ISA TECHNICAL STUDY NO. 30

Marine mineral resources: scientific and technological advances

INTERNATIONAL SEABED AUTHORITY

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DISCLAIMER

For the purposes of this study, the "Area" means "the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction" as defined by the 1982 United Nations Convention on the Law of the Sea, Article 1(1).

The "thick contours" of all maps contained in the figures in this publication represent an approximation of the 200 NM calculated from the coastline purely for a distance-reference purpose, and they do not purport to indicate any maritime claim nor actual limits of any maritime zone. For the purposes of those figures, the coastline was used as the starting point for measuring the approximate 200 NM distance. The basic datasets used for this purpose were: Flanders Marine Institute (VLIZ) (2014), Maritime Boundaries Geodatabase, version 8 in conjunction with the National Oceanic and Atmospheric Administration.

"Exploration" is defined in the Exploration Regulations adopted by the International Seabed Authority as "the searching for deposits of [polymetallic nodules, polymetallic sulphides, and cobalt crusts] in the Area with exclusive rights, the analysis of such deposits, the use and testing of recovery systems and equipment, processing facilities and transportation systems and the carrying out of studies of the environmental, technical, economic, commercial and other appropriate factors that must be taken into account in exploitation". "Exploitation" is defined in the Exploration Regulations adopted by the International Seabed Authority as "the recovery for commercial purposes of [polymetallic nodules, polymetallic sulphides, and cobalt crusts] in the Area and the extraction of minerals therefrom, including the construction and operation of mining, processing and transportation systems, for the production and marketing of metals". The term "continental shelf" follows the geological definition throughout the study.

This study is based on data publicly available at the time the project was conducted and carried out in accordance with accepted scientific and/or academic principles and standards. Any reference to methods, technologies, intellectual property or other proprietary materials, and reported data is made on an 'as is' basis and without any express or implied warranties, representations or undertakings.

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CONTENTS

ABBREVIATIONS

1994 Agreement	Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea
AUV	autonomous underwater vehicle
BSR	bottom-simulating reflector
CCZ	Clarion-Clipperton Zone
CFA	carbonate-fluorapatite
CFC	cobalt-rich ferromanganese crusts
CLCS	Commission on the Limits of the Continental Shelf
CTD	conductivity-temperature-depth
DOALOS	United Nations Division for Ocean Affairs and the Law of the Sea, Office of Legal Affairs
EEZ	exclusive economic zone
EU	European Union
g/t	grams per tonne
GHSZ	gas hydrate stability zone
HREY	heavy REY
HYACINTH	Hydrogen Acceptance in the Transition Phase EU Project
IODP	International Ocean Discovery Program
ISA	International Seabed Authority
LREY	light REY
LTC	Legal and Technical Commission
MAR	Mid-Atlantic Ridge
MSR	marine scientific research
OBIA	object based image analysis
ODP	ocean drilling program
OLA	Office of Legal Affairs
OMZ	oxygen minimum zone
PCS	pressure core sampler
PMN	polymetallic manganese nodules
PMS	polymetallic massive sulphides
ppm	parts per million
REE	rare-earth elements
REY	rare-earth elements and yttrium
ROV	remotely operated vehicle
TAG	Trans-Atlantic geotraverse
UNCLOS	United Nations Convention on the Law of the Sea
VLIZ	Flanders Marine Institute
wt.-%	weight per cent

FOREWORD

I am pleased to introduce the present study which aims to document and summarise the advances in scientific understanding and subsea technology for mineral resources from the marine realm. Given those tremendous advances over the last ten years, the Secretariat of the International Seabed Authority (ISA) undertook the task to update the 2004 study *Marine Mineral Resources: Scientific advances and economic perspectives*, jointly published at that time by the United Nations Division for Ocean Affairs and the Law of the Sea of the Office of Legal Affairs (DOALOS) and ISA.

Similar to the 2004 publication, this study provides an overview of the current knowledge of seabed mineral resources in the continental shelf and in "the Area."

Advances in the scientific understanding of marine mineral formation, deposit identification and characterization are supported by advanced remote technologies allowing for high-resolution surveys of the deep-sea which are vital to better understand the resource potential but also the potential environmental impacts of future mining activities in the Area. The key marine mineral resources of the Area include polymetallic massive sulphides (PMS), polymetallic manganese nodules (PMN), and cobalt-rich ferromanganese crusts (CFC), which form the focus of this study. Other potential future resources, including marine gas hydrates, marine metalliferous sediments, marine placers, marine evaporites and marine phosphorite deposits, are predominately found within the continental shelf environments.

The increased demand for high-tech equipment and low-carbon renewable energy technologies is driving demand for an expanding suite of metals and trace elements that are potentially insufficiently sourced from primary deposits and secondary supplies on land or subjected to environmentally problematic mining activities. Metals considered critical due to the potential insecurity of their supply and high economic importance, such as copper, zinc, nickel, cobalt, tellurium, platinum, gold, silver, molybdenum, niobium, tungsten, zirconium, and rare earth elements including yttrium (REY), might be the targets for future PMN, PMS and CFC exploitation. While assessments of PMN as surface layers seem straightforward, estimating PMS, CFC tonnages remain the biggest challenge in resource estimation. Technological advances have the potential to improve all stages of PMN, PMS and CFC resource studies, from exploration, deposit definition and assessment to feasibility, mining, processing, and environmental monitoring.

In closing, I wish to express my recognition and gratitude to DOALOS, in particular its Director Mr. Vladimir Jares, for their contribution to this study by drafting Chapter 2 on the relevant legal framework. In addition, I thank the National Oceanography Centre (NOC) of the United Kingdom for their assistance in the preparation of this study.

Michael W. Lodge
Secretary-General
International Seabed Authority

EXECUTIVE SUMMARY

This study aims to document and summarise the advances in scientific understanding and technology for mineral resources from the marine realm. UNCLOS establishes the international legal regime within which all activities in the oceans and seas must be undertaken. UNCLOS and the 1994 Agreement Relating to the Implementation of Part XI of UNCLOS (the 1994 Agreement) provide the international legal framework for activities in the Area, including by entrusting ISA with the role of organising and controlling activities in the Area, in particular administering activities relating to resources in "the area of the seabed and ocean floor and the subsoil thereof, beyond the limits of national jurisdiction" (the Area).[1] The key marine mineral resources of the Area include PMS, PMN and marine CFC, which form the focus of this study. Other potential future resources, including marine gas hydrates, marine metalliferous sediments, marine placers, marine evaporites and marine phosphorite deposits, are predominately found within the continental shelf environments.

Major advances in deposit identification and characterisation have been supported by the increased use of remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV) technologies. Improvements in remote technologies have allowed for surveying of the deep sea at far higher resolutions than previously possible. The collection of high-resolution bathymetry and data from ROV- and AUV-mounted multibeam echosounder sonars has facilitated in-depth studies of in situ marine mineral deposits to better understand what controls their formation, composition, and resource potential. These high-resolution studies are also vital to better understand the potential environmental impacts of future mining activities in the Area. In almost all cases for marine mineral deposits, the application of multidisciplinary surveys that include both geophysical and geological techniques yield the best understanding of the resource.

Marine PMS are metal-bearing deposits formed from the precipitation of minerals from hydrothermal fluids sourced from the cycling of seawater within the oceanic crust. Key elements of economic interest are copper, zinc, lead, a series of economically strategic minor and trace elements, and the precious metals, gold and silver. Over 700 sites of hydrothermal activity have been identified globally, but large uncertainties remain regarding the resource potential of PMS accumulations. The biggest barrier to resource estimation is understanding the structure of PMS deposits below the seafloor, how many inactive PMS may exist, and how well these deposits are preserved over time. Resource estimates require drill sampling to understand the third dimension of PMS deposits.

According to current understanding, a larger resource potential lies in marine

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[1] UNCLOS, Article 1(1).

CFC and particularly PMN in the Area. These iron- and manganese-rich deposits have large economic potential due to their high concentrations of target elements, including manganese, copper, cobalt, rare earth elements, nickel, and other elements important to high-tech industries, as well as their large estimated tonnages in the Area. Resource estimates for PMN are relatively well-defined for specific regions of known high nodule density, such as the area between the Clarion and Clipperton fracture zones in the Central Pacific Ocean. Given the vast areas over which they are found, however, global estimates remain poorly defined. Resource estimates for CFC require further understanding of the thickness and distribution of crusts and target elements at the sub-basin scale. In both cases, the increased use of remote technologies has improved resource estimation and understanding of deposit controls.

Other potential resources include marine gas hydrates as a non-renewable energy resource estimated to far exceed conventional gas resources. Marine metalliferous sediment deposits are varied in composition due to their generally mixed modes of formation, with inputs from multiple sources. Still, the majority of reported deposits are associated with hydrothermal activity. Marine placer deposits have been mined in shelf regions for decades and may show a wider geological distribution. Evaporites and phosphorites are deposits concentrated within continental shelf environments, with limited exploration in the Area due to the availability of the target minerals either on land or on the continental shelves.

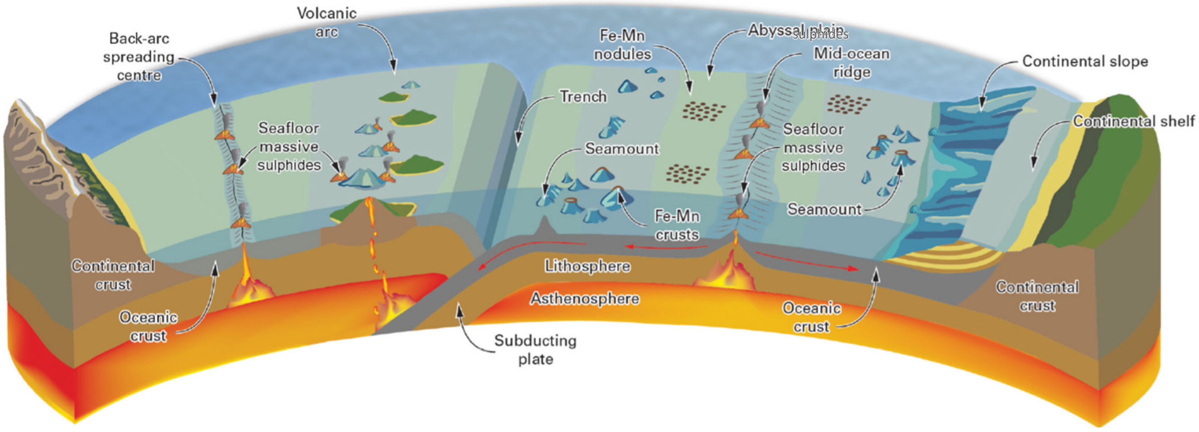
1. INTRODUCTION

1.1 Background

The Earth's oceans cover over 70 per cent of the planet, but up to 80 per cent of the oceans' floor is still unmapped and unexplored. Despite the size of our oceans, currently almost all of society's resources are mined from terrestrial deposits. The potential wealth of oceans is vast but unquantified. Given changes in resource economics and technological advances over time, furthering our understanding of the oceans will be vital to the next stage of mineral exploration as we move into increasingly complex environments. The utilisation of the mineral resources of our oceans has been historically limited to a few selected sectors and regions such as near-shore operations for aggregate mining (sand, gravel, etc.) and tin, diamonds, gold, and others in placer deposits, as well as the oil and gas industry in near-shore and offshore exploitation. Currently, technologies originally developed for the petroleum industry are used or adapted for exploration of the deep sea.

From a traditional geological perspective, the seafloor can be split into three main areas from shore to basin: the continental shelf, where water depths are less than 200 m; the continental slope, which describes the transition from shallow to deep environments; and the abyssal regions of the deep ocean, traditionally described as plains, which are generally vast areas deeper than 4,000 m (**Figure 1.1.1**).

Figure 1.1.1. The different global tectonic environments and associated ore deposits

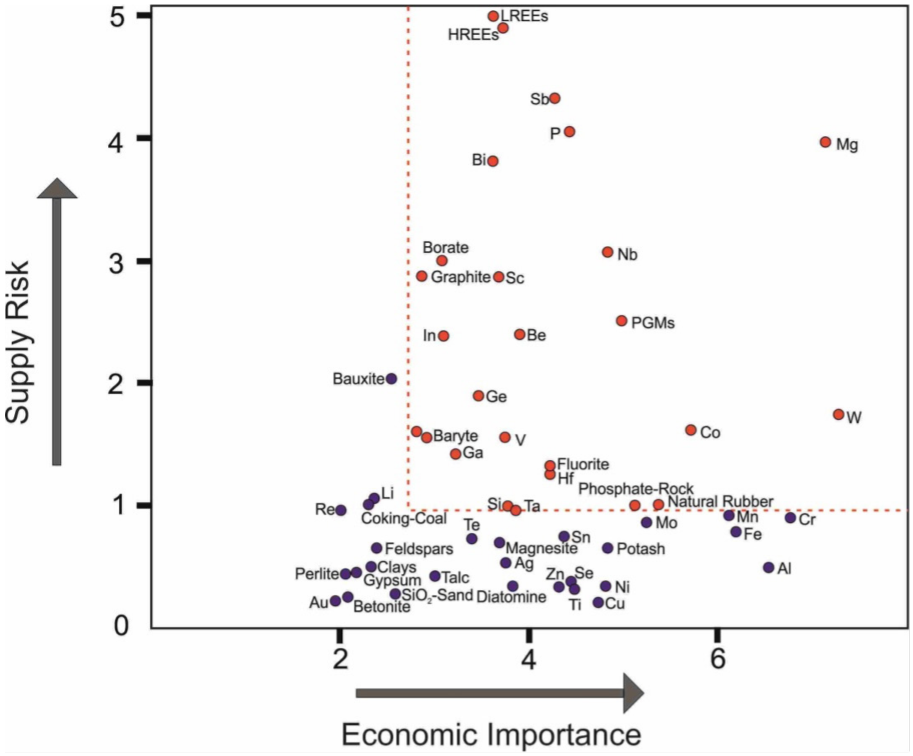


Source: Ian Longhurst, Copyright of the British Geological Survey, UKRI 2018

Deep marine mineral deposits, as they are currently recognised, were first sampled on the scientific expeditions of the HMS *Challenger* in the 1870s (Murray and Renard, 1891). Interest in the economic potential of deep-sea minerals was initiated in earnest in the 1960s when Mero (1965) described the potential resource wealth of our oceans in the form of PMN. Following this, the discovery of hydrothermal vent sites and associated metals within the surrounding sea-floor massive sulphides in the 1970s (Corliss et al., 1979) spurred interest in deep-sea exploration. This was buoyed by strong global economic growth up until the mid-1970s. A number of international resource companies started exploration projects including recovery tests on PMN and PMS. The decline in commodity prices, particularly of the key target elements associated with marine mineral deposits, and a slowdown in economic growth from 1975 up until the start of the 21st century led to a loss of appetite for the risks and challenges posed by deep-sea mining (Glasby, 2002; Sparenberg, 2019). Furthermore, the technological challenges of operating mining machinery and extracting minerals at over 4,000 m water depth made deep-sea mining not feasible. New efforts and concepts in exploration on land were successful and resulted in the end of industrial marine resource evaluation.

There has been a renewal of interest in deep-sea minerals since the start of the 21st century. This was driven by a substantial increase in commodity prices due to forecasts of increased future resource demands due to a range of factors. These include population growth, with the global population expected to be 9.7 billion by 2050 (United Nations, 2019), the rapidly expanding economies of countries such as Brazil, India, and China, and the development of low-carbon footprint technologies such as wind

Figure 1.1.2. Element criticality



Source: Adapted from European Commission, 2018 turbines, photovoltaic cells, and batteries for electric cars. These new technologies require a wider range of minor and trace elements—so-called economically strategic metals, e.g. lithium, cobalt, rare earth elements, etc. (**Figure 1.1.2**)—that are not always major commodities in today's land-based mines but extracted as by-products. However, currently, most of these metals are not extracted from the ore and end up as mine waste (Ragnarsdóttir, 2008). Some of these strategic elements are highly enriched in marine mineral deposits, and concentrations can exceed those found in land-based mineral deposits (Hein et al., 2010). With the growing demand for resources, the current land-based mining industry may have problems meeting these demands in the future, as lower grades and more challenging environmental constraints make many operations unfeasible (Carvalho, 2017). Thus, exploitation of higher-grade marine mineral deposits may be an additional or alternative solution to meet the global demand for metals, especially as PMN, CFC, and PMS would not require the removal of overburden, which is often typical for terrestrial mining operations.

This study, prepared by ISA, aims to summarise research undertaken on the scientific and technological advances in marine mineral resources since ISA's previous study on marine mineral resources in 2004, with a particular focus on the marine mineral deposits that are currently under ISA Contractor licenses (PMS, PMN, and CFC) as well as resources such as marine gas hydrates. Chapter 2 contains a detailed description of the existing legal framework, in accordance with UNCLOS, relating to the exploration and exploitation of mineral resources of the continental shelf and of the Area. It also provides an overview of the applicable legal framework concerning marine scientific research (MSR) in relation to mineral resources, and the development and transfer of marine technology. This Chapter on the legal framework was generously contributed by DOALOS.

The mineral resources described within this study are separated into two key chapters. Chapter 3 focuses on the marine resources found within the Area. Chapter 4 describes those predominantly found in the region of the geological continental shelf. Chapter 5 includes conclusions and observations.

1.2 Terminology and definitions

For the purpose of this study, standard scientific terminology is used wherever possible, including the following:

Abyssal plain: an area of the deep ocean floor, usually found at depths between 3,000 and 6,000 m, that lies between the foot of a continental rise and a mid-ocean ridge.

Base metal: a common metal such as copper (Cu), lead (Pb), or zinc (Zn).

Bathymetry: the topography of the seafloor. For this study, the bathymetry of GEBCO 2014 (Weatherall et al., 2015) is used.

Carbonate compensation depth: the depth in the oceans below which the rate of dissolution of calcite ($CaCO_3$) exceeds the supply rate of calcite, thus no calcite is usually preserved.

Continental margin: the water-covered area found in proximity to continents. The continental margin consists of three different features: the continental rise, the continental slope, and the continental shelf.

Diagenetic: when referring to the formation of CFC and PMN, indicates the precipitation of dissolved and colloidal metal complexes from interstitial water.

Gangue: traditionally non-economic minerals that are mixed with minerals of interest in an ore deposit.

GMT: generic mapping tools software (version 5.4.4; copyright: Wessel et al., 2018) is used to produce the occurrence maps of the marine mineral deposits described in this study. The command "pscost" is used to plot the cost-lines. The data interpolation (Figs. 3.2.2–3.2.7 and 3.3.2–3.3.7) is carried out using the command "surface", which applies B-spline interpolation. The data is interpolated onto a one-degree grid.

Hydrogenetic: when referring to CFC and PMN, it indicates precipitation of dissolved and colloidal metal complexes from near-bottom seawater.

Hydrothermal: forming from fluids of elevated to high temperature.

Mid-ocean ridge: underwater mountain range, formed at divergent tectonic plates through the uplift of the ocean floor due to convection currents rising in the mantle beneath the oceanic crust. Divergence at slow rates forms a graben system rather than a ridge.

Mineral processing: separating commercially valuable minerals from the gangue mineral intergrowths.

Plate tectonics: a widely approved and accepted scientific theory describing the large-scale motion of seven large plates and the movements of numerous smaller plates of the Earth's lithosphere. The outer baselines of the plates are called plate boundaries. For this study, the plate boundaries of Bird (2003) are used.

Precious metal: a rare, naturally occurring metallic chemical element of specific characteristics and high economic value, e.g. silver, gold, platinum.

Rare earth elements (REE): a set of fifteen lanthanides; lanthanum (La), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), cerium (Ce), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu), with yttrium (Y) and scandium (Sc) often added to this group of elements. Although they are relatively plentiful in the Earth's crust, they are typically dispersed, and exploitable mineral deposits are rare.

1.3 Classification of mineral resources

There are key concepts used to classify concentrations of minerals that are important to define when determining whether the deposits can be exploited, both in the terrestrial and marine realms. These terms help to distinguish between a concentration of minerals in a deposit and the factors that make this deposit a potential mine, such as feasibility of recovery.

"Mineral resources" are natural concentrations of minerals and metals and describe the occurrence and abundance of materials that may be of potential economic interest now or in the future. The discussion of a mineral resource does not account for whether exploitation of that mineral occurrence is feasible.

"Mineral reserves" are evaluated mineral resources with known abundances and volumes that are economically viable and technically feasible to produce. Mineral resources can become mineral reserves given sufficient progress in exploration, technological advances in processing and refinery, and suitable economic conditions.

Estimated resources for all mineral deposits may exceed their proven, recoverable reserves. This is particularly true for marine minerals, where sea-floor exploration is limited and many mineral resources are not yet economically recoverable. It is estimated that only 10 per cent of the ocean floor has been surveyed by ship-based sonar at average resolutions of 100 m^2 (Becker et al., 2009), so further research is required to recognise marine mineral resources and reserves. The ISA has adopted a resource classification scheme based upon the November 2013 international reporting template of the Committee for Mineral Reserves International Reporting Standards.[2]

Estimates of resources within the Area should be reported as: 1) mineral exploration results assessments; 2) mineral esources and 3) mineral reserves. Given the inherent uncertainty in estimating mineral resources and mineral reserves, these reporting standards ensure that adequate discussion of this uncertainty is included. Under the reporting code,[3]

Mineral Resources are defined as a "concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality that there are reasonable prospects for economic extraction". This considers mineralisation that has been identified, estimated, or interpreted through exploration and sampling so that the location, quantity, grade, and other geological characteristics are known.

Mineral Reserves are the "economically mineable part of a measured of indicated Mineral Resource" and include the reporting of diluting materials and losses during material mining or extraction, which are defined by studies that include modifying factors at the prefeasibility or feasibility stage. These studies "demonstrate that, at the time of reporting, extraction could reasonably be justified".

Mineral resources are characterised as inferred, indicated, or measured, depending on the level of certainty in the resource estimates. Inferred Mineral Resources have the lowest level of confidence, whereby quantity and grade are estimated using limited geological evidence and sampling so that geological and grade continuity can be implied but not verified. Inferred Mineral Resources cannot be converted into Mineral Reserves but must first be upgraded to indicated and measured Resources through continued exploration. Indicated Mineral Resources are resources that have estimated quantities, grades, densities, shapes, and physical characteristics at sufficient levels of confidence to allow for the use of modifying factors to support mine planning and the evaluation of the economic viability of that deposit and can be converted into probable Mineral Reserves. Modifying factors are "considerations used to convert Mineral Resources into Mineral Reserves" and "include, but are not restricted to, mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors". A measured Mineral Resource is a resource that has quantity, grade, density, shape, and physical characteristics

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[2] Committee for Mineral Reserves International Reporting Standards (undated). Member states. https://www.crirsco.com/templates/international_reporting_template_november_2013.pdf

[3] ISA/21/LTC/15/Annex V

estimated at sufficient levels of confidence to allow modifying factors to be used to support more detailed mine planning and a final evaluation of the economic viability of a deposit, and so can be converted into proved or probable Mineral Reserves (ISA/21/LTC/15/Annex V) [4] .

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[4] ISA/21/LTC/15/Annex V).

2. LEGAL FRAMEWORK

2.1. Overview – the United Nations Convention on the Law of the Sea

UNCLOS[6] frequently referred to as the "constitution for the oceans", entered into force in 1994. UNCLOS sets out the legal framework within which all activities in the oceans and seas must be carried out, including the conservation and sustainable use of oceans and their resources. UNCLOS includes in its preamble the goal of promoting the equitable and efficient utilization of ocean resources, the conservation of living ocean resources, and the study, protection and preservation of the marine environment. In its annual resolutions on oceans and the law of the sea, the General Assembly of the United Nations, has consistently emphasized the universal and unified character of UNCLOS as well as its strategic importance as the basis for national, regional, and global action and cooperation in the marine sector.[7] The importance of UNCLOS is also underscored by the 2030 Agenda for Sustainable Development, which calls on States to enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in UNCLOS.[8]

Under UNCLOS, coastal States are entitled to a number of maritime zones, namely internal waters, archipelagic waters where applicable, a territorial sea, a contiguous zone, an exclusive economic zone (EEZ) and a continental shelf. The high seas and the Area are maritime zones that lie beyond the limits of national jurisdiction. UNCLOS establishes the rights and duties of States in respect of each of these zones. To provide the context within which the regime applicable to the Area has been framed by the drafters of UNCLOS, the following sections will provide an overview of the relevant aspects of the continental shelf and the Area. This overview is then complemented by an analysis of relevant activities and issues across the various maritime zones such as MSR in relation to marine mineral resources and the development and transfer of marine technology.

2.2. The legal regime for the exploration and exploitation of mineral resources of the continental shelf

The continental shelf of a coastal State comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 NM from the baselines

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[6] United Nations, Treaty Series, vol. 1833, No. 31363.

[7] See, for example, United Nations General Assembly Resolution 74/19, Preamble.

[8] United Nations General Assembly, *Transforming our world: the 2030 Agenda for Sustainable Development*, 21 October 2015, A/RES/70/1, Goal 14.c, p.24.

from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend to that distance.[9] The continental margin comprises the submerged prolongation of the landmass of the coastal State, and consists of the seabed and subsoil of the shelf, the slope, and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof.[10]

Under UNCLOS, the coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 NM from the baselines from which the breadth of the territorial sea is measured, by reference to the complex scientific and technical criteria outlined in Article 76, paragraph 4.[11] In addition, the fixed points comprising the line of the outer limits of the continental shelf on the seabed either shall not exceed 350 NM from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 NM from the 2,500 m isobath, which is a line connecting the depth of 2,500 m.[12] With regard to particular sea-floor features, UNCLOS provides that on submarine ridges, the outer limit of the continental shelf shall not exceed 350 NM from the baselines from which the breadth of the territorial sea is measured.[13] However, this rule does not apply to submarine elevations that are natural components of the continental margin, such as its plateaux, rises, caps, banks, and spurs.[14]

In addition, the coastal State shall delineate the outer limits of its continental shelf, where that shelf extends beyond 200 NM from the baselines from which the breadth of the territorial sea is measured, by straight lines not exceeding 60 NM in length, connecting fixed points, defined by coordinates of latitude and longitude. Information on the limits of the continental shelf beyond 200 NM from the baselines from which the breadth of the territorial sea is measured shall be submitted by the coastal State to the Commission on the Limits of the Continental Shelf (CLCS), which is established under UNCLOS, Annex II. The CLCS makes recommendations to coastal States on matters related to the establishment of the outer limits of their continental shelf. The limits of the continental shelf established by a coastal State on the basis of these recommendations are final and binding.[15] The recommendations of the CLCS are without prejudice to the question of delimitation of the continental shelf between States with opposite or adjacent coasts.[16] Coastal States are required to deposit with the Secretary-General of the United Nations charts and relevant information, including geodetic data, permanently describing the outer limits of their continental shelf,[17] which are given due publicity by the Secretary-General.[18]

UNCLOS also provides that the outer limit lines of the continental shelf and the lines of delimitation thereof are to be shown on charts of a scale or scales adequate for ascertaining their position.[19] Where appropriate, lists of geographical coordinates of points, specifying the geodetic datum, may be substituted

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[9] UNCLOS, Article 76(1).
[10] UNCLOS, Article 76(3).
[11] UNCLOS, Article 76(4).
[12] UNCLOS, Article 76(5).
[13] UNCLOS, Article 76(6).
[14] Ibid.
[15] UNCLOS, Article 76(8).
[16] UNCLOS, Article 76(10).
[17] UNCLOS, Article 76(9).
[18] Ibid.
[19] UNCLOS, Article 84(1).

for such outer limit lines or lines of delimitation.[20] The coastal State shall give due publicity to such charts or lists of geographical coordinates and shall deposit a copy of each such chart or list with the Secretary-General of the United Nations and, in the case of those showing the outer limit lines of the continental shelf, with the Secretary-General of ISA.[21] This applies to both the outer limits established up to and those established beyond 200 NM from the baselines from which the breadth of the territorial sea is measured.

Coastal States exercise sovereign rights over the continental shelf for the purpose of exploring and exploiting its natural resources.[22] These rights are exclusive in the sense that, if the coastal State does not explore the continental shelf or exploit its natural resources, no one may undertake these activities without the express consent of the coastal State.[23] These rights do not depend on occupation, effective or notional, or on any express proclamation by the relevant States.[24] In addition, coastal States have the exclusive right to authorize and regulate drilling on the continental shelf for all purposes.[25]

The resources of the continental shelf consist of mineral and other non-living resources of the seabed and the subsoil and living organisms belonging to sedentary species, namely organisms at the harvestable stage, are either immobile on or under the seabed, or are unable to move except in constant physical contact with the seabed or the subsoil.[26] The determination of what constitutes sedentary organisms is particularly relevant in areas of the continental shelf beyond 200 NM since the superjacent waters of those areas fall under the regime of the high seas. However, the rights of a coastal State over the continental shelf do not affect the legal status of the superjacent waters or the airspace above those waters.[27]

The coastal State shall make payments or contributions in kind in respect of the exploitation of the non-living resources of the continental shelf beyond 200 NM from the baselines from which the breadth of the territorial sea is measured.[28] The payments and contributions shall be made annually with respect to all production at a site after the first five years of production at that site. For the sixth year, the rate of payment or contribution shall be 1 per cent of the value or volume of production at the site. The rate shall increase by 1 per cent for each subsequent year until the twelfth year and shall remain at 7 per cent thereafter.[29] A developing State which is a net importer of a mineral resource produced from its continental shelves is exempt from making such payments or contributions in respect of that mineral resource.[30] The payments or contributions shall be made through ISA, which shall distribute them to States Parties to UNCLOS, on the basis of equitable sharing criteria, taking into account the interests and needs of developing States, particularly the least developed and the

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[20] Ibid.

[21] UNCLOS, Article 84(2). *See* "Practice of the Secretary-General in respect of the deposit of charts and/or lists of geographical coordinates of points under the United Nations Convention on the Law of the Sea - Note by the Secretariat", SPLOS/30/12.

[22] UNCLOS, Article 77(1).

[23] UNCLOS, Article 77(2).

[24] UNCLOS, Article 77(2) and (3).

[25] UNCLOS, Article 81(1).

[26] UNCLOS, Article 77(4).

[27] UNCLOS, Article 78(2).

[28] UNCLOS, Article 82(1-2).

[29] UNCLOS, Article 82(2).

[30] UNCLOS, Article 82(3).

landlocked among them.[31]

2.3. The legal regime for the exploration and exploitation of mineral resources of the Area

The legal regime applicable to the Area is contained in Part XI of UNCLOS and the 1994 Agreement. In accordance with Article 2 of the 1994 Agreement, the provisions of the 1994 Agreement and Part XI of UNCLOS are to be interpreted and applied together as a single instrument. In the event of any inconsistency between the 1994 Agreement and Part XI, the provisions of the 1994 Agreement prevail.[32]

The Area and its resources are the common heritage of mankind, according to UNCLOS.[33] States Parties to UNCLOS have agreed that there shall be no amendments to the basic principle relating to the common heritage of mankind, and that they shall not be a party to any agreement in derogation thereof.[34]

UNCLOS defines "activities in the Area" to mean all activities of exploration for, and exploitation of, the resources of the Area.[35] For the purposes of the Area, UNCLOS defines "resources" as all solid, liquid or gaseous mineral resources in situ in the Area at or beneath the seabed, including PMN.[36] When the resources of the Area are recovered, they are referred to as minerals.[37]

Consistent with the legal status of the Area and its resources, all rights in the resources of the Area are vested in mankind as a whole, and activities in the Area shall be carried out for the benefit of mankind as a whole.[38] Financial and other economic benefits derived from activities in the Area shall be shared equitably,[39] and the Area is to be used exclusively for peaceful purposes.[40] No State shall claim or exercise sovereignty or sovereign rights over the Area, nor shall any State or natural or juridical person appropriate any part thereof.[41] All rights in the resources of the Area are vested in mankind as a whole, on whose behalf ISA shall act, and these resources are not subject to alienation.[42] The minerals recovered from the Area may only be alienated in accordance with Part XI of UNCLOS and the rules, regulations, and procedures of ISA.[43] No State or natural or juridical person shall claim, acquire, or exercise rights with respect to the minerals recovered from the Area except in accordance with Part XI of UNCLOS. Otherwise, no such claim, acquisition or exercise of such rights shall be recognized.[44]

UNCLOS establishes ISA as an autonomous international organization through which States Parties to UNCLOS organize and control activities in the Area, particularly with a view to administering the resources of the Area.[45] All parties to UNCLOS are

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[31] UNCLOS, Article 82(4).
[32] The 1994 Agreement, Article 2.
[33] UNCLOS, Article 136.
[34] UNCLOS, Article 311(6).
[35] UNCLOS, Article 1(3).
[36] UNCLOS, Article 133.
[37] Ibid.
[38] UNCLOS, Articles 137(2) and 140(1).
[39] UNCLOS, Article 140(2).
[40] UNCLOS, Article 141.
[41] UNCLOS, Article 137(1).
[42] UNCLOS, Article 137(2).
[43] Ibid.
[44] UNCLOS, Article 137(3).
[45] UNCLOS, Article 156(1) and 157(1).

ipso facto members of ISA.[46] The principal organs of ISA are: the Assembly, which is the supreme organ of ISA to which the other principal organs shall be accountable and has the power to establish general policies in conformity with the relevant provisions of UNCLOS on any question or matter within the competence of ISA;[47] the Council, which is the executive organ of ISA, has the power to establish the specific policies to be pursued by ISA on any question or matter within its competence;[48] and the Secretariat, which fulfils its administrative functions.[49] In addition, UNCLOS and the 1994 Agreement also establish "the Enterprise" as one of the organs of ISA. The functions of the Enterprise include the carrying out of mining activities in the Area directly, as well as the transporting, processing, and marketing of minerals recovered from the Area.[50] In accordance with the 1994 Agreement, ISA Secretariat shall perform the functions of the Enterprise until it begins to operate independently of the Secretariat.[51]

Activities in the Area shall be organized, carried out, and controlled by ISA on behalf of mankind as a whole in accordance with UNCLOS, and the rules, regulations, and procedures of ISA.[52] ISA, through the Assembly:

(i) decides upon the equitable sharing of financial and other economic benefits derived from activities in the Area, consistent with UNCLOS and the rules, regulations, and procedures of ISA;[53]

(ii) initiates studies and makes recommendations for the purpose of promoting international cooperation concerning activities in the Area and encouraging the progressive development of international law relating thereto and its codification;[54] and

(iii) considers problems of a general nature in connection with activities in the Area arising in particular for developing States, as well as those problems for States in connection with activities in the Area that are due to their geographical location, particularly for landlocked and geographically disadvantaged States.[55]

In addition, the Assembly has the function to consider and approve:

(i) upon the recommendation of the Council, the rules, regulations, and procedures on the equitable sharing of financial and other economic benefits derived from activities in the Area and the payments and contributions made by coastal States in respect of the exploitation of the non-living resources of the continental shelf beyond 200 NM from the baselines from which the breadth of the territorial sea is measured, taking into particular consideration the interests and needs of developing States and peoples who have not attained full independence or other self-governing status;

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[46] UNCLOS, Article 156(2).
[47] UNCLOS, Article 160(1).
[48] UNCLOS, Article 162.
[49] UNCLOS, Article 167.
[50] UNCLOS, Article 170; the 1994 Agreement, Annex, Section 2.
[51] The 1994 Agreement, Annex, Section 2.
[52] UNCLOS, Article 153.
[53] UNCLOS, Article 160(2)(g).
[54] UNCLOS, Article 160(2)(j).
[55] UNCLOS, Article 160(2)(k).

(ii) the rules, regulations, and procedures of [ISA] relating to prospecting, exploration, and exploitation in the Area, the financial management and internal administration of [ISA], and, upon the recommendation of the Governing Board of the Enterprise, to the transfer of funds from the Enterprise to [ISA], and any amendments thereto, provisionally adopted by the Council.[56]

The Council supervises and coordinates the implementation of Part XI of UNCLOS on all questions and matters within the competence of [ISA] and invites the attention of the Assembly to cases of non-compliance.[57] The Council:

(i) issues directives to the Enterprise;[58]

(ii) approves plans of work submitted by the Enterprise;[59]

(iii) exercises control over activities in the Area for the purpose of securing compliance with the relevant provisions of [UNCLOS], the rules, regulations, and procedures of [ISA], and the approved plans of work;[60]

(iv) disapproves areas for exploitation by Contractors or the Enterprise in cases where substantial evidence indicates the risk of serious harm to the marine environment;[61]

(v) establishes appropriate mechanisms for directing and supervising a staff of inspectors who shall inspect activities in the Area to determine whether [UNCLOS], the rules, regulations, and procedures of [ISA], and the terms and conditions of any contract with [ISA] are being complied with;[62] and

(vi) in cases of non-compliance, institutes proceedings on behalf of [ISA] before the Seabed Disputes Chamber.[63]

In accordance with UNCLOS, States Parties shall have the responsibility to ensure that activities in the Area, whether carried out by States Parties or state enterprises or natural or juridical persons which possess the nationality of States Parties or are effectively controlled by them or their nationals, shall be carried out in conformity with UNCLOS. The same responsibility applies to international organizations for activities in the Area carried out by such organizations.[64] In addition, damage caused by the failure of a State Party or international organization to carry out its responsibilities under UNCLOS shall entail liability and that States Parties or international organizations acting together shall bear joint and several liability.[65] However, a State Party shall not be liable for damage caused by any failure to comply with UNCLOS by a person whom it has sponsored under the Convention if the State Party has taken all necessary and appropriate measures to secure the effective compliance of

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[56] UNCLOS, Article 160(2)(f).
[57] UNCLOS, Article 162(2)(a).
[58] UNCLOS, Article 162(2)(i).
[59] UNCLOS, Article 162(2)(k).
[60] UNCLOS, Article 162(2)(l).
[61] UNCLOS, Article 162(2)(x).
[62] UNCLOS, Article 162(2)(z).
[63] UNCLOS, Article 162(2)(u).
[64] UNCLOS, Article 139(1).
[65] UNCLOS, Article 139(2).

the sponsored person or entity with the relevant provisions of UNCLOS and with such rules, regulations, and procedures issued by ISA to regulate prospecting, exploration, and exploitation of minerals in the Area.[66] The Seabed Disputes Chamber of the International Tribunal for the Law of the Sea clarified a number of matters pertaining to these provisions in its 2011 Advisory Opinion on "Responsibilities and obligations of States sponsoring persons and entities with respect to activities in the Area" (Advisory Opinion), which was rendered upon request from the Council.[67]

The general legal framework established by UNCLOS and the 1994 Agreement is further elaborated and implemented through the rules, regulations, and procedures issued by ISA to regulate prospecting, exploration, and exploitation of minerals in the Area, collectively referred to as the "Mining Code".

To date, ISA has issued regulations on prospecting and exploration for PMN,[68] PMS,[69] and CFC[70] in the Area, which further elaborate the relevant provisions of UNCLOS[71] and the 1994 Agreement and which also contain standard clauses for exploration contracts between ISA and Contractors. ISA is also developing regulations on the exploitation for mineral resources in the Area. The regulations are complemented by recommendations issued by the Legal and Technical Commission (LTC), a subsidiary organ of the Council, for the guidance of Contractors on the assessment of the environmental impacts of exploration, training, and resource classification as well as finance and reporting obligations, and on technical specifications related to relinquishment of areas under contracts for exploration for PMS and CFC.[72]

In its 2011 Advisory Opinion,[73] the Seabed Disputes Chamber clarified: the scope of the notion "activities in the Area"; the legal responsibilities and obligations of States Parties to UNCLOS with respect to the sponsorship of activities in the Area; the extent of liability of a State Party for any failure to comply with the provisions of UNCLOS, in particular Part XI, and the 1994 Agreement, by an entity whom it has sponsored; as well as the necessary and appropriate measures that a sponsoring State must take in order to fulfil its responsibility under UNCLOS.[74]

The Seabed Disputes Chamber found that the scope of "exploration" and "exploitation" as defined in the "Regulations on prospecting and exploration for PMN in the Area" (Nodules Regulations) and in the "Regulations on prospecting and exploration for PMS in the Area" (Sulphides Regulations) seem broader than the "activities in the Area" envisaged in UNCLOS. In particular, the Seabed Disputes Chamber noted that the processing and transportation are included in the notion of exploration and

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[66] Ibid.

[67] *Responsibilities and obligations of States with respect to activities in the Area, Advisory Opinion, 1 February 2011, ITLOS Reports 2011*, p. 10.

[68] Decision of the Assembly of [ISA] regarding the amendments to the Regulations on Prospecting and Exploration for [PMN] in the Area (ISBA/19/A/9) and Decision of the Council of [ISA] relating to amendments to the Regulations on Prospecting and Exploration for [PMN] in the Area and related matters (ISBA/19/C/17).

[69] Decision of the Assembly of [ISA] relating to the Regulations on Prospecting and Exploration for [PMS] in the Area (ISBA/16/A/12/Rev.1).

[70] Decision of the Assembly of [ISA] relating to the Regulations on Prospecting and Exploration for [CFC] in the Area (ISBA/18/A/11).

[71] Including UNCLOS, Annex III.

[72] Recommendations for the guidance of Contractors on the relinquishment of areas under the exploration contracts for [PMS] or [CFC] (ISBA/25/LTC/8).

[73] Responsibilities and obligations of States with respect to activities in the Area, Advisory Opinion, 1 February 2011, ITLOS Reports 2011, p. 10.

[74] Ibid.

exploitation of the Regulations, but not in that of "activities in the Area" of UNCLOS. The Seabed Disputes Chamber explained that the expression "activities in the Area", in the context of both exploration and exploitation, includes, first of all, the recovery of minerals from the seabed and their lifting to the water surface, as well as activities directly connected thereto such as evacuation of water from the minerals and the preliminary separation of materials of no commercial interest, including their disposal at sea. However, "processing", namely, the process through which metals are extracted from the minerals, and which is normally conducted at a plant situated on land, is distinguished from "exploration" and from "exploitation" and thus excluded from the expression "activities in the Area".[75]According to the Seabed Disputes Chamber, under UNCLOS and related instruments, prospecting does not require sponsorship.[76] Regarding transportation systems, the Seabed Disputes Chamber noted that transportation to points on land from the part of the high seas superjacent to the part of the Area in which a Contractor operates cannot be included in the notion of "activities in the Area", as it would be incompatible with the exclusion of transportation from "activities in the Area" under UNCLOS.[77] However, transportation within that part of the high seas, when directly connected with extraction and lifting, would be included in activities in the Area.[78] In the case of PMN, this applies, for instance, to transportation between the ship or installation where the lifting process ends and another ship or installation where the evacuation of water and the preliminary separation and disposal of material to be discarded take place.[79] As such, the Seabed Disputes Chamber concluded that "the inclusion of transportation to points on land could create an unnecessary conflict with provisions of UNCLOS such as those that concern navigation on the high seas." [80]

As regards the obligations of States Parties with respect to the sponsorship of activities in the Area, the Seabed Disputes Chamber held that States Parties have an obligation of due diligence to ensure, through their best possible efforts, that the activities in the Area carried out by the Contractor conform with UNCLOS.[81] While the standard of due diligence may vary over time and depends on the level of risk and on the activities involved, it requires the sponsoring State to take reasonably appropriate measures within its legal system, consisting of laws and regulations and administrative measures, to secure compliance by the sponsored Contractors.[82] In addition, sponsoring States have "direct obligations" under UNCLOS and related instruments, including: the obligation to assist ISA in the exercise of control over activities in the Area; the obligation to apply a precautionary approach as reflected in Principle 15 of the Rio Declaration[83] and set out in the Nodules Regulations and the Sulphides Regulations; the obligation to apply the "best environmental practices" set out in the Sulphides Regulations but equally applicable in the context of the Nodules Regulations; the obligation to adopt measures to ensure the provision of guarantees in the event of an emergency

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[75] Advisory Opinion, para 95.
[76] Advisory Opinion, para 98.
[77] Advisory Opinion, para 96.
[78] Ibid.
[79] Ibid.
[80] Ibid.
[81] Advisory Opinion, para 242.
[82] Ibid.
[83] Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3–4 June 1992 (A/CONF.151/26 (Vol. I)).

order by ISA for protection of the marine environment; and the obligation to provide recourse for compensation. Moreover, the obligation to conduct an environmental impact assessment is a direct obligation under UNCLOS and a general obligation under customary international law.[84]

The Seabed Disputes Chamber also held that, while the liability of the sponsoring State arises from its failure to fulfil its obligations under UNCLOS and related instruments, the failure of the sponsored Contractor to comply with its obligations does not in itself give rise to liability on the part of the sponsoring State. It must also be shown that there has been an occurrence of damage resulting from the failure of the sponsored Contractor.[85] In the view of the Seabed Disputes Chamber, in order for the sponsoring State's liability to arise, there must be a proven causal link between the failure of that State and the damage caused by the sponsored Contractor.[86] However, the sponsoring State is absolved from liability if it has taken "all necessary and appropriate measures to secure effective compliance" by the sponsored Contractor with its obligations.[87] This exemption from liability does not apply to the failure of the sponsoring State to carry out its direct obligations.[88] Regarding the relationship between the Contractor's liability and that of the sponsoring State, the main liability for a wrongful act committed in the conduct of the Contractor's operations or in the exercise of the ISA's powers and functions rests with the Contractor and ISA, respectively, rather than with the sponsoring State.[89] In other words, the liability of the sponsoring State and that of the sponsored Contractor exist in parallel and are not joint and several. The sponsoring State has no residual liability.[90]

As of July 2020, ISA has entered into 30 fifteen-year contracts for exploration. Eighteen of these contracts are for exploration for PMN in the Clarion-Clipperton Zone (CCZ), the Central Indian Ocean Basin and the Western Pacific Ocean. There are also seven contracts for exploration for PMS in the South-West Indian Ridge, Central Indian Ridge, South-East Indian Ridge, and the Mid-Atlantic Ridge (MAR), and five contracts for exploration for CFC in the Western Pacific Ocean.

2.4. The legal regime for other relevant activities

2.4.1. Marine scientific research in relation to mineral resources

Marine scientific research, conducted in accordance with UNCLOS, may generate knowledge relevant for the exploration and exploitation of marine mineral resources and assessing the environmental impacts of such activities. While UNCLOS does not define the MSR, it sets out a comprehensive set of rules on MSR, including the specific rights and duties of States regarding the conduct of MSR in the different maritime zones.

All States, irrespective of their geographical location, and competent international organizations have the right to conduct MSR subject to the rights and duties of other States as provided for in UNCLOS.[91] UNCLOS provides that MSR shall be conducted exclusively for peaceful purposes. It shall be conducted with appropriate scientific methods and means compatible with UNCLOS. MSR shall not unjustifiably interfere with other

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[84] Advisory Opinion, para 242.
[85] Advisory Opinion, paras 121–150, 242.
[86] Advisory Opinion, paras 181–184.
[87] Advisory Opinion, para 242.
[88] Ibid.
[89] Advisory Opinion, para 200.
[90] Advisory Opinion, para 242.
[91] UNCLOS, Article 238.

legitimate uses of the sea compatible with UNCLOS and shall be duly respected in the course of such uses. MSR shall be conducted in compliance with all relevant regulations adopted in conformity with UNCLOS, including those for the protection and preservation of the marine environment.[92] In addition, UNCLOS provides that States and competent international organizations shall promote and facilitate the development and conduct of MSR in accordance with UNCLOS.[93] UNCLOS further provides that MSR activities shall not constitute the legal basis for any claim to any part of the marine environment or its resources.[94]

Beyond the territorial sea, States shall, in accordance with UNCLOS, endeavour to adopt reasonable rules, regulations, and procedures to promote and facilitate MSR conducted in accordance with UNCLOS, and, as appropriate, to facilitate, subject to the provisions of their laws and regulations, access to their harbours and promote assistance for MSR vessels which comply with the relevant provisions regarding MSR.[95]

Coastal States, in the exercise of their jurisdiction, have the right to regulate, authorize, and conduct MSR on their continental shelf in accordance with the relevant provisions of UNCLOS.[96] In particular, MSR shall be conducted with the consent of the coastal State.[97] Also, States and competent international organizations which intend to undertake MSR on the continental shelf of a coastal State shall, not less than six months in advance of the expected starting date of the MSR project, provide that State with a full description of:

(a) the nature and objectives of the project
(b) the method and means to be used, including name, tonnage, type, and class of vessels and a description of scientific equipment
(c) the precise geographical areas in which the project is to be conducted
(d) the expected date of first appearance and final departure of the research vessels, or deployment of the equipment and its removal, as appropriate
(e) the name of the sponsoring institution, its director, and the person in charge of the project and
(f) the extent to which it is considered that the coastal State should be able to participate or be represented in the project.[98]

States and competent international organizations, when undertaking MSR on the continental shelf of a coastal State, shall:

(a) ensure the right of the coastal State, if it so desires, to participate or be represented in the MSR project, especially on board research vessels and other craft or scientific research installations, when practicable, without payment of any remuneration to the scientists of the coastal State and without obligation to contribute towards the costs of the project

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[92] UNCLOS, Article 240.
[93] UNCLOS, Article 239.
[94] UNCLOS, Article 241.
[95] UNCLOS, Article 255.
[96] UNCLOS, Article 246(1).
[97] UNCLOS, Article 246(2).
[98] UNCLOS, Article 248.

(b) provide the coastal State, at its request, with preliminary reports, as soon as practicable, and with the final results and conclusions after the completion of the research

(c) undertake to provide access for the coastal State, at its request, to all data and samples derived from the MSR project and likewise to furnish it with data which may be copied and samples which may be divided without detriment to their scientific value

(d) if requested, providing the coastal State with an assessment of such data, samples and research results or provide assistance in their assessment or interpretation

(e) ensuring, subject to the laws and regulations of coastal State, that the research results are made internationally available through appropriate national or international channels as soon as practicable

(f) inform the coastal State immediately of any major change in the research programme and

(g) unless otherwise agreed, remove the scientific research installations or equipment once the research is completed.[99]

The Coastal States shall, in normal circumstances, grant their consent for MSR projects by other States or competent international organizations on their continental shelf to be carried out in accordance with UNCLOS exclusively for peaceful purposes and to increase scientific knowledge of the marine environment for the benefit of all mankind.[100] To this end, coastal States shall establish rules and procedures ensuring that such consent will not be delayed or denied unreasonably.[101] Coastal States may in their discretion withhold their consent to the conduct of a MSR project on the continental shelf where the proposed research project:

(a) is of direct significance for the exploration and exploitation of natural resources, whether living or non-living

(b) involves drilling into the continental shelf, the use of explosives or the introduction of harmful substances into the marine environment

(c) involves the construction, operation, or use of artificial islands, installations, and structures or

(d) contains inaccurate information regarding the nature and objectives of the project or if the researching State or competent international organization has outstanding obligations to the coastal State from a prior research project.[102]

Where proposed MSR projects are on the continental shelf beyond 200 NM, coastal States may not exercise their discretion to withhold consent on projects of direct significance for the exploration and exploitation of natural resources, as long as these projects are outside specific areas which coastal States publicly designate as areas in which exploitation or detailed exploratory operations focused on those areas are occurring or will occur within a reasonable period of time.[103]

The conditions set out in UNCLOS regarding the conduct of MSR on the

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[99] UNCLOS, Article 249(1).

[100] UNCLOS, Article 246(3).

[101] Ibid.

[102] UNCLOS, Article 246(5).

[103] UNCLOS, Article 246(6).

continental shelf are without prejudice to other conditions that the coastal State may establish for the exercise of its discretion to grant or withhold consent to the conduct of a MSR project on its continental shelf.[104] For instance, the coastal State may require that there should be a prior agreement to make the research results of a project of direct significance for the exploration and exploitation of natural resources internationally available.[105]

UNCLOS also regulates the conduct of MSR in maritime areas beyond national jurisdiction. In the high seas, all States, irrespective of their geographical location, and competent international organizations, have the right to conduct MSR in conformity with UNCLOS.[106] The freedom of the high seas, under UNCLOS, includes the freedom of scientific research, subject to Parts VI and XIII.[107] That freedom must be exercised with due regard for the rights under UNCLOS with respect to activities in the Area.[108]

All States and competent international organizations have the right to conduct MSR in the Area, in conformity with the provisions of Part XI of UNCLOS.[109] Accordingly, MSR in the Area shall be carried out exclusively for peaceful purposes and for the benefit of mankind as a whole.[110] ISA may carry out MSR concerning the Area and its resources and may enter into contracts for that purpose. ISA shall promote and encourage the conduct of MSR in the Area and shall coordinate and disseminate the results of such research and analysis when available.[111] States parties shall promote international cooperation in MSR in the Area by:

(a) participating in international programmes and encouraging cooperation in MSR by personnel of different countries and of [ISA]

(b) ensuring that programmes are developed through [ISA] or other international organizations as appropriate for the benefit of developing States and technologically less developed States

(c) effectively disseminating the results of research and analysis when available, through [ISA] or other international channels when appropriate.[112]

In addition, the regulations on prospecting and exploration for mineral resources in the Area developed by [ISA] provide that they must not in any way affect the freedom of scientific research on the high seas, or the right to conduct MSR in the Area.[113]

2.4.2. Development and transfer of marine technology

Under UNCLOS, States shall cooperate in accordance with their capabilities, directly or through competent international organizations, to actively promote the development and transfer of marine science and marine technology on fair

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[104] UNCLOS, Article 249(2).
[105] Ibid.
[106] UNCLOS, Article 257.
[107] UNCLOS, Article 87(1) and (2).
[108] Ibid.
[109] UNCLOS, Article 256.
[110] UNCLOS, Article 143(1).
[111] UNCLOS, Article 143(2).
[112] UNCLOS, Article 143(3).
[113] Regulation 4 of the Regulations on Prospecting and Exploration for [CFC] in the Area; Regulation 4 of the Regulations on Prospecting and Exploration for [PMS] in the Area; Regulation 4 of the Regulations on Prospecting and Exploration for [PMN] in the Area.

and reasonable terms and conditions.[114] In addition, States shall promote the development of the marine scientific and technological capacity of States which may need and request technical assistance in this field, particularly developing States, including land-locked and geographically disadvantaged States, with regard to the exploration, exploitation, conservation, and management of marine resources, the protection and preservation of the marine environment, MSR, and other activities in the marine environment compatible with UNCLOS, with a view to accelerating the social and economic development of the developing States.[115]

In addition, States shall endeavour to foster favourable economic and legal conditions for the transfer of marine technology for the benefit of all parties concerned on an equitable basis.[116] To this end, States shall promote, directly or through competent international organizations: the acquisition, evaluation and dissemination of marine technological knowledge and facilitate access to such information and data; the development of appropriate marine technology; the development of the necessary technological infrastructure to facilitate the transfer of marine technology; the development of human resources through training and education of nationals of developing States and countries, and especially the nationals of the least developed among them; and international cooperation at all levels, particularly at the regional, subregional, and bilateral levels.[117]

In order to achieve these objectives, States have an obligation, in accordance with UNCLOS, to endeavour to:

(a) establish programmes of technical cooperation for the effective transfer of all kinds of marine technology to States which may need and request technical assistance in this field, particularly the developing land-locked and geographically disadvantaged States, as well as other developing States which have not been able either to establish or develop their own technological capacity in marine science and in the exploration and exploitation of marine resources or to develop the infrastructure of such technology

(b) promote favourable conditions for the conclusion of agreements, contracts, and other similar arrangements under equitable and reasonable conditions

(c) hold conferences, seminars, and symposia on scientific and technological subjects, in particular on policies and methods for the transfer of marine technology

(d) promote the exchange of scientists and of technological and other experts and

(e) undertake projects and promote joint ventures and other forms of bilateral and multilateral cooperation.[118]

UNCLOS also contains several provisions concerning the promotion of international cooperation in the development and transfer of marine technology. For instance, international cooperation for the development and transfer of marine technology is to be carried out, where feasible and appropriate, through existing bilateral, regional, or multilateral programmes, and also through expanded

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[114] UNCLOS, Article 266(1).
[115] UNCLOS, Article 266(2).
[116] UNCLOS, Article 266(3).
[117] UNCLOS, Article 268.
[118] UNCLOS, Article 269.

and new programmes in order to facilitate MSR, the transfer of marine technology, particularly in new fields, and appropriate international funding for ocean research and development.[119] Also, in the field of transfer of marine technology, States have an obligation to endeavour to ensure that competent international organizations coordinate their activities, including any regional or global programmes, taking into account the interests and needs of developing States, particularly land-locked and geographically disadvantaged States.[120] States, in promoting cooperation with regard to the development and transfer of marine technology, are required to have due regard for all legitimate interests including the rights and duties of holders, suppliers, and recipients of marine technology.[121]

ISA is empowered to take measures in accordance with UNCLOS to acquire technology and scientific knowledge relating to activities in the Area and to promote and encourage the transfer to developing States of such technology and scientific knowledge so that all States Parties benefit therefrom.[122] UNCLOS also provides that ISA and States Parties are to cooperate in promoting the transfer of technology and scientific knowledge relating to activities in the Area so that the Enterprise and all States Parties may benefit therefrom.[123] In particular, ISA and States Parties shall initiate and promote programmes for the transfer of technology to the Enterprise and to developing States with regard to activities in the Area, including facilitating the access of the Enterprise and of developing States to the relevant technology under fair and reasonable terms and conditions.[124] UNCLOS further provides that ISA and States Parties have an obligation to initiate and promote measures directed towards the advancement of the technology of the Enterprise and the domestic technology of developing States, particularly by providing opportunities to personnel from the Enterprise and from developing States for training in marine science and technology and for their full participation in activities in the Area.[125]

In addition, the 1994 Agreement foresees that transfer of technology for the purposes of Part XI of UNCLOS shall be governed by the following principles:

> (a) The Enterprise, and developing States wishing to obtain deep-seabed mining technology, shall seek to obtain such technology on fair and reasonable commercial terms and conditions on the open market or through joint venture arrangements.
>
> (b) If the Enterprise or developing States are unable to obtain deep seabed mining technology, [ISA] may request all or any of the Contractors and their respective sponsoring State or States to cooperate with it in facilitating the acquisition of deep seabed mining technology by the Enterprise or its joint venture, or by a developing State or States seeking to acquire such technology on fair and reasonable commercial terms and conditions, consistent with the effective protection of intellectual property rights. States Parties undertake to cooperate fully and effectively with [ISA] for this purpose and to ensure that Contractors sponsored by them also cooperate fully with [ISA].

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[119] UNCLOS, Article 270.
[120] UNCLOS, Article 272.
[121] UNCLOS, Article 267.
[122] UNCLOS, Article 144.
[123] Ibid.
[124] Ibid.
[125] Ibid.

> (c) As a general rule, States parties shall promote international technical and scientific cooperation with regard to activities in the Area either between the parties concerned or by developing training, technical assistance, and scientific cooperation programmes in marine science and technology and the protection and preservation of the marine environment.[126]

With regard to international cooperation in the development and transfer of marine technology, States shall cooperate actively with competent international organizations and [ISA] to encourage and facilitate the transfer to developing States, their nationals, and the Enterprise of skills and marine technology with regard to activities in the Area. In addition, UNCLOS further contains a number of objectives for ISA. These include ensuring that: on the basis of the principle of equitable geographical distribution, nationals of developing States, whether coastal, land-locked, or geographically disadvantaged, must be taken on for the purposes of training as members of the managerial, research, and technical staff constituted for its undertakings; the technical documentation on the relevant equipment, machinery, devices, and processes is made available to all States, in particular developing States which may need and request technical assistance in this field; adequate provision is made by ISA to facilitate the acquisition of technical assistance in the field of marine technology by States which may need and request it, in particular developing States, and the acquisition by their nationals of the necessary skills and know-how, including professional training; and that States which may need and request technical assistance in this field, in particular developing States, are assisted in the acquisition of necessary equipment, processes, plant, and other technical know-how through any financial arrangements provided for in UNCLOS.[127]

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[126] The 1994 Agreement, Annex, Section 5.

[127] UNCLOS, Article 274.

3. MINERAL RESOURCES IN THE AREA

3.1. Marine polymetallic sulphides

3.1.1. Definition

Marine PMS are metalliferous enrichments of high- and low-temperature hydrothermal mineral precipitates. There is obvious evidence that they represent the modern analogues of volcanic-hosted massive sulphide deposits on land that are one of today's major producers of base, trace, and precious metals on Earth (Singer, 1995). PMS form on and below the seafloor along mid-ocean ridges and in back-arc basins and submarine volcanic arcs over thousands of years through seawater-derived fluids that have interacted with a magmatic heat source and basement rocks within the oceanic crust. Due to variations in the distance to the heat source, composition of basement rocks, fluid-rock interactions, local hydrology, and fluid evolution, the composition and temperature of these fluids, and consequently the overall composition, size, and structure of PMS sites vary significantly (Hannington et al., 2010). In some areas, PMS accumulation reaches magnitudes that make them of economic interest for potential exploitation.

The predominant minerals forming PMS are iron sulphides (pyrite/marcasite: Fe_2S, pyrrhotite: $Fe_{1-x}S$), as well as key minerals of economic interest such as copper (chalcopyrite: $CuFeS_2$; isocubanite: $CuFe_2S_3$) and zinc sulphides (sphalerite/wurtzite: ZnS). Other minerals such as lead sulphides (galena: PbS), the precious metals gold and silver, and other metals (cobalt, selenium, indium, tellurium, bismuth, germanium, gallium, etc.) occur either as accessories or inclusions in one of the main sulphide phases. In addition, secondary sulphides, carbonates, oxides, and hydroxides can form during weathering processes of the PMS, such as copper sulphides (bornite: Cu_5FeS_4; chalcocite: Cu_2S; covellite: CuS), copper oxychlorides (atacamite: $Cu_2Cl[OH]_3$), and many more.

Hydrothermal fluids are the source for PMS formation, but they also host an adapted biological ecosystem (Desbruyères et al., 2006). This fauna relies on the production of biomass by chemo-synthetic microorganisms for their existence (Fisher et al., 2007).

3.1.2. Formation

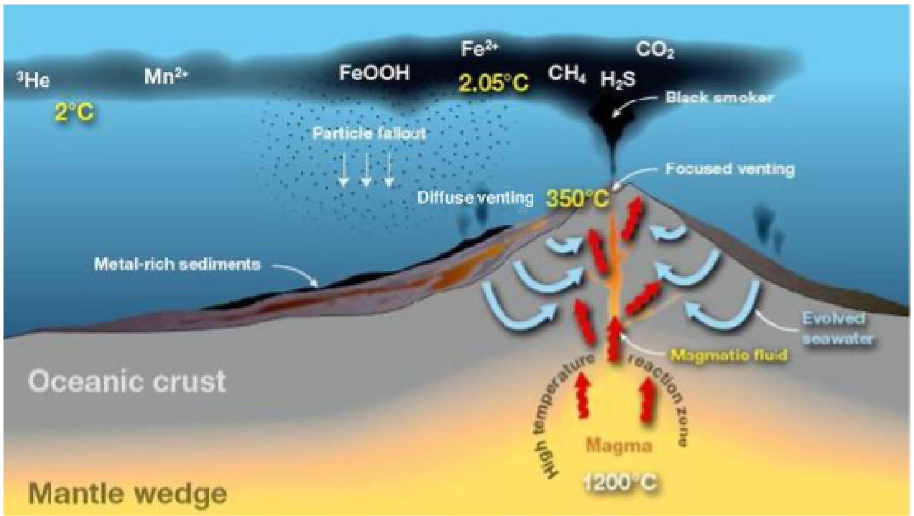
Cold seawater infiltrates through cracks into the oceanic crust, is heated to high temperatures and modified to an acidic and reduced fluid several kilometres below the seafloor (Figure 3.1.1). After being heated to peak temperatures of 450°C or higher in some cases (German and Seyfried, 2003), the seawater-derived fluid leaches metals from the basement rocks (e.g. basalt or gabbro-pyroxenite). This process results in a change of the composition, salinity, redox potential, and density of the fluid. Then, the modified seawater (i.e. hydrothermal fluid) becomes buoyant and rises eventually to the seafloor in pipe-like, narrow structures which are controlled by magmatic diking, tectonic faulting, or just rock vesicularity. Once it reaches the seafloor, the hydrothermal fluid is discharged vertically as focused flow at chimney vent sites or diffusive flow at larger mound structures into the overlying water column, where it comes in contact with the cold near-bottom seawater (2–4°C). As soon as the density of the hydrothermal plume equilibrates with the density of the bottom water horizon, the plume starts dispersing laterally and can travel several tens of kilometres. It has been estimated that only about 5 per cent of the dissolved metals precipitate as sulphides and sulphates in black and white smoker chimneys (Rona, 1984). The remaining 95 per cent of the dissolved metals are transported in hydrothermal plumes and precipitate as fallout of suspended fine-grained particles that can form metalliferous sediments (see Section 4.2.).

While for most PMS the source of metals is considered to be leached from the basement rock, some PMS deposits, like the Papua New Guinea-Australia-Canada-MANUS hydrothermal field (Manus Basin), have some of their metals provided by magmatic fluids (Yang and Scott, 1996).

Regardless of the source of the metals, all PMS form episodically, with alternating active and inactive phases. Over thousands of years, chimney structures collapse, and their debris piles up as mounds. Diffuse low-temperature flow or hot hydrothermal fluids from a new hydrothermal cycle alter and remobilise existing mineral accumulations, deposit new sulphide precipitates, and generate new stockwork mineralisation at depth. The size and shape of mounds depend on the host environment. Basalt-hosted systems like the Trans-Atlantic Geotraverse (TAG) site form conical mounds with 40–50 m height and diameters of up to 200 m (Figure 3.1.2). Sediment-hosted systems like the Okinawa Trough and Middle Valley also form large mounds (≤300 m diameter, ≤50 m height) with sediments acting as a host to trap the metals (Takai et al., 2012; Zierenberg et al., 1998). In contrast, ultramafic-hosted PMS only form "flat mounds" with the majority of mineralisation occurring sub-surface and in extensive stockwork (Fouquet et al., 2010).

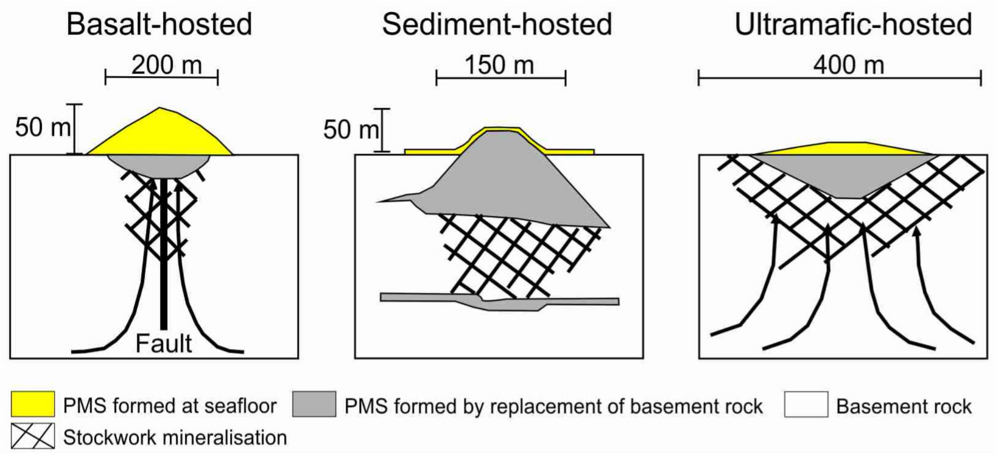
In general, not all hydrothermal vents form PMS deposits. Two examples are the Lost City vent field at 30°N, 30 km off-axis of the MAR (Kelley et al., 2001) and the Von Damm vent field 13 km off-axis of the Mid-Cayman spreading centre (Connelly

Figure 3.1.1. Basics of hydrothermal vent site formation



Source: GNS Science

Figure 3.1.2. Variations in the mound shape and sulphide accumulations of PMS deposits of different host rock compositions in mid-ocean ridge settings



Source: Modified from Fouquet et al., 2010 and Zierenberg et al., 1998

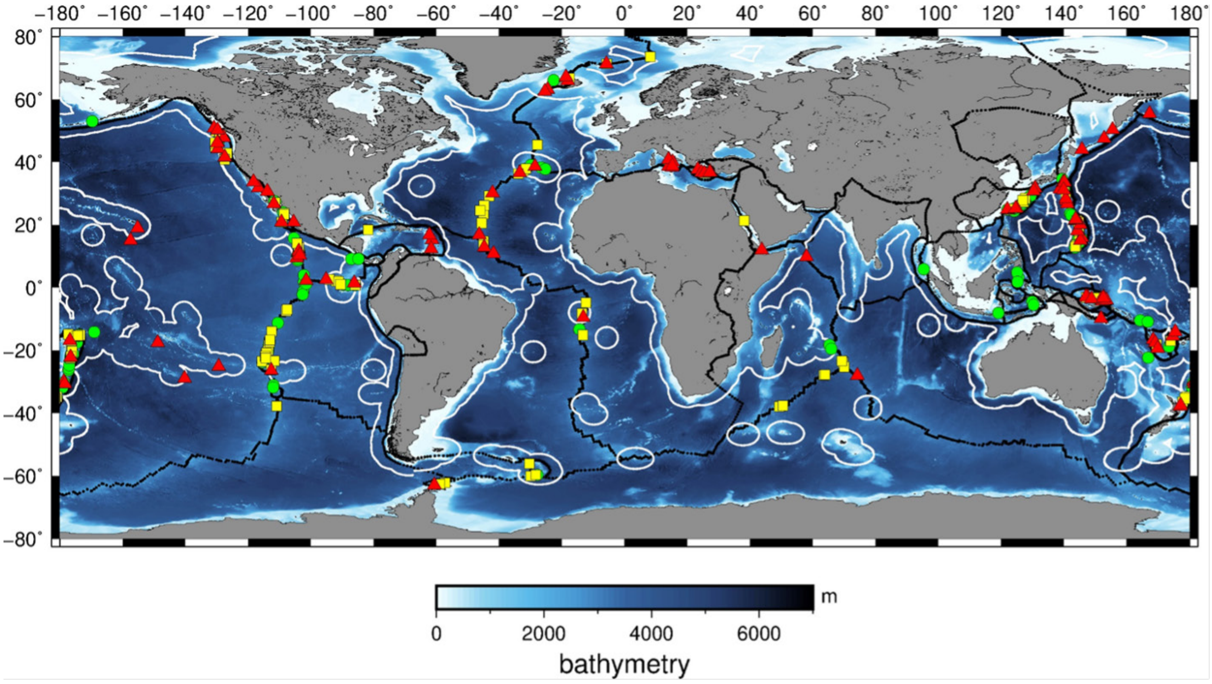
et al., 2012). While the Lost City vent field is a serpentinite-hosted system with highly alkaline fluids that form carbonate-hydroxide chimneys, the Von Damm vent field is hosted in gabbro and peridotite with slightly acidic fluids that form talc-silica chimneys with less than 5 per cent disseminated sulphides (Hodgkinson et al., 2015).

3.1.3. Occurrence

Since hydrothermal venting was first discovered at the Galapagos Rift in 1977 (Corliss et al., 1979) more than 600 sites of hydrothermal activity have been identified globally (Monecke et al., 2016 and references therein) and summarised in the InterRidge Vents Database Version 3.4 (Beaulieu and Szafranski, 2019). Based on the known abundance and distribution of vent fields, and the Earth's heat flux, it is assumed that they occur with a frequency of 1–4 per 100 km length spreading axis (Baker, 2007). This suggests that the number of vent fields discovered will likely increase in the future, with Beaulieu et al. (2015) proposing up to three times more, while Petersen et al. (2016) suggest that between 1,000 to 5,000 PMS deposits may exist. These estimates only account for areas proximal to the neovolcanic zones. Any older and inactive PMS deposits located several hundreds of kilometres off-axis and are buried under thick layers of pelagic sediments or lava flows are not currently discoverable. With regard to these sites, it still remains unknown how well these deposits are preserved over time (Monecke et al., 2016; Petersen et al., 2016). Furthermore, not all of today's globally known vent sites are visually confirmed, which means that 50 per cent are inferred from physical or chemical tracers in the water column (Beaulieu et al., 2013) and not all of these inferred vent sites will be associated with PMS accumulations (e.g. Lost City and Von Damm vent fields). For this study, only confirmed vent sites, PMS, and sulphide-bearing low temperature precipitates are included (**Figure 3.1.3**).

According to "geopolitical" statistics, the majority of vent sites are estimated to be located in the Area (58 per cent), whereas 36 per cent occur on continental shelves within 200 NM from the baselines from which the breadth of the territorial sea is measured, as defined by UNCLOS. The remaining six per cent are located in areas included in submissions to the CLCS in accordance with Article 76 of UNCLOS, that is, continental shelves the outer limits

Figure 3.1.3. Global distribution of confirmed hydrothermal vent sites (green circles), PMS occurrence (yellow squares) and sulphide-bearing low-temperature precipitates (red triangles)



Source: Data compiled using the InterRidge Global Database of Active Submarine Hydrothermal Vent Fields, version 3.4 (Beaulieu and Szafranski, 2019), VLIZ Maritime Boundaries Geodatabase, version 8 (2014) and NOAA
Note: The distribution of data records does not indicate where vent sites and PMS deposits are absent.
Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Thick black lines represent plate boundaries. Data compiled using the InterRidge Global Database of Active Submarine Hydrothermal Vent Fields, Version 3.4 (Beaulieu and Szafranski, 2019), and VLIZ Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

of which potentially extend beyond 200 NM (Petersen et al., 2016). Currently, seven contracts for PMS exploration in the Area have been granted. Three of the contract areas are located in the Atlantic Ocean and are held by the Government of the Russian Federation, the Institut français de recherche pour l' exploitation de la mer and the Government of the Republic of Poland. The other four contract areas are in the Indian Ocean. They are held by the China Ocean Mineral Resources Research and Development Association, the Government of the Republic of Korea, the Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany, and the Government of India.

The occurrence of PMS can be related to four main geo-tectonic environments (Hannington et al., 2010). Sixty-five per cent of PMS occurrences have been found in mid-ocean ridge settings. This group can be further divided based on the total spreading rates varying from ultrafast-fast (>8–12 cm per year), intermediate (4–8 cm per year) to slow-ultraslow (4–<2 cm per year). Alternatively, mid-ocean ridge settings can be divided based on their host rocks (basalt, ultramafic, sediment). The remaining 35 per cent of global vent sites occur in back-arc basins, submarine volcanic arcs, and intraplate volcano settings (Hannington et al., 2010), with individual group sizes being 22, 12 and 1 per cent respectively.

3.1.4. Resource potential

Although more than 360 vent sites with associated PMS accumulations are known today, the total metal content and the sub-surface extent of PMS deposits are not well understood.

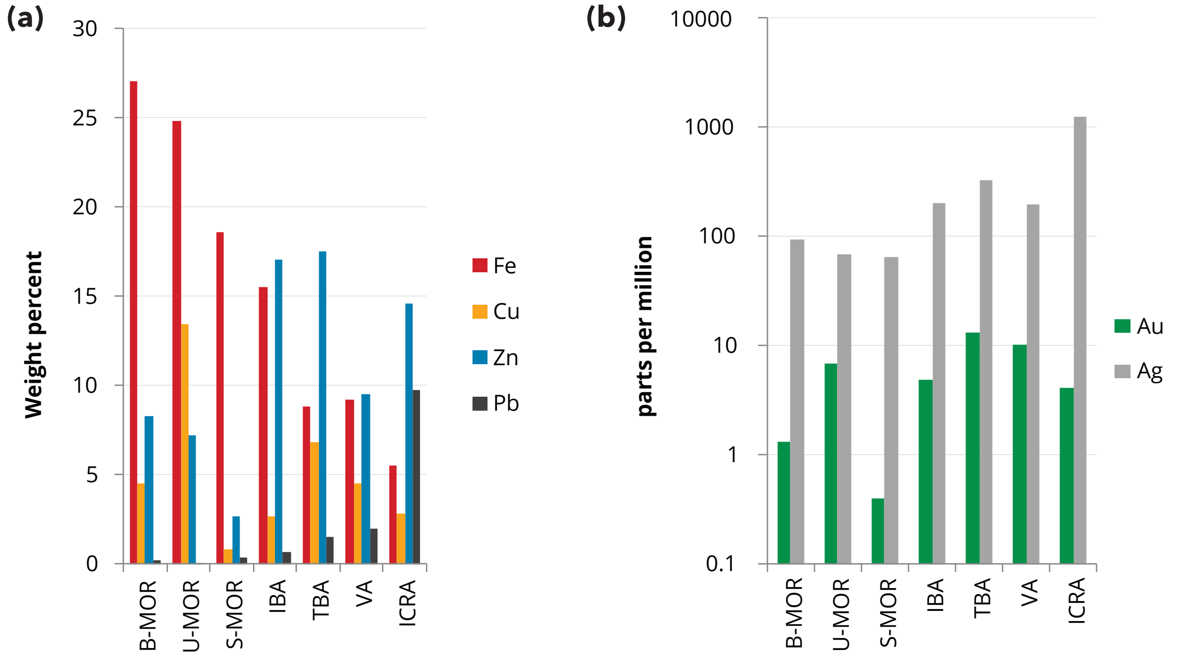
There are several reasons for this:

- not all vent sites have been sampled
- some data, especially from the contractor areas, are not publicly available
- strongly biased sampling towards easily recoverable high-temperature chimneys that are not representative of the entire deposit
- random sampling rather than the grid pattern
- very limited sites being drilled.

Most PMS deposits are small in size and tonnage, with a highly variable composition. Not all metals hosted in these deposits are of economic interest, e.g. iron sulphides which are the dominant phase in deposits at mid-ocean ridges (Figure 3.1.4.A). The highest concentrations of copper can be found in deposits of ultramafic settings, with a mean metal content of 14 weight per cent (wt.-%) (Petersen et al., 2016). In contrast, PMS occurrences in intraoceanic and transitional back-arc settings yield the highest zinc concentration, with 17 to 17.5 wt.-% respectively. Precious metals such as silver and gold only form trace components of PMS. Still, they can be highly enriched in some deposit types, like silver in intracontinental rift arc settings and gold in transitional back arc and volcanic arc settings (Figure 3.1.4.B). Other metals, such as cobalt, selenium, indium, tellurium, bismuth, germanium, and gallium, may be present at levels of a few g/t in some PMS (Monecke et al., 2016).

Deposits where sub-surface drill cores and surface grab samples are available are rare (Table 3.1.1). However, those deposits where they do exist show that base metal concentrations are enriched towards the surface in some deposits (TAG, Bent Hill-Middle Valley and Solwara 1). In contrast, at the Snakepit site, concentrations are almost identical. This could be related to

Figure 3.1.4. Mean concentrations of Fe, Cu, Zn, Pb, Au and Ag in PMS deposits formed in different geo-tectonic settings



Legend: B-MOR: basalt-hosted mid-ocean ridge (n=51), U-MOR: ultramafic-hosted mid-ocean ridge (n=12), S-MOR: sediment-hosted mid-ocean ridge (n=3), IBA: intraoceanic back-arc (n=36), TBA: transitional back-arc (n=13), VA: volcanic arc (n=17), ICRA: intracontinental rift arc (n=5). Data from Petersen et al. (2016) with "n" representing the number of deposits.

Table 3.1.1. Comparison of the average geochemical bulk composition of surface samples versus drill cores

Location	Sample number	Cu (wt.-%)	Zn (wt.-%)	Pb (wt.-%)	Au (ppm)	Ag (ppm)
TAG, MAR						
Surface samples	176	5.30	8.35	0.03	2.66	171
Core samples	311	2.52	0.47	<0.01	0.35	5
Snakepit, MAR						
Surface samples	93	9.03	4.59	0.03	1.77	62
Core samples	14	10.16	4.65	0.03	0.60	16
Middle Valley, Bent Hill						
Surface samples	166	0.73	2.77	0.03	0.42	17
Core samples	87	1.19	1.51	0.02	0.08	4
Solwara 1, Manus Basin						
Surface samples	250	9.73	5.36	1.08	14.96	174
Core samples	984	5.22	0.51	0.10	4.31	24

Source: Hannington et al., 2010

the low quantity of analysed sub-surface samples. Only more analysis can reveal the true nature of this observation.

Size estimates of PMS deposits are mostly incomplete (Hannington et al., 2010). Many deposits are overestimated with regard to their size because of debris from collapsed chimneys and dusting of the seafloor by metalliferous sediments, masking barren sub-sea-floor areas between adjacent chimneys and sulphide mounds. Furthermore, the thickness and the continuity of individual sulphide layers cannot be properly addressed without drilling. However, it is assumed that the sulphide layers likely vary as observed in volcanic-hosted massive sulphide deposits on land (Galley et al., 2007).

A first-order tonnage model of 62 PMS deposits by Hannington et al. (2010) suggests that the median deposit size is 70,000 tonnes, with more than one third of PMS deposits being less than 3,000 tonnes in size. Only eight deposits yield tonnages larger than 2 million tonnes. Two of these large deposits are located in back-arc and volcanic arc settings (Sunrise and Solwara 1). The other six PMS deposits are found in mid-ocean ridge settings, five in the slow-spreading North Atlantic Ridge (TAG, Krasnow, Semyenov, Puy des Folles, and Zenith-Victory) and one in the

Table 3.1.2. Mineral resource estimate for Solwara 1

Class	Domain	Tonnes	Cu (%)	Zn (%)	Au (g/t)	Ag (g/t)
Indicated	Sulphide dominant	1,030,000	7.2	0.4	5	23
Inferred	Chimney	80,000	11	6	17	170
	Consolidated sediment	27,000	4.1	1.4	4.5	49
	Sulphide dominant	1,330,000	8.1	0.6	5.8	25

Note: Data from AMC Consultants Pyt. Ltd. (2018) at 2.6 per cent Cu equivalent cut-off and an effective date of 1 January 2018.

intermediate-spreading Juan de Fuca Ridge (Middle Valley). This suggests that a large deposit size correlates with slow to ultraslow spreading systems where hydrothermal activity occurs over long periods of time (Hannington et al., 2010; Hannington et al., 2011; Beaulieu et al., 2015; German et al., 2016).

Overall, the global resource potential for today's known PMS deposits is estimated to be 600 million tonnes covering an area of 3.2 million km^2 surface outcrop with an average grade of 3.6 wt.-% copper, 7.9 wt.-% zinc, 1.7 g/t gold, and 115 g/t silver. Grades and size could be notably less below the seafloor (Hannington et al., 2010). Some small PMS deposits could be incorporated into a single mining operation to make it economically viable. In addition, commercial feasibility also depends on, inter alia, distance to land, water depth, and environmental impact.

Currently, there are no mineral reserve estimates for PMS deposits. One preliminary economic assessment is available for Solwara 1 (Table3.1.2.) in Papua New Guinea (AMC Consultants Pty. Ltd., 2018). The indicated and inferred resource was tested by drill holes with different spacing (indicated: <10–50 m; inferred: <100–200 m) and core recovery (indicated: >70 per cent; inferred: very variable). In addition, surface chimney material was included as an inferred resource. The estimates were performed using ordinary kriging and a cut-off grade of 2.6 per cent copper equivalent (AMC Consultants Pty. Ltd., 2018).

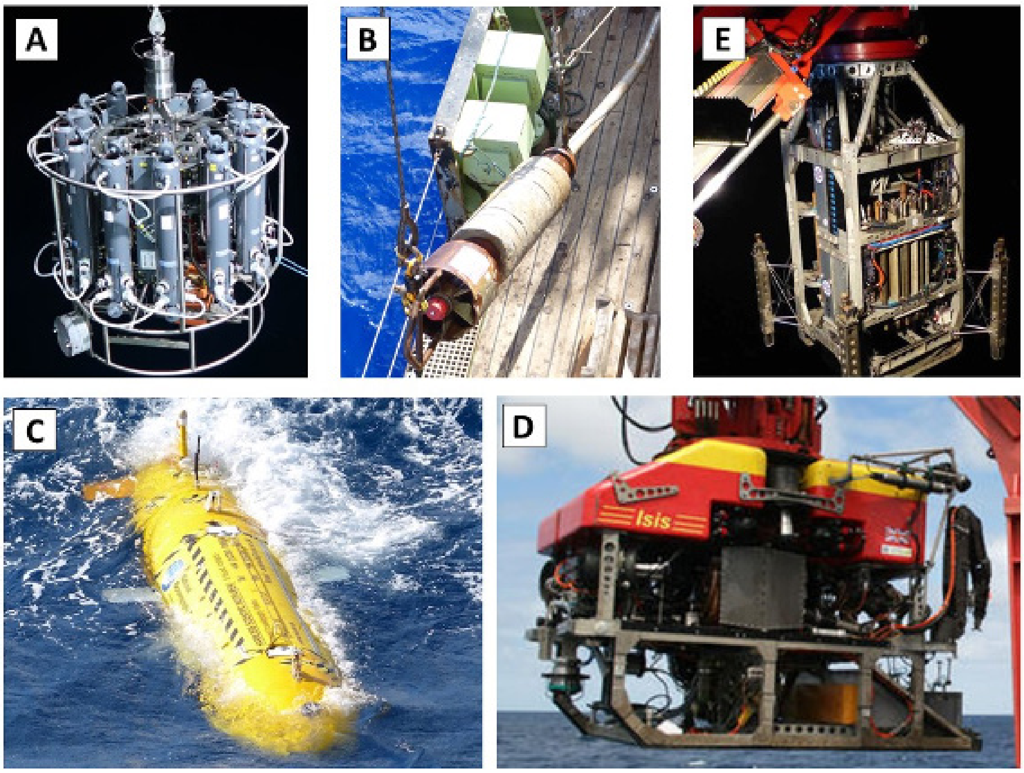
3.1.5. Technological advances

It is apparent that activities in the Area will change with respect to their development, and in each of those steps, various advancing technologies may be used. In this regard, exploration and exploitation of PMS deposits can be divided into four main steps:

1. Regional target identification
2. Local target confirmation and characterisation
3. Assessment of the resource potential
4. Mining.

Steps 1 to 3 require multi-purpose vessels with various technologies ranging from deep-sea mapping techniques, video, and photographic systems to sampling and drilling equipment (Figure 3.1.5). In contrast, step 4 operations require specialised equipment such as extractors, collectors, lifting and dewatering equipment, production support vessels, and bulk carriers to transport the ore back to land for treatment and processing.

Figure 3.1.5. Various equipment used for the exploration and assessment of PMS deposits: A) CTD for hydrocast profile, B) gravity core for sediment sampling, C) AUV used for high-resolution mapping, sonar surveys and photography transects, D) ROV used for video transects and grab sampling of geological and biological material, E) remotely lander-based drilling rig.



Source: National Oceanography Centre (A-D) and British Geological Survey (E)

During step 1, a regional assessment of the target area is conducted. The topography of the seafloor is mapped using ship-mounted or ship-towed multibeam swath bathymetry and sonar systems. Hydrocast profiles are performed to identify temperature, redox potential, and turbidity anomalies in the water column to locate the hydrothermal plume. For this task, either conductivity-temperature-depth (CTD) rosette systems or miniature autonomous plume recorders (German et al., 2016) are used. In addition, geophysical surveys using magnetic susceptibility or electric self-potential can be done, as PMS have a clearly distinguishable signature compared to their surrounding rocks. Alternatively, geological sampling of sediments with coring equipment (gravity, piston, box, or grab) or rock sampling with dredges can be conducted with sediments and rocks exhibiting dispersed geochemical halos around the vent sites.

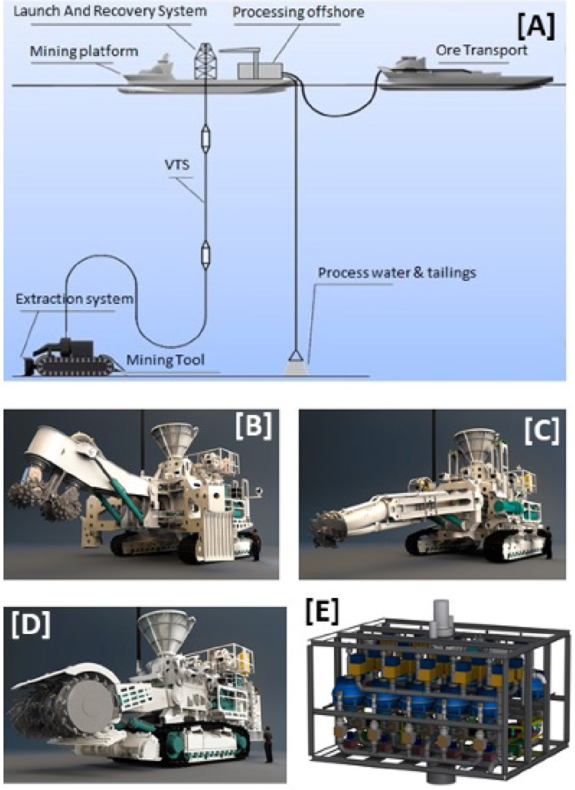
During step two, ROVs and AUVs are used to characterise the target further. This is done by high-resolution bathymetric and sonar surveys on a systematic grid pattern and video transects. Additional sensors such as CTD, MAPR, and many more can be mounted on the ROV and AUV to provide data of the water column and seafloor further. Sampling equipment like TV-guided grabs and ROV manipulator arms as well as coring equipment and ROV-operated push-cores allow a two-dimensional characterisation of the target.

To allow the assessment of the interior of the deposit and the PMS deposit's resource potential, systematic drilling and sampling is required in step 3. Two main drilling systems are available for this task: a) an onboard Derrick-type drilling system; or b) a lander-type sea-floor drilling rig. The first type is deployed from specialised vessels like, for example, the Joint Oceanographic Institutions Deep Earth Sampler Resolution and D/V Chikyu, and requires very complex and expensive campaigns. In contrast, the lander-type drilling rig can be deployed from multipurpose vessels to reduce the operation costs.

Although manned submersibles have played a very important role in the forty-year history of hydrothermal vent site discoveries, the future clearly lies in autonomous, robotic systems.

No commercial mining operation on PMS has currently commenced. Nautilus Minerals Niugini Ltd. had identified a mining method suitable for PMS sites (AMC Consultants Pty. Ltd., 2018) and designed, constructed, and tested the required machinery. The fleet of sea-floor production tools included a cutting and collector machine in addition to a subsea slurry lift pump for transport to the sea surface (Figure 3.1.6), where a specially-designed production support vessel would dewater the slurry before the ore gets transferred to bulk carriers and transported to a land-based treatment and processing facility. Technologies for the vertical as well as the ship-to-ship transport at sea were also investigated during the European Union's 7th framework project Blue Mining (www.bluemining.eu).

Figure 3.1.6. Seafloor production chain (A) and equipment (B-E): auxiliary and bulk cutter (B, C), collecting machine and subsea slurry lift pump (E)



Source: Blue Mining (2018) and Nautilus Minerals Niugini Ltd (2019)

3.2. Marine polymetallic nodules

3.2.1. Definition

PMN were first reported on the *HMS Challenger* in the 19th century (Murray and Renard, 1891). Mero initiated interest in these nodules as a potential metal resource in the 1960s (Mero, 1962). They are concretions of iron and manganese oxides and (oxy-) hydroxides that commonly form on and within marine sediments around a solid nucleus, ranging in diameter from <1 up to 20 cm (Petersen et al., 2016; von Stackelberg, 2000). They are found in a wide range of environments and are commonly separated into four main genetic types according to the source of fluids from which they form: hydrogenetic; diagenetic; mixed-type; and hydrothermal (Halbach et al., 1981; Halbach et al., 1988). PMN are very rich in a range of valuable elements that vary according to the environment of formation, including manganese, iron, nickel, cobalt, copper, and titanium, as well as molybdenum and REY, zirconium, and lithium (Cronan, 2000; Hein et al., 2013). Their mineralogy is dominated by manganese oxyhydroxides—vernadite ((Mn_4+, Fe_3+, Ca, Na)$(O, OH)_2$ x nH_20); todorokite ((Na,Ca,K,Ba,Sr)1-

$x(Mn,Mg,Al)_6O_{12}{\cdot}x$ 3-4 H_2O); and birnessite ($(Na0.{}_3Ca_{0.1}K_{0.1})(Mn^4+,Mn^3+)_2O_4$ $\cdot x$ 1.5 H_2O)–as well as amorphous iron oxyhydroxides alongside detrital silica, carbonate, and CFA ($Ca_5(PO_4,CO_3)_3F$) (Halbach et al., 1981; Halbach et al, 1988).

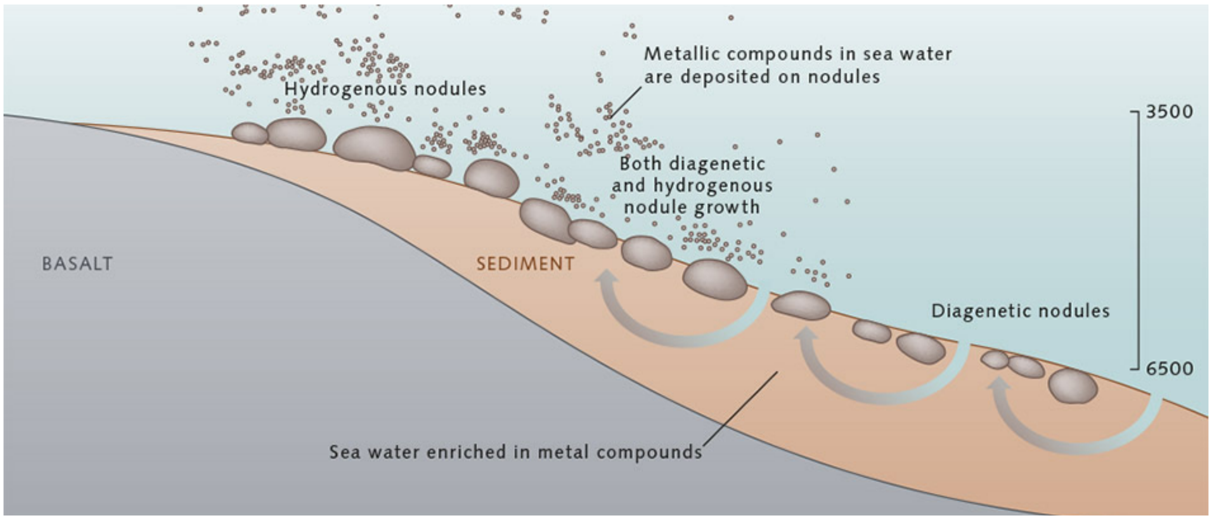
3.2.2. Formation

PMN form through the precipitation of iron and manganese oxides and (oxy) hydroxides around a solid core. Their formation is thought to follow a simple chemical-colloid model, similar to CFC (see Section 3.3. below). Electrostatically charged iron and manganese colloids within the water column or pore fluids attract dissolved metals of opposing charge through electrostatic interactions (Koschinsky and Halbach, 1995; Hein and Koschinsky, 2014). Although seawater generally has relatively low concentrations of dissolved metals, the iron and manganese colloids are efficient scavengers and sorb trace metal complexes slowly over time. These accumulate by accreting around a central nucleus, commonly bone or rock detritus. Slow rates of formation (~1–20 mm per million years; Menendez et al., 2018) allow for significant enrichment of numerous trace metals to well above continental crust averages.

Three main factors are thought to promote PMN formation. Firstly, a source of iron, manganese, and trace metals in the surrounding environment, such as from seawater, pore, or hydrothermal fluids (**Figure 3.2.1;** e.g. Glasby, 1977). Metals can be released into pore fluids during diagenetic reactions. These occur when there is sufficient primary productivity in surface waters to sustain benthic bacterial communities that maintain diagenetic reactions in the underlying sediments. These sediments also need to allow pore fluids to move and transport metals to sites of PMN formation. Secondly, nodule formation requires slow detrital and biogenic sedimentation and bioturbation to avoid burial and maintain a position at the seafloor. Low biogenic sedimentation rate requirements mean that PMN are normally found near or below the carbonate compensation depth of the seawater column (Hein and Koschinsky, 2014; Lusty et al., 2018). Thirdly, deep-ocean currents need to be sufficient to remove sediment from the PMN surfaces and thus maintain oxygenated waters at depth.

Growth rates as well as chemical and mineralogical composition of nodules can be related to a range of factors,

Figure 3.2.1. Formational fluids that influence nodule composition



Source: World Ocean Review

including availability and supply of formational material, sediment fluxes, properties of the overlying water mass, and bioturbation processes (Verlaan et al., 2004; Mizell et al., 2016). Nodules can be defined by genetic types based on key patterns in their growth rates and composition. The different nodule types most commonly discussed are related to the different formational fluids that affect both their chemical and mineralogical composition (e.g. Hein et al., 1997; Hein and Koschinsky, 2014). These include hydrogenetic (metals sourced directly from seawater), diagenetic (metals sourced from sediment pore fluids under oxic to suboxic conditions), mixed type (both hydrogenic and diagenetic) or hydrothermal (influenced by hydrothermal plume manganese).

Hydrogenetic PMN have some of the slowest growth rates, generally below 10 mm per million years. Hydrogenetic mineralogy is dominated by mixed iron and manganese oxyhydroxides such as iron-rich vernadite, and generally have low manganese to iron ratios <2.5, and higher concentrations of iron, cobalt, and REY (Hein et al., 2010; Menendez et al., 2018). Diagenetic PMN generally exhibits faster growth rates of hundreds of millimetres per million years due to higher dissolved metal content in pore fluids and is dominantly composed of manganese oxides like todorokite (Halbach et al., 1981; Halbach et al, 1988). Geochemically, they have higher manganese to iron ratios >4, and higher proportions of manganese, nickel, and copper (Wegorzewski et al., 2015). Purely diagenetic nodules are rare but are found in some locations such as the Peru Basin (Mizell et al., 2016). Hydrothermal PMN is less common and are usually formed of pure manganese oxides with low trace metal contents except for barium, potassium, lithium, and magnesium. The majority of PMN sampled globally are mixed-type nodules, i.e. they experienced periods of alternating hydrogenetic and diagenetic formational fluids. However, these microvariations in composition between hydrogenetic and diagenetic cannot be distinguished without microscale analysis; hence most nodule bulk compositions indicate a mixed-type genesis (e.g. Benites et al., 2018).

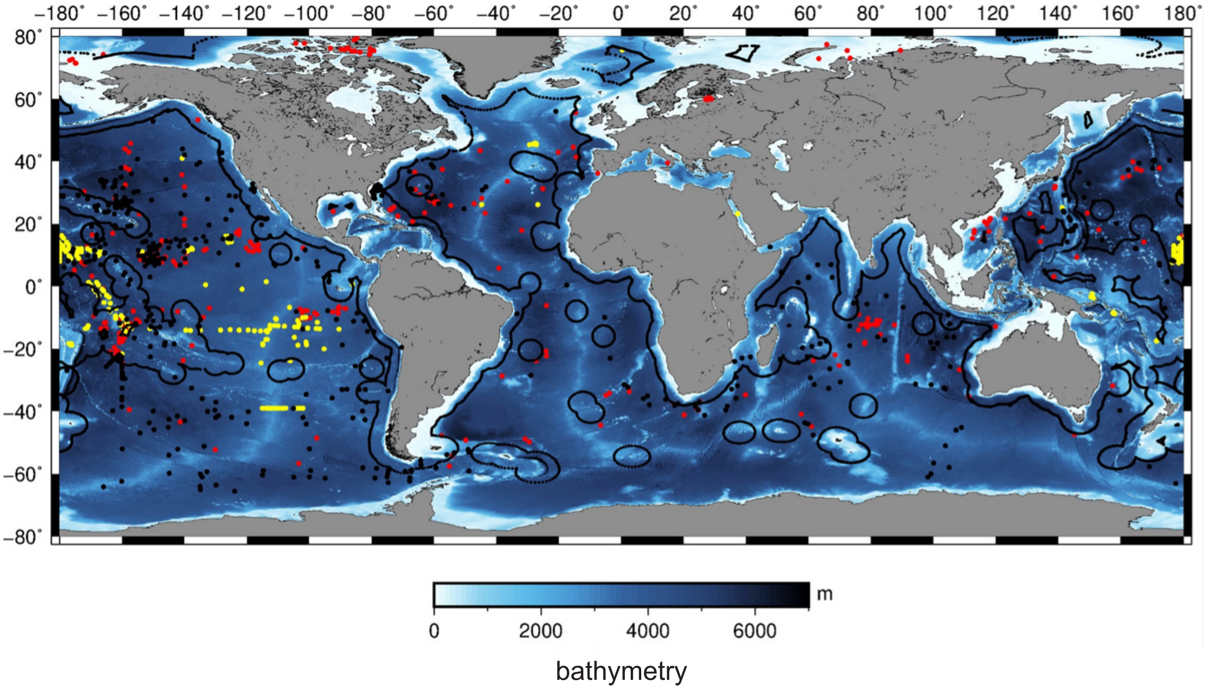
3.2.3. Occurrence

PMN are most frequently observed on abyssal plains (**Figure 3.2.2**) but have been sampled in a range of other environments including seamount summits. They are also found in freshwater and saline lakes (e.g. Shkolnik et al., 2016).

Some of the most promising PMN sites occur on consolidated, stable oceanic crusts that allow prolonged nodule growth and scavenging periods. Hence, the most extensive nodule fields are observed on the abyssal plains between 3,500 and 6,500 m water depths that cover up to 70 per cent of the global oceans (ISA, 2004; Rona, 2008; Hein et al., 2013). Other regions of young oceanic crust (younger than 10 million years) that experience high sedimentation (≥1 cm per thousand years) and have complex bathymetry (relief of more than 300 m) are excluded.

Generally, the highest-grade nodules (particularly for copper, manganese, and nickel) are also observed in areas of high primary bioproductivity at or below the level of the carbonate compensation depth. A region that fulfils these criteria has been highlighted as a key region for nodule exploration and potential exploitation is the area between the Clarion and Clipperton fracture zones of the Pacific Ocean (ISA, 2013). As of 2019, there were eighteen contracts for PMN exploration in the Area, sixteen of which were for PMN fields within the CCZ (ISA, 2019). Likely target metals in this region include copper, manganese, molybdenum, nickel, cobalt, and lithium. High concentrations of PMN have also been reported near the

Figure 3.2.2. The distribution of PMN in the global oceans



Source: Marineregions.org

Note: Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and they do not purport to indicate any maritime claim nor actual limits of any maritime zone. The background shows bathymetry with 2 minutes sampling. All dots show the reported sampling location of PMN. Red dots represent analyses for PMN, yellow dots for PMN analysed in bulk with associated sediments and black dots for nodules with no genetic type designated. Compiled from published data sources and VLIZ Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Cook Islands in the central Pacific, in the Central Indian Basin, the Peru Basin, and the Atlantic Ocean. While the focus on the CCZ, Central Indian Basin, and Cook Island regions has resulted in relatively well-known PMN abundance and composition in these areas, there are fewer resource estimates for the rest of the global oceans (Hein et al., 2013). Estimating nodule distribution and tonnages remains the largest source of uncertainty in resource modelling.

3.2.4. Resource potential

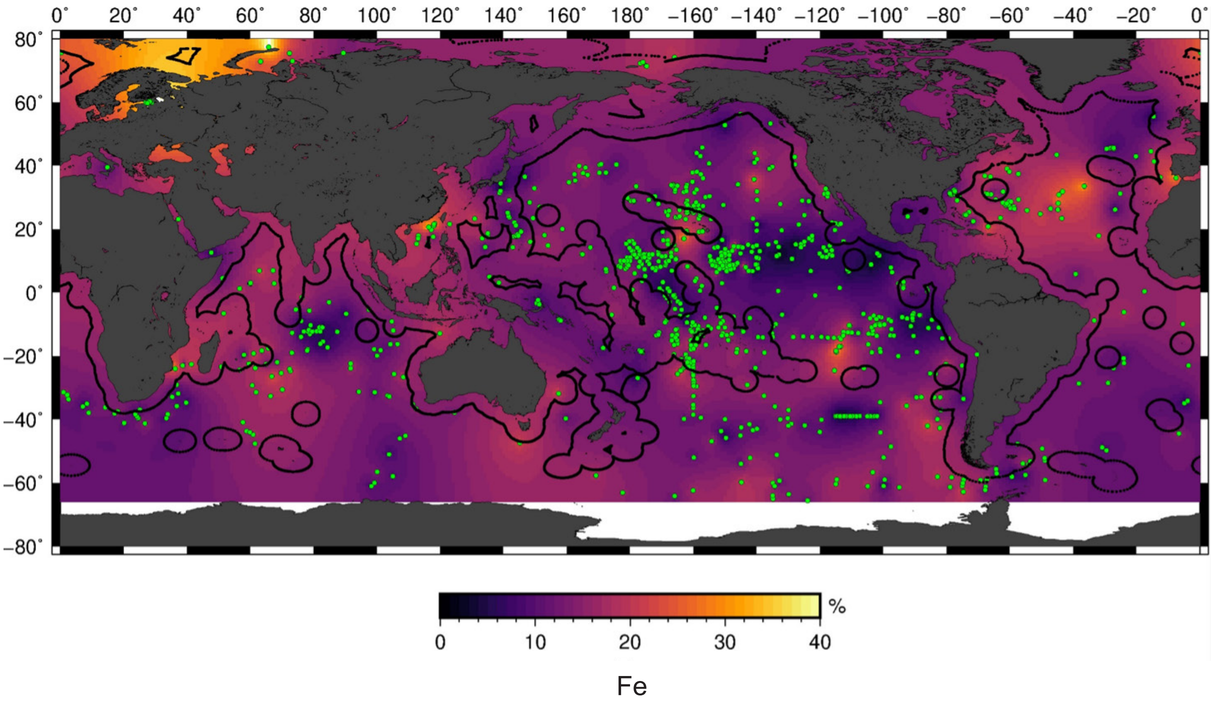
As PMN are effectively a two-dimensional deposit, tonnage estimates rely on understanding nodule distribution, abundance and density over large surface areas of abyssal plains (Petersen et al., 2017). Nodule abundance can vary due to a range of factors including sedimentation rate, the local bathymetry, nodule size, strength of bottom currents (which prevent accumulation of sediments), and burial rates of organic matter (von Stackelberg, 2000; Hein et al., 2013; Petersen et al., 2017). In order to understand this better, more widespread mapping of in situ nodules is required.

The resource potential of PMN is determined by both their chemical composition and tonnage. Traditionally, the key elements of interest in PMN are cobalt, copper, manganese, and nickel (Figs. 3.2.3–3.2.7; Glasby et al., 2015). Tonnages for these key elements in PMN are estimated to exceed those of terrestrial reserves (Hein et al., 2013). However, because of the rapid expansion of technologies and their resource requirements, other trace elements within PMN have further increased the resource potential due to valuable by-products such as lithium, molybdenum, zirconium, and REY (Spickermann, 2012; Hein et al., 2013). The composition of PMN is known to vary at different scales, from differences between ocean basins down to concentration variations within individual nodules. It is estimated that the CCZ in the Pacific Ocean hosts 21,100 million dry tonnes of PMN (Hein et al., 2013; Hein and Koschinsky, 2013). Due to their slower formation rates and relative richness in cobalt and REY, PMN with high hydrogenetic content proportions is the most favorable.

Numerous resource models have been proposed for the PMN of the CCZ, but they largely rely on surveys that cover only a small proportion of the total area (Chitre and Hari, 2018). Estimates put total reserves at ~6,000 million tonnes of manganese, ~270 million tonnes of nickel, and ~44 million tonnes of cobalt (Hein et al., 2013; Hein et al., 2015). These all exceed the known total manganese, nickel, and cobalt reserves based on land. Large and prospective PMN fields are not found in the Atlantic Ocean due to high sedimentation rates in many parts of the Atlantic. This confines nodule fields to relatively small basins in the deep Atlantic, although Menendez et al. (2018) highlight that PMN from the northwest Atlantic basin could supply up to 7.2 million tonnes of cobalt and 3.8 million tonnes of rare earth elements and yttrium.

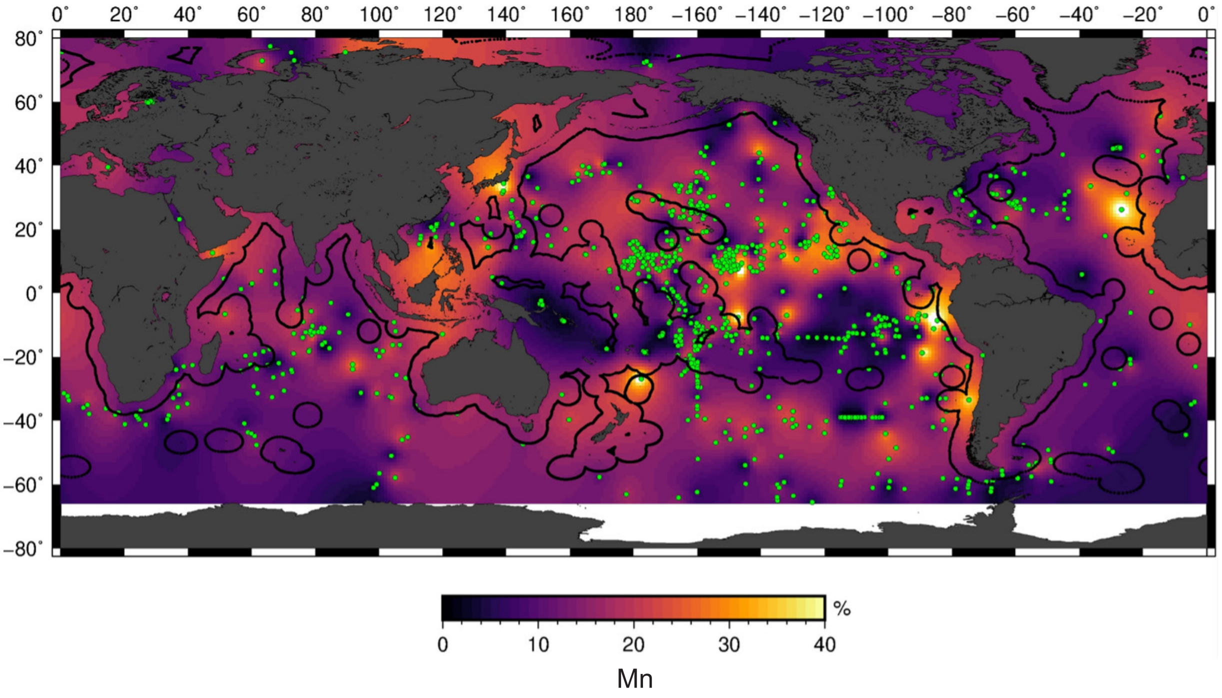
There have been a number of suggested benefits of exploiting PMN deposits over land-based deposits. As PMN forms on and within the uppermost sediments on

Figure 3.2.3. Distribution and concentration of elemental Fe in PMN (wt.-%)



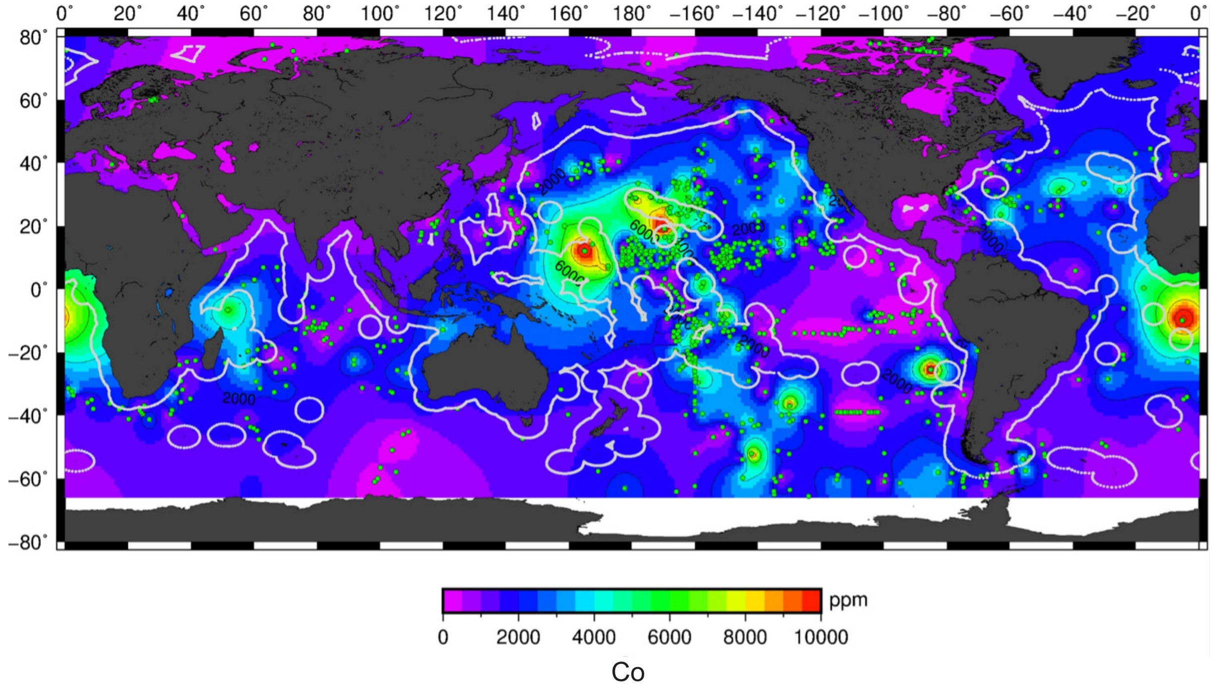
Source: Marineregions.org
Note: Known nodule locations denoted by green points. Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Figure 3.2.4. Distribution and concentration of elemental Mn in PMN (wt.-%)



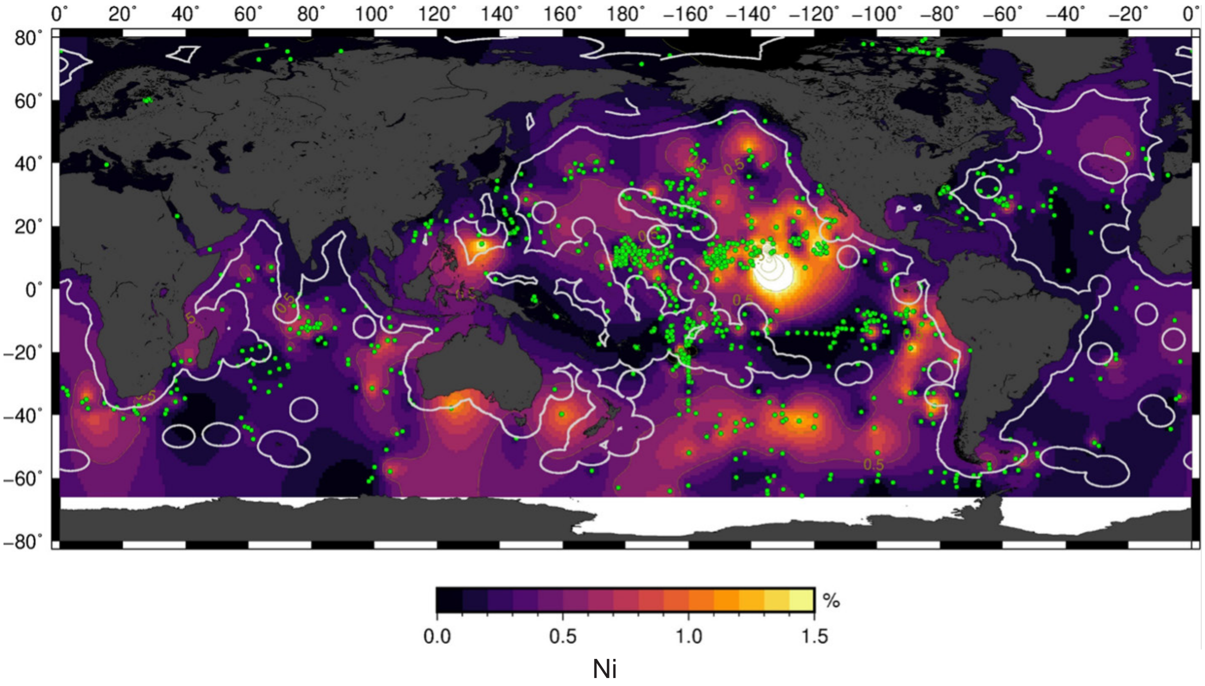
Source: Marineregions.org
Note: Known nodule locations denoted by green points. Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Figure 3.2.5. Distribution and concentration of elemental Co in PMN (ppm)



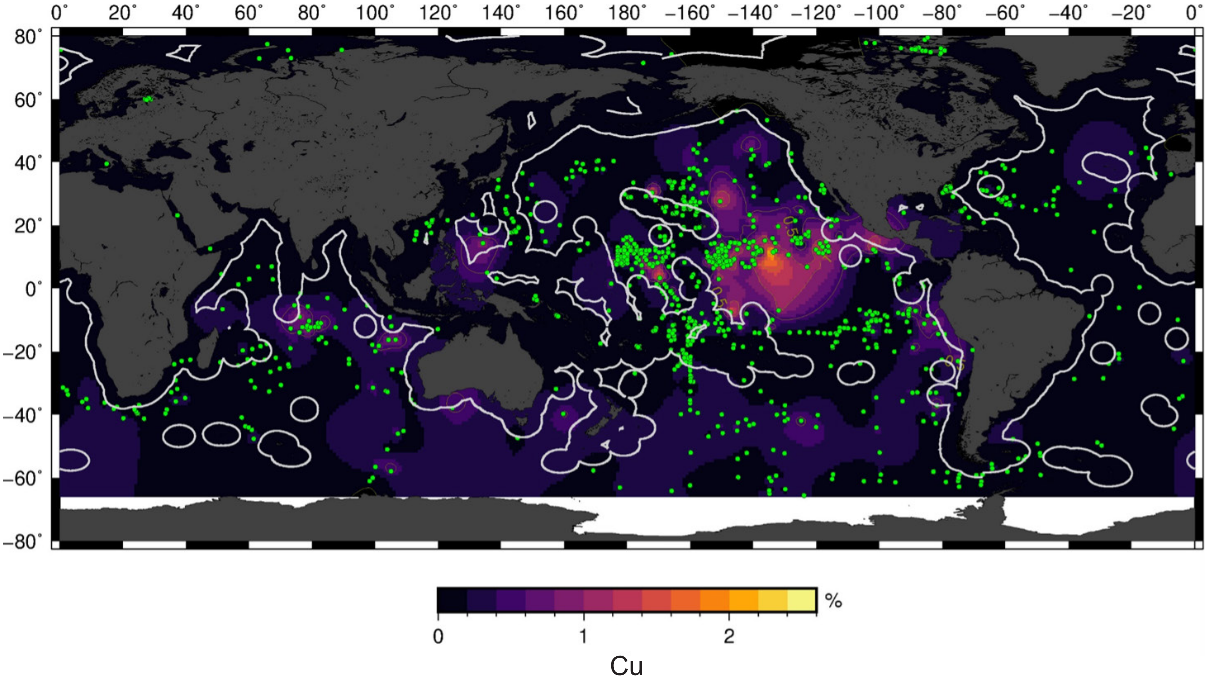
Source: Marineregions.org
Note: Known nodule locations denoted by green points. Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Figure 3.2.6. Distribution and concentration of elemental Ni in PMN (wt.-%)



Source: Marineregions.org
Note: Known nodule locations denoted by green points. Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Figure 3.2.7. Distribution and concentration of elemental Cu in PMN (wt.-%)



Source: Marineregions.org
Note: Known nodule locations denoted by green points. Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and they do not purport to indicate any maritime claim nor actual limits of any maritime zone (this represents the exclusive economic zones if all coastal States had declared exclusive economic zones up to 200 nautical miles). Compiled from published data sources and VLIZ Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

the deep seafloor, there is no overburden to remove before ore recovery. It has also been suggested that the remote nature of these deposits means that no local human populations will be affected and there will be no permanent mining infrastructure built (Hein et al., 2013; Lodge and Verlaan, 2018). A proper assessment of the ecosystem is required.

3.2.5. Technological advances

The technology required to operate mining machinery and collect PMN on abyssal plains at water depths of 3,500–6,500 m remains one of the biggest barriers to exploitation. Recent studies highlight the importance of using new technologies to improve our understanding of PMN, in terms of in situ distribution and abundance and the potential impacts of mining nodules.

As they are a two-dimensional deposit, surveying for PMN would be a relatively simple exercise, but progress is hindered by the vast area of the abyssal plains in the global oceans (Hein et al., 2013). While deposits are moderately well understood in targeted regions, such as the CCZ and Central Indian Basin, these depend on relatively small areas of ground-truthed data when compared to the total area of abyssal plains. Piper et al. (1987) mapped PMN distribution in the Pacific using data from 2,500 bottom camera stations and several sediment cores. In order to better understand the high variability of PMN coverage and expand the number of known prospective sites, more extensive surveying is required. Mapping of PMN is commonly done from vessel-based equipment such as hydro-acoustic backscatter and deep-towed side scan sonar. While large areas can be covered in relatively short amounts of time using these methods, the resolution is insufficient to identify changes in nodule density (Petersen et al., 2017). Usually, towed cameras are used to ground truth, alongside box corers for point sampling. While both of these methods are valid, they have very limited coverage and may not represent the large-scale trends across a nodule field. The deep sea needs to be explored more thoroughly and at higher resolutions. The best solution for remote surveying is likely one using AUVs, vehicles that carry out pre-programmed missions without an operator. Different technology mounted on AUVs can greatly improve our understanding of PMN abundance, e.g. cameras followed by Object Based Image Analysis (OBIA) and high-resolution multibeam backscatter (LeBas and North, 2016). Automated OBIA distinguishes areas of images that have similar pixel values and patterns. When calibrated against the physical characteristics of samples collected from the same areas, this provides objective estimates for PMN density. Sonar backscatter responses have been observed to correlate well with ground-truthed PMN abundances and could be a powerful tool for remote mapping. Potential advances in battery technologies and the design of AUVs may allow for fleets of AUVs to survey unaided for longer time periods. Future improvements to AUV capabilities, such as the ability to survey as a self-organising fleet, will have the potential to significantly improve our understanding of the deep sea as a whole (Petersen et al., 2017). This technology will also be important for the study of nodule-associated ecological habitats.

The technologies proposed to transport the exploited PMN are largely based on methods from the petroleum and placer mining sectors (Hein et al., 2013). At the seafloor, a hydraulic nodule collector is proposed to collect PMN and separate nodules from sediments at depth, tethered and controlled from a support ship at the surface. This sea-floor mining tool would likely need support from ROVs and AUVs. The biggest technological challenge is transporting nodules from ~5 km depths up to the surface at a sufficient rate to make PMN mining sustainable. Pilot test mines were given trials in 1978 by the Ocean

Management Group (a joint venture by the *Arbeitsgemeinschaft Meerestechnisch Gewinnbare Rohstoffe*, Germany, the USA, and Canada), with 800 tonnes of PMN successfully pumped from the seafloor of the Pacific Ocean. While this trial was on a small scale, Glasby et al. (2015) have suggested that at contemporary metal prices, nodules would need to be mined at a rate of 5,000 tonnes a day (1.8 million tonnes a year) to be profitable, which would require a riser pipe of sufficient diameter to transport PMN at that rate without clogging. Two different technologies have been suggested, the airlift and the serial centrifugal pump system (Volkmann and Lehnen, 2018). The airlift system uses injections of compressed air (generated on the support ship) at different points up the riser to reduce slurry density and aid recovery. The nodules would be hydraulically transported to the surface via the riser in a slurry of fragmented nodules, seawater, and some sediments. On the ship, this slurry would then be dewatered and stored ready for transport to processing facilities. Residual seawater and particles from the dewatering process would be returned to the ocean near the seafloor. Volkmann and Lehnen (2018) also suggest applying strip-mining techniques commonly used in high-tech terrestrial farming (Hunt and Wilson, 2015) to improve process efficiency. Idealised production plans do not yet account for factors such as machine downtime and bad weather, which may hinder operations. Even under these idealised operational conditions, current technologies are unlikely to reach the suggested production rates required to make abyssal nodule fields economical at this time (Volkmann and Lehnen, 2018; Van Nijen et al., 2018). Furthermore, these technologies require further field testing (Lusty et al., 2018). Future changes, such as improved nodule-harvesting efficiency and higher metal prices may make these deposits economically feasible. However, the impact of increased metal supply arising from sea-floor mining on the market will hurt its economic viability. It will likely limit the number of simultaneous deep-sea mining operations that can be sustained.

Processing PMN to extract valuable elements is thought to be a relatively simple process, especially when compared to some of the more complex terrestrial deposits for elements such as cobalt. Many of the target elements, such as cobalt and nickel, can be extracted by hydrometallurgical methods, using fluids to extract key phases (Mohwinkel et al., 2014; Hein et al., 2015; Zubkov et al., 2018). These are preferable to pyro-metallurgical methods (using heat for extraction) because they generally have lower energy requirements, being done at lower ambient temperatures. Nodules would require mechanical particle size reduction, after which leaching agents can be added to extract the desired metals. Leaching agents can be chemical or biological. Bioleaching agents are preferred because they have fewer associated environmental impacts and can be used at low temperature and atmospheric pressure, so they are lower in cost and energy consumption (Johnson, 2014). Bioprocessing techniques using microbes are also being developed which have the potential for low energy, selective metal extraction (Zubkov et al., 2018). An emerging area of considerable potential for selective metal extraction is the development of deep eutectic liquid solvents. These are effectively reusable liquids designed to bind with dissolved metals at low temperatures and then release them, thereby concentrating them. The energy saving and selectivity of the process is ideal for reducing the energy footprint and hence cost of processing PMN (Zubkov et al., 2018).

3.3. Marine CFC

3.3.1. Definition

CFC are iron and manganese-rich precipitates that form on hard-rock substrates. They are commonly observed on the flanks of sea-floor structures such as seamounts, guyots, ridges, and plateaus (e.g. Bonatti, 1972). They can form accumulations that vary in thickness from sub-millimetre coatings up to 250 mm (e.g. Usui and Someya, 1997). They are generally split into three main genetic types according to their dominant formational fluids: hydrogenetic, diagenetic, and hydrothermal. Given the dominantly hydrogenetic nature of CFC deposits, CFC form very slowly at rates of between 1 and 5 mm per million years (Hein and Koschinsky, 2014) and are highly enriched in a range of trace elements, including cobalt, tellurium, molybdenum, platinum, and REY (Bau et al., 2014). The economic interest in CFC stems from these high concentrations of elements and other important and rare metals that are critical to new technologies (e.g. Hein et al., 2000; Muiños et al., 2013). Their mineralogy is dominated by iron oxyhydroxides and manganese oxyhydroxides.

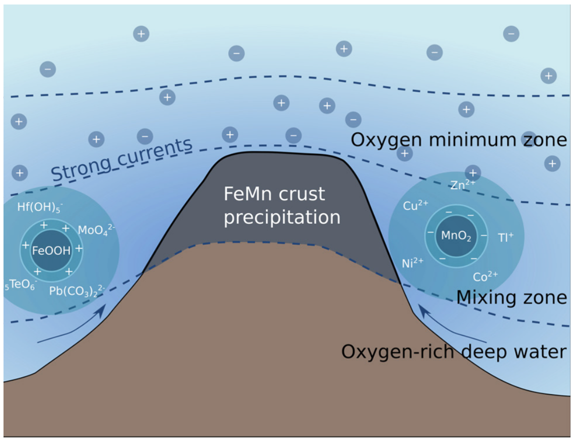
3.3.2. Formation

Like PMN, CFC are thought to form through simple colloid chemistry. Iron and manganese oxyhydroxides precipitate from the water column as colloidal particles onto solid substrates. These colloidal particles attract dissolved trace metals of opposing electrostatic charge, which accumulate slowly over time through both electrostatic and chemical reactions (Halbach, 1986). The very slow formation rates of 1–5 mm per million years, combined with the high porosity and specific surface areas (mean of 325 m^2 per gram), supports the enrichment of many trace metals well above the mean concentrations measured in continental crusts (Hein et al., 2000).

The formation of CFC is thought to have four main prequisites. Firstly, it requires a supply of manganese and iron (Halbach et al., 1982). The main sources of manganese in ocean basins come from terrestrial inputs, hydrothermal fluids, and diagenetic pore fluids released from ocean basin and continental shelf sediments (Elderfield, 1976; Bender et al., 1997). Iron in oceans is predominantly sourced from dust inputs as well as from rivers carrying dissolved iron from the continental crust, hydrothermal fluids, and diagenetic sediment pore fluids (e.g. Duce and Tindale, 1991; Archer and Johnson, 2000; Elrod et al., 2004; Windom et al., 2006). The second prerequisite is oxidised waters to trigger the precipitation of the hydrated iron and manganese oxide species that form the bulk of CFC, from dissolved iron and manganese in seawater (Koschinsky and Halbach, 1995). The presence of an Oxygen Minimum Zone (OMZ) is suggested to act as a reservoir for dissolved metals by encouraging the accumulation of dissolved metal species in their reduced form. The interaction of these metal-rich reduced waters with the oxidised waters initiates the precipitation of CFC (Koschinsky and Halbach, 1995). Thirdly, crusts need a hard substrate to precipitate onto that is free from sediment (Halbach et al., 1982). Hence, areas with sufficiently high current speeds promote crust precipitation. These elevated flow speeds commonly occur around sea-floor obstructions such as seamounts and guyots, where crust occurrences are widely reported (e.g. Roden, 1987; Nishimura, 1992). Finally, this hard substrate should be stable over sufficient time periods to allow for the slow precipitation of crusts and accretion of metals from seawater, as mass-wasting from slope instability can destroy or erode accumulated crusts (Hein et al., 1988; Verlaan et al., 2004).

CFC largely fall between two main endmembers, depending on the formational fluids. These endmembers are hydrogenetic and hydrothermal crusts. The majority of CFC are hydrogenetic, forming directly from seawater, and those that form in the proximity of hydrothermal vent sites can also display hydrothermal signatures (e.g. Kuhn et al., 1998; Bau et al., 2014; Dubinin et al., 2018; Menendez et

Figure 3.3.1. Scheme of ferromanganese crust formation on seamount structures



Source: adapted from Koschinsky and Halbach, 1995

al., 2018). Hydrothermal CFC are generally rich in molybdenum, lithium, and barium compared to hydrogenetic CFC, but the specific composition is highly dependent on the characteristics of the hydrothermal fluid (e.g. Goto et al., 2015; Hein et al., 2016). Proximal hydrothermal fluids can also show elevated nickel, chromium, zinc, and vanadium and generally have low concentrations of rare earth elements (e.g. Michard and Albarède, 1986; Bau, 1991; Hodkinson et al., 1994; Hein et al., 1997). Hydrothermal CFC are thought to constitute less than one per cent of the world's marine manganese deposits, given the restricted environments in which they form, but show very high growth rates on the order of hundreds to thousands of millimetres per million years (Glasby et al., 2015; Goto et al., 2012).

Hydrogenetic CFC generally have extremely slow growth rates compared to hydrothermal CFC. These slow formation rates allow for the extreme enrichment of numerous elements of economic interest from seawater, such as cobalt, tellurium, REY, platinum, nickel, molybdenum, and copper (Bau et al., 2014; Hein et al., 2016). The chemical and mineralogical composition of hydrogenetic CFC varies on all scales, from global right down to local and between individual crust layers (Hein et al., 2013). The composition of CFC is likely due to the prevailing environmental conditions during formation and hence their formational waters, which vary spatially and have changed over time (Menendez et al., 2018). Numerous environmental factors are thought to affect composition by changing the characteristics of the overlying water mass and inputs to CFC. These include differences in primary biological productivity near the sea surface and oxygen levels in the overlying waters (Verlaan et al., 2004). These factors are all interlinked and can vary the availability of different elements to crusts on a regional to local scale.

On global to regional scales, changes in water-mass movement and ocean chemistry, and fluxes from continents to the ocean, can affect CFC composition. For example, elevated concentrations of calcium and phosphorus are usually associated with phosphatisation events that are widely recorded in CFC, especially from the Pacific Ocean. CFC in the Central Pacific generally show two distinct growth periods. The older crust growth has undergone phosphatisation, with the replacement of carbonate by CFA phases and impregnation of phosphorite in CFC layers, whereas younger crust horizons are not phosphatised (Koschinsky et al., 1997). This is thought to occur when the overlying water column goes from oxic to suboxic, for example through increased surface primary productivity. Under these suboxic conditions, some crust phases undergo partial re-dissolution, some elements are remobilised, and the composition of crusts can be changed (Koschinsky et al., 1997). Because these phosphatisation events are widespread, they can be correlated across multiple seamounts (Hein et al., 1985; Glasby et al., 2007).

On regional to local scales, the composition of CFC also reflects the degree of dilution from detrital and diagenetic phases. The addition of detrital material to CFC at continental margins also causes distinct differences in composition compared to

CFC from open-ocean environments. Continental-margin CFC grow in complex environments with higher terrestrial inputs of dissolved and particulate matter than the open ocean and may also be influenced by metal fluxes from shelf sediments (Hein et al., 2000; Conrad et al., 2017).

Generally, continental-margin CFC show higher proportions of iron, silica, aluminium, and chromium and have faster growth rates. Both of these factors contribute to lower enrichment in economically valuable elements, due to dilution and shorter accretion times (e.g. Koschinsky et al., 1996; Hein et al., 1997; Hein et al., 2016; Conrad et al., 2017). This is particularly the case for Arctic crusts, which show some of the highest growth rates measured in hydrogenous crusts, up to 42.1 mm per million years (Hein et al., 2017), as well as high mean iron-manganese ratios of 2.67, twice that of the Atlantic mean (Hein et al., 2013; Hein et al., 2017). Further exploration for marine minerals in previously unexplored areas is likely to improve our understanding on the range of compositions and forms of CFC. Furthermore, due to the redox-sensitive nature of the behaviour of many economic trace elements (e.g. cobalt, tellurium, and platinum), local variations in oxygen conditions can lead to local variations in CFC composition (e.g. Hein et al., 1997; Hein et al., 2015; Mizell et al., 2016; Berezhnaya et al., 2018). Hence, many factors that are still poorly understood and insufficiently mapped may play an important role in local physical and chemical variations, such as microtopography (Usui et al., 2017; Lusty et al., 2018).

3.3.3. Occurrence

Figure 3.3.2 shows the sampling locations of CFC from publicly available literature and reports. As stated in Section 3.3.2, four prerequisites are thought to support crust growth. One of the most important factors for crust deposition is a sediment-free hard substrate (e.g. Glasby, 2006; Hein et al., 2009; Du et al., 2017). This means that crusts are predicted to accumulate in areas with either low detrital and biogenic sedimentation or where the seafloor morphology discourages sediment accumulation. Hence, bathymetric highs, such as seamounts, guyots, ridges, plateaus, and their slopes, are an ideal environment for hydrogenetic crust precipitation if the slopes are sufficiently steep to discourage the accumulation of thick sediment packages, or local currents are high enough to remove sediments (Bonatti, 1972; Hein et al., 2000; Glasby, 2006). These bathymetric highs also act as sea-floor obstructions, promoting upwelling and turbulent flow. This leads to increased mixing of oxygen-rich bottom waters with waters from OMZ, potential reservoirs for dissolved metals. This is thought to promote CFC formation and enrichment.

Hydrogenetic CFC are typically found in water depths between 400 and 7,000 m. Studies have used seamount distributions in oceans to estimate crust occurrence and suggest higher seamount numbers in the Pacific Ocean than in the Atlantic and Indian oceans. The occurrence of hydrothermal CFC is limited to hydrothermally-active oceanic environments such as spreading centres, back arc basins, hot spot volcanoes, and island arcs. They have been reported from the Izu-Bonin-Mariana Arc in the Pacific (Usui et al., 1986; Usui et al., 1989), at the Pitcairn Islands hotspot in the eastern Pacific (Scholten et al., 2004), and on seamounts in the Tyrrhenian Sea (Eckhardt et al., 1997).

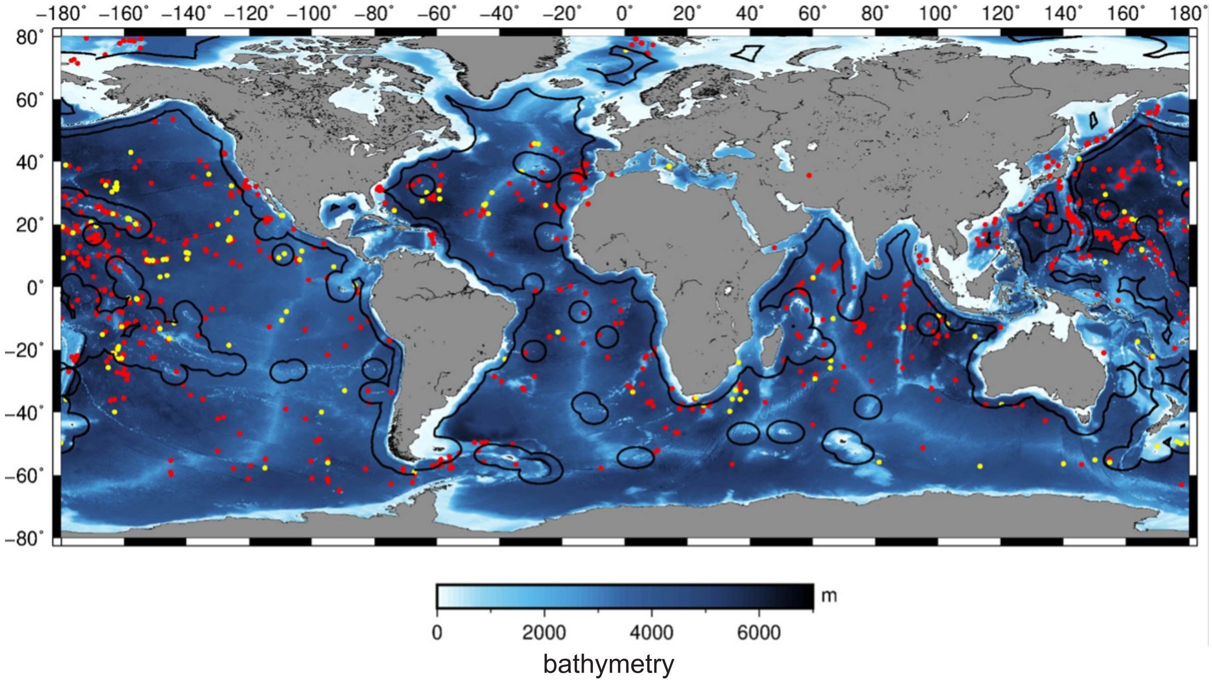
3.3.4. Resource potential

The resource potential of CFC has been widely discussed since the 1980s, following initial studies into the economic potential of PMN (e.g. Mero, 1962; Halbach et al., 1982; Aplin and Cronan, 1985; Manheim, 1986). In the past, the key elements of interest in CFC were cobalt, nickel, and copper (**Figures 3.3.3–3.3.7**). Terrestrial deposits could fill gaps in demand for these key elements, but the real interest is in the polymetallic nature of CFC. The increased demand for high-tech equipment and low-carbon renewable energy technologies is driving demand for an expanding suite of trace elements not sourced from primary ores on land. In particular, elements considered critical due to potential insecurity of their supply and high economic importance, such as cobalt, tellurium, molybdenum, platinum, niobium, tungsten, zirconium, and REY, might be targetted for future CFC exploitation (e.g. Hein et al., 2010; Hein et al., 2013; Kashiwabara et al., 2014). As of 2019, five exploration contracts have been granted for CFC exploration in the Area (ISA, 2019). Four of these are in the western Pacific Ocean: China Ocean Mineral Resources Research and Development Association, Japan Oil, Gas and Metals National Corporation, the Republic of Korea and Ministry of Natural Resources and Environment of the Russian Federation whereas one is on the Rio Grande Rise in the southern Atlantic Ocean, the Companhia De Pesquia de Recursos Minerais.

CFC may have a number of benefits if exploited, like PMS and PMN (see **Section 3.2.4**), as well as similar environmental considerations due to their remote occurrence (see **Section 3.2.6**). However, crusts also generally have higher concentrations of target elements, meaning that potentially smaller areas would need to be mined for the same amount of metal extracted. Also, the polymetallic nature of CFC means that there is a value added with each extracted economic element and with less gangue material production.

CFC are effectively a tri-dimensional deposit, and their resource potential has

Figure 3.3.2. The distribution of CFC in the global oceans

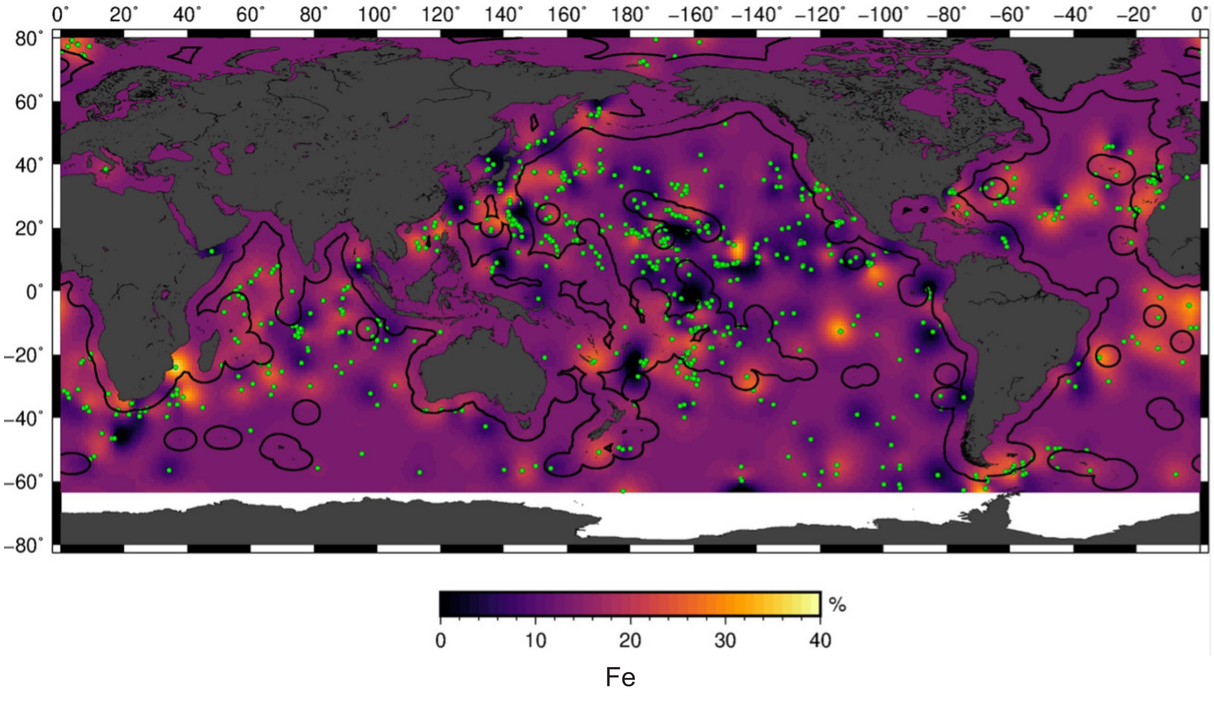


Source: Marineregions.org

Note: Red and yellow dots indicate the locations of CFC and of manganese-encrusted rocks, respectively. Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. The background shows bathymetry with 2 minutes sampling. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

to be quantified by measurements of thickness and growth on their basaltic rock substrate, unlike PMN. The most promising areas identified are thought to have the thickest and most enriched crusts. These correspond to areas that are tectonically stable to allow crusts to precipitate slowly and scavenge metals from seawater, deposits that are dominantly hydrogenetic, and have the least dilution by non-economic detrital and biogenic phases. The area thought to have the most significant resource potential is a region in the central and western equatorial Pacific known as the Prime Crust Zone (e.g. Usui and Someya, 1997; Hein and Koschinsky, 2014). This is due to the great age of the seafloor in this area, the high number of seamounts and guyots, low detrital flux, and the high measured concentrations of economically strategic elements in CFC. For example, the highest cobalt concentrations measured so far in CFC have been within the Prime Crust Zone (average of 0.67 wt.-%, 362 crust samples) whereas Atlantic crusts have lower average cobalt concentrations (0.36 wt.-%, 43 samples) (Hein and Koschinsky, 2014). In particular, CFC within the Prime Crust Zone show thallium, tellurium, and cobalt contents exceeding those of the terrestrial reserve base (Hein et al., 2013). The high concentrations of REY and scandium also pose an economically important by-product in CFC. While total REY and scandium concentrations are generally

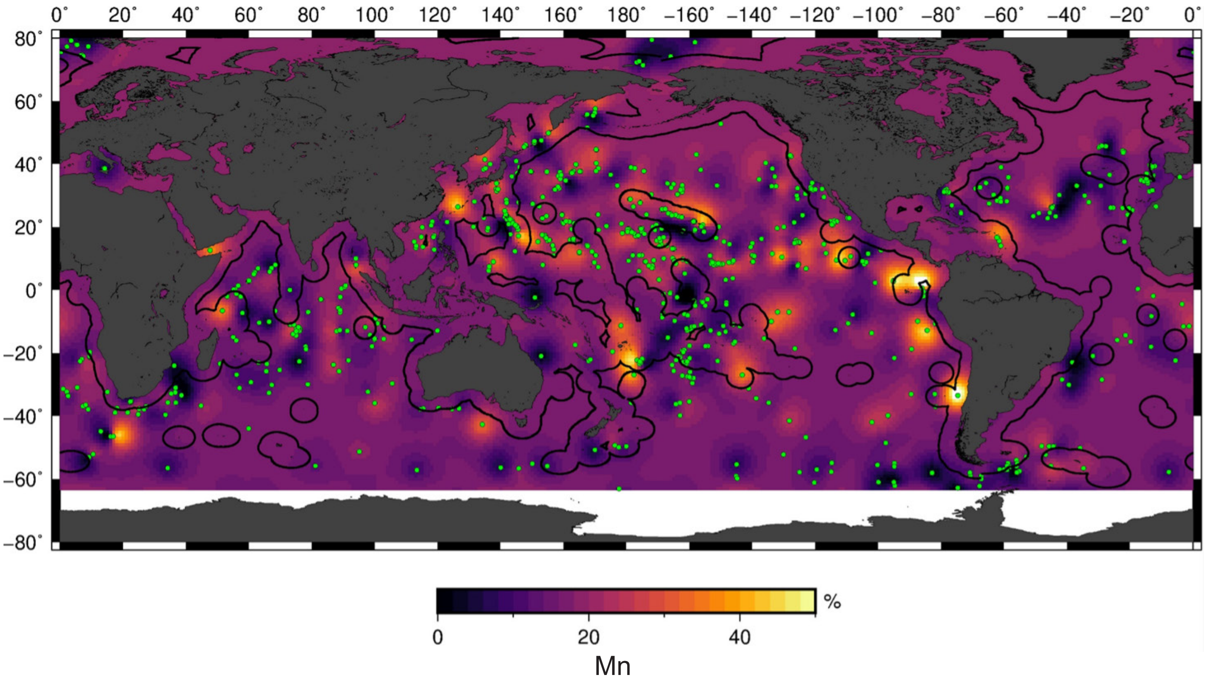
Figure 3.3.3. The distribution and concentration of elemental Fe in CFC (wt.-%)



Source: Marineregions.org

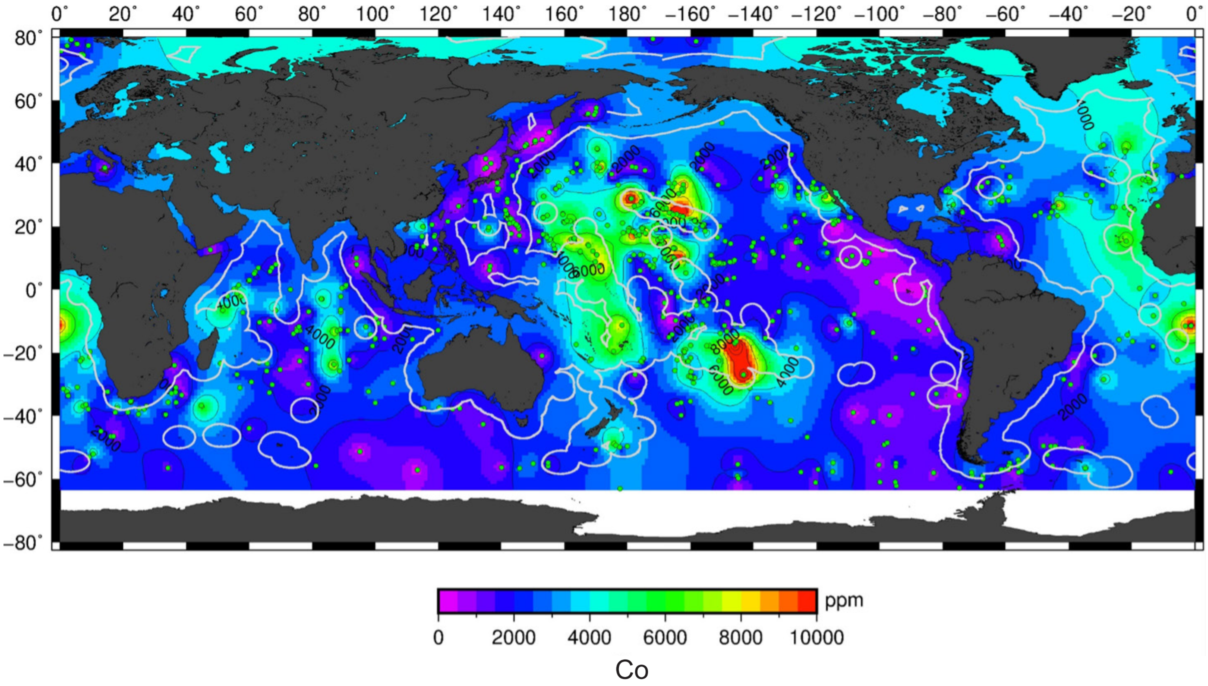
Note: Known crust locations denoted by green points. Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Figure 3.3.4. The distribution and concentration of elemental Mn in CFC (wt.-%)



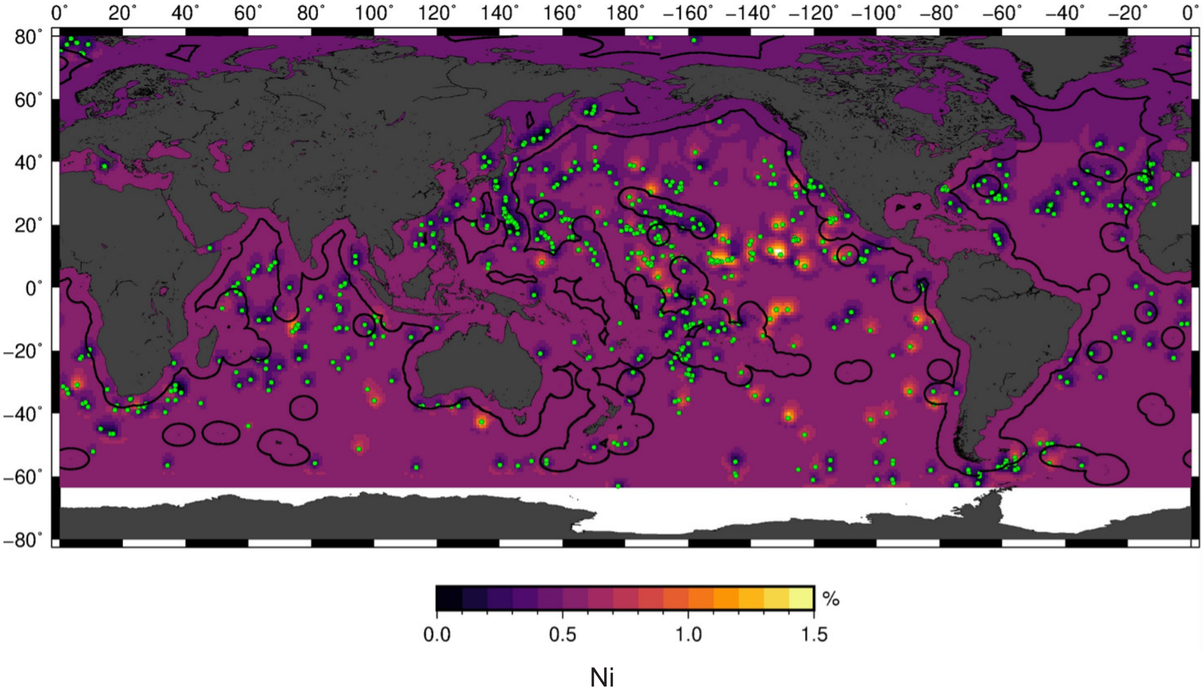
Source: Marineregions.org
Note: Known crust locations denoted by green points. Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Figure 3.3.5. The distribution and concentration of elemental Co in CFC (ppm)



Source: Marineregions.org
Note: Known crust locations denoted by green points. Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone (this represents the exclusive economic zones if all coastal States had declared exclusive economic zones up to 200 nautical miles). Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

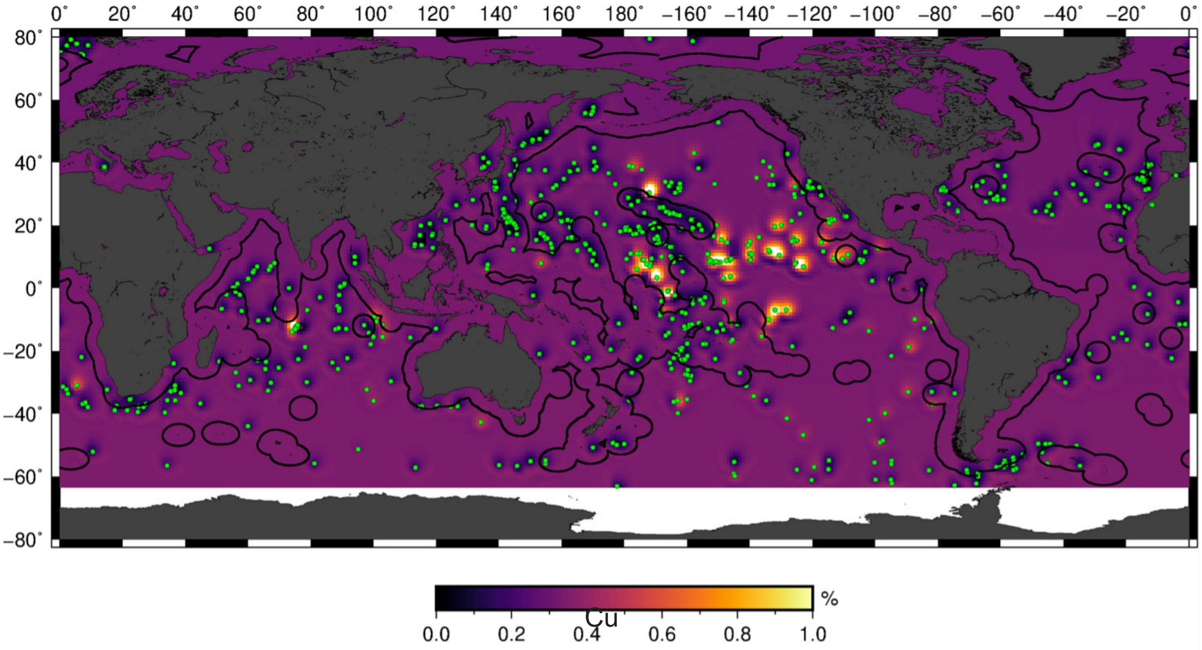
Figure 3.3.6. The distribution and concentration of elemental Ni in CFC (wt.-%)



Source: Marineregions.org

Note: Known crust locations denoted by green points. Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

Figure 3.3.7. The distribution and concentration of elemental Cu in CFC (wt.-%)



Source: Marineregions.org

Note: Sample locations denoted by green points. Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

comparable to land-based mines, the relative proportions of the rare earth elements are an important consideration. Land-based mines, which are mostly carbonatite-hosted, are richer in light rare-earth elements (REE) relative to heavy REE (~1 per cent). Heavy REE generally have greater economic value due to their wide application in technology. Hydrogenetic CFC are rich in rare earth elements and have high concentrations of these valuable heavy REE, averaging 18 per cent of the total REE content in the Prime Crust Zone (Hein et al., 2013). Crusts also have much lower concentrations of radioactive thorium than land-based deposits, on the order of tens of parts per million (ppm) rather than hundreds of ppm making them easier to process.

Estimating CFC tonnages remains the biggest challenge in resource estimation. There are two significant unknowns for calculating CFC tonnages: the CFC distribution on seamount structures; and the variation in thickness. CFC distribution has been proposed to depend on a number of variables as described in Section 3.3.3, but detailed distribution at the scale of the individual seamount is still unknown and has only been mapped in detail on a few seamounts (Usui et al., 2016; Yeo et al., 2018; Lusty et al., 2018). Furthermore, distributions of crust thicknesses are highly variable even over local spatial scales, and the thickness distribution of in situ crust is as yet unquantified (Hein et al., 2009). Past studies have all relied on spot sampling for thickness measurements and hence only point data is available, making accurate resource estimates for CFC difficult. Recent studies have also used statistical space interpolation to estimate regional CFC resources (Du et al., 2017). Du et al. (2017) discuss a potential method for evaluating resources at the scale of individual seamounts. Still, they highlight the need for a greater understanding of the fundamental assumptions applied to models at this scale. Sato and Usui (2017) apply a different technique for modelling CFC grades, using estimates of metal fluxes per unit area. This method means that deposit tonnages are not included within the model. Information on thicknesses, bulk crust composition, and physical properties such as density are not required. Such a method could be used on a regional scale to determine key prospective areas for targeting sampling but requires further ground-truthing and relies on accurate estimates of metal fluxes to oceans, which remain poorly constrained for many regions. Evaluation of prospective CFC may benefit from first identifying mine sites that can be viable for extended production periods, potentially over separate structures (Hein et al., 2009). Selecting sites that are both technologically feasible to mine and likely to support a 20-year mining operation could highlight areas requiring further characterisation. Hein et al. (2009) conclude that prospect sites are flat-topped guyots at water depths less than 2,500 m with limited sediment cover, and CFC thicknesses of at least 3 cm. Another consideration is the proximity of a potential mine site to shore, with closer ones being easier to maintain and supply than those that are more remote. These considerations allow the economic potential, such as minimum metal grades or minimum production rates required to sustain operations, to be evaluated according to contemporary metal prices.

Fewer studies on the resource potential of CFC deposits have been carried out than for PMN. While the Pacific Prime Crust Zone is moderately well characterised in terms of composition, the widespread use of spatially imprecise sampling techniques (e.g. dredging) means that current understanding of in situ crust distribution and thickness is insufficient to fully quantify its resource potential, although estimates have been made. Conservative crust tonnage estimates of 7,533 million dry tonnes were made for the Prime Crust Zone (Hein and Koschinsky, 2013), based on assumptions of mean crust thicknesses and seamount coverage (Hein et al., 2009). Halbach et al. (2013) estimated total CFC resources in oceans to be 35,100 million dry tonnes, using wider assumptions including those on crust occurrence between stipulated depths on all seamounts and guyots (Halbach et al, 2013).

3.3.5. Technological advances

Technological advances have the potential to improve all stages of CFC resource studies, from exploration to mining, processing, and environmental monitoring.

In historical studies and exploration for CFC, sampling has relied on point sampling methods such as dredging and mapping from towed cameras. The biggest unknown in resource estimates is the tonnage of CFC, as little is known about local-scale patterns in distribution and variability because there are very few high-resolution mapping studies (Glasby, 2000; Petersen et al., 2016; Usui et al., 2017). Studies on this scale are critical for understanding what controls crust abundance, thickness, and formation (Hein et al., 2000; Glasby et al., 2007). Ideally, multidisciplinary exploratory expeditions should take place to fully quantify CFC and their associated biology (Usui et al., 2017). The ability to observe, image, and sample in situ CFC at high spatial resolutions is improved by using towed cameras, AUVs, and ROVs. A range of geophysical techniques can improve understanding of CFC distribution. Acquisition of shipboard echo-sounder and acoustic backscatter data can be used to locate regions of potential CFC outcrops. Still, AUV-mounted or deep-towed equipment allows for higher resolution surveys due to the reduced distance between substrate and detector (e.g. Kim et al., 2013). Ideally, in situ crust thickness variations could be mapped remotely, potentially through the development and application of a multispectral seismic tool or gamma radiation (Hein and Koschinsky, 2014). While gamma radiation seems a promising tool for distinguishing CFC from the underlying basement, the rapid attenuation in seawater poses a challenge to the widespread application of this technique (Hein et al., 2000). A more promising approach for determining crust thickness and distribution is the deployment of high-frequency sub-bottom profiler data that can be acquired from AUVs. Trials of this technology have proven successful in previous studies of CFC (Nishida et al., 2015; Neettiyah et al., 2015).

Improvement in geochemical analytical capabilities means that it is now possible to measure the concentrations of a larger suite of elements than in the past. For CFC, this means that trace elements, such as tellurium and platinum, that could be drivers for exploration and exploitation can now be measured to high precision and accuracy using techniques such as inductively-coupled plasma mass spectrometry. Historical samples that were originally analysed for major-element content (e.g. iron and manganese concentrations) may require re-analysis to fully characterise the deposits and resource potential of strategic elements.

No test mining has yet been undertaken for CFC (Lusty et al., 2018). Beyond the characterisation stage, the technological capabilities required to harvest CFC remain in the early stages. This is primarily due to the difficulty separating the CFC ore from the non-economical substrate (gangue). Given the firm attachment of CFC to substrates of variable morphology and mechanical properties, separating CFC from gangue to minimise dilution of ore grade at 2,000 m water depths remains a significant engineering challenge (Hein et al., 2013). CFC extraction may use similar cutting technologies to those used for sea-floor massive sulphide deposits (Lusty et al., 2018). Once separated from the substrate, CFC material may require similar metal recovery and processing methodologies to those envisaged for PMN due to similarities in mineralogy and matrix, adapted to maximise extraction of target elements (see Section 3.2.5; Hein and Koschinsky, 2014; Zubkov et al., 2018). Fragmented ore material needs to be brought to the surface, where it may be processed on a ship or transported and processed at land-based plants.

4. MARINE MINERAL RESOURCES OF THE CONTINENTAL SHELF

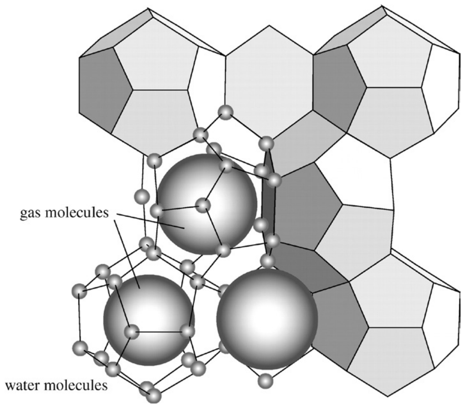
4.1. Marine gas hydrates

4.1.1. Definition

Gas hydrates, also called clathrates, are naturally occurring crystalline structures (Figure 4.1.1) composed of water and gas, where a gas molecule (basically methane (CH_4)) is trapped within the molecular cavity of a hydrogen-bonded water lattice (Collett et al., 2013; Xu and Ruppel, 1999). They occur under low temperature (<26.85°C) and moderate pressure (>0.6 megapascals) conditions (Sloan, 2003) when sufficient quantities of methane and water are present. Gas hydrates are found within permafrost areas on land at depths below the subsurface ranging from 130 to 2,000 m, and in marine sediments from the seafloor down to 1,100 m depth below the seafloor (Collett, 2002; Kvenvolden and Lorenson, 2001). They are widespread within the sediments at water depths greater than 300–500 m (Minshull et al., 2019). Gas hydrates dissociate when ambient pressure and temperature are outside their phase stability limits for a given water salinity. Under normal temperature and pressure conditions, methane hydrate may produce up to 170 times its volume of methane gas. Therefore, gas hydrates are considered to be a fossil fuel resource.

Gas hydrates were initially studied as a way to ensure that the flow of produced oil and gas would mitigate the cloggingof pipelines. The current knowledge about gas hydrates suggests that large volumes of methane are stored within gas hydrates, and that existing oil and gas extraction techniques can be applied to recover this methane. Hydrate dissociation is a safety hazard due to oil and gas production activities. Gas hydrates are a potential source of geohazard because their dissociation may release methane into the ocean and atmosphere (Collett et al., 2013) and may destabilize the seafloor (Sultan et al., 2004).

Figure 4.1.1: Typical molecular structure of a gas hydrate with water molecules attached to each other and encaging gas molecules (methane)



Source: Maslin et al., 2010

4.1.2. Formation

The main factors controlling the formation of gas hydrates are pressure-temperature stability conditions, gas source, gas migration pathway, availability of water, and suitable host sediment or "reservoir" (Collett et al., 2013). Gas hydrates form when small methane (or other gas) molecules contact with water under low temperature and moderate pressure (Sloan, 2003). A small molecule of hydrocarbon (<0.9 nm) is trapped within water cages formed by van der Waals forces (Bonnefoy et al., 2005) and with cavities separated by 0.5 nm (Chong et al., 2016). The most common hydrate-forming gas is methane ($CH_4n_hH_2O$) (Kvenvolden et al., 1993), but other gases including ethane, carbon dioxide, and hydrogen sulphide may be found associated with gas hydrates.

Natural gas is formed by biogenic or thermogenic degradation of organic material. Biogenic gas consists mainly of methane (Cicerone and Oremland, 1988). It is produced within shallow sediments by the decomposition of organic matter by micro-organisms via carbon dioxide reduction and fermentation (Collett et al., 2013; Whiticar et al., 1986). The rate of microbial conversion of organic carbon to methane is assumed to be a function of the ambient temperature of the sedimentary section and the rate of water flux through the sediment, with the rate of water flux being controlled by the permeability of the sediments (Collett et al., 2013). Thermogenic methane is generated by the deep burial of organic material and degradation by thermochemical alteration. During early thermal maturation, methane is produced along with other hydrocarbon and non-hydrocarbon gases and is commonly associated with crude oil generation. Natural gas can also be produced by abiotic processes. The alteration of mantle peridotite, called serpentinisation, generates hydrogen that can then react by Fisher-Tropsch or Sabatier-type reactions with seawater carbonate to form abiotic methane.

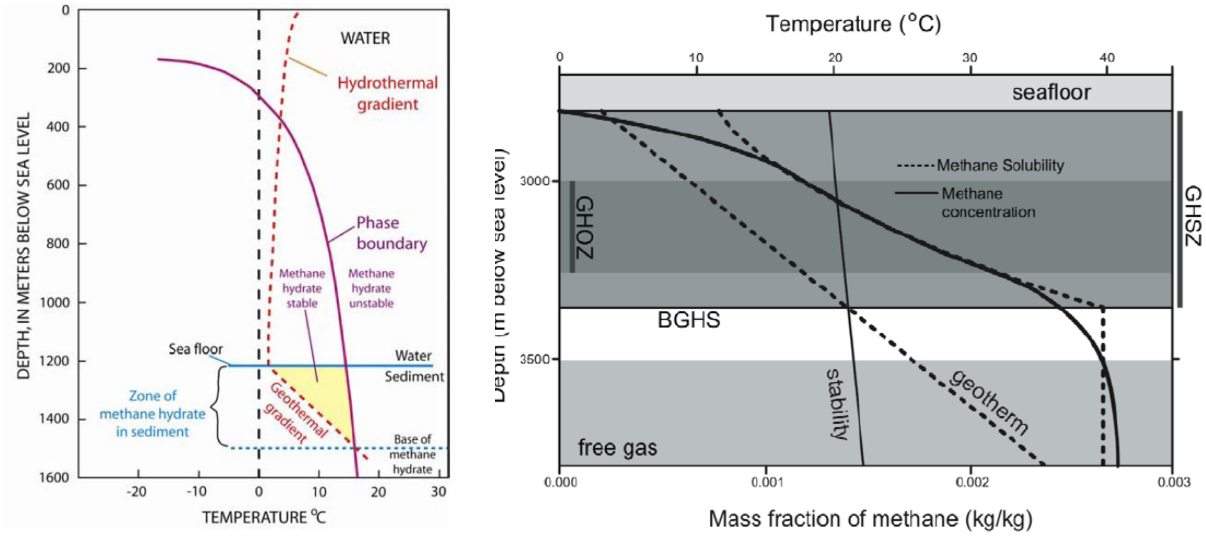
Early studies of gas hydrates suggested that most methane stored in gas hydrate deposits is derived from a microbial origin. However, later studies, e.g. in northern Alaska (Collett, 2008), Canada (Dallimore and Collett, 2005), and Europe (Minshull et al., 2019), documented that methane of thermogenic origin is also widespread and forms highly-concentrated methane hydrate accumulations. Usually, whether from a biogenic or thermogenic origin, the methane stored in gas hydrates is not generated within the gas hydrate stability zone (GHSZ). The gas migrates from deeper to shallower sediments via molecular diffusion, advection (gas dissolved within migrating water) as bubbles, or a separate continuous gas phase due to buoyancy or differences in gas pressure (Collett et al., 2013). Coarse-grained sediments favour migration by capillary invasion, whereas fracturing dominates in fine-grained media (Jain and Juanes, 2009). Methane hydrate forms only when the concentration of methane in the pore waters exceeds its solubility. A solid hydrate film forms at the interface and acts as a barrier to prevent further contact, requiring fluid surface renewal for continued hydrate formation (Sloan, 2003).

Hydrate structures vary with the size and the chemical nature of gas molecules and ambient pressure and temperature conditions (Chong et al., 2016). The cubic structure I (sI), cubic structure II (sII), and the hexagonal structure (sH) have been identified to be the three main structures of gas hydrates (Englezos, 1993; Veluswamy et al., 2014). In each structure, water molecules arrange in different patterns, forming cavities of different diameters to reside in gas (Chong et al., 2016; Sloan and Koh, 2007).

4.1.3. Occurrence

Gas hydrates occur within marine sediments and in permafrost areas – where the ground remains below the freezing point for two or more years – or in deep-lake regions. In this study, the focus is placed on gas hydrates observed within marine sediments. Marine sediments are estimated to host 99 per cent of the world’s gas hydrate deposits (Ruppel, 2018).

Figure 4.1.2. Three-phase stability conditions for methane in the ocean (liquid water + hydrate + vapour) (left) and hydrate stability zone within the oceanic sediments (right)



Source: modified from Sloan et al., 2010

The stability of gas hydrates is controlled by the pressure-temperature and salinity conditions (Kvenvolden and Lorenson, 2001). Still, their occurrence within the sediments is controlled by the presence of enough gas and water, water chemistry, sediment porosity and permeability, lithology (Kraemer et al., 2000), and gas migration pathways (Minshull et al., 1994). They are observed in nature in different modes: occupying pores of coarse-grained sediment; nodules disseminated within fine-grained sediment; filling fractures; or a massive unit composed mainly of solid methane hydrate with minor amounts of sediment (Sloan and Koh, 2008; Waite et al., 2009). In the pores, hydrate can be floating (pore-filling hydrate; Chong et al., 2016) or bridging the neighbouring mineral grains (cementing hydrate; e.g. Santamarina et al., 2015).

The upper- and lower-depth limits for potential gas hydrate occurrence are controlled by the hydrate-forming gases (e.g. **Figure 4.1.2**) and the subsurface pressure, temperature, and salinity conditions. The upper limit of methane hydrate occurrence in continental polar regions is about 150 m depth with surface temperatures below 0°C. In oceanic sediments, it is at water depths exceeding 300 m with seabed water temperatures usually above 0°C (**Figure 4.1.2**). The lower limit of methane hydrate occurrence is determined by the depth at which the temperature of the hydrate-phase boundary is equal to the temperature structure of the system controlled by the seabed temperature and geothermal gradient. The theoretical lower limit is about 2,000 m below the seabed. However, it is typically much less than 2,000 m, depending on local temperature, pressure and water chemistry (Collett et al., 2013).

For this study, the upper limit of the methane hydrate stability zone was modelled globally (**Figure 4.1.3**), using the phase boundary of pure methane in seawater of constant salinity of 3.5 wt.-% (Tishchenko et al., 2005) and combining the GEBCO 2014 global bathymetry (Weatherall et al., 2015) with two-minute spatial sampling and the global sea-floor temperature dataset from Reid and Manfia (1994). No attempt was made to calculate the thickness of the methane hydrate stability zone globally, because such an estimation would suffer from the scarcity of worldwide geothermal gradient information. The global map of the thickness of the GHSZ can be found, for example, in Kretschmer et al. (2015) and Ruppel and Kessler (2017), and needs to be interpreted cautiously. Local studies of the thickness of the GHSZ suffer much less from the geothermal data scarcity. Within the Area, abrupt lateral geothermal gradient variations might be expected due to the local magmatic/tectonic conditions. Modelling studies usually consider the phase boundary of pure methane to estimate the upper and lower boundaries of GHSZ. However, hydrates with gas from a thermogenic origin may contain other gases, modifying the hydrate phase-stability conditions from that of pure methane hydrate. Sophisticated modelling approaches have been proposed to calculate the amount of methane stored in hydrates globally (e.g. Kretschmer et al., 2015) or in the Arctic (Marin-Moreno et al., 2016). However, these models may underestimate this amount because the thermogenic methane contribution is unconstrained or not considered.

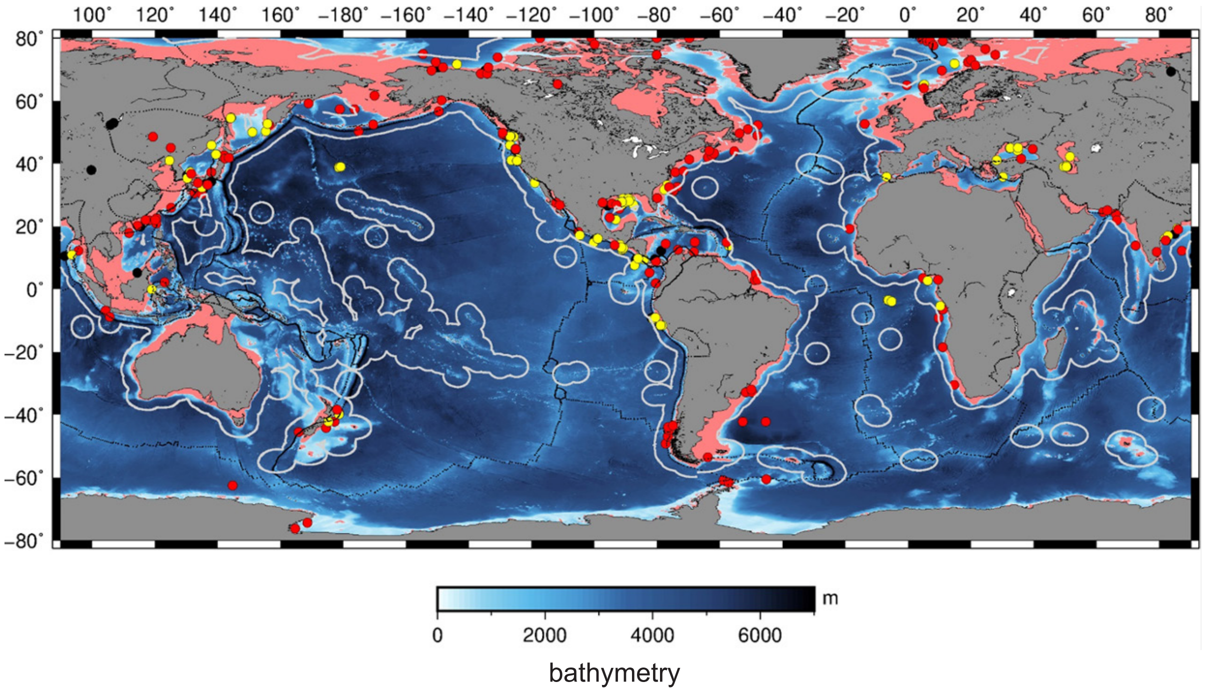
The occurrence of offshore gas hydrates on continental margins is traditionally inferred from multi-channel seismic profiles, when a reverse polarity seismic reflector to that of the seafloor is observed lying roughly parallel to the seafloor at depths as great as 1,100 m below the seafloor (Collett et al., 2013). This reflector, called the bottom-simulating reflector (BSR), is observed due to the strong impedance contrast between gas hydrate-bearing sediments with faster P-wave velocities and the underlying zone of free-gas with lower P-wave velocities and marks the base of the hydrate stability zone. However, BSRs may not be observed if, for example, free gas is not present below the gas hydrate-bearing sediments, or they can be associated with non-hydrate-related features such as the Opal-CT transition. BSRs are easily spotted on seismic sections from highly tectonised areas as a reflection cutting the strata, whereas, in less deformed areas, it can be parallel to bedding and more difficult to identify. Other sea-floor and sub-sea-floor features that can be used as gas hydrate indicators if found within the GHSZ are gas seepage, pore water chlorinity anomalies, seismic chimneys, anomalies in seismic velocity and electrical resistivity, zones of anomalous sea-floor reflectivity, the presence of a conventional petroleum province, and various sea-floor features (cold seeps without gas, acoustic backscatter anomalies, mud volcanoes, pockmarks, and pingos).

The presence of gas hydrates has been observed through direct sampling during numerous expeditions including past Deep Sea Drilling Programs and Ocean Drilling Program (ODP) legs (e.g. 164, Blake Ridge, and Caroline Rise in Paull et al., 2000; 204, Central Cascadia Accretionary Complex), recent International Ocean Discovery Program (IODP) expeditions (e.g. 311, Northern Cascadia Margin in Riedel et al., 2006; 353, Krishna-Godavari and Mahandi basins, Bay of Bengal, off-shore India in Clemens et al., 2014; 372A, Tuaheni Landslide Complex, offshore New Zealand in Pecher et al., 2019), and industrial or national sea-floor drilling surveys.

Methane hydrates with sI structure and methane from a biogenic origin were observed in the Gulf of Mexico (Milkov et al., 2000), Ulleung Basin (Ryu et al., 2013), Nankai Trough (Ashi et al., 2002), and South China Sea (Liu et al., 2014). Thermogenic natural gas hydrate deposits form sII or sH hydrate structures and occur in a wider range of conditions where pure methane hydrate is not stable. They have been found or inferred in several locations including the Gulf of Mexico (Brooks et al., 1984), Caspian Sea (Diaconescu and Knapp, 2002; Diaconescu et al., 2001), the Northern Cascadia Margin (Pohlman et al., 2005), and in several European marine waters (Minshull et al., 2019).

The map of the distribution of gas hydrate observations (**Figure 4.1.3**) shows that

Figure 4.1.3. Distribution of recovered (yellow circles) and inferred (based on seismic data) gas hydrates (red circles) and gas hydrate drilling expeditions (black circles)



Source: Marineregions.org

Note: Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Compiled from published data sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA. The pink area shows our modelling results for the upper limit of methane hydrate stability and covers the zone where the hydrate is not stable. Note that the data points follow the border of this zone. The lower limit of methane hydrate stability is not calculated in this study due to the scarcity of geogradient data. The background shows bathymetry with 2-minutes sampling.

marine gas hydrate research to date has mostly focused on marine regions next to the coasts. Gas hydrates are one of the unconventional fossil fuel energy resources that can be exploited in the foreseeable future. Therefore, although the GHSZ extends far beyond the limits of national jurisdiction, national gas hydrate research programmes have been focused exclusively within national jurisdiction for future exploitation purposes. Only three drilling expeditions and two seismic expeditions reported gas hydrate occurrence in the Area. The scarcity of gas hydrate occurrence in the Area is therefore more likely to be due to an observational bias, since the pressure and temperature conditions in some places in the Area are suitable for gas hydrate formation and required amounts of gas and water are likely to be present in these locations. The lack of gas hydrate drilling expeditions in the Area is due to the lack of reasonable targets at a sufficient level of site surveys. The seismic expeditions aiming at finding gas hydrates are also focused within national jurisdiction, for the same reasons. Numerous seismic expeditions with different objectives than gas hydrate research have been carried out in the Area. These expeditions did not report the occurrence of BSR likely because: (1) the experiments were not designed to resolve the shallow sediments; (2) the data were not processed to find gas hydrates; and (3) since the objectives of these expeditions were different to gas hydrate research, additional effort was not provided to analyse the existing data for gas hydrate indicators. Therefore, our database of gas hydrate occurrence indicates a significant gap in marine gas hydrate research in the Area.

4.1.4. Resource potential

Estimation of the resource potential usually focuses on the origin and saturation of methane, volume of the GHSZ, and porosity and permeability of the hosting deposit. Vast amounts of natural gas hydrate resources have been identified in various locations around the world. However, global estimates of the resource potential remain speculative due to the lack of worldwide knowledge about parameters controlling gas hydrate occurrence (e.g. geothermal gradients, water chemistry, potential gas migration pathways, gas saturation, etc.). In the 1990s the gas hydrate resource estimate was about 20,000 GT of carbon, whereas in recent years, because of the increasing understanding of the limiting factors for hydrate formation and the acquisition of more data, the estimate of the resource potential has decreased to less than about 1,000 GT of carbon. This estimate is still vast compared to conventional gas resources (Pinero et al., 2013). However, there is a substantial mismatch between the global estimates of total gas hydrates and those suitable for recovery (Chong et al., 2016), which have been estimated to be about 150 GT of carbon (Boswell and Collett, 2011).

Currently, four different methane hydrate occurrence types are known: (1) sand-dominated reservoirs, (2) clay-dominated fracture reservoirs, (3) massive methane hydrate deposits exposed on the seafloor, and (4) low-concentration disseminated deposits encased in largely impermeable clays (Boswell and Collett, 2011; Collett et al., 2013; Milkov and Sassen, 2002). The first two of these occurrence types provide the necessary permeability to produce highly-concentrated hydrate accumulations, and they have been described as "worthy of further exploration" (Boswell, 2007; Collett et al., 2013).

4.1.5. Technological advances

The two most important IODP science platforms, the Joint Oceanographic Institutions Deep Earth Sampler Resolution and D/V Chikyu (which offers a marine drilling riser with blowout preventer), have previously drilled gas hydrate-hosting sediments worldwide. The semi-submersible drillship M. G. Hulme Jr. of Japan used in Nankai Trough project, D/V Uncle John, and D/V Q4000, operated by Helix Energy Solutions and used in the Gulf of Mexico Joint Industry Project are other platforms used in hydrate drilling (Collett et al., 2013).

Gas hydrate drilling is challenging because, in order to quantify the in situ natural gas occurrence, cores must be sealed in autoclaves which keep them at in situ pressure and temperature conditions (Collett et al., 2013). An example of this technology is the ODP Pressure Core Sampler (PCS). The PCS acquires information about gas concentrations, but does not give insight into the physical structure of gas hydrates (Milkov, 2004). A top-driven rotation is used in the ODP PCS for coring. Other gas hydrate-bearing sediment coring mechanisms include: (1) HYACINTH (HYdrogen ACceptance IN the Transition pHase EU project) pressure-coring system, which uses fluid circulation for coring; (2) Fugro Pressure Corer or HYACINTH percussion corer, which uses a water hammer driven by the fluid pumped down the pipe; and (3) HYAC (HYdrogen ACceptance EU project) rotary corer driven by fluid pumped down the drill pipe to rotate the cutting shoe (Collett et al., 2013).

Downhole logging tools allow the acquisition of continuous records of lithological physical properties of the well formation. Wireline logging tools measure resistivity, density, and porosity, and sonic string allows vertical seismic profiling to infer the petrophysical properties of methane hydrate-bearing sediments. Logging While Drilling enables logging before drilling operations and thus allows geohazard mitigation. The available Logging While Drilling tools include natural gamma ray, density, neutron porosity, borehole calliper, resistivity, sonic, pressure gauge, formation sampler, nuclear magnetic resonance, and Seismic While Drilling (Collett et al., 2013).

The HYACINTH core transfer and analysis system allows for analysis of the core while it is being transferred. It is a pressure core manipulator and shear transfer module integrated with a Geotek Pressure Multi-sensor Core Logger for the collection of acoustic P-wave velocity, gamma ray attenuation, and X-ray image data up to 25 million years. Pressure core characterisation tools advanced technologically after the growth of core transfer and analysis systems. They can be categorized as (1) core manipulators, (2) core cutters, (3) effective stress chambers, (4) direct shear chambers, (5) biologic sub-samplers, (6) controlled depressurization chambers, and (7) instrumented pressure testing chambers. Infrared imaging to identify sediments cooled by hydrate dissociation and Multi-Sensor Core Logger (P-wave) to infer the physical properties and geochemical analysis such as chloride concentrations, are usually carried out once the core is on deck (Collett et al., 2013).

Gas hydrate production varies fundamentally from other unconventional natural gas sources since gas hydrates are solid structures. Techniques to recover methane from gas hydrates involve dissociating the natural gas hydrates in situ, in addition to creating a pathway for gas to flow. The three most commonly studied techniques for dissociating methane hydrate are thermal stimulation, depressurization, and inhibitor injection (Chong et al., 2016). Thermal stimulation and depressurisation involve changing the temperature and pressure conditions of the gas hydrate system, whereas chemical inhibitor injection changes the phase boundary of the hydrate system. For thermal stimulation, hot water, electromagnetic heating, and in situ combustion techniques are used. Due to the endothermic nature of gas hydrates, depressurization techniques need to be accompanied by other methods such as thermal stimulation. The two main types of chemical inhibitors are thermodynamic inhibitors, which change the phase boundary, and kinetic inhibitors, which slow down the hydrate formation (Chong et al., 2016). Because of the complexity of the interdependencies of the different processes occurring during methane production from gas hydrates, over the past decade several computer codes have been developed to understand the thermal, hydrological, chemical, and mechanical response of gas hydrate systems (e.g. De La Fuente et al., 2019). These codes ultimately allow for the different hydrate production techniques to be tested and for estimates of the energy potential of a particular gas hydrate reservoir to be generated.

Japan (Yamamoto et al., 2014), the USA, Canada, India, Malaysia, the Republic of Korea and China (Li et al., 2018) have successfully conducted pilot production of gas hydrates. Japan, the USA, China and India aim for commercial-scale production of gas hydrates in the coming decade. Scientific studies have proposed that in the future, gas hydrates could be used to transport stranded natural gas securely (Kida et al., 2013).

4.2. Marine metalliferous sediments

4.2.1. Definition

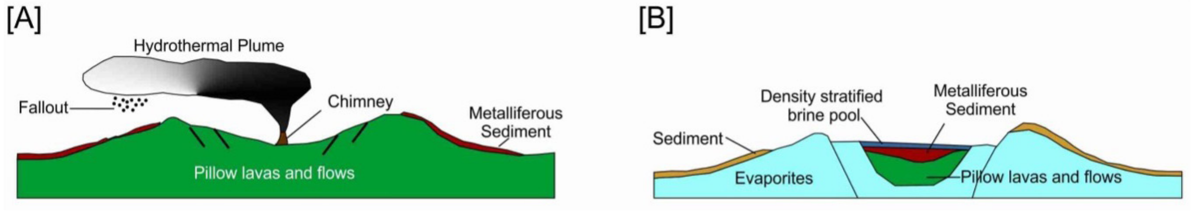
Metalliferous sediments are unconsolidated, metal-enriched sedimentary deposits. They are considered the modern analogues of lithified and un-lithified ancient marine sediment deposits of paleo-oceans and are found in today's ophiolite belts such as Oman and Cyprus (Fleet and Robertson, 1980; Robertson and Hudson, 1973). Metalliferous sediments form through plume fall-out and mass wasting related to hydrothermal vent activity (James and Elderfield, 1996; Mills and Elderfield, 1995) and/or uptake of dissolved metals from seawater (Boström and Petersen, 1969; Gurvich, 2006), or are related to hot brine pools (Degens and Ross, 1969). As their formation may be linked directly to the degradation of PMS deposits, the metal content of metalliferous sediments is also heavily dependent on the fluid and source rock composition of the hydrothermal vent site. In general, metalliferous sediments are enriched in iron and manganese that form oxides and (oxy-) hydroxides, trace amounts of sulphide minerals (such as pyrite, marcasite, sphalerite, and chalcopyrite), silica polymorphs (including quartz and amorphous silica), barite, and many more. Transitional metals such as cobalt, nickel, gold, silver, and vanadium, as well as rare earth elements and uranium, can be enriched locally (German et al., 1993; Takaya et al., 2018). Although metalliferous sediments were already discovered during the HMS Challenger expedition in 1873–1876 (Murray and Renard, 1891), they have been neglected as a potential resource of metals, as well as an exploration tool for the location of hydrothermal vent sites (Gurvich, 2006).

4.2.2. Formation

Deep-sea metalliferous sediments are often polygenetic, meaning that their components are derived from more than one source. The majority of sediment accumulations can be directly linked to hydrothermal processes occurring on the flanks and axis of spreading ridges where the discharge of hydrothermal fluids occurs (Figure 4.2.1.A). Once the high-temperature hydrothermal fluids mix with cold near-bottom seawater, very fine-grained particles precipitate as plume fallout (Dymond, 1981). In addition, clastic sulphide debris forms due to the weathering and mass wasting processes of sea-floor massive sulphide mounds (Metz et al., 1988; Mills and Elderfield, 1995; Halbach et al., 1998). Most of these sediments are accumulated in small depressions, in so-called sediment ponds (Rona et al., 1993), where they form alternating layers of red-brown mud with intercalated layers of carbonate ooze or sulphide debris (Figure 4.2.2). Further away from the ridges, where sedimentation rates are low, metals from seawater can be scavenged and are either incorporated into or adsorbed onto particles predominately composed of iron and manganese (oxy-) hydroxides (Boström and Petersen, 1969; Marching and Erzinger, 1986; Gurvich, 2006; Li and Schoonmaker, 2014).

In contrast, metalliferous sediments of the Red Sea form from different mechanisms (4.2.1.B). Along the central axis of the Red Sea, rifted graben structures with

Figure 4.2.1. The difference in the formation of metalliferous sediments in mid-ocean ridge settings (A) and the Red Sea (B)



Source: Modified from Zierenberg, 1990

submarine brine pools occur that originate from the exhalation of high-salinity brines. Sulphides like pyrite, sphalerite, and chalcopyrite precipitate from a lower brine layer, whereas iron (oxy-)hydroxides and amorphous silica precipitate from an upper brine layer with these minerals later forming clay mineral phases by diagenetic processes (Weber-Diefenbach, 1977). The high-salinity, elevated temperature and heavy-metal, concentrations of the brines ensure a hostile environment for organisms (Watson and Waterbury, 1969). Thus, bioturbation, sulphate-reduction, and oxidation processes are inhibited, resulting in undisturbed accumulations that are further protected from weathering by overlying anoxic brines. The overall metalliferous sulphide accumulations span an area of 60 km^2 and can reach up to 20 m thickness (Zierenberg, 1990).

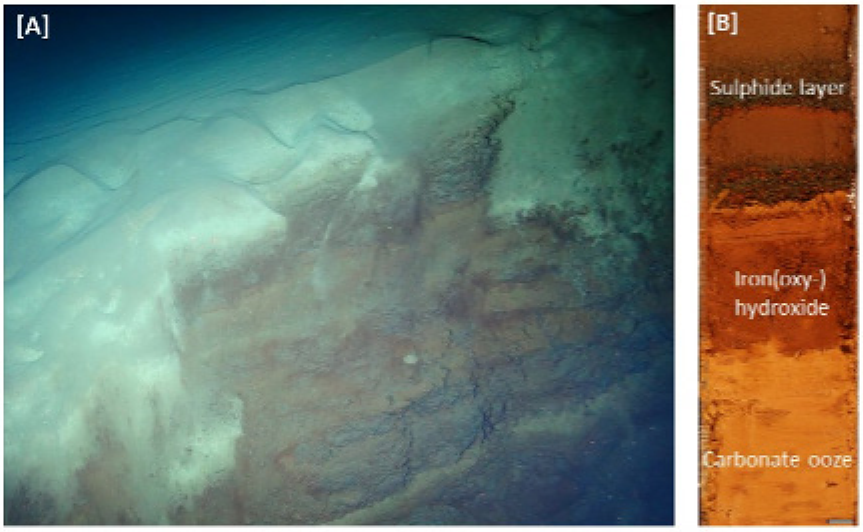
4.2.3. Occurrence

The greatest accumulations of metalliferous sediments are found in mid-ocean ridge settings where their precipitation is directly linked to hydrothermal activity. They are widely distributed in the Pacific Ocean and occur in the Indian, Atlantic, and Arctic oceans (Figure 4.2.3). The largest field of metalliferous sediment accumulation can be found in the southeast Pacific, covering an area of approximately 10 million km^2. The second largest fields were identified adjacent to the East Pacific Rise and at the Rodrigues Triple Junction. Smaller accumulations are hosted in back-arc settings, such as the Manus Basin and North Fiji Basin. The smallest deposits of metalliferous sediments are found in the vicinity of hydrothermal vent sites like TAG, Rainbow, Grimsey, and many more along the mid-ocean ridges of all oceans. The Red Sea hosts 23 sites of metalliferous sediments, with Atlantis Deep II forming the largest deposit.

4.2.4. Resource potential

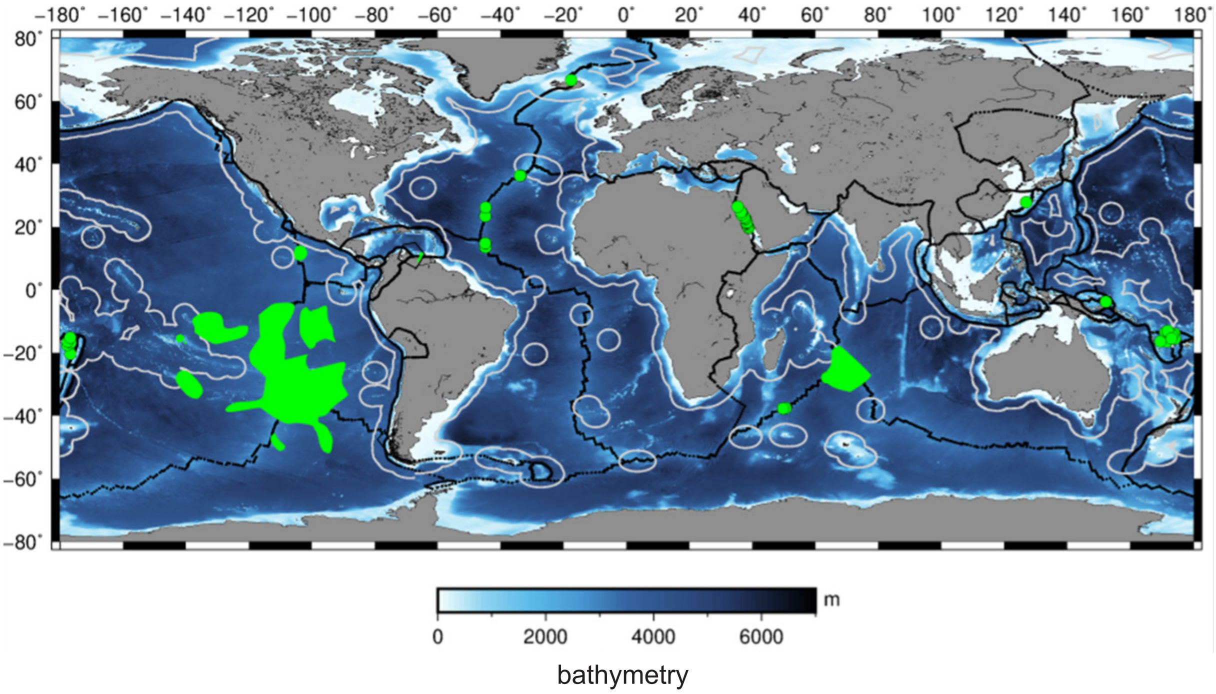
No resource potential has been estimated for the global occurrence of metalliferous sediments. Takaya et al. (2018) propose a rare-earth oxide resource potential for red REE-rich clays near Minamitori Island would be 1.2 million tonnes of rare-earth oxides. However, their estimates are based on 25

Figure 4.2.2. Sediment accumulation from the TAG hydrothermal vent area: A) outcrop of metalliferous sediments at a fault scarp overlain by carbonate ooze, B) sulphide layers in iron-rich hydrothermal sediment that alternate with carbonate ooze



Source: National Oceanography Centre

Figure 4.2.3. Global distribution of marine metalliferous sediments



Source: Marineregions.org
Note: Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone. Data compiled from Gurvich (2006) and reference therein; Dekov et al. (2008), Hrisheva et al. (2007), Hu et al. (2017), Rusakov et al. (2013), and Pan et al. (2018); and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA. The distribution of data records does not indicate where metalliferous sediment deposits are absent.

non-grid-sampled sediment cores over an area of 105 km^2 down to a maximum depth of 10 m below the seafloor, with concentrations maps extrapolated using ArcGIS software.

The only significant resource potential has been estimated for the Atlantis II Deep basin in the Red Sea. Manafai International Trade is the current exploration lease holder. The lease was granted by the Ministry of Petroleum and Mineral Resources of Saudi Arabia and the Ministry of Energy and Mines of the Republic of Sudan in 2010. An original resource estimate by *Preussag Aktiengesellschaft*, which was mandated by the Saudi-Sudanese Red Sea Joint Commission for a five-year technical feasibility study between 1977 and 1982, was reassessed by Manfai International, and additional studies were conducted by the company. The current resource estimate comprises 89 million tonnes of dry salt-free ore at 3.75 million tonnes of zinc, 0.81 million tonnes of copper, 4 million tonnes of manganese, 5,000 tonnes of cobalt, 7,000 tonnes of silver and 47 tonnes of gold (www.manafai.com/project-details.php).

4.2.5. Technological advances

Due to their link with the occurrence of PMS, the exploration strategies for metalliferous sediments are very similar. The leading technologies include mapping and sonar devices to identify depressions that can act as sediment traps. Otherwise, hydrocast profiles are conducted to identify geochemical anomalies in the water column, and coring equipment is used to assess the thickness and subsurface composition of the sediments.

Although there are currently no mining activities planned for the extraction of metalliferous sediments, in general, a similar approach as for PMN is assumed (see **Section 3.1.5**). Metalliferous muds from the Red Sea would require a slightly different approach based on their composition. Mustaffa and Amann (1978) propose that they could be extracted by suction. A vibrating/cutting head with a seawater jet system will be used to dilute and liquify the mud, then transported through pipes and risers to a surface platform or vessel by a pump system. Like PMS, the extracted sediment-water mix will be dewatered before being transported to land for further processing. No process for the extraction of the REE-rich sediments has been proposed yet, although a similar approach is likely.

4.3. Marine placer deposits

4.3.1. Definition

Marine placers are aggregations of primarily heavy minerals, with higher densities than surrounding minerals that allow their concentration to economic levels through physical and chemical processes (Roy, 1999). Key marine placers that have been exploited until now include gold, diamonds and other gemstones, cassiterite (tin), chromite (chromium), ilmenite (titanium), magnetite (iron), and zircon (zirconium), as well as industrial materials such as sand and gravels.

4.3.2. Formation

Marine placers form through the physical and chemical movement, redistribution, and concentration of heavy metallic and other minerals, native and precious metals due to differences in their physical properties. Placers can form through two differing processes of mineral sorting: through the removal of gangue material to form residual "washout" placers; or through the transport and accumulation of economic minerals with respect to their specific weight. Source rocks on land undergo physical weathering processes. The transport of heavy minerals from rivers to oceans from source to deposit allows for the sorting of minerals due to differences in density. High-density minerals are concentrated into topographic lows or relative to their specific weight, in particular along continental margins due to changes in the flow energies of the carrying water masses. The physical characteristics of minerals, such as hardness and solubility, determine their resistance to mechanical and chemical weathering, and govern the distances across which the minerals are carried from the source. Two key placer environments are observed in the marine realm: washout placers and continental shelf placers (Kudrass, 2000).

Washout placers involve the removal of less dense, non-economic minerals to leave behind a residual accumulation of target minerals to economically significant concentrations. Colluvial/eluvial washout placers form close primary chemical and physical weathering sites in rivers. Host minerals within the source rock are removed through preferential chemical weathering and are transported in solution, leaving behind liberated, more resistant minerals. These minerals are then able to concentrate through physical transportation and deposition. Debris flow placers are another form of washout placer that form during high-energy, high-flow events, such as floods, that see large changes in flow energy over short time periods.

Continental shelf placers can be divided into transgressive lag placers and subsiding shelf placers. Transgressive lag placers form during times of relative sea level rise (marine transgressions), whereby there is limited addition of new sediment and increased erosion of the shoreline, with the removed material transported along the coast and offshore. Therefore, these deposits may be found on scoured platforms, with higher grades concentrating in scoured pits. Subsiding shelf placers occur when there is addition of new sediment fluxes from marine erosion in surrounding areas, and represent some of the most economically significant placer deposits, including diamonds, gold, ilmenite, and rutile.

4.3.3. Occurrence

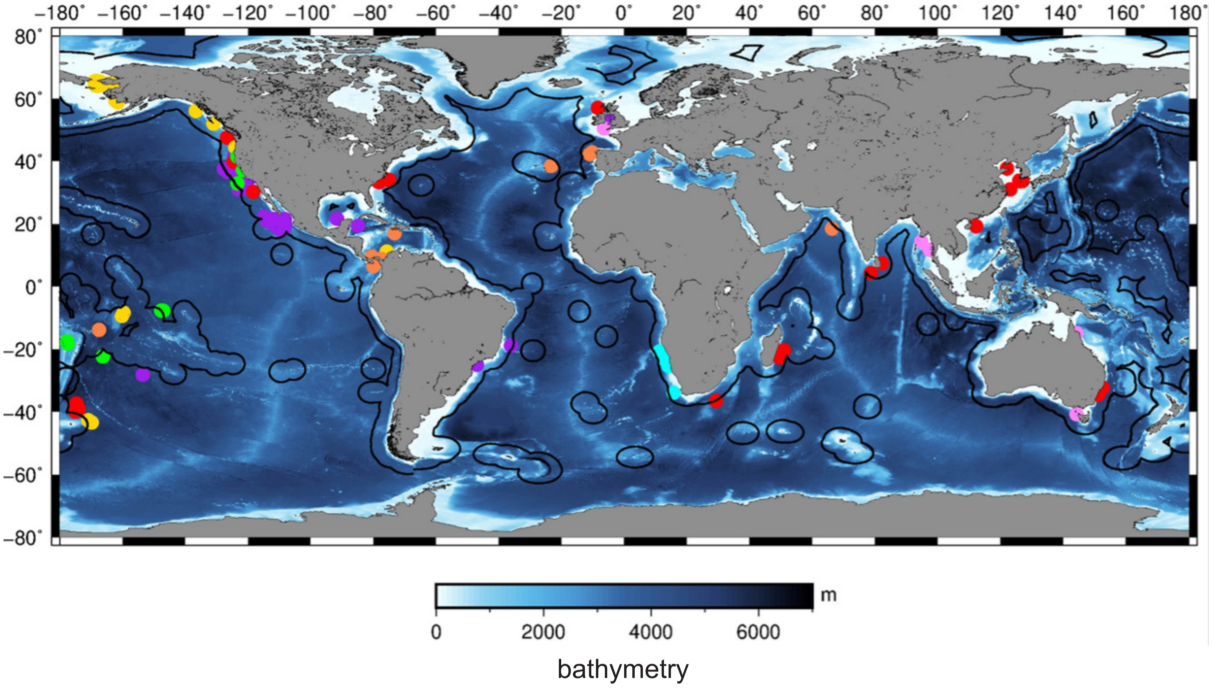
Figure 4.3.1 shows the currently known extent of economically significant placer deposits. Due to the reliance of deposit formation on proximity to continental source rocks, most marine placers are found and expected in near-shore to continental-shelf regions (e.g. Li et al., 2015; Rona, 2008). Therefore, all significant known deposits that have been exploited in the past or present lie within national jurisdiction. Provenance studies and an understanding of the physical properties of ore types are useful for understanding where other placer deposits might be found (e.g. Li et al., 2015).

Due to the large variation in conditions expected in dynamic environments such as the continental shelf, large variations in the location, frequency, and resource potential of placer deposits are also predicted (Li et al., 2015). Heavy mineral enrichments are reported in nearshore environments and have been well documented (e.g. Lenoble et al., 1995; Bryan et al., 2007).

4.3.4. Resource potential

Due to their widespread occurrence in shallow waters, nearshore, and continental shelf environments, as well as a long history of exploitation, mining infrastructure and technology, placer deposits require less capital expenditure than more complex and deeper marine minerals such as PMS, PMN and CFC (Bortnikov et al., 2015). The main placer minerals that are exploited in terms

Figure 4.3.1. Global distribution of marine placers



Source: Marineregions.org
Legend: Au=gold, Cr=green, diamonds=cyan, Fe=orange, Sn=pink, Ti=red, Zr=purple. The background shows bathymetry with 2 minutes sampling. Compiled from published sources and VLIZ Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.
Note: Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone (this represents the exclusive economic zones if all coastal States had declared exclusive economic zones up to 200 nautical miles). The background shows bathymetry with 2 minutes sampling. Data compiled from published sources and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

of tonnage are sand and gravel aggregates. As these are most commonly mined from beach and nearshore deposits, they are not included in Figure 4.3.1. Other resources that have been exploited include barium, chromium, gold, iron, REE, antimony, titanium, thorium, tungsten, and zirconium, as well as biogenic deposits for industrial materials (ISA, 2004; Rona, 2008). The most significant heavy mineral placers include offshore Namibia (diamonds), Alaska (gold), Australia (monazite [(Ce,La)PO4], rutile [TiO2], and zircon [ZrSiO4]), India (magnetite [Fe2+Fe3+2O4]), Indonesia (cassiterite [SnO2], and New Zealand (titanomagnetite [Fe2+(Fe3+,Ti)2O4]) (Bryan et al., 2007). Other regions that have large placer potential or have been exploited in the past include within the Russian Arctic zone (diamonds, gold, platinum, tin, titanium, REE; Bortnikov et al., 2015) and South Africa (diamonds, gold). With the increased demand for REE, particularly heavy REE, for high-tech manufacturing, there is potential for increased monazite (for light REE) and xenotime [YPO4] (for heavy REE) exploitation (Ellefson et al., 2015; Bern et al., 2016).

Due to the expected limitations on the transportation of economic mineral grains from their source due to their higher densities and faster settling rates than gangue minerals, exploration and exploitation has focused on shallow continental shelf environments. It is possible that deeper deposits, beyond the continental shelf, exist due to transportation processes such as submarine mass debris flows in canyons. Predicting the location, frequency, and resource potential of these events is highly challenging, and therefore it is unlikely that significant exploration will extend to the deeper waters of the Area for now.

4.3.5. Technological advances

Generally, exploration potential within the Area for deeper placer deposits remains low due to difficulties in the prediction of mass flow events and the restricted nature of these flows. With improvements in remote submarine mapping capabilities, such as longer operational times for AUVs and plans for wide-scale high-resolution bathymetric maps for the major ocean basins, it may be possible to identify promising areas for exploration by following predicted transport routes from economic mineral source regions. Geophysical exploration tools could also be adopted. For example, the spatial distribution of heavy mineral placers deposits may be mapped using geophysical rock magnetic approaches (Bryan et al., 2012). Improvements to benthic electro-magnetic profiling may also allow for faster surveying and a better characterisation of the deposits to assess, for example, their degree of sedimentary sorting (e.g. Cioppa et al, 2010).

Furthermore, advances in analytical techniques allow more precise provenance surveys based on the chemistry of placer deposits. Improved understanding of the mineral transport and concentration mechanisms from source rock to placer deposit will help to define new target areas (e.g. Krippener et al., 2014; Li et al., 2015). Zhou et al. (2007) also highlighted the importance of using geographical information systems to complete accurate resource assessments, particularly when combining the different types of historical datasets common for resources with a long history of exploitation such as placers.

4.4. Marine evaporite deposits

4.4.1. Definition

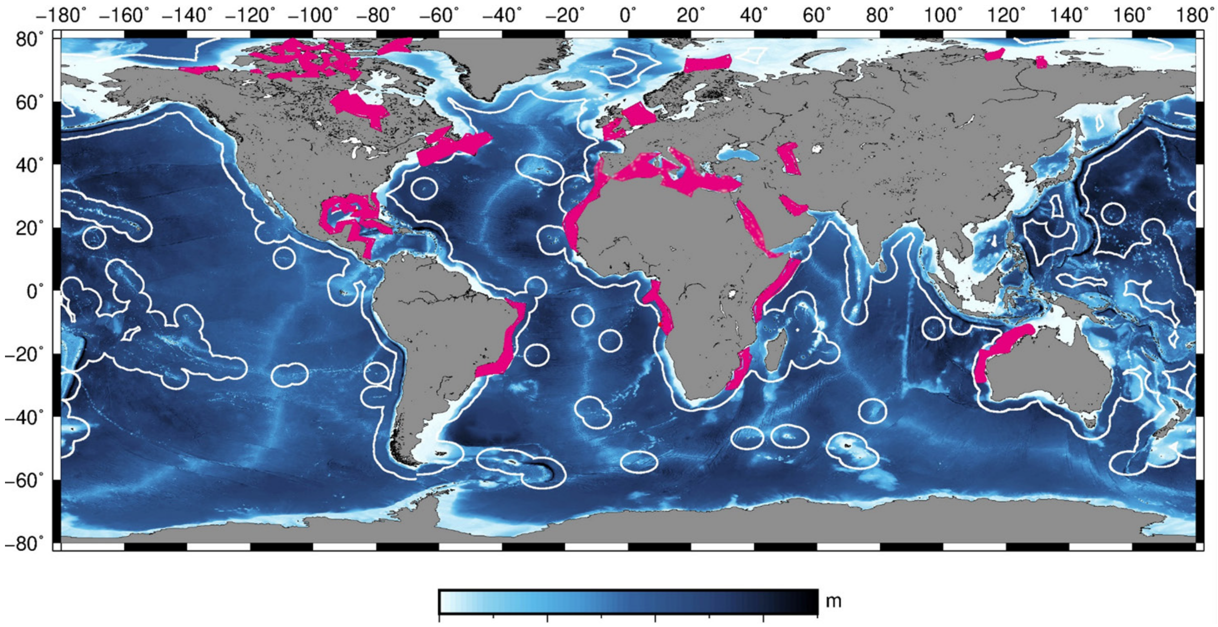
Marine evaporite deposits are formed through the evaporation of salt-bearing fluids/brines within restricted basins leaving behind salts including anhydrite, halite, gypsum, potash, and sodium chloride. These deposits are important both as a resource and for the formation of large hydrocarbon reserves. Salts can flow under elevated temperature and pressure conditions encountered in buried sediments, which allows them to form domes and structures that can act as traps for significant hydrocarbon reserves to accumulate. Hence, in the marine realm, the bulk of research and mining has focussed on the oil prospectivity of large-scale salt structures, rather than on the exploitation of the evaporites themselves.

4.4.2. Formation

Marine evaporite deposits are formed within basins that experience restricted circulation during their formation. This is common during the early stages of an ocean basin's lifecycle. During the early stages of continental rifting, small ocean basins can form with a limited influx of water. When combined with high levels of evaporation, this can lead to the concentration of brines. The formation of these salt-rich restricted basins can be observed at distinct time periods in Earth's history during extensive continental rifting, with significant salt giants of the Atlantic margins being formed during the Triassic-Jurassic. Subsequent burial of salt horizons through sedimentation in later stages of continental rifting has preserved these evaporite horizons at depth in numerous ocean basins. They consist of anhydrite, gypsum, halite, and potash-bearing minerals (Holser et al., 1988).

Salt can form laterally extensive horizons within sedimentary sequences that are kilometres thick on passive continental margins, which are the regions that preserve the earliest stages of ocean basin formation. These evaporite horizons can be brought close to the surface through flow under a sediment overburden, which can form deformation structures such as salt domes. The location of buried evaporite deposits in major ocean basins is generally known due to these distinct salt-tectonic deformation structures and are recognised by seismic surveys. As these salt horizons are commonly associated

Figure 4.4.1. Global known and estimated distribution of marine evaporites (pink fields)



Source: Marineregions.org

Note: Thick white contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone (this represents the exclusive economic zones if all coastal States had declared exclusive economic zones up to 200 nautical miles). Compiled from published data sources; estimated fields are compiled from ISA (2000), ISA (2004), and Warren (2006); and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

with the accumulation of hydrocarbons, the majority of research on buried salt bodies has focussed on the petroleum potential in these regions (e.g. Warren, 2006). Figure 4.4.1 shows the present known and estimated occurrence of anhydrite, halite, potash, and magnesium salts in the marine realm. The most significant of these evaporite deposits extend from terrestrial deposits onto the continental shelf, such as the Gulf of Mexico. Other regions of giant salt plays include the Mediterranean Sea, northeast Brazil, northeast Canada, northwest Africa, East Africa, and Western Australia. While some of these deposits have the potential to extend into the Area, little is known about the magnitude and abundance of these deposits.

4.4.3. Resource potential

There are no reported estimates for potential marine evaporite resources. Large evaporitic deposits are found and mined extensively on land in regions of now-uplifted ocean basin margins. Potash deposits are the most economical, but less widespread than gypsum and salt (Warren, 1999). The existence of proximal hydrothermal brines can sometimes increase the potential of evaporite resources. For example, the Dead Sea could be a potential resource of common salt, but it is also enriched in iron, manganese, lead, zinc, and lithium (Gavrieli et al., 2001). Salts are also easily made through the evaporation of seawater, while the widespread manufacture of salts in coastal regions means that evaporitic minerals are widely available at low costs. The abundance of material and ease of manufacturing on land means little economic value in recovering buried evaporites from the marine realm. The focus on evaporitic deposits in these regions remains an indicator of potential hydrocarbon accumulation, and this is likely to stay the case in the near future.

4.4.4. Technological advances

Well-established geophysical techniques from the petroleum sector efficiently recognise buried salt horizons within thick sedimentary sequences offshore. Given the deeply buried nature of marine mega-evaporitic basins, it is highly unlikely that evaporites will be recovered from these deposits in the future.

4.5. Marine phosphorite deposits

4.5.1. Definition

Marine phosphorite deposits are sedimentary deposits of rocks with high concentrations of phosphorus, defined as having phosphorous concentrations exceeding 9 wt.-% (Blatt and Tracy, 1996). They are critical for the production of fertilizers and so are vital for the agricultural sector. Phosphorite commonly exists as a range of heavy mineral phases, such as apatite ($Ca_5(PO_4)_3(F,Cl,OH)$) and CFA phases, that form authigenically from seawater during diagenetic processes rather than detritally.

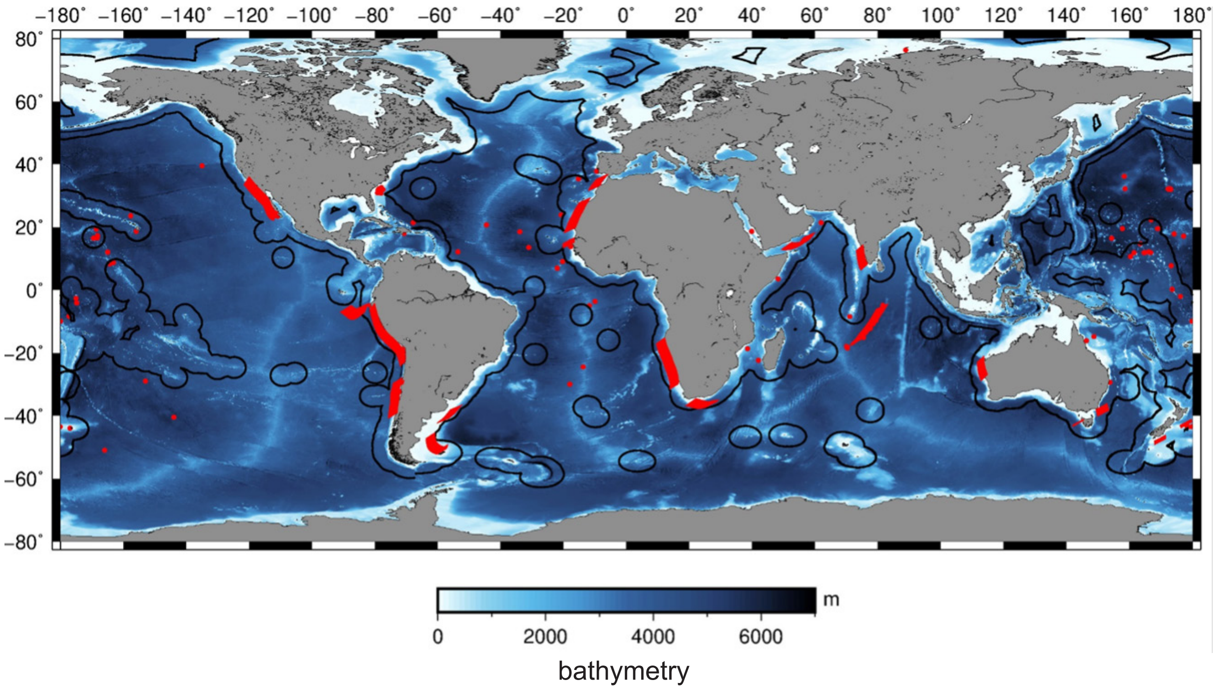
4.5.2. Formation

The formation of phosphorites is related to the cycling of phosphorus (P) in the marine environment and subsequent processes of P concentration and precipitation. Phosphorus in seawater is thought to be sourced from decaying marine organisms, bone material, and faecal pellets. This material can be carried from depths where it has settled to shallow waters through the upwelling of bottom waters. These deep, phosphorous-rich waters upwell due to sea-floor obstructions, such as at continental margins and seamounts within tropical to sub-tropical regions. This upwelling "fertilises" the upper ocean at continental margins and seamounts and encourages high primary biological productivity in surface waters. This cycle continues through high productivity and the sinking and burial of biological matter within the oxygen minimum zones on the continental shelf. It leads to a concentration of phosphorous-rich matter in these environments. Phosphorites are usually observed as nodules, pavements, and as infills and replacements in sedimentary rocks through phosphogenesis (Baturin and Bezrukov, 1979; Defforey and Peytan, 2018). This can occur on a range of scales, from basin-wide to locally, and the various mechanisms of phosphatisation at specific sites are still being investigated. Furthermore, older phosphorites, largely deposited in ancient shallow seas, can be deformed and reworked through time. Phosphorus-bearing phases in sediments undergo diagenesis in marine sediments, with dissolved P being released into interstitial waters, concentrating and then reprecipitating.

4.5.3. Occurrence

Marine phosphorites are observed in four main environments: (1) at continental margins; (2) on seamounts; (3) on islands and atolls; and (4) within lagoon environments. These occurrences follow a model of P-concentration and upwelling driven by sea-floor obstructions and oceanic flow regimes (Hein et al., 2005). Known and predicted areas of phosphorite deposits are shown in Figure 4.5.1. Large land-based deposits, such as those observed on Nauru, have the potential to extend into shallow waters. Continental margins pose the most promising environments in terms of tonnages for phosphorite deposits (e.g. Peru-Chile margin; Burnett, 1990), but variations in

Figure 4.5.1. Global known and estimated distribution of phosphorites (red fields)



Source: Marineregions.org
Note: Thick black contours represent an approximation of the 200 nautical miles calculated from the coastline purely for a distance-reference purpose, and do not purport to indicate any maritime claim nor actual limits of any maritime zone (this represents the exclusive economic zones if all coastal States had declared exclusive economic zones up to 200 nautical miles). Compiled from published data sources including fields compiled from ISA (2004) and ISA (2000); and VLIZ , Maritime Boundaries Geodatabase, version 8 (2014), in conjunction with NOAA.

composition between continental margin and seamount phosphorite could mean different environments may have different target elements. Key sites of known marine phosphorite occurrence include offshore Namibia, eastern Australia, western Mexico, the northeast Atlantic, and the Chatham Rise off New Zealand (Rona, 2008).

4.5.4. Resource potential

Phosphorite resources are estimated to be extensive in the marine realm but are also abundant in terrestrial environments. However, no offshore phosphorite resources are currently being exploited. The phosphate content of these offshore deposits is highly variable, and the large variation in textures and morphologies, from crusts to replacement structures to nodules, means that evaluation of resource potential is difficult, and little work has been done on submarine phosphorites resource estimation.

There are two main areas within continental margin environments in respect of which steps were taken to process applications for leases for exploration for marine phosphorites. These include sites offshore Namibia (Namibian Marine Phosphate Ltd.) and offshore Baja California (Odyssey Marine Exploration and Exploraciones Oceanicas). For example, estimates for resources on the Namibian shelf suggest that, given tonnages of 6,900 million tonnes of phosphorites and average grades of 19 wt.-% phosphorus pentoxide, the Namibian deposit has the potential to provide up to five per cent of the estimated global phosphorite resources (Compton and Bergh, 2016). In the future, there is potential for added value to phosphorite deposits through diversification of the resource. Marine phosphorites pose a potentially important resource of REY. Rare earth elements are split into light REY including La to SM (LREY) and heavy REY including Eu to Lu and Y (HREY), important in the manufacture of numerous modern electronic products. In particular, there is a high demand for HREY. This is due to imbalances in the elemental composition of current land-based resources. The vast majority of REY exploited on land are sourced from carbonatite REY ores composed of >99 per cent LREY. The need for a deposit enriched in HREY has rejuvenated interest in phosphorites as a potential future resource, with HREY being an important by-product of phosphorite mining (e.g. Daessle and Carriquiry, 2008). Seamount phosphorites, in particular, have been observed to have relatively high proportions of HREY (Hein et al., 2016).

4.5.5. Technological advances

Technologies for recovering marine phosphorites will vary according to the predominant morphology of the phosphorite resource. For nodular phosphorites, sea-floor mining equipment is likely to resemble that currently used for placer deposits of diamonds that operate in similar water depths or dredging methods. Collecting and separating phosphorite crusts and sediments will likely be more complex and will face similar technological challenges as CFC (**Section 3.3.5**). In deposits that are mixed phosphorite-CFC, there is potential for simultaneous collection and then separation during processing to minimise waste, through both crushing and physical sorting and hydrometallurgical methods.

5. CONCLUDING OBSERVATIONS

With an increasing demand for low-carbon footprint technologies, a wider range and greater resources of economically strategic elements are required to meet manufacturing demand. Currently, many of these elements are only extracted as by-products from terrestrial mines. Hence, new resources for many of these elements will be required in the future, with marine minerals providing one such potential source. The scientific and technological advances that have most significantly impacted our knowledge of marine mineral deposits are summarised below and include high-resolution remote sensing techniques for the detection of marine minerals, from photographic surveys to geophysical measurements. The three key resources of the Area and the geological environments they are commonly associated with are: PMS, found predominately along mid-ocean ridges, and to a minor degree in backarc-basin, arc-volcano, and intraplate environments; PMN, in abyssal plains; and CFC, observed in a range of environments from seamounts and guyots to ridges.

The five main marine mineral resources described in this study commonly found on the continental shelf include gas hydrates, metalliferous sediments, placers, evaporites, and phosphorites. The large range of different deposits found in these environments partly reflects the dynamic, varied nature of the continental shelf, which acts as the interface between the deep ocean and the continental crust and has varied inputs including terrestrial influxes. Occurrences of metalliferous sediments have been documented in the Area. A few single occurrences of gas hydrates and phosphatized concretionary sediments were also identified.

For PMS, formed by fluids that form hydrothermal precipitates, the majority of deposits may be relatively small in size and tonnage but can have economically significant concentrations of metals including copper, zinc, silver, gold, and typically a high share of economically strategic elements. Resource estimates require an understanding of the third dimension, and widespread, comprehensive drilling campaigns are necessary in order to understand the global potential. The potential of extinct deposits off-axis remains unquantified. Still, improvements in remote sensing techniques and understanding of regional patterns in geology suggest that further work in this area is favourable. While no commercial mining of PMS is underway, mining technology has been constructed and tested. Currently, seven contracts in the Area have been granted for exploration in the Atlantic and Indian oceans.

For PMN, the most promising sites are in abyssal-plain regions of old, stable oceanic crust with low sedimentation rates. A key region that fulfils the criteria is within the area between the Clarion and Clipperton fracture zone in the Pacific Ocean, estimated to contain 21,100 million dry tonnes of nodules with high concentrations of cobalt, manganese, copper, and nickel. As a two-dimensional deposit, estimating nodule distribution and tonnages remains the largest source of uncertainty in resource modelling over the vast areas of the abyssal plains where nodules can be found. Improvements in remote surveying and processing capabilities, such as combined AUV photographic surveys, automated Object Based Image Analysis and multibeam backscatter recording, are promising tools for increasing the density of observational data. Of the mineral deposits found dominantly within the Area, PMN represent some of the most extensively-studied deposits and are some of the best characterised on the sub-basin scale. Currently eighteen of the thirty contracts in the Area have been concluded for the exploration of PMN.

For CFC, extreme enrichments in cobalt, tellurium, and rare earth elements make them a promising source of materials for the high-tech industry. Resource models rely on an improved understanding of the controls on crust distribution and variations in crust thickness at the scale of the seamount. Significant challenges remain for the removal of crust from the underlying substrate (gangue) at the seabed, and the potential environmental impacts of mining in seamount environments are not yet fully quantified. While there are considerably fewer studies on the resource potential of CFC than PMN, the region of the Pacific Prime Crust Zone is moderately well characterised, and there are four exploration contracts in this location in the Area.

Within the continental shelf regions, gas hydrates present a potentially significant source of unconventional fossil fuel energy, particularly methane. They are found in permafrost areas on land, but the vast majority of gas hydrates are hosted within marine sediments in the oceans. Most research has been focussed on the continental shelf within 200 NM, with only five expeditions reporting gas hydrates in the Area. While it has been estimated that the resource potential of unconventional gas resources far exceeds that of conventional resources, a significant proportion of unconventional gas hydrates are deemed unsuitable for recovery. Engineering challenges of gas hydrate recovery from deep waters likely means that exploration will be limited to continental shelf within 200 NM for the foreseeable future.

Metalliferous sediments form through various mechanisms and are commonly polygenetic. Generally, hydrothermal plume-sourced sediments are found near marine plate boundaries. Still, overall low grades mean that these metalliferous sediments are of low economic significance, with comparable low-grade and high-tonnage deposits widespread in the terrestrial realm. Rare earth element-enriched muds have been suggested to be a potentially significant source of rare earth elements, but further work is required to fully constrain the extent, occurrence, and tonnage of these deposits. Significant occurrence of metalliferous muds in the Red Sea could pose an important source of zinc, copper, manganese, silver, and gold. Still, they form through unique geological processes which are not known to occur elsewhere on the planet.

Placer deposits concentrate minerals to economic levels through physical processes and are mostly restricted to near-shore and continental shelf regions. They are the only marine minerals that have a significant history of mining. In particular, placers are, and have been, exploited for industrial minerals (e.g. aggregates and gravels), heavy minerals (e.g. rutile and magnetite), and precious minerals (e.g. diamonds and gold). The widespread exploitation of near-shore and beach placers means that, in general, mining and processing technologies are well-established and constraints on transportation distances of target minerals means that exploration in the Area is limited and possibly uneconomic.

Evaporites, the most economically significant type being potash-bearing, are found buried within marine sediments and restricted basins such as the Dead Sea. The ease with which salts can be inexpensively manufactured on land through the evaporation of seawater means that evaporites are widely available at low cost, and recovery from deep marine environments is unlikely to be economic.

Phosphorites are an important resource of phosphorus which is vital for the agricultural industry. They are observed in varied marine environments and are commonly associated with upwelling, such as along continental margins, on seamounts, islands, and atolls. While abundant in the marine realm, they are also widespread in terrestrial environments, and marine phosphorites are currently not exploited and there are no active phosphorite exploration activities in the Area. In the future, they may be a viable resource of rare earth elements, in particular the heavy rare earth elements.

For all marine minerals, improvements in the understanding of resource potential and potential impacts of marine mining are required. The significant advances in marine exploration capabilities mean that high-resolution, multidisciplinary marine surveys can allow for increased certainty in both resource estimates and environmental impact surveys, and the deployment of remote surveying technologies will improve data coverage of our vast ocean environments going forward.

TABLES AND FIGURES

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