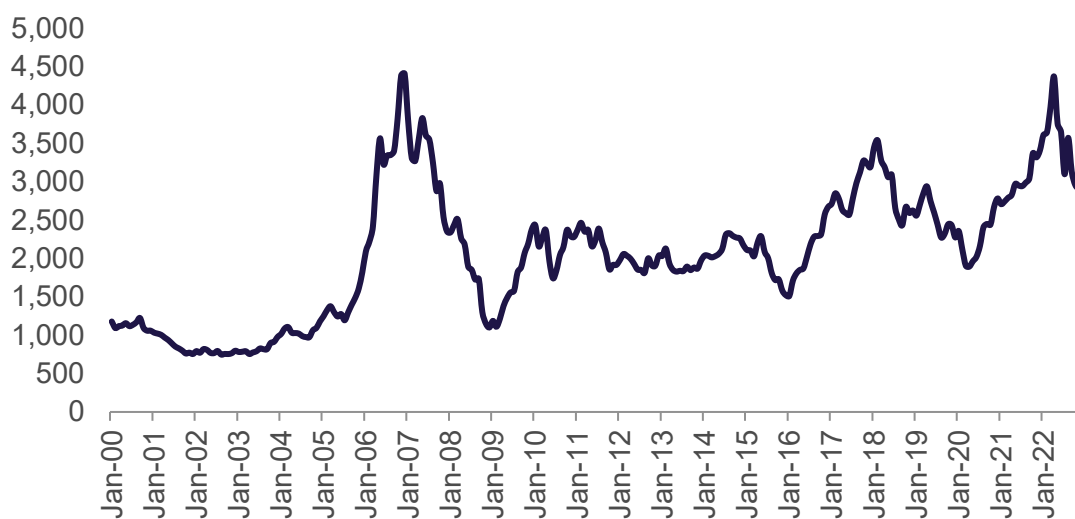
Element	2018	2019	2020	2021	2022
Ce	2.06	1.87	1.68	1.49	1.49
La	2.18	1.87	1.64	1.45	1.45
Pr	63.29	53.78	44.13	93.62	146.68
Nd	49.67	44.37	45.42	99.25	146.68
Dy	176.14	233.09	252.69	410.38	408.60
Tb	452.46	500.30	628.73	1,332.70	2,200.14
Eu	51.09	34.48	29.58	32.80	31.43
Y	3.19	3.00	2.91	4.10	13.62
Sc	1,071.62	1,028.69	929.63	920.00	848.62
Sm	1.89	2.17	2.30	2.31	4.19
Gd	11.38	17.60	12.88	34.40	73.34
Ho	57.87	67.04	62.95	128.00	199.06
Er	25.36	27.75	26.28	35.00	57.62
Yb	18.25	15.93	14.44	16.96	16.76
Lu	638.82	611.55	607.59	832.00	838.15
Global basket price	16.91	16.47	16.85	30.22	41.51

Data: CRU

### 3.6 Zinc

As with many other metals, the international benchmark for zinc pricing is the LME price, established daily and publicly available. This price refers to what is known as “special high-grade,” 99.995% pure zinc.

Zinc concentrate containing typically 50% to 55% zinc is a freely traded product. Zinc miners typically receive 85% of the LME price as payment for the zinc content, less a negotiable treatment charge.

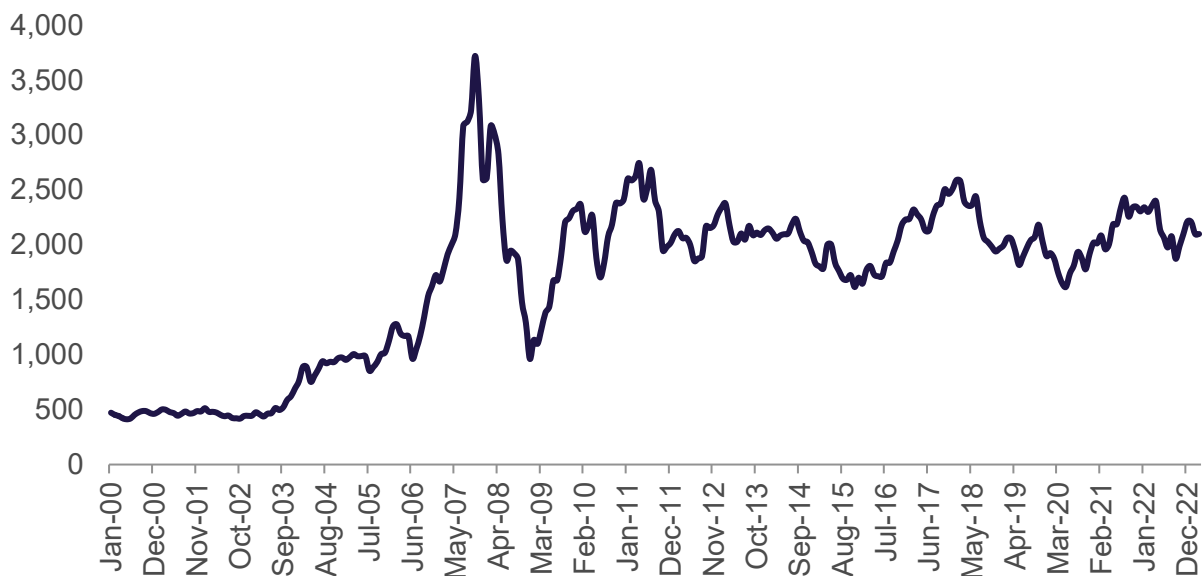


**Figure 36. Historical LME Cash Zinc Prices, 2000— 2022, \$/t**



### 3.7 Lead

LME valuations are used by the industry as the main pricing benchmark. The LME specification calls for 99.97% grade lead, which can be produced by both primary and secondary producers. A higher specification 99.99% (4N) lead tends to trade at a modest premium to LME grade, reflecting the additional upgrading costs for the seller. “Hard” (alloyed) lead typically commands a premium over “soft” (pure) lead, reflecting the cost of alloying. The degree of tightness/metal availability in each market is also a factor that impacts the prices of the two. Most of the lead is supplied to buyers on a long-term contractual basis, with volumes and pricing typically negotiated on an annual basis, though multi-year deals are becoming more prevalent.

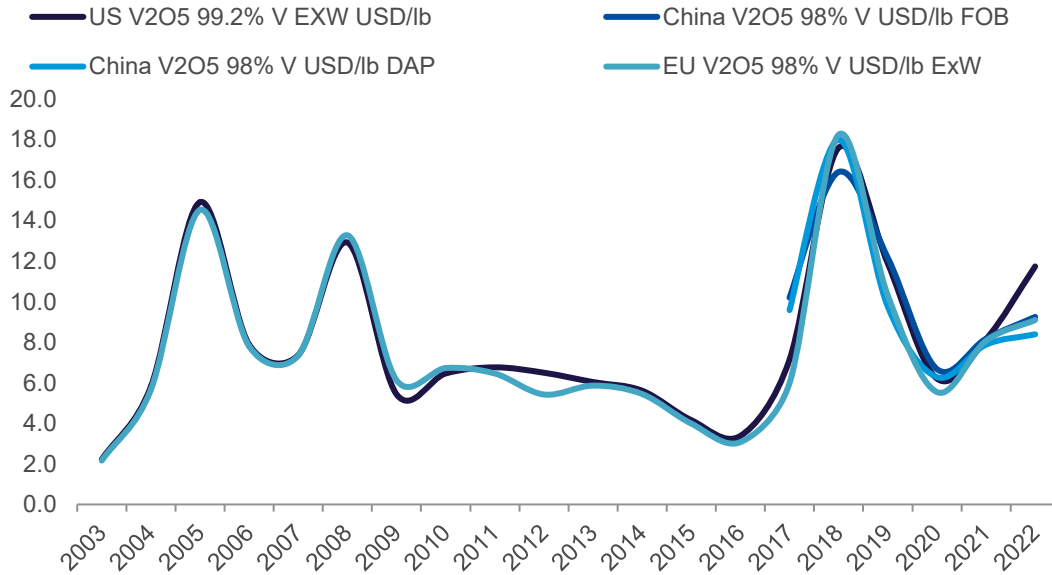


Data: CRU

Figure 37. Historical LME Lead Prices, 2000-- 2022, \$/t

### 3.8 Vanadium

There is no terminal market for vanadium products. In general, the most liquid spot markets exist for ferrovandium, while less liquid markets exist for vanadium pentoxide and vanadium carbide nitride in China. Sporadic purchases occur for other vanadium containing products, which can come on contract or spot; however, there is limited transparency. All vanadium products are principally priced on their vanadium content. Therefore, oxide and alloy prices should generally be comparable, though discounts and premiums are applicable in individual situations.

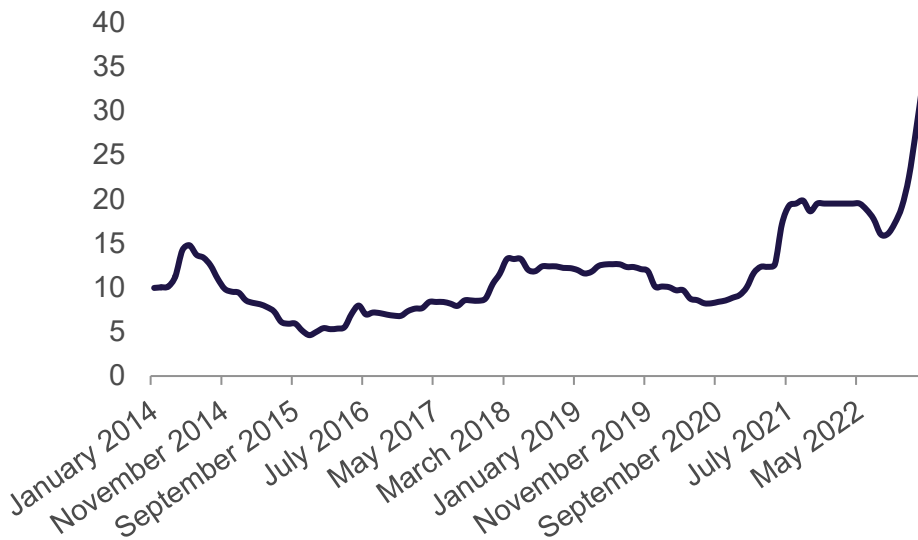


Data: CRU

**Figure 38. Historically Assessed Vanadium Pentoxide Prices, U.S.D/pound V2O5 2003-2022**

### 3.9 Molybdenum

Molybdenum concentrate producers can either sell their product on a spot basis or enter long-term contracts with roasters; with the latter typically generating more favorable terms, as this allows the roaster to better manage capacity utilization. However, long-term contract arrangements may also prove challenging for both parties, due to the high variability in specification/quality delivered from by-product molybdenum concentrate producers. Price benchmarks for molybdenum oxide are priced on a 60% molybdenum benchmark for the U.S. and European Union (EU) and presented on a U.S.D/pound basis.



**Figure 39. Molybdenum Oxide U.S. 60% Molybdenum Ex Works Price, January 2014 – February 2023, \$/pound**

### 3.10 Antimony

Antimony and antimony trioxide (ATO) do not have exchange-backed pricing structures, but rather are reported by several independent price assessors. The products and locations that are known to be reported are shown in the table below. Due to the close relationship between antimony metal and ATO (metal is the key feedstock for ATO production in China), prices are **highly correlated** and affect one another. The table below shows the primary antimony price benchmarks and their respective units.

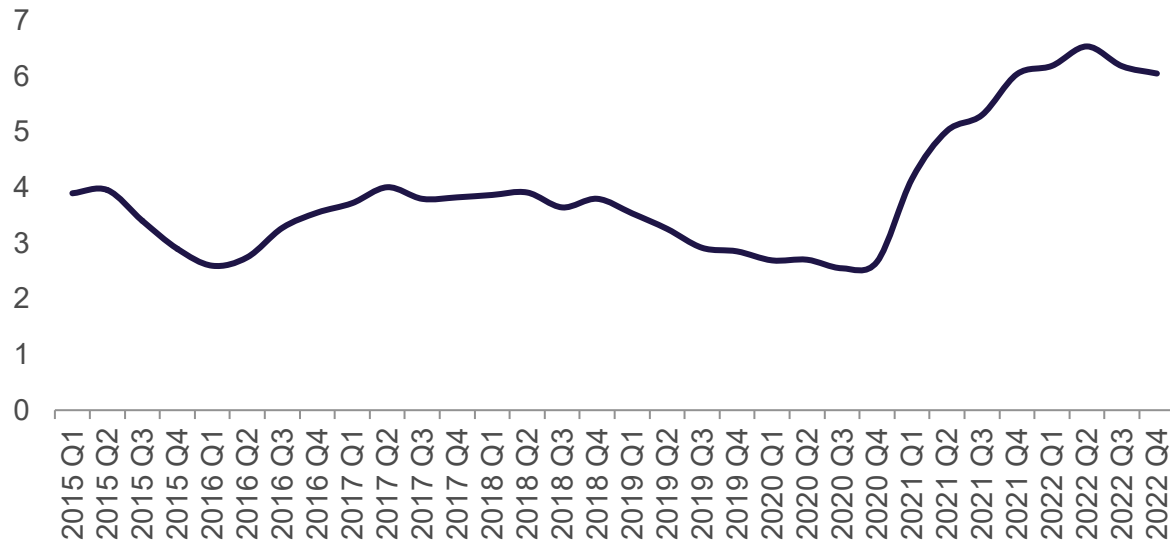
**Table 16.**  
**Antimony Price Benchmarks**

Price Assessor	Price Index Name	Price Base
CRU	Minor Metals U.S. Sb 99.65% Sb EXW	\$/pound
CRU	Minor Metals EU Sb 99.6% Sb EXW	\$/t
Fastmarkets	Antimony max 100 ppm Bi, in-whs Rotterdam	\$/t
Fastmarkets	Antimony MMTA standard grade II, ddp China	yuan/t
Fastmarkets	Antimony MMTA standard grade II, in-whs Rotterdam	\$/t
Asian Metal	Antimony trioxide 99.5% min FOB China	\$/t
Asian Metal	Antimony ingot 99.65% min FOB China	\$/t

DATA: CRU, Fastmarkets, Asian Metal

Antimony prices are driven by the following three factors:

- **Demand in end-use markets:** Due to widespread usage of antimony in everyday applications – e.g., flame retardants, plastics, and positron emission tomography (PET) – this has been relatively stable.
- **Supply availability in China:** China holds a highly dominant position in global supply, and so fluctuations in Chinese supply transit into price fluctuations worldwide. Ore availability and the increasing stringency of environmental restrictions have been major factors influencing supply availability.
- **International competitiveness of Chinese antimony:** Factors such as the country’s relative cost of production (wages, power, and exchange rates) and ease of trade (noting trade tensions with the U.S.) can influence price.



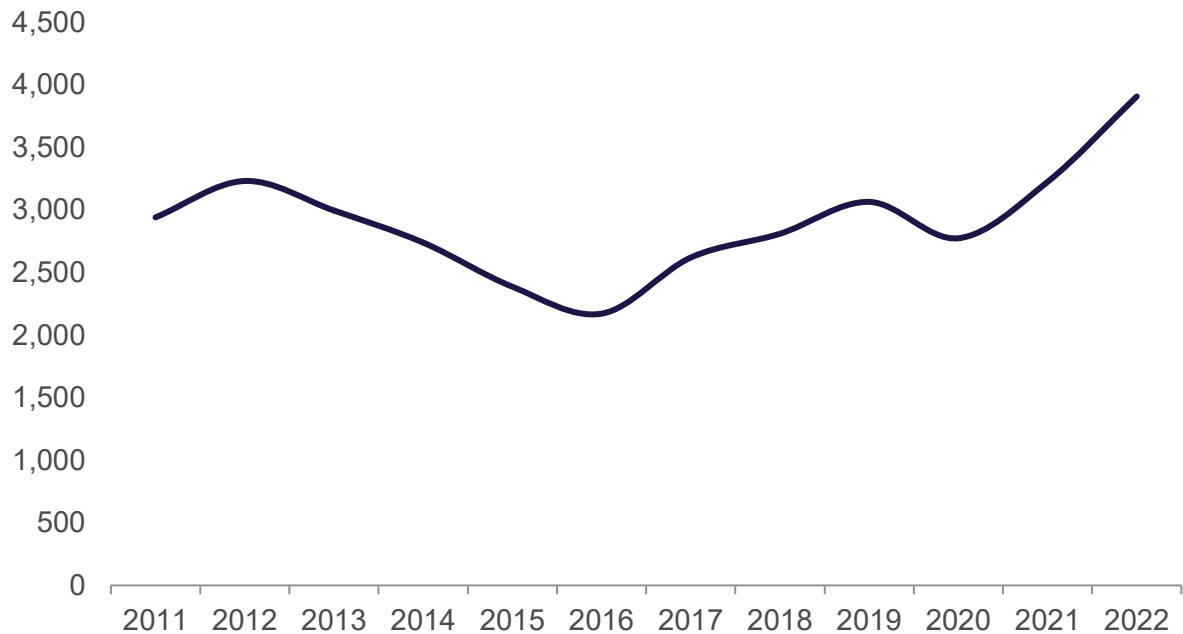
DATA: CRU

**Figure 40. Quarterly Antimony Prices, U.S. EXW, 99.65% Antimony, \$/pound**

### 3.11 Titanium

There is no broadly adopted benchmark price for titanium dioxide (TiO<sub>2</sub>) concentrate, with mineral sands traditionally being sold based on long-term contracts. For TiO<sub>2</sub> pigment prices, there is also no standard market price as prices agreed are dependent on product specification and producer brand. The most widely available source of data for both concentrate pricing and pigment pricing comes from the USGS, which provides historical unit prices in the U.S. for ilmenite, rutile, slag, and pigment.

Trade data may also give a helpful approximation of trends; however, this is generally muddled due to a lack of product detail (specifications, Incoterms, spot and/or contract, and so on). CRU has assessed prices for U.S. imports of titanium dioxide (Harmonized System of Nomenclature code 282300 from 2011-2022). This import price has been used for the mineral valuation for titanium contained within the PMNs.



DATA: CRU, S&P Global

**Figure 41. U.S. Import Prices of Titanium Dioxide, 2011-2022, \$/t**

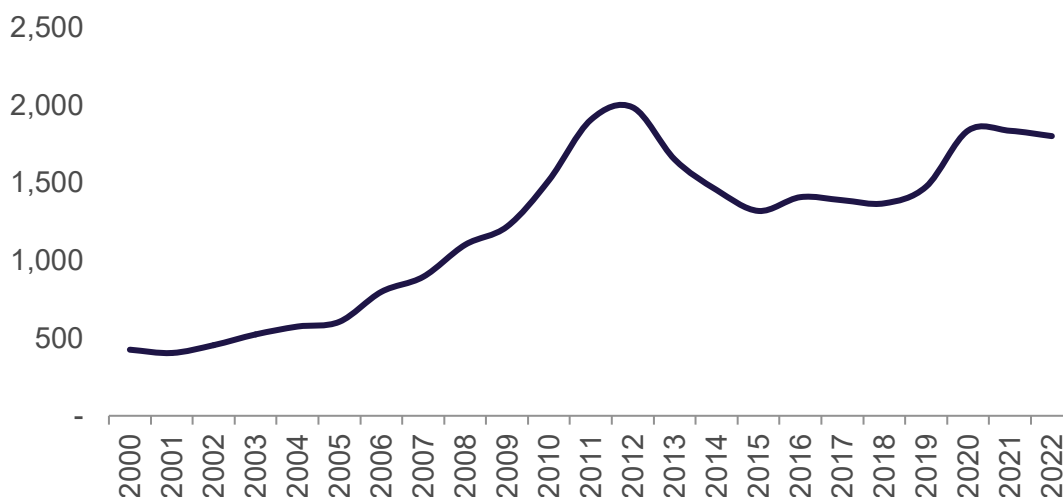
### **3.12 Gold**

LME Gold combines daily prompts (including spot) out to 25 days with monthly and quarterly dates along a tradeable five-year forward curve. In this way, the system seamlessly blends the daily structure of the London over the counter market, and the monthly futures approach of existing exchange offerings. Gold prices are typically reported in U.S.D/ounce.

**Table 17.**  
**Key Drivers of Gold Price Fluctuations**

<b>Inflation Expectations</b>	As a hedge against devaluation of currencies due to high inflation rates.	Increase in gold price in 2009 was among others due to the fear that monetary expansion would lead to higher inflation eventually.
<b>Interest Rates</b>	Main difference from bonds is that gold pays no interest. Low interest rates increase the appeal of holding gold, while high rates lower it.	Negative real rates experienced in the 1970s correlate with an increase in the price of gold and low interest rates also contributed to their increase in 2012.
<b>U.S. Dollar</b>	A strong dollar is generally negative for gold and vice versa. An appreciation of the dollar reduces production costs in countries that depreciated against the dollar. An upward dollar reduces buying power of non-dollarized economies, pushing down price of commodities.	A strong dollar during 2014-15 is one of the main reasons behind the fall in gold prices during that period.
<b>Safe Haven</b>	Gold is seen as a haven in times of financial crises and/or geopolitical risk	Uncertainty causes upward pressure on gold price, although it is usually temporary, depending on the nature of the event. E.g., 2009 GFC, post-2011 eurozone debt crisis as well as during the height of the Covid-19 pandemic.
<b>Portfolio Diversification</b>	Gold is valued (usually less) as a component in investment portfolios due to its low correlation with other assets such as bonds and stocks	Over the past decade, portfolio diversification was a major cause in the increase of investment vehicles such as exchange-traded funds (ETFs).
<b>Central Bank Positions</b>	Central banks, including the IMF own more than 15% of the world's gold stock	One factor that contributed to a depressed market for gold (bear market), was that the Central Banks took on a predominantly commercial role between 1989 and 2009.

Source: CRU



DATA: CRU

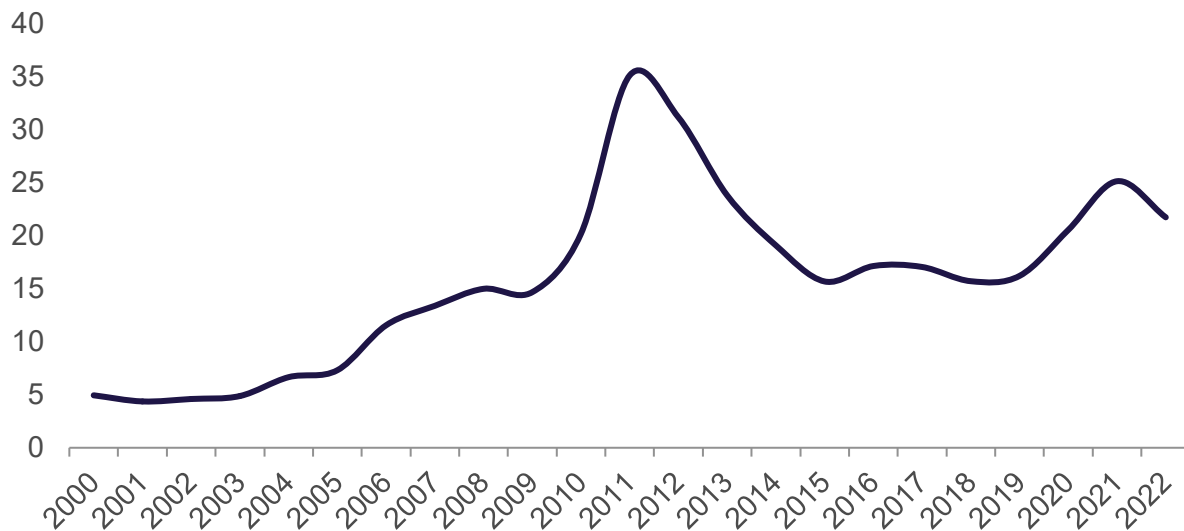
**Figure 42. Historical Gold Prices, 2000-- 2022, \$/oz**

### 3.13 Silver

**London Bullion Market Association:** The price of silver is determined daily at the London Bullion Market Association (LBMA). This reflects the daily dynamics of the physical silver market and sets the price in U.S.D per Trojan ounce.

**New York Mercantile Exchange and Commodity Exchange:** The spot price of silver is determined by the forward month's futures contract with the most volume. At times, this contract can be the current month, or it might be two or more months out in time. The spot price fluctuations of silver today are mostly determined by the COMEX. The COMEX division of the New York Mercantile Exchange is still the most significant future contract trading market for silver and consequently it has the most influence on silver's fluctuating worldwide fiat currency spot price values.

The physical market for silver bullion items tracks the silver spot price but silver bullion product prices hover over the silver spot price. In other words, if silver's spot price is \$20 ounce, you will find most bullion products priced above \$20 ounce.



DATA: CPM, USGS, WBMS, COMEX, LME, TOCOM, LBMA, SHFE, Company Accounts, CRU

**Figure 43. Historical silver prices, 2000— 2022, \$/ounce**

Summary of Known Critical Minerals in in U.S. Federal Waters: The U.S. OCS and EEZ is endowed with CM in each of OCS and EEZ regions but less so in the Gulf of Mexico OCS where CM deposits appear to be limited to possible nearshore phosphorites off west central Florida and modest heavy mineral sand in beach deposits off Mississippi and Texas. Scientific research exploration efforts supported by the USGS and other institutions to understand the formation and distribution of deep sea mineral occurrences such as PMN, CRC, and SMS has laid the foundation for needed exploratory activities and resource assessments.

Figures 2 through 15, 26, and 27 show the major and minor CM that are found deep sea mineral deposits in U.S. OCS and EEZ. PMN and CRC share similar polymetallic mineral assemblages because they form, in part, by similar mechanisms. SMS deposits are found in the Pacific OCS off northern California and Oregon and in the Guam and Northern Mariana Island OCS.

In general, abundant PMN are found in the Pacific where water depths range from 3,000 meters to 6,000 meters on abyssal plains on sediments composed of pelagic silicious or calcareous oozes or red clays. Biogeochemical influences largely determine abundances since it is thought that organic biofilms aid the mineral fixation and precipitation process. In general, PMN areas are biodiverse with very low biomass. Some fauna need hard substrates such as deep sea sponges and corals use PMN.

Knowledge of PMN occurrence in the U.S. Pacific OCS and EEZ is assembled from scientific cruises that were not designed as resource assessments. The most promising areas for resource surveys are those geographically proximate to known abundant PMN deposits such as the Kingman Reef and Palmyra Atoll EEZ which is on the western boundary of the ISA issued contract areas and Jarvis Island EEZ, which is geographically proximal to PMN deposits in the Cook Islands EEZ. An arc along the eastern boundary of the Northern Mariana Islands OCS may be prospective for abundant PMN. It is proximal to newly issued PMN contract areas issued by the ISA to Beijing Pioneer Hi-Tech Development Corporation. Similarly, the Wake Island EEZ should be prioritized for PMN resource exploration.

In the Atlantic OCS, the Blake Plateau is an area where resource surveys for PMN would be beneficial. These current driven PMN deposits where the current keeps sediment from accumulating and is the source of dissolved minerals are also coincident with CRC and phosphorites.

A good example of the techniques and methods for PMN exploration and resource assessment is outlined in McConnell et al. (2018) and in the NI43-101 resource disclosures issued by Nauru Ocean Resources Inc., and DeepGreen Metals now dba as The Metals Company (AMC Consultants 2019).

CRC and PMN have many similarities in mineral content and in how and where they form with the exception that CRC tend to be found on seamounts and on un-sedimented ridges between 400 meters and 7,000 meters in places where currents keep the seabed free of sediment accumulation. Thicker CRC tend to be found on seamounts where the flanks of the seamounts intersect the OMZ because low oxygen water contain more dissolved Mn. The OMZ transects across ocean basins between 800 meters and 1,200 meters. CRC growth is aided by bacterial activity in pods of ocean productivity around seamounts that otherwise are in low ocean productivity areas. Biomass and biodiversity on seamounts are active areas of research. The marine ecology on seamounts differs across oceans and latitude but also fish and sessile habitats change vertically on any given seamount that include zones of high biomass and high biodiversity.

CRC have been well documented by USGS and other research scientists in the Pacific OCS off southern California. Areas within the U.S. OCS and EEZ supported by scientific research that remain underexplored and promising for significant CRC deposits are the U.S. Pacific Island OCS and EEZ, especially those are within and proximal to the PCZ. These include the Northern Mariana Island and Guam OCS, Wake Island EEZ, Howland Island and Baker Reef EEZ, Hawaii OCS, Johnston Atoll EEZ, and Kingman Reef and Palmyra Atoll EEZ. Also prospective for CRC is the American Samoa OCS and Jarvis Island EEZ.

These environmental considerations will need to be carefully studied and assessed before any mineral extraction feasibility study is done. However, the ISA issues CRC contract areas in international waters, and the ISA's technical committees are tasked with addressing these questions. This should not preclude environmental and resource surveys. Efficient and cost effective resource surveys can be done using a rapid drop cobalt crust sampler supported by hull mounted multibeam. Environmental and habitat surveys can be accomplished with AUVs equipped with high resolution multibeam, an array of environmental sensors and cameras. ROV surveys are the slowest and hence most expensive but are useful for precision and interrogative sampling.

SMS deposits show present-day mineralization processes and help complete the circle in understanding the origin of important VMS deposits that had formed on the ocean floor in the past but are now on land. SMS deposits can occur where new seafloor is being created at spreading centers and where old seafloor is being destroyed at subduction zones.

SMS deposits in the U.S. OCS and EEZ are in the Escanaba Trough in the Pacific OCS off northern California and Oregon. These copper-zinc-cobalt-silver deposits forming in a seafloor spreading center are analogous to the large Windy Craggy onshore VMS mineralization in western Canada. SMS deposits



in the Guam and Northern Mariana Islands OCS are forming where seafloor is being destroyed at subductions zones. The SMS deposits in the Guam and Northern Mariana Islands OCS are analogous to Kuroko-type VMS deposits in Japan.

Active vents at SMS deposits are high biomass and biodiverse environments populated by dense chemosynthetic communities including tubeworms, clams, and mussels around which non-chemosynthetic megafauna such as crabs, sponges, shrimp, and fish abound (Carey et al. 1987; Van Dover et al. 1990; Van Dover and Hessler 1990). Hydrothermal vents are transient and ephemeral. The chemosynthetic communities quickly die off when the active vent shifts to another location and rapidly recolonize to the newly active vent. The non chemosynthetic mega fauna move to the environment that suits their feeding needs and competitive hierarchy. It is common to find 'dead' zones with the remains of chemosynthetic communities around and off axis from the main active vent sites. In addition to the high temperature challenges at active vents, SMS prospectors tend to look for mineralization at inactive sites with lower biomass.

The ISA awards SMS contract areas in international waters and their technical commissions are addressing practices to mitigate impact on habitat and environment. Vent fauna appear to be much more resilient than megafauna in CRC and PMN habitat primarily has a function of food supply in the different habitats. Norway has developed regulations for deep sea mining and the government has submitted a proposal to open areas for deep sea mining to the Norwegian Parliament that if passed, could be in effect by the end of 2023 (Fouche and Adomaitis 2023).

In contrast to PMN and CRC, SMS deposits are three-dimensional. Most of the sampling of SMS deposits has been through analysis of vent fluids and surficial samples at and in the vicinity of sulfide chimney structures at active or inactive hydrothermal vent sites. The grade and tonnage of altered and enriched sediment and stockwork will not be understood until the deposits are drilled and cored. Very few SMS deposits have been systematically drilled. Exploration methods include water column chemistry surveys and multibeam water column images to find active vents followed by AUV or deep tow electromagnetic surveys to identify surface and buried alteration zone in inactive, blanketed, and off axis area to identify drilling prospects. Once prospects are drilled and cored by geotechnical drillship or seafloor drill, then high resolution ocean bottom seismic or high-resolution three dimensional (3D) seismic surveys can provide imaging of the stockworks, and base of mineralization needed for volume and pre-feasibility studies.

The U.S. OCS and EEZ is also endowed with CM found in nearshore phosphorite deposits and HMS. Both phosphorite and monazite HMS are sources of REY CM. The principal phosphorite deposits are continuous with world class land phosphorite deposits in Florida and southeast Georgia. Offshore extensions of phosphate bearing formations are confirmed off Georgia in the Atlantic OCS and are likely off central Florida in the Gulf of Mexico OCS. Phosphorite deposits are coincident with CRC deposits in the Atlantic OCS on the Blake Plateau, and the Pacific OCS off southern California, the Hawaii OCS and associated with CRC prospective areas in the U.S. Pacific Island OCS and EEZ. Coincidence with biologic communities is expected to be site-specific.

The principal HMS deposits rich in ilmenite, zircon, and monazite is in east central Florida and southeast Georgia where they have been mined since the mid-20th century. Barrier islands in this area are enriched in HMS. Transitory nearshore sands bars and buried beach sands are likely to contain HMS but resource sand surveys would need to be undertaken.

Side scan, multibeam echosounder, sub-bottom profiler, and induced polarization electromagnetic surveys combined with vibracoring, and a mobile HMS separation lab would be methods used for offshore HMS resource surveys.

## 4 Service/Industry Overview

Because there is not yet an active industry in deep sea minerals, a robust service industry for deep sea minerals has not yet evolved. To help understand the U.S. and global resource survey capability for deep sea marine mineral has evolved into 1) government-supported national marine research institutions that use their own limited marine site survey resources for their own government's purposes in their own EEZ or to support their state-sponsored ISA marine mineral concessions, and 2) capable commercial marine survey and site characterization companies with broad, modern assets and new technologies that could be applied to deep sea mineral resource survey and production support but are generally depth limited to the deepest application for deep water oil and gas—3,000 meters.

The U.S. and global marine survey capability was fostered and advanced through collaboration by governments, navies, and marine research institutions, especially since the 1950s. Tools and techniques first developed for simple sonar depth mapping and for imaging shallow sediments, for example, evolved into the modern multibeam echosounder used today. Similar cooperation occurred in other nations such as the United Kingdom (UK), France, Germany, Australia, New Zealand, Japan, China, Korea, and Russia to produce the marine survey toolkit. The modern manifestations of these national marine research institutions provide the marine survey support for marine minerals in their own national EEZ and in their state-sponsored ISA issued exploration blocks, such as Japan's JOGMEC (Japan), KIOST and KORDI (Korea), Yuzhmorgeologiya (Russia), COMRA (China), Ifremer (France), and GEOMAR (Germany).

The development of a commercial marine survey was largely driven by offshore oil and gas development, provision of hydrographic services, applied oceanographic services, and nearshore engineering in ports and harbors. Marine technologies used to support oil and gas split into two camps. The first camp that led the way was the offshore two dimensional (2D) and 3D seismic survey industry that made important advances in deep water oil and gas exploration that became a multi-billion dollar business in the 1990s and 2000s. The advanced technology used in this first camp to image deep water oil and gas reservoirs does not translate well to marine mineral applications except for the subcategories of ocean bottom seismic and controlled-source electromagnetic methods, but these would need to be redesigned for marine mineral applications.

In the second camp are the marine site survey companies that evolved within the safety and regulatory framework associated with offshore oil and gas development that also used their assets as hydrographic service providers. These companies used the same hydrographic tools as academic research institutions: the modern suite consists of multibeam echosounders, side scan sonar, sub-bottom profilers, and high resolution 2D (HR2D) and 3D (HR3D) seismic systems and seabed sampling systems.

The second camp also supported oil and gas companies' efforts in deep water, so they acquired and developed technologies such as ROVs, AUVs, deepwater geotechnical drill ships and seafloor drills. These companies also acquired vessels equipped with deep water multibeam systems to support the telecom industry.

It is in the second camp that a commercial marine mineral resource survey and support capability will arise if the market supports it. However, these companies would need to invest in deepwater AUV and ROVs capable of operating at depths of 4,000 meters to 6,000 meters.

It is also important to note that the private companies that are working to develop deep water marine mineral projects do not own marine survey assets but instead contract them out from marine site survey companies that have some assets that can be deployed deeper than 3,000 meters.

Other providers are companies that support navies with equipment for deep sea salvage such as ultra-deep ROVs (4,500 meters or deeper) and ultra-deep water winches (4,500 meters to 7,000 meters).

## 4.1 Methods

This section was compiled by SMEs with experience in deepwater marine site characterization, familiarity with the companies involved, and knowledge about applications of the general commercial marine site survey capability to deepwater and near shore marine mineral resource surveys.

## 4.2 Findings

Currently, existing facilities on land will likely be refining the deep-sea minerals as these facilities are already designed for refining minerals, which dominantly occur in PMNs. Although these existing facilities are designed for the refinement of onshore resources, the same technologies are required to process the same minerals from deep-sea resources. An example of this type of contract between an entity who will harvest deep-sea minerals was announced in 2023 by TMC. TMC entered a non-binding Memorandum of Understanding (MoU) with Pacific Metals Company LTD (Pamco) in Japan. TMC, based in Canada, is among companies who already have rights in the CCZ to begin commercial operations to mine PMNs when the ISA regulations are finalized. Pamco is designing facilities to effectively process these nodules and is estimating the costs of processing the nodules with their existing facilities.

The MoU between TMC and Pamco is the only published indication showing how minerals may be processed after harvesting. Companies with similar models and facilities to Pamco may be similarly contracted to process PMNs and other deep-sea minerals. Other companies who process minerals and materials mined onshore with similar compositions to PMNs include almost no competitive companies based in the U.S., except for MP Materials, headquartered in Nevada, who is a top company in producing REE resources.

## 4.3 U.S. Companies Involved in Polymetallic Nodule Activities

**Company:** Impossible Metals, Inc.

**Size/Year of Formation:** <20 full-time employees (FTE)/ 2020

**Headquarters:** Pasadena, CA

**U.S./Non-U.S.:** U.S.

Impossible Metals designs and builds underwater robotic vehicles which collect critical battery metals from the seabed while protecting the seafloor ecosystem. Impossible Minerals have signed a partnership with a global offshore logistics company that, as a member of a consortium, holds a seabed mining exploration permit. Impossible Metals delivered a Stage 1 Proof of Concept on both robotics and bioextraction in early 2023 called the Eureka 1.

- Operator/junior miner involved in research and development of unique extractors for own projects.
  - a. Novel approach to extraction by picking individual nodules off the seafloor with a robotic collector/extractor to reduce environmental impacts.
- Unknown if qualifies as U.S. small business.

**Company:** Seafloor Investigations LLC

**Size/Year of Formation:** <20 FTE/ 2009

**Headquarters:** Bellingham WA

**U.S./Non-U.S.:** U.S.

Seafloor Investigations LLC is a turnkey geologic and environmental nodule collection contractor/laboratory management.

- Exploration/characterization contractor

- a. Nodule resource and environmental data acquisition specialist. Instrumented box cores. Mobile labs. Contractor for several CCZ Operators.
- Qualifies as small businesses.

**Company:** Argeo

**Size/Year of Formation:** <50 FTE/ 2017

**Headquarters:** Asker Norway

**U.S./Non-U.S.:** U.S. (satellite office)

Argeo is a geophysical contractor specializing in AUV.

- Exploration/characterization contractor
  - a. Assets for nodule exploration includes one vessel and four AUV of which three are rated to 6,000 meters.
- Unknown if qualifies as U.S. small business.

**Company:** Fugro

**Size/Year of Formation:** >5,000 FTE/ 1962

**Headquarters:** Leidshendam, Neth.

**U.S./Non-U.S.:** U.S. full assets and operations

Fugro is a full service land and marine data acquisition and geotechnical contractor and positioning specialist.

- Exploration/characterization contractor
  - a. Assets for nodule exploration includes a global fleet of geophysical/light geotechnical vessels, two 4,500 meters rated AUV and management and access to one 6,000 meters AUV. Have scientific consultants on staff. Full metocean services capability (ROV).
- Does not qualify as small business.

**Company:** Ocean Infinity

**Size/Year of Formation:** <500 FTE/ 2016

**Headquarters:** Austin, TX

**U.S./Non U.S.:** U.S. (Survey Ops Center in Sweden)

Ocean Infinity is an AUV specialist and marine survey contractor that is developing autonomous vessels.

- Exploration/characterization contractor
  - a. Assets for nodule exploration includes multiple vessels and more than eight AUV of which all are rated to 6,000 meters. Pioneered deployment of multiple AUV. Has traditional marine survey assets and operations.
- Does not qualify as small business.

**Company:** Saildrone

**Size/Year of Formation:** <50 FTE/ 2007

**Headquarters:** Alameda, CA

**U.S./Non U.S.:** U.S.

Saildrone is an innovator in low cost autonomous deep-water ocean mapping.

- Exploration/characterization contractor

- a. Assets for nodule exploration are the Sairdrone vehicles that can provide low hull mounted multibeam bathymetry uncrewed and autonomously. Limited to seafloor mapping.
- May qualify as small business.

**Company:** Odyssey Marine Exploration

**Size/Year of Formation:** <50 FTE/ 1994

**Headquarters:** Tampa, FL

**U.S./Non U.S.:** U.S.

Odyssey Marine Exploration is an Operator/junior miner. Odyssey delineates marine minerals and seeks licenses to explore and exploit. Odyssey has polymetallic license in Cook Island through subsidiary community interest company (CIC).

- Operator/junior miner involved in exploration/characterization for own projects.
  - a. Has some marine survey equipment but contracts for others.
- Unknown if qualifies as U.S. small business.

**Company:** Ocean Minerals LLC dba Moana Minerals

**Size/Year of Formation:** <20 FTE/ 2016

**Headquarters:** Houston, TX

**U.S./Non U.S.:** U.S.

Ocean Mineral LLC is an operator/junior miner. Ocean Minerals LLC delineates marine minerals and seeks licenses to explore and exploit. Ocean Minerals LLC has polymetallic license in Cook Islands through subsidiary Moana Minerals.

- Operator/junior miner involved in exploration/characterization for own projects.
  - a. Operates a geophysical marine/research vessel. Allied with Deep Reach Technology for exploitation engineering services.
- Qualifies as small business.

**Company:** Deep Reach Technology

**Size/Year of Formation:** <20 FTE/ 1981

**Headquarters:** Houston, TX

**U.S./Non U.S.:** U.S.

Deep Reach Technology offers engineering services for the development of polymetallic mining systems.

- Engineering contractor for exploitation/extraction.
  - a. Engineering services. Involved in pioneering nodule exploitation design for PMNs.
- Qualifies as small business.

**Company:** Allseas

**Size/Year of Formation:** >3000 FTE/ 1985

**Headquarters:** Châtel-Saint-Denis, Switzerland

**U.S./Non U.S.:** U.S. full assets and operations

Allseas is a major offshore contractor specializing in special purpose ships for pipelay and heavy lift. For PMNs, it is an exploitation facilitator for junior miners. It agreed to engineer and convert a drillship for TMC to develop their polymetallic mineral properties in the CCZ. Successful full integrated nodule collection and lift test was performed in 2022 in the CCZ. It is also investing with other sponsoring states to explore for nodules in the CCZ.

- Exploitation/extraction operator
  - a. Drill ships and engineering.
- Does not qualify as small business.

**Company:** Transocean

**Size/Year of Formation:** >5,000 FTE/1973

**Headquarters:** Vernier, Switzerland

**U.S./Non U.S.:** U.S. full assets and operations

Transocean is a major offshore drilling contractor that also has an equity business model using its drill ships. For PMNs, it is an exploitation facilitator for junior miners. It agreed to engineer and convert a drillship for Global Sea Mineral Resources (GSR) to develop their polymetallic mineral properties in the CCZ. It also has a relationship with Moana Minerals LLC that holds exploration licenses in Cook Islands.

- Exploitation/extraction operator
  - a. Drill ships and engineering.
- Does not qualify as small business.
- We have not found any companies involved with refining PMN in the U.S. because there is no current production.
- Assay services for PMN have been provided by:
  - a. ALS whose global operations office is in Houston, Texas. +1 281 530 5656. This office can recommend which of their laboratories specialize in analysis of PMN.  
<https://www.alsglobal.com/en/geochemistry>
- Processing of PMN requires a custom flowsheet and plant design. Hazen Research is a leading metallurgical design company located in Golden, Colorado. +1 303 279 4501. Consulting with a metallurgical specialist like Hazen Research may help locate metal refiners in the U.S. that assimilate PMN into their metal refining plants.
- There are lead refiners that may be able to process cobalt and nickel from PMN such as Doe Run Resources Corporation in Missouri, U.S.

#### 4.4 Non-U.S. Companies Involved in Polymetallic Nodule Activities

**Company:** Ocean Floor Geophysics

**Size/Year of Formation:** <50 FTE / 2007

**Headquarters:** Burnaby, BC, Canada

**U.S./Non U.S.:** Non-U.S.

Ocean Floor Geophysics is a specialist offshore electromagnetic survey contractor and interpretation services. Specializes in SMS multiphysics.

- Exploration/characterization contractor
  - a. Has 3,000-meter rated AUV but subcontracts for others. Can perform geophysical surveys.

**Company:** Green Minerals

**Size/Year of Formation:** <20 FTE/ 2020

**Headquarters:** Asker Norway

**U.S./Non U.S.:** Non-U.S.

Green Minerals is a startup junior miner for minerals in the Norwegian EEZ. Has interests for PMNs in CCZ.

- Operator /junior miner developing exploration/characterization for own projects.
  - a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation and processing plans.

**Company:** Adepth Minerals

**Size/Year of Formation:** <20 FTE/2020

**Headquarters:** Bergen, Norway

**U.S./Non U.S.:** Non U.S.

Adepth is a startup junior miner for minerals in the Norwegian EEZ.

- Operator/junior miner developing exploration/characterization for own projects.
  - a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation and processing plans.

**Company:** Loke Minerals

**Size/Year of Formation:** <50 FTE/ 2019

**Headquarters:** Stavanger, Norway

**U.S./Non U.S.:** Non U.S.

Loke Minerals is a start-up junior miner for minerals in the Norwegian EEZ. Acquired UK Seabed Resources interests for PMNs in CCZ.

- Operator/junior miner developing exploration/characterization for own projects.
  - a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation plans.

**Company:** TMC

**Size/Year of Formation:** <50 FTE/2011

**Headquarters:** Vancouver, BC Canada

**U.S./Non U.S.:** Non U.S.

TMC is an operator/junior miner. TMC delineates marine minerals and seeks licenses to explore and exploit. TMC holds several polymetallic licenses in the CCZ.

- Exploration/characterization operator for own projects.
  - a. Contracts for services.
- Exploitation
  - a. Partnered with Allseas to develop the NORI D mineral property in the CCZ. Successfully tested the nodule collection and lift system on the mineral property in the CCZ in 2022

**Company:** GSR (DEME)

**Size/Year of Formation:** <50 FTE/2007

**Headquarters:** Zwijndrecht, Belgium

**U.S./Non U.S.:** Non U.S.

GSR is a subsidiary of the dredging company, DEME. It holds polymetallic exploration licenses in the CCZ.

- Exploration/characterization operator for own projects.
  - a. Has some marine survey capability and contracts for others.
- Exploitation

- a. Developed a nodule collection system that has been successfully tested on the mineral property in the CCZ.
- b. Transocean has partnered to convert drillship to mining vessel.

**Company:** Boskalis

**Size/Year of Formation:** >5000 FTE/ 1910

<mailto:sander.steenbrink@boskalis.com>

**Headquarters:** Papendrecht, Netherlands

**U.S./Non U.S.:** Non-U.S.

Boskalis is a global dredging company.

- Have interest in Chatham Rock Phosphate Ltd.
- Own Gardline, a global marine survey and geotechnical company capable of some aspects of PMN exploration and coring.

#### 4.4.1 Polymetallic Nodule Contracts issued by the International Seabed Authority in International Waters

The current list of PMN contract areas issued by the International Seabed Authority is shown in Table 17. As discussed earlier, national oceanographic research organizations have provided the resource survey support over many years for their state sponsored PMN concessions.

Understanding where and which nations have plans to produce PMN is of interest to U.S. efforts. The license areas that have been acquired is a good indicator of where abundant PMN have been located and where resource assessments have advanced. Some of these areas are geographically proximal to U.S. OCS and EEZ areas in the Pacific and serve, along with what sparse historical data such as has been compiled in this report to prioritize areas for resource assessments in the U.S. OCS and EEZ.

**Table 18.**  
**ISA PMNs exploration contracts**

Contractor	Contract Date	Expiration Date	Sponsoring State	Location
Interoceanmetal Joint Organization	29/03/2001	28/03/2021 (1st) 28/03/2026 (2nd)	Bulgaria, Cuba, Czech Republic, Poland, Russian Federation and Slovakia	CCZ
JSC Yuzhmorgeologiya	29/03/2001	28/03/2021	Russian Federation	CCZ
Government of the Republic of Korea	27/04/2001	26/04/2021	Korea	CCZ
China Ocean Mineral Resources Research and Development Association	22/05/2001	21/05/2021	China	CCZ
Deep Ocean Resources Development Co. Ltd.	20/06/2001	19/06/2021 (1st) 19/06/2026 (2nd)	Japan	CCZ
Institut français de recherche pour l'exploitation de la mer	20/06/2001	19/06/2021	France	CCZ
Government of India	25/03/2002	24/03/2022 (1st) 24/03/2027 (2nd)	India	Indian Ocean
Federal Institute for Geosciences and Natural Resources of Germany	19/07/2006	18/07/2026 (1st)	Germany	CCZ
Nauru Ocean Resources Inc.	22/07/2011	21/07/2026	Nauru	CCZ
Tonga Offshore Mining Limited	11/01/2012	10/01/2027	Tonga	CCZ
Global Sea Mineral Resources NV	14/01/2013	13/01/2028	Belgium	CCZ



Contractor	Contract Date	Expiration Date	Sponsoring State	Location
UK Seabed Resources Ltd.	08/02/2013	07/02/2028	UK	CCZ
Marawa Research and Exploration Ltd.	19/01/2015	18/01/2030	Kiribati	CCZ
Ocean Mineral Singapore Pte Ltd.	22/01/2015	21/01/2030	Singapore	CCZ
UK Seabed Resources Ltd	29/03/2016	28/03/2031	UK	CCZ
Cook Islands Investment Corporation	15/07/2016	14/07/2031	Cook Islands	CCZ
China Minmetals Corporation	12/05/2017	11/05/2032	China	CCZ
Beijing Pioneer Hi-Tech Development Corporation	18/10/2019	17/10/2034	China	Western Pacific Ocean
Blue Minerals Jamaica Ltd	04/04/2021	03/04/2036	Jamaica	CCZ

Source: (Herzig et al. 2002)

Of these ISA PMN contract holders, The Government of India, Nauru Ocean Resources, Tonga Offshore Mining Ltd, Global Sea Mineral Resources NV, UK Seabed Resources Ltd, Marawa Research and Exploration Ltd, Ocean Mineral Singapore Pte Ltd. Cook Islands Investment Corp. and Blue Minerals Jamaica have engaged some of the commercial companies listed in this report to further their resource assessments. The others have relied on their national/institutional capability.

We have not found any companies involved with refining PMN outside of U.S. because there is no current production.

Assay services for PMN have been provided by:

- ALS whose global headquarters is in Milton, QLD, Australia. +61 7 3367 7900. This office will recommend which of their laboratories specialize in analysis of PMN.  
<https://www.alsglobal.com/en/geochemistry>

Processing of PMN requires a custom flowsheet and plant design. Hazen Research is a leading metallurgical design company located in Golden, Colorado. +1 303 279 4501. Consulting with a metallurgical specialist like Hazen Research may help locate metal refiners in the U.S. that assimilate PMN into their metal refining plants.

There are refiners may be able to process cobalt and nickel from PMN with headquarters and/or have operations in Canada.

These are: Glencore Canada, Sherritt International, Vale Canada Ltd, and First Cobalt Corporation.

There are likely to be companies in Norway, Australia, and Mexico that may be able to process PMN. We recommend contacting a metallurgical consultant such as Hazen to located refiners who could accommodate PMN within their process.

## 4.5 U.S. Companies Involved in Other Critical Minerals Activities

### 4.5.1 Cobalt-Rich Ferromanganese Crusts

The following companies have capabilities for exploration, resource assessment, or extraction of CRCs:

**Company:** Seafloor Investigations LLC

**Size/Year of Formation:** <20 full-time employees (FTE)/2009

**Headquarters:** Bellingham WA

**U.S./Non-U.S.:** U.S.

Seafloor Investigations LLC is a turnkey geologic and environmental nodule collection contractor/laboratory management firm.

- Exploration/characterization contractor
  - a. Can contribute to a cobalt crust exploration and characterization scope.

**Company:** Argeo

**Size/Year of Formation:** <50 FTE/ 2017

**Headquarters:** Asker Norway

**U.S./Non-U.S.:** U.S. (satellite office)

Argeo is a geophysical contractor specializing in AUVs.

- Exploration/characterization contractor
  - a. Assets for cobalt crust investigation includes one vessel and four AUVs of which three are rated to 6,000 meters. Can subcontract seafloor drill.

**Company:** Fugro

**Size/Year of Formation:** >5,000 FTE/ 1962

**Headquarters:** Leidshendam, Neth.

**U.S./Non-U.S.:** U.S. Full assets and operations

Fugro is a full service land and marine data acquisition and geotechnical contractor and positioning specialist.

- Exploration/characterization contractor
  - a. Assets for cobalt crust exploration includes a global fleet of geophysical/light geotechnical vessels, two 4,500-meter rated AUVs and management and access to one 6,000-meter AUV. Have scientific consultants on staff. Full metocean services capability. ROVs. Has geotechnical drill ships and seafloor drills. Developed a prototype fast cobalt crust sampler.

**Company:** Ocean Floor Geophysics

**Size/Year of Formation:** <50 FTE / 2007

**Headquarters:** Burnaby, BC, Canada

**U.S./Non U.S.:** Non-U.S.

Ocean Floor Geophysics is a specialist offshore electromagnetic survey contractor and interpretation services. Specializes in SMS multiphysics.

- Exploration/characterization contractor
  - a. Has 3,000-meter rated AUV but subcontracts for others. Can perform geophysical surveys.

**Company:** Ocean Infinity

**Size/Year of Formation:** <500 FTE/ 2016

**Headquarters:** Austin, TX

**U.S./Non U.S.:** U.S. (Survey Ops Center in Sweden)

Ocean Infinity is an AUV specialist and marine survey contractor that is developing autonomous vessels.

- Exploration/characterization contractor
  - a. Assets for nodule exploration includes multiple vessels and more than eight AUVs of which all are rated to 6,000 meters. Pioneered deployment of multiple AUVs. Has traditional marine survey assets and operations. Assets can be applied to cobalt crust surveys and environmental investigations.

**Company:** Saildrone

**Size/Year of Formation:** <50 FTE/ 2007

**Headquarters:** Alameda, CA

**U.S./Non U.S.:** U.S.

Saildrone is an innovator in low cost autonomous deep-water ocean mapping.

- Exploration/Characterization Contractor
  - a. Assets for cobalt crust exploration are the Saildrone vehicles that can provide low hull mounted multibeam bathymetry uncrewed and autonomously. Limited to seafloor mapping.

**Company:** Odyssey Marine Exploration

**Size/Year of Formation:** <50 FTE/ 1994

**Headquarters:** Tampa FL

**U.S./Non U.S.:** U.S.

Odyssey Marine Exploration is an operator/junior miner. Odyssey delineates marine minerals and seeks licenses to explore and exploit that could include cobalt crusts.

- Operator/junior miner involved in exploration/characterization for own projects.
  - a. Has some marine survey equipment but contracts for others.

**Company:** Green Minerals

**Size/Year of Formation:** <20 FTE/ 2020

**Headquarters:** Asker Norway

**U.S./Non U.S.:** Non-U.S.

Green Minerals is a startup junior miner for cobalt crust and SMS minerals in the Norwegian EEZ.

- Operator/junior miner developing exploration/characterization for own projects.
  - a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation and processing plans.

**Company:** Adepth Minerals

**Size/Year of Formation:** <20 FTE/2020

**Headquarters:** Bergen, Norway

**U.S./Non U.S.:** Non U.S.

Adepth is a startup junior miner for cobalt crusts and SMS minerals in the Norwegian EEZ.

- Operator/junior miner developing exploration/characterization for own projects.
  - a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation and processing plans.

**Company:** Loke Minerals

**Size/Year of Formation:** <50 FTE/ 2019

**Headquarters:** Stavanger, Norway

**U.S./Non U.S.:** Non U.S.

Loke Minerals is a start-up junior miner for cobalt crusts and SMS minerals in the Norwegian EEZ.

- Operator/junior miner developing exploration/characterization for own projects.

- a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation plans.
- Table 19. ISA Cobalt-Rich Ferromanganese Crust Contracts

**Company:** Boskalis  
**Size/Year of Formation:** >5,000 FTE/ 1910  
<mailto:sander.steenbrink@boskalis.com>  
**Headquarters:** Papendrecht, Netherlands  
**U.S./Non U.S.:** Non-U.S.

Boskalis is a global dredging company.

- Have interest in Chatham Rock Phosphate Ltd.
- Own Gardline, a global marine survey and geotechnical company capable of some aspects of CRC exploration and coring.

We have not found any companies involved with refining CRC in the U.S. because there is no current production.

Assay services for CRC can be provided by:

- ALS whose global operations office is in Houston, Texas. +1 281 530 5656. This office will recommend which of their laboratories specialize in analysis of PMN.  
<https://www.alsglobal.com/en/geochemistry>

Processing of CRC requires a custom flowsheet and plant design. Hazen Research is a leading metallurgical design company located in Golden, Colorado. +1 303 279 4501. Consulting with a metallurgical specialist like Hazen Research may help locate metal refiners in the U.S. that assimilate CRC into their metal refining plants.

Lead refiners may be able to process cobalt and nickel from PMN such as Doe Run Resources Corporation in Missouri, U.S.

#### 4.5.1.1 CRC Contracts issued by the International Seabed Authority in International Waters

The current list of CRC contract areas issued by the International Seabed Authority is shown in Table 19. As discussed earlier, national oceanographic research organizations have provided the resource survey support over many years for their state-sponsored CRC concessions. Note that the Brazilian government voluntarily terminated its agreement with the ISA for exploration off its coast in the South Atlantic Ocean.

Understanding where and which nations have plans to produce CRC is of interest to U.S. efforts. The license areas that have been acquired is a good indicator of where abundant CRC have been located and where resource assessments have advanced. Some of these areas are geographically proximal to U.S. OCS and EEZ areas in the Pacific and serve, along with what sparse historical data such as has been compiled in this report to prioritize areas for resource assessments in the U.S. OCS and EEZ.

**Table 19. ISA Cobalt-Rich Ferromanganese Crust Contracts**

Contractor	Contract Date	Expiration Date	Sponsoring State	Location
Japan Organization for Metals and Energy Security (JOGMEC)	27-Jan-14	26-Jan-29	Japan	Western Pacific Ocean
China Ocean Mineral Resources Research and Development Association (COMRA)	29-Apr-14	28-Apr-29	China	Western Pacific Ocean

Contractor	Contract Date	Expiration Date	Sponsoring State	Location
Ministry of Natural Resources and Environment of the Russian Federation	10-Mar-15	09-Mar-30	Russia	Magellan Mountains, Pacific Ocean
Companhia De Pesquisa de Recursos Minerais	09-Nov-15	Voluntary termination effective 27 Jun 2022	Brazil	Rio Grande Rise, South Atlantic Ocean
The Republic of Korea	27-Mar-18	26-Mar-33	Republic of Korea	Western Pacific Ocean

Source: International Seabed Authority

The ISA CRC contract holders have relied on their national/institutional capability for their resource assessment and extraction research.

We have not found any companies involved with refining CRC outside of U.S. because there is no current production.

Assay services for CRC can be provided by:

- ALS whose global headquarters is in Milton, QLD, Australia. +61 7 3367 7900. This office can recommend which of their laboratories specialize in analysis of CRC.  
<https://www.alsglobal.com/en/geochemistry>

Processing of CRC requires a custom flowsheet and plant design. Hazen Research is a leading metallurgical design company located in Golden, Colorado. +1 303 279 4501. Consulting with a metallurgical specialist like Hazen Research may help locate metal refiners in the U.S. that assimilate CRC into their metal refining plants.

There are refiners may be able to process cobalt and nickel from CRC with headquarter and/or have operations in Canada.

- These are Glencore Canada, Sherritt International, Vale Canada Ltd, and First Cobalt Corporation.

#### 4.5.2 Seafloor Massive Sulfides (SMS)

The following companies have capabilities for exploration, resource assessment, or extraction of SMS.

**Company:** Seafloor Investigations LLC

**Size/Year of Formation:** <20 full-time employees (FTE)/2009

**Headquarters:** Bellingham WA

**U.S./Non-U.S.:** U.S.

Seafloor Investigations LLC is a turnkey geologic and environmental nodule collection contractor/laboratory management.

- Exploration/characterization contractor
  - a. Can contribute to a SMS exploration and characterization scope.

**Company:** Argeo

**Size/Year of Formation:** <50 FTE/ 2017

**Headquarters:** Asker Norway

**U.S./Non-U.S.:** U.S. (satellite office)

Argeo is a geophysical contractor specializing in AUVs.

- Exploration/characterization contractor
  - a. Assets for SMS investigation includes one vessel and four AUVs of which three are rated to 6,000 meters. Has capability for EM AUV acquisition and interpretation. Can subcontract seafloor drill?

**Company:** Fugro

**Size/Year of Formation:** >5,000 FTE/ 1962

**Headquarters:** Leidshendam, Neth.

**U.S./Non-U.S.:** U.S. full assets and operations

Fugro is a full service land and marine data acquisition and geotechnical contractor and positioning specialist.

- Exploration/characterization contractor
  - a. Assets for SMS exploration includes a global fleet of geophysical/light geotechnical vessels, two 4,500-meter rated AUVs and management and access to one 6,000-meter AUV. Have scientific consultants on staff. Full metocean services capability (ROVs). Has geotechnical drill ships and seafloor drills.

**Company:** Ocean Floor Geophysics

**Size/Year of Formation:** <50 FTE / 2007

**Headquarters:** Burnaby, BC, Canada

**U.S./Non U.S.:** Non-U.S.

Ocean Floor Geophysics is a specialist offshore electromagnetic survey contractor and interpretation services. Specializes in SMS multiphysics.

- Exploration/characterization contractor
  - a. Has 3,000-meter rated AUV but subcontracts for others. Can perform geophysical surveys.

**Company:** Ocean Infinity

**Size/Year of Formation:** <500 FTE/ 2016

**Headquarters:** Austin, TX

**U.S./Non U.S.:** U.S. (Survey Ops Center in Sweden)

Ocean Infinity is an AUV specialist and marine survey contractor that is developing autonomous vessels.

- Exploration/characterization contractor
  - a. Assets for SMS exploration includes multiple vessels and more than eight AUVs of which all are rated to 6,000 meters. Pioneered deployment of multiple AUVs. Has traditional marine survey assets and operations. Assets can be applied to SMS surveys and environmental investigations.

**Company:** Saildrone

**Size/Year of Formation:** <50 FTE/ 2007

**Headquarters:** Alameda CA

**U.S./Non U.S.:** U.S.

Saildrone is an innovator in low cost autonomous deep-water ocean mapping.

- Exploration/characterization contractor
  - a. Assets for SMS exploration are the Saildrone vehicles that can provide low hull mounted multibeam bathymetry uncrewed and autonomously. Limited to seafloor mapping, but has advantage is hydrothermal plume detection if plumes are in bubble phase.

**Company:** Odyssey Marine Exploration

**Size/Year of Formation:** <50 FTE/ 1994

**Headquarters:** Tampa, FL

**U.S./Non U.S.:** U.S.

Odyssey Marine Exploration is an operator/junior miner. Odyssey delineates marine minerals and seeks licenses to explore and exploit that includes SMS.

- Operator/junior miner involved in exploration/characterization for own projects.
  - a. Has some marine survey equipment but contracts for others.

**Company:** Green Minerals

**Size/Year of Formation:** <20 FTE/ 2020

**Headquarters:** Asker Norway

**U.S./Non U.S.:** Non-U.S.

Green Minerals is a startup junior miner for cobalt crust and SMS minerals in the Norwegian EEZ.

- Operator/junior miner developing exploration/characterization for own projects.
  - a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation and processing plans.

**Company:** Adepth Minerals

**Size/Year of Formation:** <20 FTE/2020

**Headquarters:** Bergen, Norway

**U.S./Non U.S.:** Non U.S.

Adepth is a startup junior miner for cobalt crusts and SMS minerals in the Norwegian EEZ.

- Operator/junior miner developing exploration/characterization for own projects.
  - a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation and processing plans.

**Company:** Loke Minerals

**Size/Year of Formation:** <50 FTE/ 2019

**Headquarters:** Stavanger, Norway

**U.S./Non U.S.:** Non U.S.

Loke Minerals is a start-up junior miner for cobalt crusts and SMS minerals in the Norwegian EEZ.

- Operator/junior miner developing exploration/characterization for own projects.

- a. No marine survey or drilling assets. Will contract for exploration and drilling services.
- Developing exploitation plans.

**Company:** Boskalis

**Size/Year of Formation:** >5000 FTE/ 1910

<mailto:sander.steenbrink@boskalis.com>

**Headquarters:** Papendrecht, Netherlands

**U.S./Non U.S.:** Non-U.S.

Boskalis is a global dredging company.

- Have interest in Chatham Rock Phosphate Ltd.
- Own Gardline, a global marine survey and geotechnical company capable of some aspects of SMS exploration and coring.

#### 4.5.2.1 SMS Contracts issued by the International Seabed Authority in International Waters

The current list of SMS contract areas issued by the International Seabed Authority is shown in Table 20. As discussed earlier, national oceanographic research organizations have provided the resource survey support over many years for their state-sponsored SMS concessions.

Understanding where and which nations have plans to produce SMS is of interest to U.S. efforts. These SMS concessions do not plot in geographic proximity to any SMS prospects in the U.S. OCS and EEZ. SMS deposits that share the same geologic setting as U.S. Guam and Northern Mariana Islands OCS SMS areas are within the EEZ of Japan. Each of these ISA SMS contract areas are spreading center SMS settings and are analogous to the Escanaba Trough SMS prospects in the U.S. Pacific OCS.

**Table 20.**  
**ISA Seafloor Massive Sulfides Contracts**

Contractor	Contract Date	Expiration Date	Sponsoring State	Location
China Ocean Mineral Resources Research and Development Association	18 Nov 2011	17 Nov 2026	China	Southwest Indian Ridge
Government of the Russian Federation	29 Oct 2012	28 Oct 2027	Russian Federation	Mid-Atlantic Ridge
Government of the Republic of Korea	24 Jun 2014	23 Jun 2029	Korea	Central Indian Ridge
Institut français de recherche pour l'exploitation de la mer (Ifremer)	18 Nov 2014	17 Nov 2029	France	Mid-Atlantic Ridge
Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany	06 May 2015	05 May 2030	Germany	Central Indian Ocean
The Government of India	26 Sep 2016	25 Sep 2031	India	Central Indian Ocean
Government of the Republic of Poland	12 Feb 2018	11 Feb 2033	Poland	Mid-Atlantic Ridge

Of these ISA SMS contract holders, the Government of India, Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany, and the Government of the Republic of Poland



have engaged some of the commercial companies listed in this report to further their resource assessments. The others have relied on their national/institutional capability.

Assay services for SMS can be provided by:

- ALS whose global operations office is in Houston, Texas. +1 281 530 5656. This office can recommend which of their laboratories specialize in analysis of SMS.  
<https://www.alsglobal.com/en/geochemistry>

Processing of SMS requires a custom flowsheet and plant design. Hazen Research is a leading metallurgical design company located in Golden, Colorado. +1 303 279 4501. Consulting with a metallurgical specialist like Hazen Research may help locate metal refiners in the U.S. that assimilate SMS into their metal refining plants.

Another metallurgical process and pilot plant design company is Metalox Engineering in Dania Beach Florida +1 954-591-0941. <https://metalox.tech/en/>. They are a small business that specializes in hydrometallurgical refining of sulfides.

There are major copper refiners in the U.S. that process sulfide ore such as BHP.

#### **4.5.3 Shallower Deposits (Phosphorites and Heavy Mineral Sands)**

The following companies have capabilities for exploration, resource assessment, or extraction of phosphorites or HMS.

**Company:** Odyssey Marine Exploration  
**Size/Year of Formation:** <50 FTE/ 1994  
**Headquarters:** Tampa, FL  
**U.S./Non U.S.:** U.S.

Odyssey Marine Exploration is an operator/junior miner. Odyssey delineates marine minerals and seeks licenses to explore and exploit. Odyssey has a license for phosphorites in Mexico.

- Operator/junior miner involved in exploration/characterization for own projects.
  - a. Has some marine survey equipment but contracts for others.

**Company:** Fugro  
**Size/Year of Formation:** >5,000 FTE/ 1962  
**Headquarters:** Leidshendam, Netherlands  
**U.S./Non-U.S.:** U.S. full assets and operations

Fugro is a full service land and marine data acquisition and geotechnical contractor and positioning specialist.

- Exploration/characterization contractor
  - a. Has shallow vessels and has long working relationship with Army Corps. of Engineers and BOEM for sand surveys.

**Company:** APTIM  
**Size/Year of Formation:** >3,000 FTE/ 1962  
**Contact:** Beau Suthard, Coastal, Ports and Marine lead  
**Contact Info:** beau.suthard@aptim.com  
**Headquarters:** Baton Rouge, LA

**U.S./Non U.S.:** U.S.

APTIM specializes in nearshore infrastructure and sand surveys.

- Exploration/characterization contractor
  - a. Has shallow vessels and working relationship with Army Corps. of Engineers and BOEM for sand surveys.

**Company:** Boskalis

**Size/Year of Formation:** >5,000 FTE/ 1910

<mailto:sander.steenbrink@boskalis.com>

**Headquarters:** Papendrecht, Netherlands

**U.S./Non U.S.:** Non-U.S.

Boskalis is a global dredging company.

- Have interest in Chatham Rock Phosphate Ltd.
- Own Gardline, a global marine survey and geotechnical company.

## 4.6 Current Needs and Uses

The following section details the various needs and uses for critical and economically valuable non-critical minerals found in PMNs, cobalt-rich ferromanganese crusts, SMS, phosphorite, and heavy mineral sands deposits.

### 4.6.1 Uses for Critical Materials and Economically Valuable Non-Critical Minerals Related to Undersea Mineral Deposits

The table below summarizes the key end-uses (excluding REE) of critical minerals contained within PMNs. A full, detailed breakdown of individual commodity end-uses is provided in the section below. This section has been condensed to include both the needs and uses of critical minerals contained across all underwater deposit types and has also been adapted to include both critical and economically valuable, but non-critical minerals as well.

Overview of demand by end use sector and application of critical minerals:

- **Primary end-use sectors:** Commodities
  - **Batteries:** Cobalt (Li-ion cells), nickel, manganese, copper, zinc (used as an anode material), Lead (lead-acid batteries), and vanadium (anode and cathode for vanadium redox flow batteries)
  - **Automotive:** Zinc (hot dipped-galvanized sheet for autobody sheet), molybdenum (used in cast iron for vehicle parts)
  - **Construction:** Copper (civil and building construction, air conditioning and utilities), molybdenum, antimony, zinc
  - **Steelmaking:** Zinc (galvanizing process), manganese (high strength low alloy steels and stainless steels), nickel (stainless steel), vanadium (hardening steel properties)
  - **Chemicals:** Cobalt, vanadium, manganese
- Data: CRU

### 4.6.2 Cobalt-Principal CM in CRC and PMN; Present in SMS

Cobalt has historically been highly sought-after for its excellent mechanical applications including high strength, corrosion resistance and bio-inert properties. However, cobalt's status as a transition metal also

gives it excellent electrochemical properties, which lends it to chemical applications such as catalysts, pigments, and energy storage. The demand for cobalt can be broken down into two main categories: metallurgical and chemical.

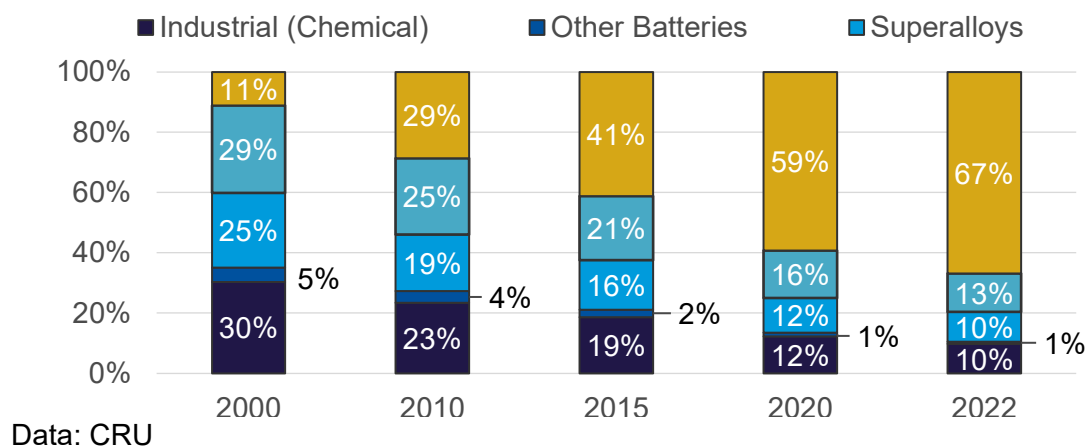
**Metallurgical end-uses:** Cobalt is used in the production of super alloys, high-speed steel, hard facing tools, carbides and diamond tools, and magnets for its strength and resistance to high temperature and wear. “Superalloys” is a broad-brush term used for alloys that exhibit one of several key characteristics, including high mechanical strength, good thermal creep resistance, and resistance to oxidation and corrosion. Nickel-based superalloys (many of which contain substantial amounts of cobalt) tend to be used for high-temperature applications, while cobalt-based superalloys tend to be used for applications that require corrosion resistance or bio-inertness. Demand is dominated by activity in western Europe and North America, with some amount of manufacturing also occurring in China. Other metals have various application in the industry. They are used in various cutting tools and magnets. The demand for this use is heavily concentrated in China.

**Chemical/non-metallurgical end-uses:** Cobalt is used in the form of cobalt oxide in Li-ion cells for electronic devices, and in the form of cobalt sulphate for electric vehicle batteries. Other cobalt salts are used in catalysts, as drying agents, and as steel adhesives. The widespread use of portable electronic devices has vastly contributed to an increase in rechargeable battery manufacturing. Most production is in east Asian countries—China, Korea, and Japan. The next stage of Li-ion battery application surge is coming from EV application and is also expected to be concentrated in China, Korea, and Japan.

### 4.6.3 Cobalt Within the U.S.

Cobalt production within the U.S. has two current operations. Eagle, which produces cobalt alongside a nickel and copper concentrates, as well as Missouri Cobalt’s Madison operation, which has continued to ramp-up production of cobalt sulphate in its integrated refinery. CRU understands that all this material is sold through an offtake agreement with Glencore, with only minimal projects in the pipeline to assist in potential production. The U.S. has an estimated 69 thousand tons (kt) of cobalt reserves, which accounts for less than 1% of total reserves globally.

Consumption of cobalt in the U.S. differs from the rest of the world since there is minimal battery-making capacity within the U.S. In 2022, according to the USGS (2023a), around 40% of cobalt consumption was used in superalloys, 35% in various chemical applications, 15% in various metallic applications, and 10% in cemented carbides for cutting and wear-resistant applications.



**Figure 44. Global Cobalt Demand by Major End-Use Sector, 2000 – 2022, Percent of Total Demand**

#### 4.6.4 Nickel-Principal CM in CRC and PMN; Present in SMS

Global nickel consumption in 2022 reached 3.0 million metric tons, up by 5% over the previous year. The primary uses for nickel include:

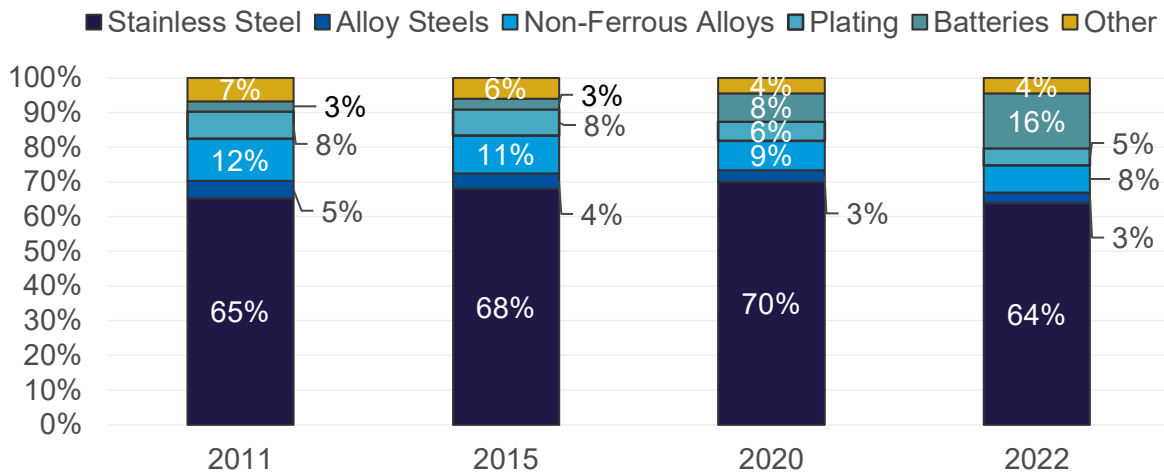
**Stainless steel production (~64% of total nickel demand):** Nickel is a key alloying element in stainless steel, contributing to its corrosion resistance, and this application is by a significant margin the largest end use for nickel.

**Batteries (~16% of total nickel demand):** Nickel sulphate is a key raw material in lithium-ion batteries (LIBs) that power EVs, typically as part of the cathode chemistries ‘nickel-manganese-cobalt’ (NMC) and ‘nickel-cobalt-aluminum.’ Within these, NMC batteries are steadily becoming more nickel-intensive, as this increases energy density while reducing total raw material costs (through cobalt substitution).

#### 4.6.5 Nickel within the U.S.

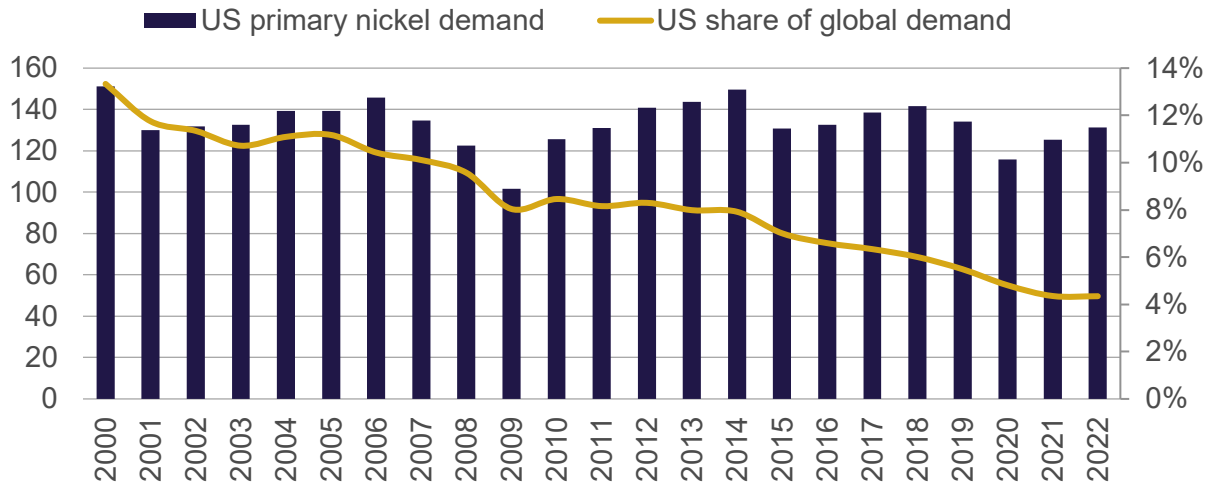
The only operating nickel mine within the U.S. is the Eagle Mine in Michigan. Construction of the mine commenced in 2010, Lundin acquired Eagle from Rio Tinto in 2013, commercial production was achieved in 2014. It is a shallow underground nickel-copper mine operating long-hole stopping. The mineral deposit contains an estimated 4.1 million metric tons of ore reserves at 3.6% nickel and 2.9% copper and operates with an average production rate of 2,000 t/d. The mine is scheduled to close in 2025.

According to the USGS, nickel demand within the U.S., ~85% of total demand is attributable to stainless steel and nickel-containing alloys. Historically, the U.S. has been reliant on Canada, Norway, Australia, and Finland for most of its primary nickel imports, and due to its lack of production. For total primary nickel demand, the U.S. currently makes up ~4% of the global total, a share that has been steadily decreasing over the last 20 years as demand has grown elsewhere, especially China.



Data: CRU

Figure 45. Nickel Demand by End-Use Sector, 2011 - 2022, % of Total Demand

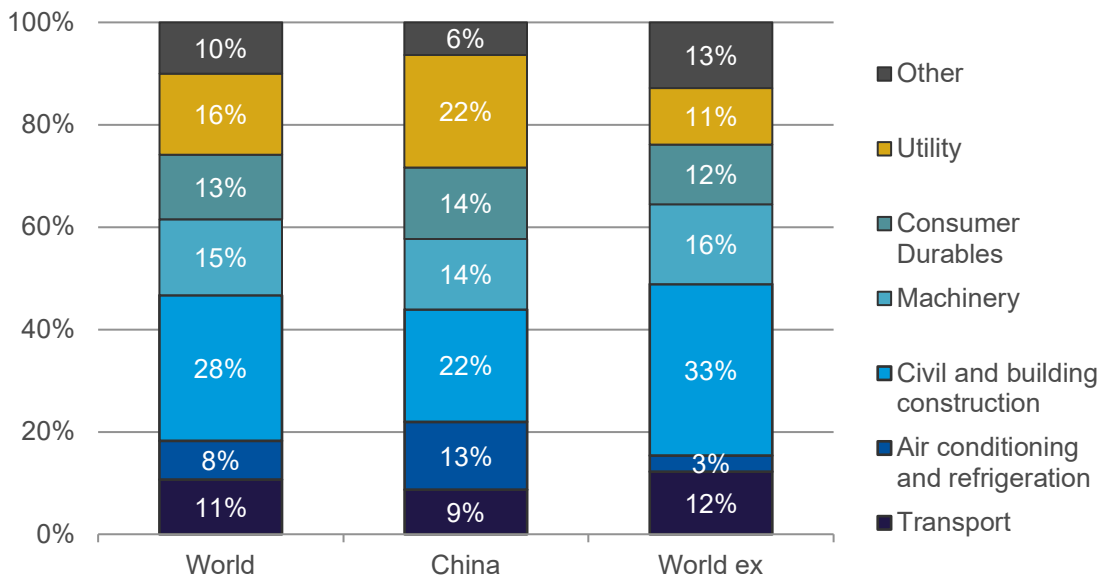


Data: CRU

Figure 46. U.S. Primary Nickel Demand, 2000 - 2022, kt Ni

#### 4.6.6 Copper- Principal Economic Mineral in SMS; Present in CRC and PMN

Copper is used primarily for its superior electrical and thermal conductivity among other properties. The largest two end-use sectors for copper are construction and utilities, amounting to 44% of end-use demand. Most of this will be in the form of wire and cables, and tubing and piping. Air conditioner manufacturing consumes a large proportion of Chinese copper demand compared with the rest of world. As a result, a slowdown in any of these industrial sectors will have an impact on copper demand further upstream.

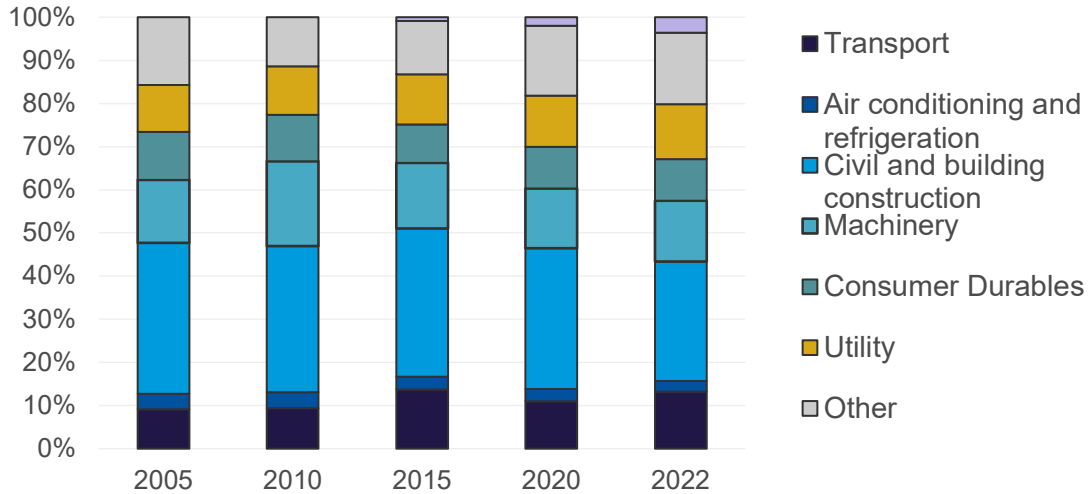


DATA: CRU

Figure 47. Global Refined Copper Demand by End-Use Sector, % of Total Demand

#### 4.6.6.1 Copper Within the U.S.

While copper is not included in the U.S. critical minerals list, we have included copper within this analysis because of its future importance within many decarbonization applications. In 2022, the U.S. consumed ~2.2 meitnerium of copper, with the largest driver of demand from civil and building construction. EV demand for copper has increased nearly threefold over the last four years, and decarbonization related applications are expected to be the main driver of future copper demand.



DATA: CRU

**Figure 48. U.S. Copper Consumption by End Use, 2005 - 2022, % of Total Copper Demand**

The largest copper mines by production in the U.S. are the Morenci, Birmingham Canyon, Sierrita, Bagdad, and Mission Complex operations. In total, the U.S. produced just under 1.3 meitnerium of contained copper within concentrates, cement, and recoverable EW cathodes. The balance of the demand has historically been made up through copper ores and concentrates through Mexico and Canada (greater than 99% of total copper ore/concentrate imports). For refined copper, Chile, Canada, and Mexico are key suppliers into the U.S. market. According to the USGS, ~86% of all unmanufactured copper imported into the U.S. comes from refined copper.

#### 4.6.7 Manganese- Principal CM in PMN and CRC

Between 85% to 90% of all manganese is consumed in steelmaking. Two primary functions—alloying element and deoxidizer. Crucially, manganese ferroalloys are used in the production of primary steel (i.e., non-recycled steel). Iron ore often contains levels of sulfur and phosphorus that must be adjusted. The addition of manganese in the steelmaking process plays a pivotal role, due to its ability to combine with sulfur and its potent deoxidization capacity—some 30% of manganese used today as a sulfide former and deoxidant. The remaining 70% of the manganese used only as an alloying element. The concentration of manganese in steel depends on the desired properties of the steel being made. The manganese content in steel depends on the requirements for its end use and consumption in steel mills is driven by steel product grades.

#### 4.7 Other Metallurgical Uses

The second largest application of manganese as an alloying agent is in the production of aluminum, yielding an alloy that is more workable during manufacture along with other benefits depending on the alloy.

## 4.8 Non-Metallurgical Uses

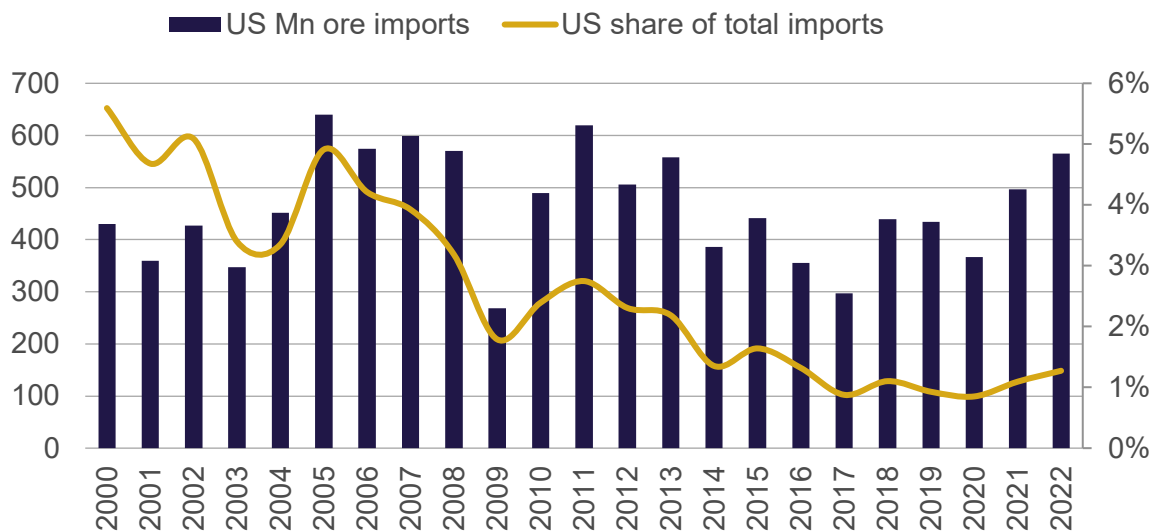
An important non-metallurgical application of manganese is in the form of manganese dioxide, which is used as a depolarizer in dry-cell batteries. Chemicals are another important end-use. For example, potassium permanganate is one of the best-known manganese products. It is a powerful oxidizing agent used in various applications including purifying drinking water and treating wastewater. There are numerous other applications of manganese oxide and salts, these include the coloring of bricks and tiles, driers and as a pigment for paints, etc.

Manganese sulphate and oxide are widely used as a product in fertilizers and animal feed, and as an intermediate product in the chemical industry. Magnesium sulphate has a further use as a cathode material in LIBs for which consumption has been growing rapidly in recent years with the adoption of EVs. Manganese ore used as an oxidizing agent in treating uranium ore to produce the oxide-concentrate known as “yellow cake.”

### 4.8.1 Manganese within the U.S.

According to the USGS Mineral Survey (2023a), manganese ore production of at least 20% manganese in the U.S. has not existed for nearly 50 years. Most ore in the U.S. are consumed within the steel industry. Ore is sourced from Gabon, South Africa, and Mexico. The U.S. only imports ~1% of the total traded manganese globally, compared to China, which imports nearly 70% of manganese ore, mainly from South Africa in 2022.

In executive orders EO 13953 and EO 13953 the Trump Administration, expressed his intent to expand and strengthen domestic mining and processing capacity of critical minerals. Manganese is included on the list of critical minerals. The current Biden Administration., signed EO 14017, aiming to identify opportunities to strengthen battery-metal supply chains.



Data: CRU

Figure 49. U.S. Manganese Ore Imports, 2000 - 2022, Mt ore, % of total global imports

### 4.8.2 Molybdenum-Present in CRC

Molybdenum consumption can broadly be split into two categories based upon end-use, metallurgical (~90% of demand) and chemical (~10%). In metallurgical applications, molybdenum is added in various proportions (typically 0% to 10% molybdenum) to improve certain characteristics of an alloy, including

strength-to-weight ratio, corrosion resistance, and reduced temper embrittlement and thermal expansion. The largest metallurgical applications are in:

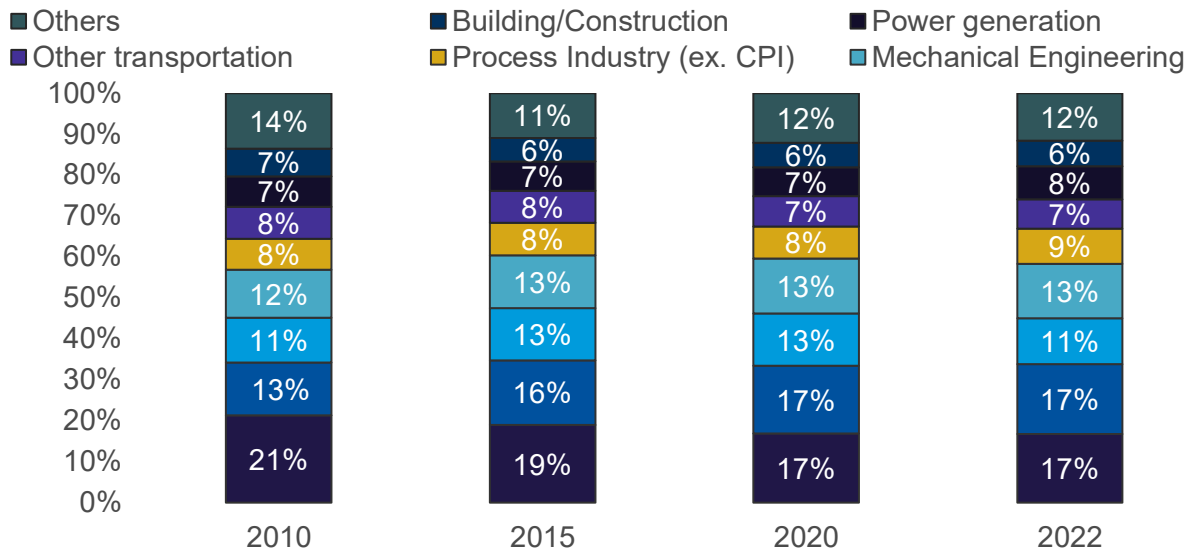
Constructional steels (typically 2% contained molybdenum), which are the largest end use. Stainless steels for consumer goods (predominantly the 300-series, in which the 316 contains 2% to 3% molybdenum). Tool and high-speed steels (ATS/ HSS) for mechanical engineering and automotives (1 to 10% molybdenum, improves hardness and abrasion-resistance at high temperatures); and cast iron for automotive parts (high-temperature performance and strength-to-weight ratio).

Molybdenum is also used in superalloys that are required in aerospace jet-engine and power-plant turbine blades. The single largest such industry is aerospace, where the jet-engine turbine blades, landing gears and airframes rely upon the ability of molybdenum containing superalloys to withstand a high-temperature, corrosive environment. Such superalloys include ATI’s nickel-based ATI 720, which contains between 2.75% and 3.25% molybdenum.

Most chemical applications are catalytic, such as in hydrodesulphurization reactions in the oil and gas industry. Further chemical applications include use as a solid-state lubricant (using small quantity of high purity molybdenum metal), or else in dyes or pigments.

These forms require far higher purity and as such the molybdenum concentrates used must have lower impurities to metallurgical, and so as would be expected, chemical grade can carry a premium over metallurgical.

Consumption of molybdenum in chemical applications is driven by demand growth for a range of chemicals, plastics, and pharmaceuticals. Global population growth and rising wealth in emerging countries are the key drivers. The opening of new water treatment and desalination plants will also drive growth. There will be robust demand growth for niche applications including fertilizer micronutrients and corrosion inhibitors.



Data: CRU

Figure 50. Molybdenum demand by end-use, percent of total demand, 2010 – 2022



### 4.8.3 Rare Earth Elements- Principal CM in HMS (Monazite); Present in Phosphorite, CRC, and PMN

#### 4.8.3.1 REEs Demand by End Use Sector

To ensure the greatest accuracy, CRU analyses commodity demand empirically using a “ground up” approach wherever possible. For example, when looking at rare earths in the automotive sector we look carefully at prevailing motor designs and compare this with the results of in-house modelling of automotive sales. A similar method can be used for estimating rare earth demand in the wind turbine sector and can be used to benchmark demand in other sectors.

Unfortunately, this is not possible to do for all end uses. For smaller markets with less data available, we start from an assumed market size (derived from trade data, industry knowledge and analyst estimates) and apply growth estimates tied to relevant economic markers (for example, when looking at rare earth demand in metals and alloys, we tie much of our long-term modelling to the CRU Steel Long-term Outlook).

The main end uses for REEs are shown in the next chart, along with the elements used and the main drivers of demand.

**Table 21.**  
**REEs End-Use Demand, % of total demand**

End Use	Share of global demand % (2022)	Element/form	Application
Permanent Magnets	33	Neodymium, praseodymium as metals. Smaller amounts of dysprosium, samarium, terbium	Wind turbines, automotives, consumer electronics
Metal Alloys	17	Cerium, lanthanum as oxides or compounds	Cast iron, high-strength low-alloy (HSLA) steel, stainless, magnesium and aluminum alloys
Catalysts	15	Lanthanum, cerium, neodymium, praseodymium as oxides or compounds	Fluid catalytic cracking, automotive catalytic converters
Polishing Powders	15	Cerium as oxide, lanthanum, neodymium	Flat and optical glass, display panels, computer hard disk drives (HDD)
Glass Additives	4	Mostly cerium, lanthanum with minor amounts of other REEs as oxides or compounds	Glass coloring, ultraviolet protection, impurity removal
Ceramics	6	Mostly yttrium, with some neodymium, lanthanum, cerium, praseodymium as oxides	Refractories, engineering and electronic ceramics
Phosphors	4	Yttrium mostly, praseodymium, cerium, lanthanum and europium as oxides	Lighting
Other	5	N/A	N/A
Total	100	N/A	N/A

Data: CRU

#### 4.8.3.2 REEs in the U.S.

The U.S. has only one operating REE operation. Mt. Pass in California has been operational since 1952 and produced ~42 kt REO in 2022. MP Materials owns the operation. The production of finished products will take place on a MP Materials owned facility in Fort Worth, Texas. In February 2022, the U.S. Department of Defense awarded MP Materials with a \$35 million U.S. dollar contract to build a heavy rare earth elements processing facility at Mountain Pass.

The U.S. has estimated reserves of 1.8 mtu of REO, less than China, Russia, and Brazil for estimated reserves. To supplement currently low production volumes by investing in cooperation with Australia's Lynas Rare Earths to construct a separation plant for \$120 million U.S. dollars. In addition to this processing line, the only other active project within the U.S. is the Rare Earth Element Resources Bear Lodge project within Wyoming, however, a projected start date of the project has yet to be announced at the publication of this report.

In 2020, the Trump Administration declared the absence of domestic mining and processing capacity for REEs along with the dependence on China supply as a national emergency. This is documented in executive orders EO 13953 and EO 13953. Concurrently, the Biden Administration expressed intent to address REE supply chain insecurities in EO 14017.

#### 4.8.4 Titanium- Principal CM in CRC and PMN

Titanium is the ninth most abundant element in the earth's crust. It is mostly found with iron in the form of ilmenite ( $\text{FeTiO}_3$ ) but can also occur naturally in a near pure titanium dioxide ( $\text{TiO}_2$ ) form, known as rutile. Titaniferous magnetites (or titanomagnetites) are typically processed by the steel industry and produce a titaniferous slag as a waste/by-product.

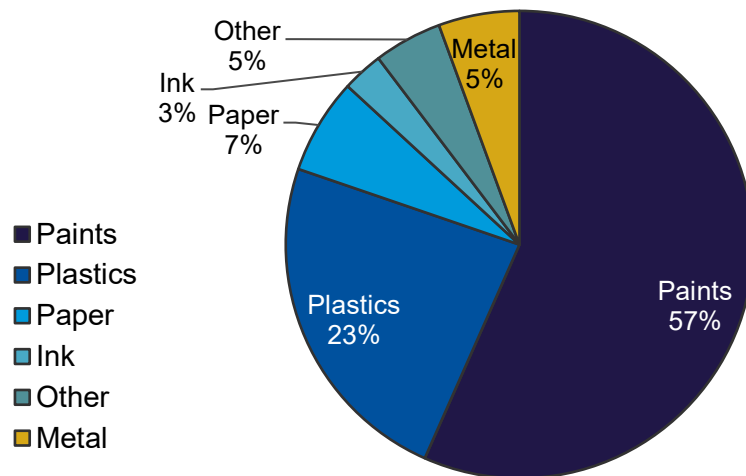
Titanium end use demand can be broken down into two distinct categories:

1. Refined  $\text{TiO}_2$ , primarily for use in white pigment, which constitutes ~ 95% of  $\text{TiO}_2$  concentrate demand.
2. Titanium sponge used to produce metal, which constituted 5% of demand.

**Refined  $\text{TiO}_2$**  is predominantly used as a **white pigment in surface coatings** (paint, varnish, and lacquer), plastics and paper markets; together, these account for over 90% of total demand. **Specialty whitener applications** such as inks, fibers, rubber, sunscreen, food colorings, and pharmaceuticals make up the other ~8% of total global refined  $\text{TiO}_2$  demand.

- **In surface coatings**,  $\text{TiO}_2$  pigments provide functional characteristics such as opacity, whiteness, brightness, hiding power, and durability. In plastics and paper, especially paper coatings, opacity and color development are major considerations.
- **White pigment was originally achieved using lead oxide, but the toxic nature of this pigment meant that a more consumer-friendly alternative was required.** This led to the introduction of  $\text{TiO}_2$  as a substitute, due to its property of having the highest refractive index of all the alternatives.
- **Its lack of toxicity also increases its usage in goods for human consumption**, such as sunscreen and toothpaste.

**Titanium metal** primarily feeds into the **aerospace** industry, where titanium-aluminum-vanadium alloys are used for the airplane body due to their outstanding strength-to-weight ratio.



DATA: CRU

**Figure 51. Titanium Dioxide Typical Demand Share, % of Total Demand**

#### 4.8.5 Vanadium-Present in PMN and CRC

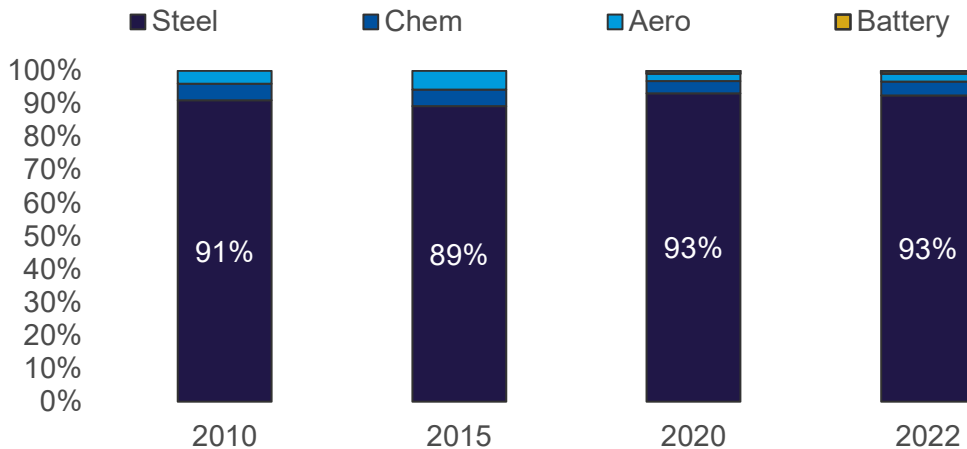
Vanadium is a high value, soft, ductile, grey metal with characteristics that allow for its use in alloying steel and other metals as well as being used in other industries.

**Steel (~90% of total demand):** For steel and other alloys, the high strength-to-weight ratio of vanadium allows production of harder steel alloys with lower weights. Vanadium addition increases strength through precipitation hardening as vanadium forms stable carbides and nitrides in steel.

**Aerospace (~4% of total demand):** Titanium-aluminum-vanadium alloys are consumed in jet engine components, airframes, and in dental applications, with the most common alloy containing 2.5% vanadium in the final form. Higher vanadium concentrations are also found for these alloys for higher strength and temperature range applications.

**Chemical (~4% of total demand):** Chemical uses of vanadium tend to focus on the use of the metal as a catalyst in chemical production. The metal is used as a catalyst in manufacturing sulfuric acid and maleic anhydride as well as in the making of some ceramics. Vanadium is also used in pollution control technology, known as the Stretford Process, to remove hydrogen sulfide gases from flue gases. Vanadium is further used in glass making as it can be added to glass to produce blue or green tint, while glass coated with vanadium dioxide (VO<sub>2</sub>) can block infrared radiation at specific temperatures.

**Battery (~2% of total demand):** Vanadium readily forms several stable oxidation states (II, III, IV, and V), which allow it to be infinitely reused as both the anode (+) and the cathode (-) in vanadium redox flow batteries. These batteries compete in the grid storage market, specifically in time-shifting energy with ties to variable renewable energy sources (wind, solar).



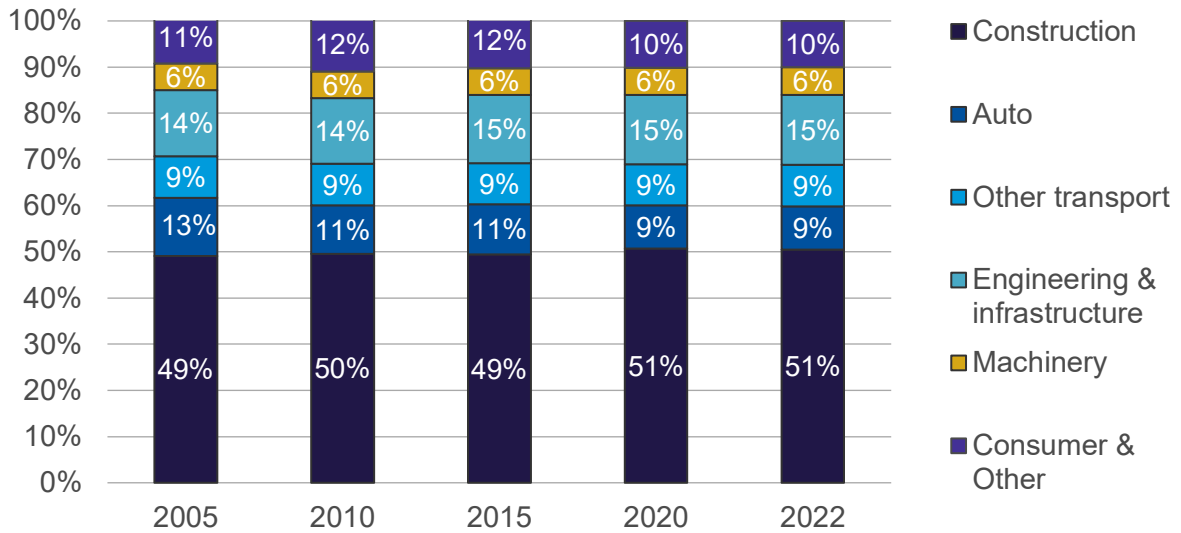
DATA: CRU

**Figure 52. Vanadium Demand by End-Use, % of Total Demand, 2010 – 2022**

#### 4.8.6 Zinc-Principal CM in SMS, CRC and PMN

Zinc—the fourth most widely consumed metal in the world following iron, aluminum, and copper—is an excellent anti-corrosion agent and bonds well with other metals. It is also moderately reactive and a fair conductor of electricity. It is well-recognized for its effectiveness in protecting steel against corrosion by galvanizing, and as such this accounts for 60% of total zinc consumption. Galvanized zinc is widely used in multiple industrial applications such as automobile bodies, air conditioners, chain-link fences, guard rails, heat exchangers, roofing panels, steel frames, washing machines, and more. The ability to die-cast complicated components make zinc indispensable in a multitude of industry and household products. It also has important markets in the brass (copper and zinc), construction, and chemicals industries, and constitutes an essential nutritional element. Key zinc end uses are:

- **Galvanization:** Around 60% of zinc is used in galvanization of steel products. Galvanized steel is widely used in multiple industrial applications such as automobile bodies, air conditioners, chain-link fences, guard rails, heat exchangers, roofing panels, steel frames, and washing machines.
- **Industrial use:** Zinc is used as an anode material for batteries with a standard electrode potential of 0.8 volts. Zinc dusts and powders are an indispensable raw material for a multitude of everyday products including batteries, ceramics, cosmetics, glass, pharmaceuticals, plastics, rubber and paints.
- **Fertilizer industry:** Zinc sulphate is used in animal feed as a source of zinc. Zinc sulphate is produced by reacting zinc with sulfuric acid.
- **Production of alloys:** Zinc is commonly used for alloy production, out of which brass (copper + zinc) is the most common due to its strength and corrosion resistance. This alloy is mainly used for construction of musical instruments due to its acoustic properties. Nickel silver alloy and bronze are other widely used zinc alloys.

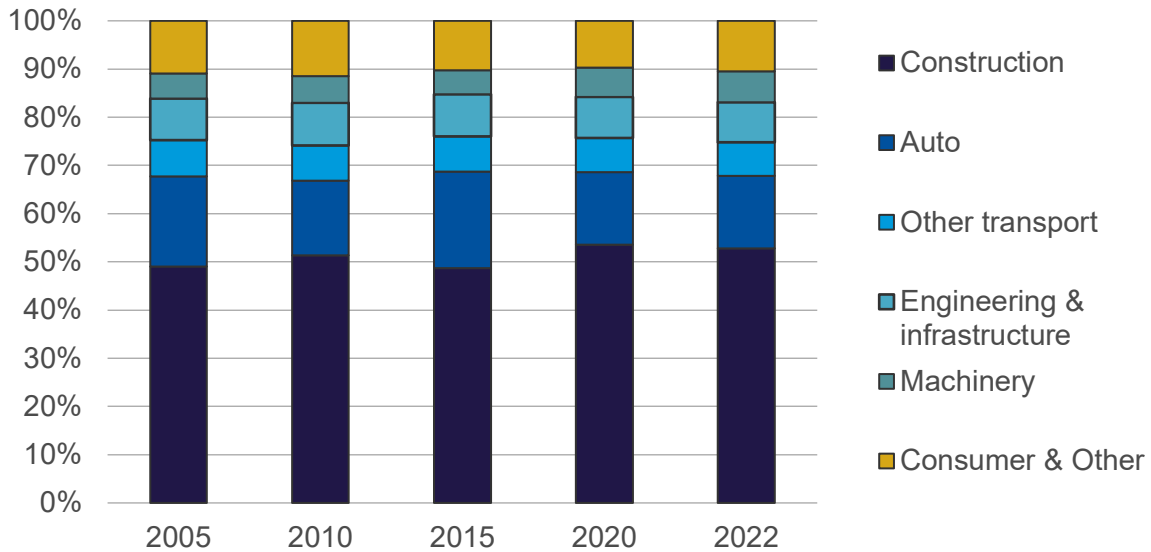


DATA: CRU

**Figure 53. Zinc Demand by End-Use, % of Total Demand, 2005 – 2022**

#### 4.8.6.1 Zinc within the U.S.

Since 2005, the U.S. has produced between 700 to 830 kt of zinc in any given year with the largest mine, Red Dog in Alaska, representing ~71% of total zinc production in the U.S. in 2022. It is the second-largest producer of zinc in the world and a major source of revenue for corporations in Alaska. The operation is an open-pit truck-and-loader that is using conventional drill and blast mining methods. Red Dog’s concentrate is shipped to Teck’s metallurgical facilities in Trail, British Columbia, and customers in Asia and Europe. In 1989, Red Dog was developed through an innovative operating agreement between the operator Teck and the land-owner NANA, a Regional Alaska Native corporation owned by the Inupiat people of northwest Alaska. The main pit is out of ore, but in 2010 the mine began extracting ore from an adjacent pit, estimated to last until 2031. In late 2017, Teck started a U.S. \$135 million mill upgrade project. The mill project was completed in 2020 and managed to increase average throughput by about 15% over the remaining mine life, helping to offset lower grades and harder ore. As of December 2021, Red Dog has a Mineral Reserve estimate of 42.9 meitnerium with a zinc grade of 12.6%. Teck’s three-year guidance for Red Dog in 2023-2025 is at 510 to 550 kt of zinc and 85 to 95 kt of lead.



DATA: CRU

**Figure 54. U.S. Zinc Demand by End-Use, % of Total Demand, 2005 – 2022**

As shown in the figure above, most of the zinc consumed in the U.S. is for the construction sector, followed by transportation and automotive applications. While the U.S. is a net exporter of zinc ores and concentrates through Red Dog’s mine in Alaska, the U.S. is a large importer of refined zinc, mainly from Canada, Mexico, Peru and Spain.

#### 4.8.7 Lead- Principal Economic Mineral in SMS; Present in PMN and CRC

Lead demand is driven by the metal’s main use in the manufacture of batteries, which account for ~85% of total lead consumption, alongside a combination of developments in the broader world economy.

Historically, lead was used in a wide variety of applications, but these narrowed in the second half of the 20th Century—initially due to technological advances, but also environmental and health pressures.

By the 21<sup>st</sup> century, lead consumption has become dominated by a single application, lead-acid batteries (LABs). This leaves lead usage highly vulnerable to future substitution by other battery technologies. However, the LAB market itself encompasses a wide range of uses, broadly divided into:

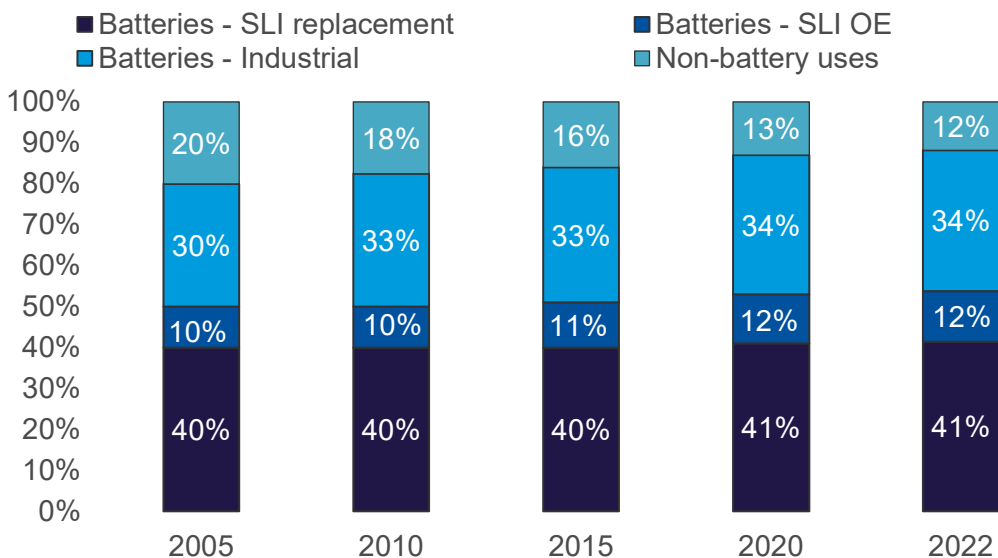
**Automotive applications:** Starter, lighting, and ignition batteries in original equipment in new vehicles, and replacement of failed batteries in existing vehicles.

**E-bikes:** The e-bike population surged to ~200 million in the early 2000s, predominantly in China, and at its peak, new and replacement e-bike LABs accounted for ~a quarter of Chinese lead consumption. However, previously rampant e-bike growth has slowed sharply, even falling in 2014-2015, amid tighter regulations. Moreover, LIBs have made swift inroads into LABs’ dominance in this sector, notably in exports.

**Industrial applications:** Motive power storage and reserve (standby) batteries. The performance and design of LABs have improved in recent decades. Improvements in grid alloy design has reduced the need to maintain batteries through topping up of electrolyte. This has enabled the sealing of batteries and the development of valve-regulated LABs. Industrial back-up power LABs are used in a wide range of applications where a stand-by source of electricity must be constantly and instantly available. For example, telecommunications usage has grown as mobile communication networks have rapidly

expanded their geographical coverage, density, and need for higher carrying capacities; every transmission mast requires batteries as back-up to guarantee the integrity of the network in the event of a power cut. Computer networks and data storage have similar requirements for uninterruptible power supply.

Outside the LAB sector, other end uses for lead, such as glass production, stabilizers that prevent the decomposition of polyvinyl chloride, rolled and extruded products, ammunition and cable sheathing, will continue to represent a flat and small portion of demand.



DATA: CRU

**Figure 55. Lead Demand by End-Use, % of total demand, 2005 – 2022**

#### 4.8.8 Antimony- CM Present in CRC, PMN and SMS

Antimony (chemical symbol Sb) is a minor metal, growing in strategic importance. Antimony or Sb, mainly found in stibnite in nature, is a brittle, silvery-white metal, which are mainly used in refractory applications. In its modern applications, antimony is used to enhance a range of properties of materials with which it is alloyed or mixed.

One of the key benefits of antimony is its heat and flame resistance properties. These make it a valuable addition to flame retardants for products ranging from children’s toys to automobile seat covers, to fiberglass engine covers on light aircraft. The use of antimony in other applications is the result of its effect on other physical properties, such as improving hardness, strength, and electrical characteristics of lead electrodes in LABs. Antimony is also used in ceramics and high-quality glass, where it is used as a fining agent to remove bubbles and as a pigment to increase opacity.

Due to its various end uses, demand for antimony is controlled by the performance of a select range of industries. Demand is also affected by the substitution levels within each industry, with several alternatives capable of performing similar roles to antimony in several end-uses.

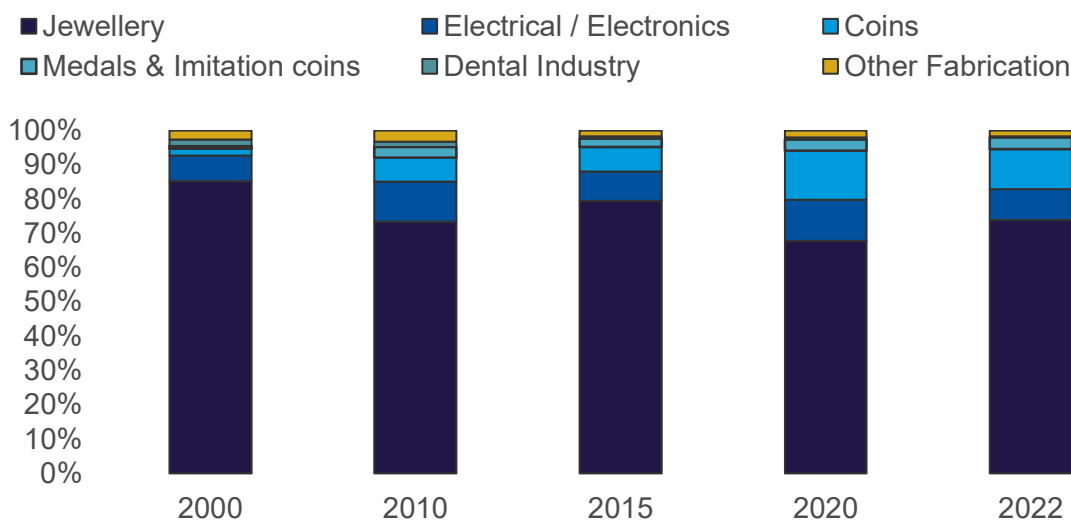
It is classified as a Critical Raw Material in China, the EU, and U.S. There is a growing demand for antimony, as the trioxide, in flame retardants for a wide range of plastics used in construction, manufacturing, and general fabrication materials. Antimony is also required as a catalyst in PET and plastics manufacture and as an ingredient for ceramics, high value technical glass, electronics, and protozoan drugs. Western consumption of trioxide is heavily dependent on China through imports and the

supply of ingot to the Western trioxide producers. China has the largest reserves; it is the highest importer of ores and concentrates. It is also the largest producer of ingot and trioxide.

#### 4.8.9 Gold- Economic Metal Present in SMS

Jewelry is the most common end use in gold fabrication demand, being responsible for 74% of global consumption (~2,128 tons in 2022). Gold is also used in investment portfolios to protect purchasing power, reduce volatility, and minimize losses during periods of market shock. Gold has long been central to innovations in electronics. Today the unique properties of gold and the advent of 'nanotechnology' are driving new uses in medicine, engineering, and environmental management.

Historically, gold fabrication demand has been in a consistent decline as general consumer spending habits have seen more declines in jewelry. However, while gold is highly valued for its excellent electrical conductivity, lack of corrosion, and ease of use, these gains do not offset the declines seen for jewelry in terms of overall gold fabrication demand.



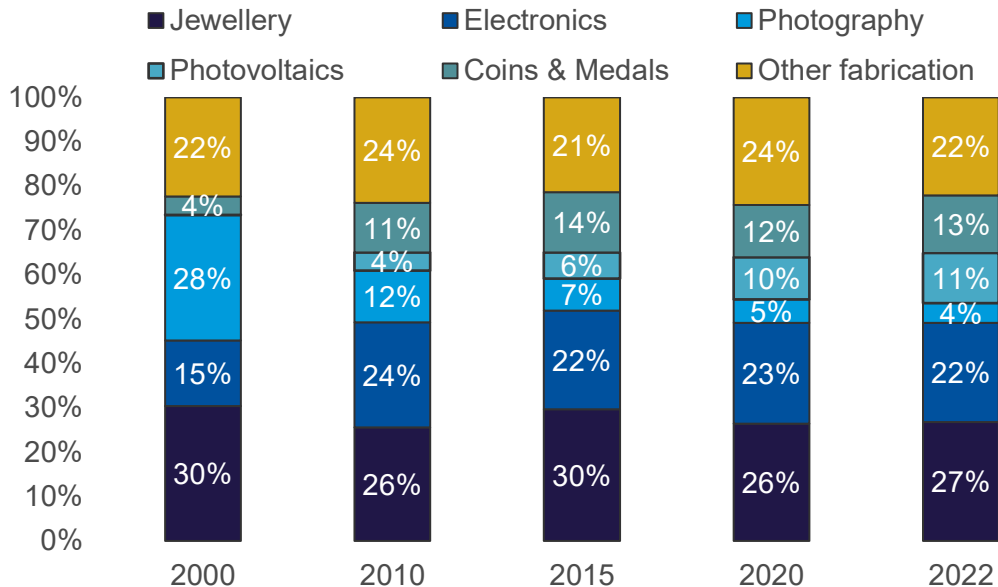
DATA: CRU

Figure 56. Gold Fabrication Demand by End-Use, 2000 - 2022, % of total demand

#### 4.8.10 Silver-Principal Economic Metal in SMS

Silver is often analogized to its rarer cousin, gold, given its ancient usage in jewelry (today: 27%) and coinage (8%); and yet the market has a crucial distinction—its far greater prevalence in industrial applications. Silver is used, like gold, in electronics for its excellent electrical conductivity, lack of corrosion, and ease of mechanical use, but given its lower price point and higher availability, it sees far more widespread usage. Silver paste’s use as a current collector in photovoltaic cells has garnered significant attention, given the rapid proliferation of solar energy; however, CRU notes that there are significant efforts already under way to thrift out the intensity of silver here, to make solar more cost-competitive with other energy sources.





DATA: CRU

**Figure 57. Silver Fabrication Demand by Major End-Use Sector, 2000 - 2022, % of total demand**

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**Appendix A: Illustrations  
(also submitted digitally)**

# U.S. CRITICAL MINERALS

Identified by the Secretary of the Interior as essential to the economic and national security of the United States

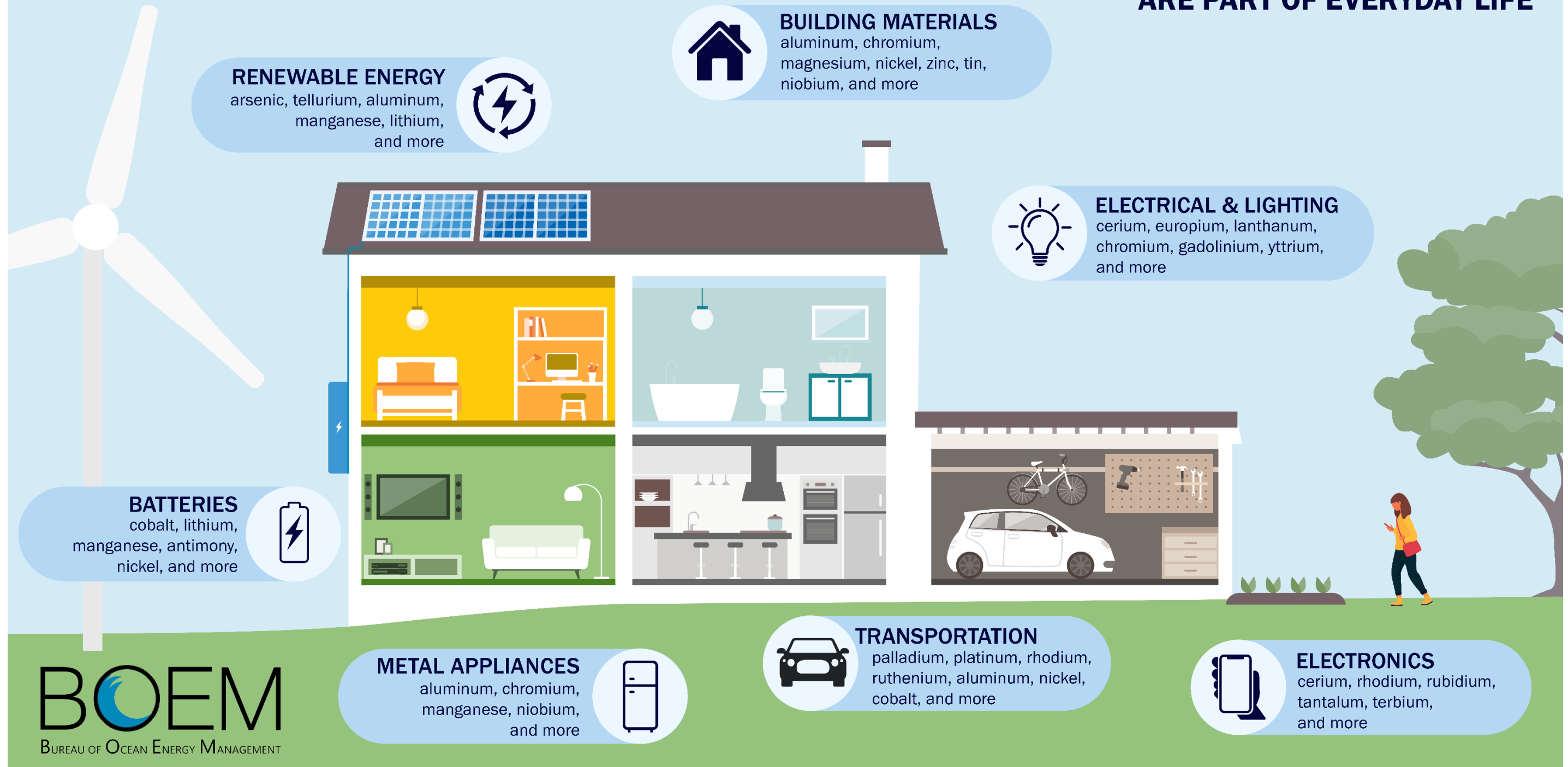


 present in the outer continental shelf (OCS) or exclusive economic zone (EEZ)

<b>ALUMINUM</b>	 transportation, construction, packaging, machinery, energy	<b>ERBIUM</b>	 lasers, fiber optics, optical amplifiers	<b>LUTETIUM</b>	medical technology	<b>SCANDIUM</b>	 fuel cells, alloys
<b>ANTIMONY</b>	 batteries, flame retardants	<b>EUROPIUM</b>	 nuclear energy	<b>MAGNESIUM</b>	 manufacturing steel	<b>TANTALUM</b>	electronics, capacitors
<b>ARSENIC</b>	 semi-conductors	<b>FLUOROSPAR</b>	transportation, cement, steel, gasoline	<b>MANGANESE</b>	 manufacturing steel, batteries	<b>TELLURIUM</b>	 solar cells, steel making
<b>BARITE</b>	 cement, petroleum	<b>GADOLINIUM</b>	 magnets, electronics, medical technology	<b>NEODYMIUM</b>	 magnets, medical lasers, industrial lasers	<b>TERBIUM</b>	magnets, fiber optics, lasers, electronics
<b>BERYLLIUM</b>	aerospace, defense	<b>GALLIUM</b>	electronics, LEDs	<b>NICKEL</b>	 stainless steel, batteries	<b>THULIUM</b>	alloys, lasers
<b>BISMUTH</b>	 medicine	<b>GERMANIUM</b>	fiber optics, night vision applications	<b>NIObIUM</b>	 steel, superalloys	<b>TIN</b>	 protective coatings, steel alloys
<b>CERIUM</b>	 metallurgy, glass, ceramics, transportation	<b>GRAPHITE</b>	batteries, fuel cells, lubricants	<b>PALLADIUM</b>	 catalytic convertors, transportation	<b>TITANIUM</b>	 white pigment, alloys for steel
<b>CESIUM</b>	research and development	<b>HAFNIUM</b>	nuclear energy, alloys, ceramics	<b>PLATINUM</b>	 catalytic convertors, transportation	<b>TUNGSTEN</b>	 metal making
<b>CHROMIUM</b>	 stainless steel	<b>HOLMIUM</b>	 lasers, medical technology, nuclear energy	<b>PRASEODYMIUM</b>	 magnets, batteries, aerospace alloys	<b>VANADIUM</b>	 alloying agent for iron and steel
<b>COBALT</b>	 batteries, superalloys	<b>INDIUM</b>	LCD screens	<b>RHODIUM</b>	 catalytic converters, transportation, electronics	<b>YTTERBIUM</b>	 catalysts, scintillometers, lasers, metallurgy
<b>DYSPROSIUM</b>	 magnets, lasers, data storage devices	<b>IRIDIUM</b>	fertilizer, crude oil refining	<b>RUBIDIUM</b>	 electronics	<b>YTTRIUM</b>	 ceramic, catalysts, lasers, metallurgy, phosphors
		<b>LANTHANUM</b>	 ceramics, glass, batteries	<b>RUTHENIUM</b>	 electrical contacts, chip resistors	<b>ZINC</b>	 production of galvanized steel
		<b>LITHIUM</b>	 rechargeable batteries	<b>SAMARIUM</b>	 magnets, nuclear energy, medical technology	<b>ZIRCONIUM</b>	 ceramics, corrosion resistant alloys

# CRITICAL MINERALS

ARE PART OF EVERYDAY LIFE



**BOEM**  
BUREAU OF OCEAN ENERGY MANAGEMENT

# WHERE ARE CRITICAL MINERALS?

## POLYMETALLIC NODULES



also known as manganese nodules, spherical, ranging from 2-15 cm, found on the seafloor

**nickel, copper, cobalt, manganese, rare earth elements, possibly titanium, tellurium, lithium**

3,500 to 6,000 meters deep

Occur on or near the top of soft sediments of abyssal plains

## COBALT-RICH FERROMANGANESE CRUSTS



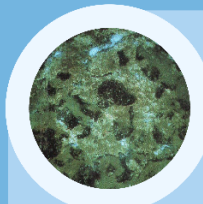
also known as polymetallic crusts, layered encrustations forming on rocks, typically less than 25 cm thick

**manganese, cobalt, nickel, copper, rare earth elements, possibly tellurium, scandium, platinum**

400 to 7,000 meters deep

Occur on the sides and summit of seamounts and ridges

## HYDROTHERMAL DEPOSITS



accumulations formed in fractures and cavities as a result of from hot waters in the Earth's crust. Seafloor Massive Sulfide (SMS) Deposits are a significant subset of hydrothermal deposits and denote the large presence of sulfide minerals.

**copper, zinc, gold, silver, and potentially antimony, bismuth, gallium, tellurium, germanium**

100 to 7,000 meters deep

Occur globally along active tectonic boundaries



## HEAVY MINERAL SANDS

**NEARSHORE MINERALS**  
also called placer deposits, sedimentary deposits that accumulate within sand, silt, and clay in coastal environments

**ilmenite, magnetite, rutile, monazite, zircon**



## PHOSPHORITES

**NEARSHORE MINERALS**  
also called phosphorite rock, derived from invertebrate shells, vertebrate bones, and upwellings near continental margins and shelves

**Carbonate-fluorapatite, rare earth metals**

PACIFIC UPWELLING COLD SEEPS

# FORMATION OF COBALT RICH FERROMANGANESE CRUSTS



## COBALT-RICH FERROMANGANESE CRUSTS

layered, cobalt-rich encrustations forming on rocks, typically less than 25 cm thick

manganese, cobalt, nickel, copper, rare earth elements, possibly tellurium, scandium, platinum

600 to 7,000 meters deep

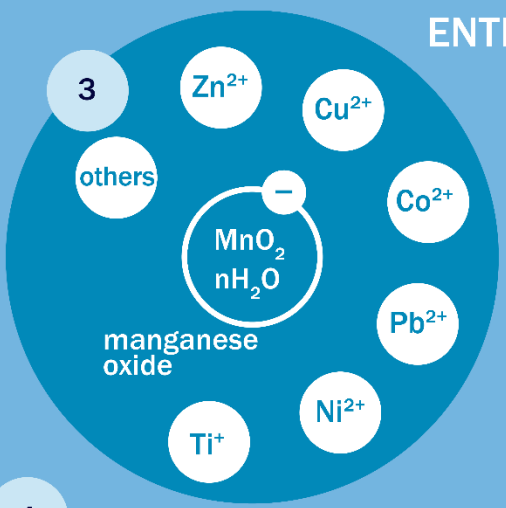
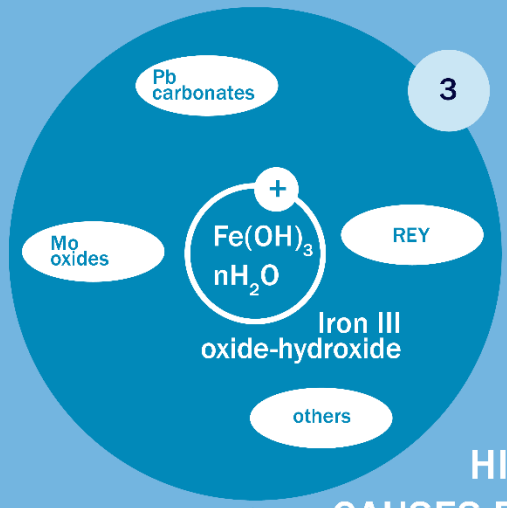
Occur on the sides and summit of seamounts and ridges

growth of <10 mm/million years

DISSOLVED MINERALS ENTER OCEANS VIA RIVERS **1**

**2** COLD CURRENT UPWELLINGS DISPERSE DISSOLVED MINERALS

**3** IONIC BONDS CREATED



HIGH TURBIDITY CAUSES PRECIPITATION OF OXIDES **4**

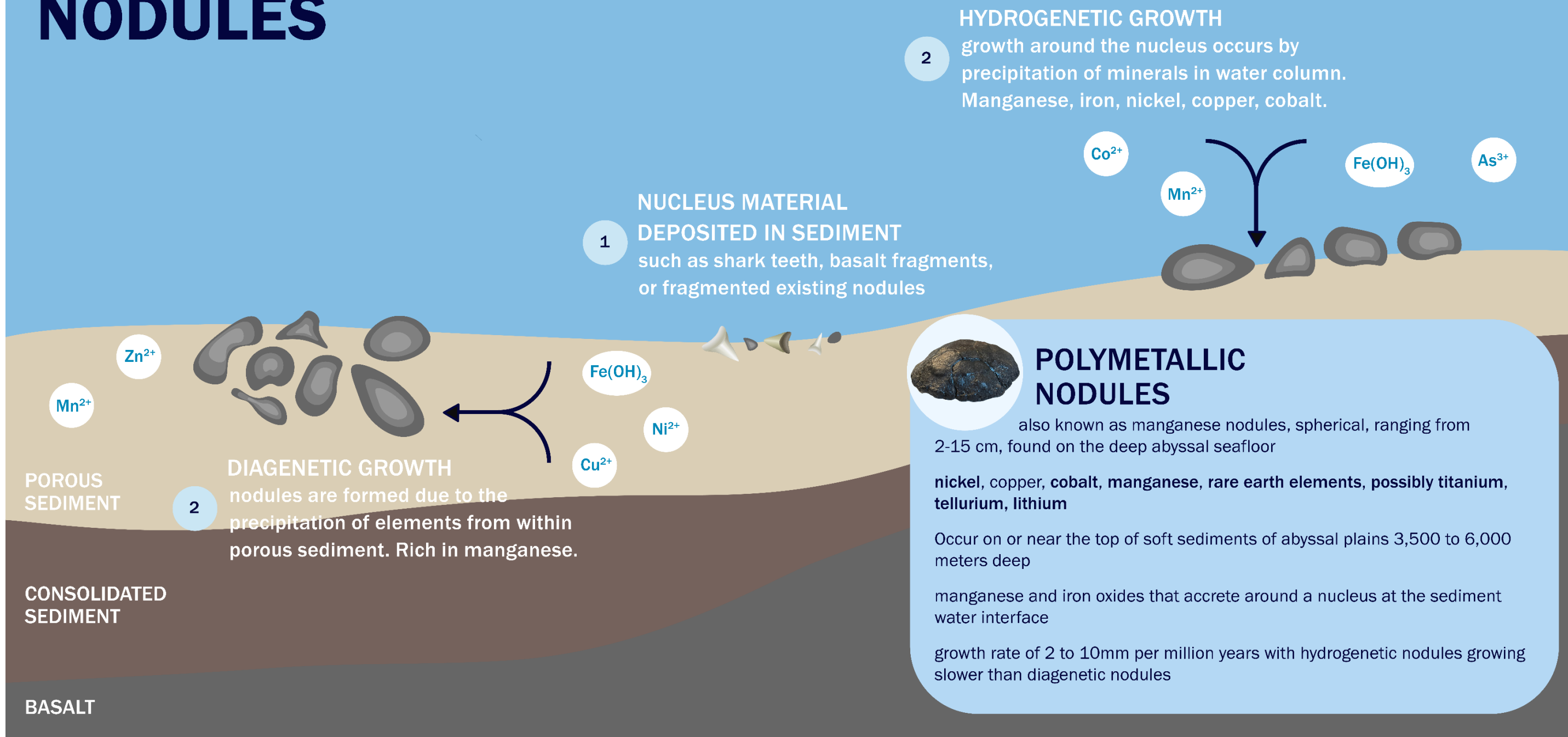
**2** HYDROTHERMAL VENTS DISPERSE DISSOLVED MINERALS

SEAMOUNTS

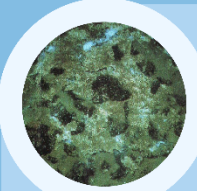
RIDGES



# FORMATION OF POLYMETALLIC NODULES



# FORMATION OF SEAFLOOR MASSIVE SULFIDE (SMS) DEPOSITS



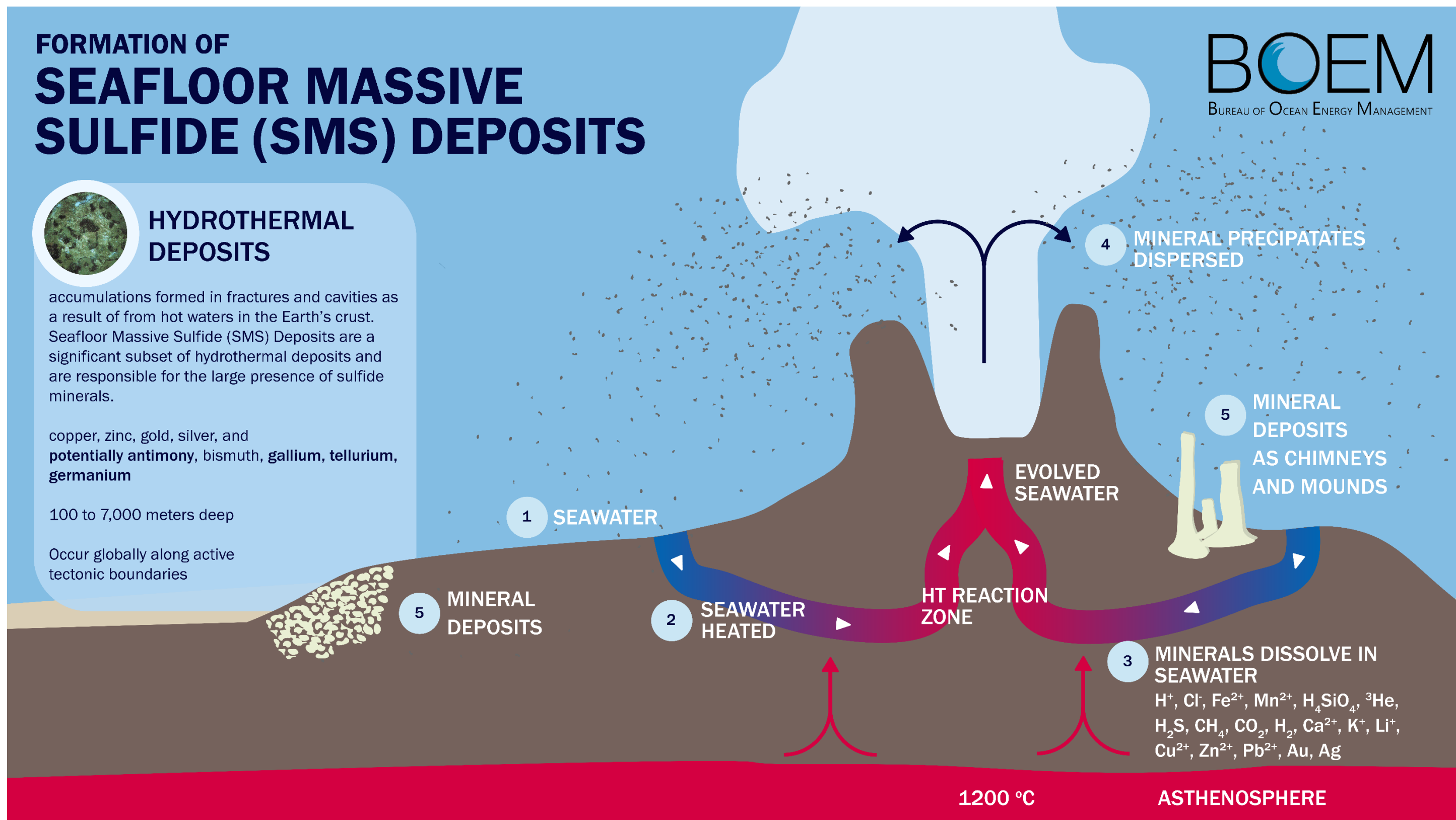
## HYDROTHERMAL DEPOSITS

accumulations formed in fractures and cavities as a result of from hot waters in the Earth's crust. Seafloor Massive Sulfide (SMS) Deposits are a significant subset of hydrothermal deposits and are responsible for the large presence of sulfide minerals.

copper, zinc, gold, silver, and potentially antimony, bismuth, gallium, tellurium, germanium

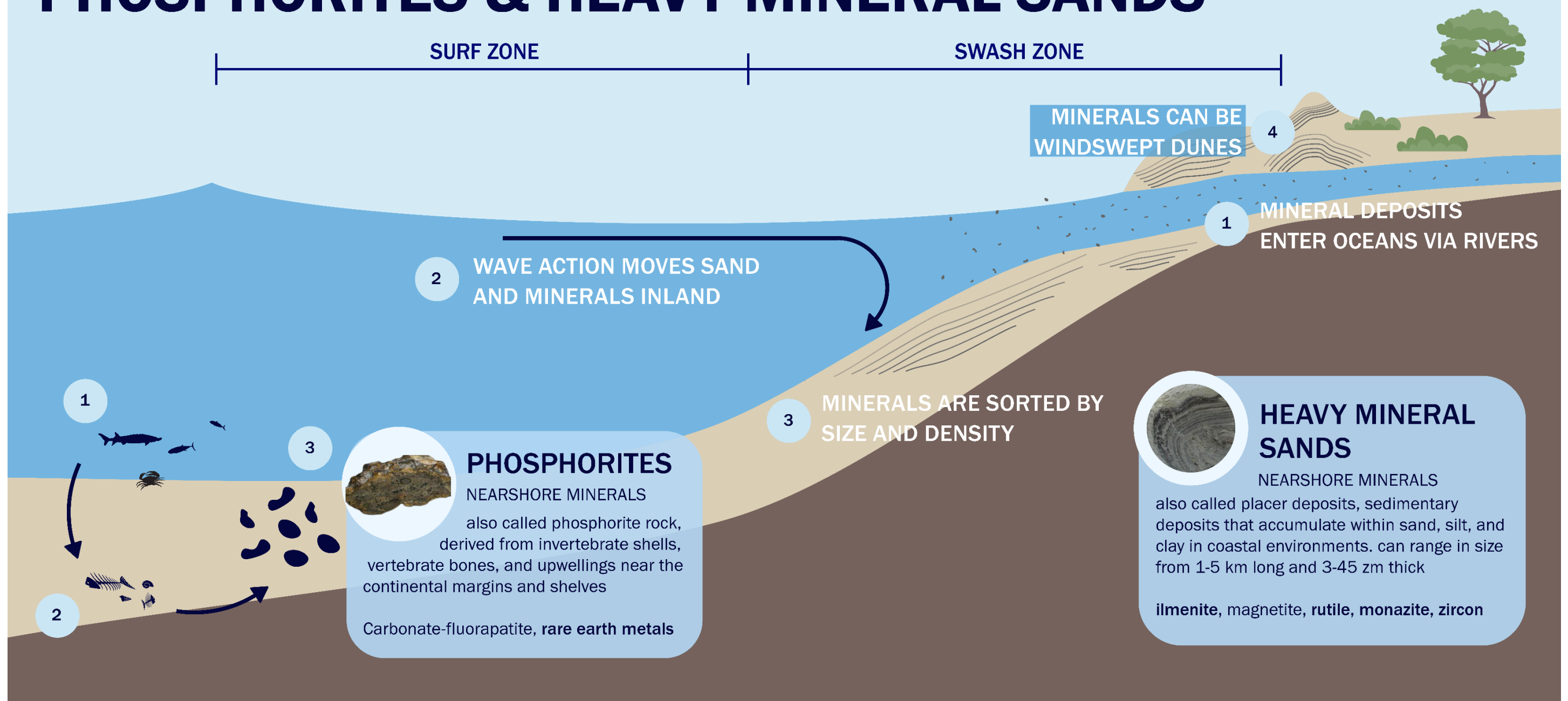
100 to 7,000 meters deep

Occur globally along active tectonic boundaries



Appendix A.6. Formation of Seafloor Massive Sulfide (SMS) Deposits

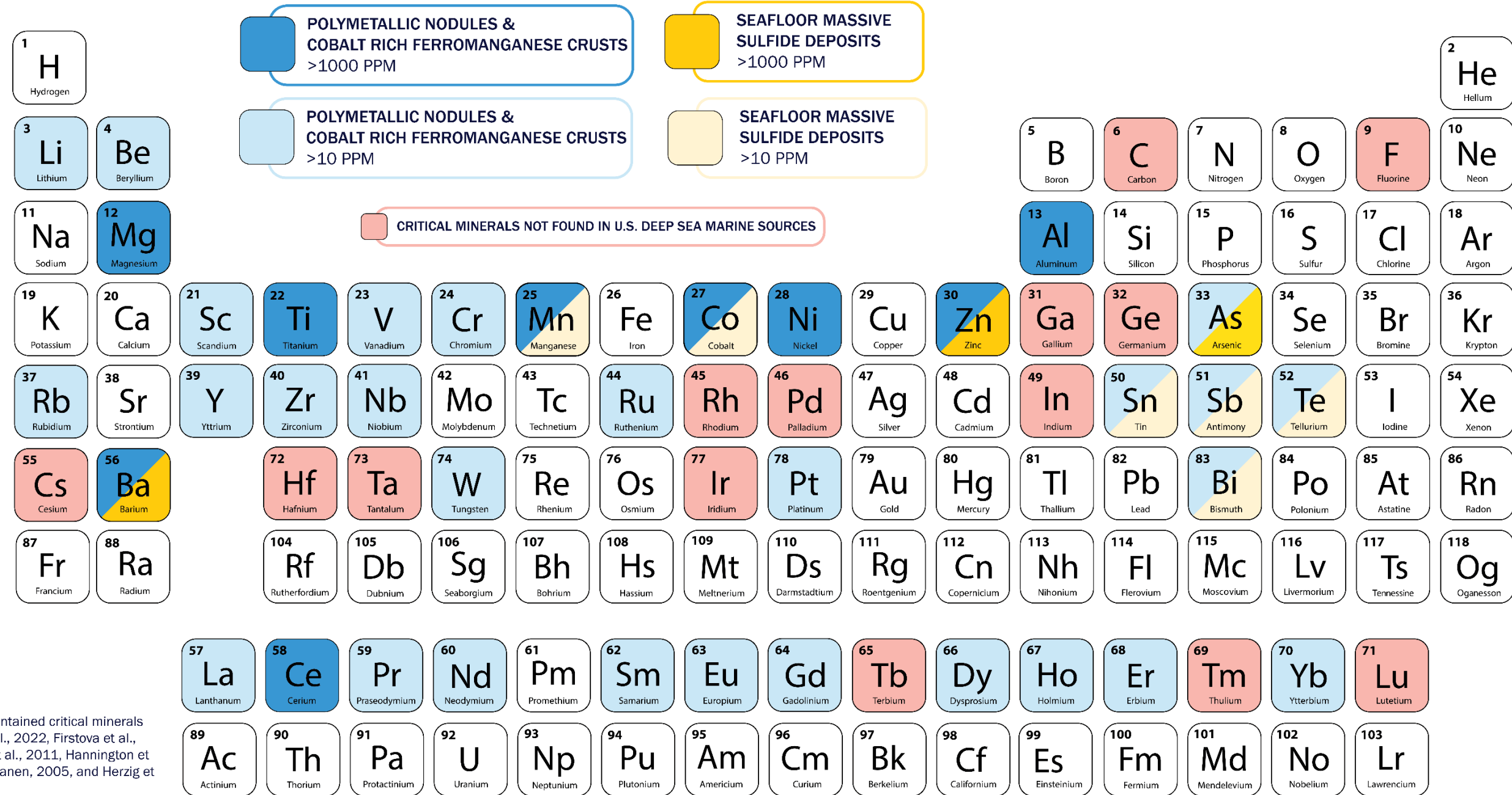
# FORMATION OF SHALLOWER DEPOSITS: PHOSPHORITES & HEAVY MINERAL SANDS



Appendix A-7. Formation of Shallower Deposits, Phosphorites & Heavy Mineral Sands

# U.S. CRITICAL MINERALS

## FROM DEEP SEA MARINE SOURCES



Estimates of contained critical minerals from Mizell et al., 2022, Firstova et al., 2019, Herzig et al., 2011, Hannington et al., 2010, Tormanen, 2005, and Herzig et al., 2022

# USES FOR POLYMETALLIC NODULES

**Ni**

**NICKEL**

stainless steel, superalloys, nonferrous alloys, rechargeable batteries, coining, and more

**Y**

**YTTRIUM**

compact fluorescent lamps, LEDs, TVs, ceramics, medical applications, and more

**Co**

**COBALT**

rechargeable batteries, petroleum industry, alloys, steel, paints, pigments, and more

**Te**

**TELLURIUM**

thermoelectric applications, steel, solar cells, and more

**Mn**

**MANGANESE**

iron and steel, alloys, batteries, construction, machinery, agriculture, and more

**Li**

**LITHIUM**

batteries, ceramics, glass, lubricating greases, medical, air treatment, and more

**Ti**

**TITANIUM**

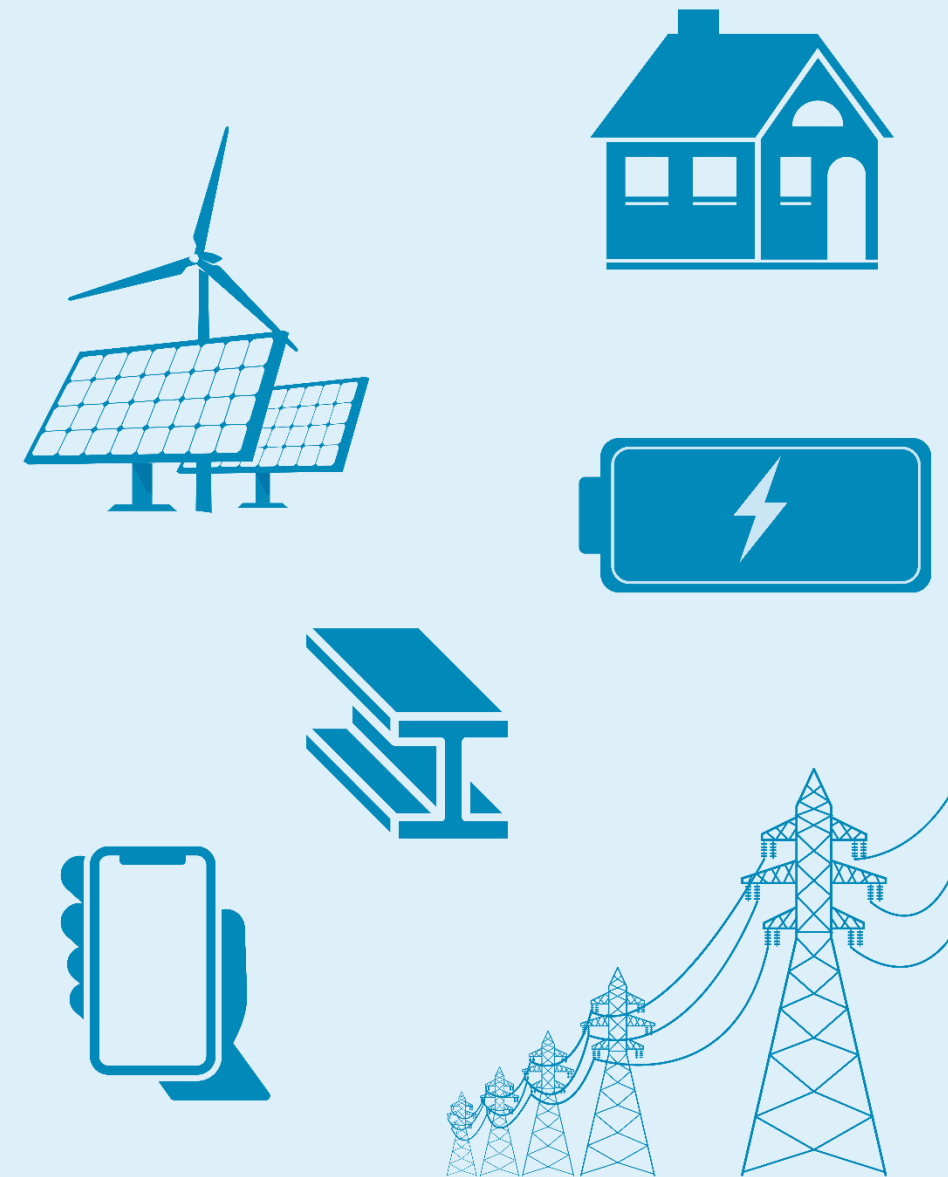
pigment, alloys, and more

**Cu**

**COPPER**

power transmission, telecommunication, machinery, electronics, and more

economically important non-critical mineral



# CURRENT STATE OF INDUSTRY AND TECHNOLOGY

