MINDeSEA

Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials

MINDeSEA

Deliverable 2.3-5: Workshop

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2.3	Workshop Report
Long Title	
Deliverable 2.3 – Workshops dedicated to the main themes of the work packages	
Short Description	
This document presents a resume of activities of the MINDeSEA invited talk at the international conference "Deep Sea Minerals" celebrated on 21 October 2021 in Bergen-Norway (onsite/online event due to COVID-19 pandemic restrictions).	
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D2.3- 5th MINDeSEA invited talk and discussion panel on critical minerals

"Deep Sea Minerals Conference"

19-21 October 2021

Bergen (Norway)

Project and Workshop Overview

The project "Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials" (MINDeSEA) results of the collaboration between eight GeoERA Partners and four Non-funded Organizations at various points of common interest for exploration and investigation on seafloor mineral deposits. The project MINDeSEA is sponsored by the European as an ERA-NET action under Horizon 2020 and is designed with the following objectives:

1) Characterise deposit types; 2) Characterise the trace element content of the deposit type including CRM; 3) Identify the principal metallogenic provinces; 4) Develop harmonised mineral maps and datasets of seabed deposits incorporating GSO datasets, along with mineral-potential and prospectivity maps; 5) Demonstrate how the cases study results can be used in off-shore mineral exploration; 6) Analyse present-day exploration and exploitation status in terms of regulation, legislation, environmental impacts, exploitation and future directions. 7) Demonstrate efficiency of a pan-European research approach to understanding seabed minerals and modes of exploration.

International presentation and discussion session on the need for critical minerals were presented by MINDeSEA in cooperation with organizers and industry and research centers from Norway. Due to the COVID-19 pandemic restrictions this event was planned as face to face / online format. Eight sessions were prepared to establish an arena where participants and other stakeholders can exchange knowledge and views concerning relevant issues within deep-sea mining: DEEP SEA MINING - STATE OF THE ART; FORMATION & DISTRIBUTION OF MINERALS IN THE NORWEGIAN SEA; DEEP SEA DEPOSITS; LICENSE TO OPERATE; MINERAL RESOURCE INVENTORY; CRITICAL MINERALS; EXPLORATION TECHNOLOGY AND METHODOLOGY; EXPLORERS - COMPANY PRESENTATIONS.

MINDeSEA participation at the Conference

Venue: Deep Sea Minerals (19-21 October 2021 Bergen-Norway)

Organizers-Sponsors: Geopublishing, TGS, Fearnley Securities, PGS, CGE Ocean Technology

Session nº: 6- Critical Minerals, October 21

Talk: **"GeoERA-MINDeSEA project database and cartography of European seabed mineral deposits"**

Panel discussion: on critical minerals featuring Karen Hanghøy, Frances Wall, Francisco Javier González Sanz, and Tom Einar Jensen; moderated by Henrik Schiellerup, Director Resources & Environment at the Geological Survey of Norway and MINDeSEA member.

Stakeholders: addressed to industry professionals, environmental groups, policymakers, the geoscience community, and other stakeholders (35 conference presenters, 200 attenders).

Official website: https://events.geonova.no/event/deep-sea-minerals-2021/

Objectives of MINDeSEA at the Conference

The objectives were:

1. To introduce stakeholders to the research of seabed mineral deposits and content and findings of the MINDeSEA project.

2. To further expand the MINDeSEA stakeholder network to relevant universities and industries, and to explore new working relationships beyond the project partners.
3. To connect the MINDeSEA project with on-going activities at the European and the Norwegian framework.
4. To improve the awareness and understanding of the research, technological, legal and environmental challenges in seabed exploration and mining.

Workshop Framework and Deliverable

The workshop series were celebrated in a dual format, face to face and via teleconference due to the COVID-19 pandemic situation.

The need for critical minerals is now expected to be greater than the supply from the mining industry and recycling, Norway is in an excellent position to become a leader in the exploration for deep-sea minerals. The race has started, and at this conference, we will address challenges and opportunities that lie ahead. Norway is preparing for the 1st licensing round for deep-sea minerals, and Europe should be prepared to manage the new mining frontiers in a sustainable way.

The deliverable includes this workshop report, the agenda and website announcements for the event; digital news on the talk and a document with the Abstracts Book, including the MINDeSEA talk (see pp. 48-50) provided to all participants, and the project presentation.

This project has been supported by the European Union's Horizon 2020 research and innovation programme, GeoERA (Grant Agreement Nº 731166, project GeoE.171.001).

NCS EXPLORATION

DEEP SEA MINERALS

ABSTRACTS

Exploring Norwegian Waters
October 19-21 2021
Scandic Bergen City
Bergen Norway

Abstract collection will only be distributed digitally.

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EXPLORING NORWEGIAN WATERS

OCTOBER 19-21 2021

SCANDIC BERGEN CITY

BERGEN NORWAY

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ICEBREAKER HOST: GCE OCEAN TECHNOLOGY

GCE Ocean Technology

HOT VENTS BENEATH ARCTIC ICE

The new research vessel RV Kronprins Haakon is used for the 2021 cruise to the Aurora seamount. Photo: HACON

More than 4 000 meters under an ice-covered ocean lies the Aurora seamount with its hydrothermal vents and associated fauna.

Hydrothermal vents on the seafloor host unique faunas that are often completely isolated from sunlight. Instead of photosynthesis, they depend on the chemical energy provided by mineral-rich boiling hot water originating from the Earth's interior.

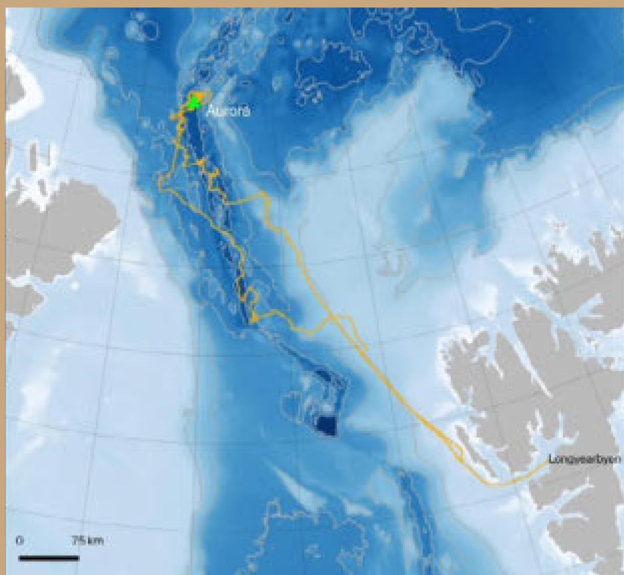
In early October, an international group of scientists, led by the **Norwegian research institutions Centre for Arctic Gas Hydrate, Environment and Climate** (CAGE) and the **Norwegian Institute for Water Research** (NIVA), went to explore such a hot vent– the Aurora seamount - located on the westernmost part of the Arctic Ocean Gakkel Ridge.

The project aims at investigating the role of the Gakkel Ridge and Arctic Ocean as a steppingstone for connectivity of vent faunas between the Pacific and the Arctic Mid-Ocean Ridges.

This will be the third time Aurora is visited by a scientific cruise. However, the two previous cruises never managed to study the seamount and the fauna up close. This time, a remotely operated vehicle (ROV), also named Aurora, will gather videos, pictures as well as rocks and biological samples.

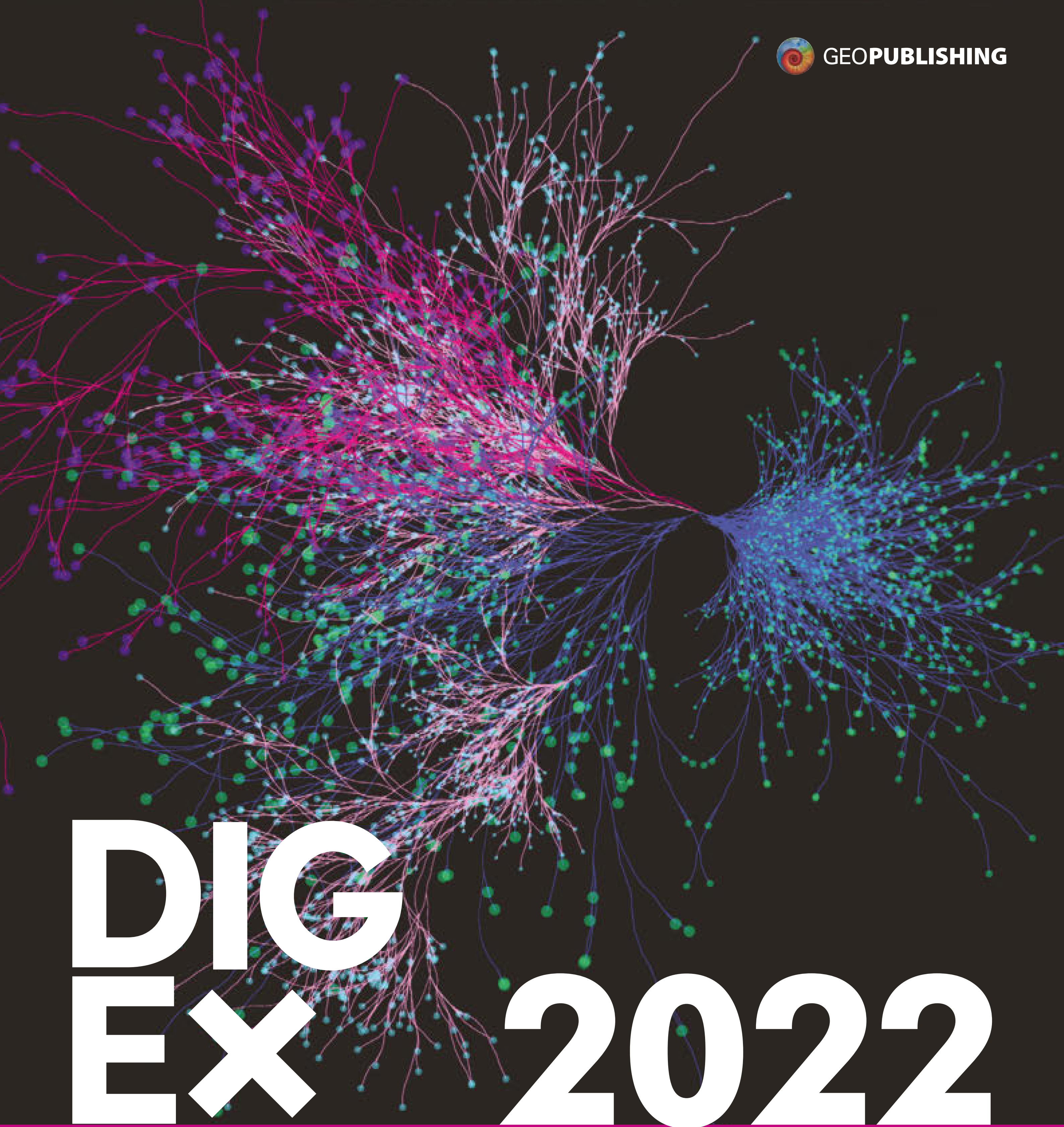
The expedition is funded by the Research Council of Norway. The project name is *HACON – Hot Vents in an Ice-covered Ocean*. On geoforskning.no, you can read more about the project and follow the cruise through regular updates until the end of October.

RONNY SETSÅ, EDITOR AT GEOFORSKNING.NO



The Aurora seamount is located in the Fram Strait northeast of Greenland on the western part of the Gakkel Ridge. The yellow line depicts the route of the 2019 expedition. The 2021 expedition will follow a similar route. Illustration: HACON

Pictures from the Aurora hydrothermal vent field showing the wall of a sulphide mound (left) and a chimney structure (right). Illustration: HACON



WELCOME TO BERGEN

Linn Katrin Pilskog is Deputy Major of Bergen

Bergen is the Gateway to the Fjords of Norway. As a UNESCO World Heritage City and a European City of Culture, the Bergen region has the ideal combination of nature, culture and exciting urban life all year around.

Bergen has a population of roughly 286,000 and is the second-largest city in Norway. The city is surrounded by mountains and Bergen is known as the "city of seven mountains.

Trading in Bergen may have started as early as the 1020s. According to tradition, the city was founded in 1070 by king Olav Kyrre and was named Bjørgvin, 'the green meadow among the mountains'. It served as Norway's capital in the 13th century, and from the end of the 13th century became a bureau city of the Hanseatic League. Until 1789, Bergen enjoyed exclusive rights to mediate trade between Northern Norway and abroad and it was the largest city in Norway until the 1830s when it was overtaken by the capital, Christiania (now known as Oslo). The city was hit by numerous fires over the years.

What remains of the quays, Bryggen, is a World Heritage Site.

The Bergen School of Meteorology was developed at the Geophysical Institute starting in 1917, the Norwegian School of Economics was founded in 1936, and the University of Bergen in 1946.

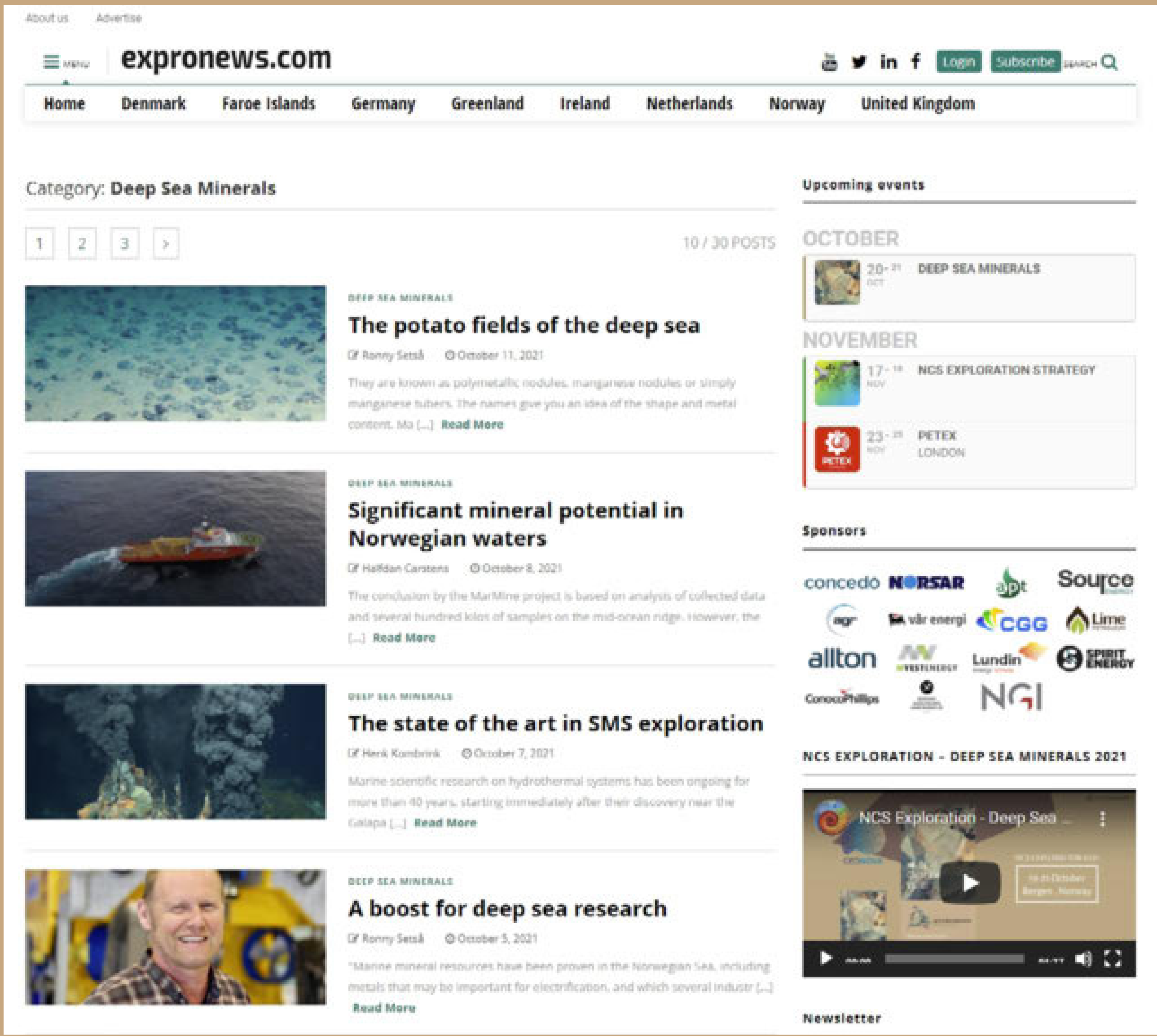
The city is an international center for aquaculture, shipping, the offshore petroleum industry and subsea technology, and a national centre for higher education, media, tourism and finance. Bergen Port is Norway's busiest in terms of both freight and passengers, with over 300 cruise ship calls a year bringing nearly a half a million passengers to Bergen.

Natives speak a distinct dialect, known as Bergensk.

Bergen has a mild winter climate, though with a lot of precipitation. From December to March, Bergen can be, in rare cases, up to 20 °C warmer than Oslo, even though both cities are at about 60° North. The Gulf Stream keeps the sea relatively warm, considering the latitude, and the mountains protect the city from cold winds from the north, north-east and east.

Bergen has an average of 235 rainy days per year.

Source: Wikipedia, visitbergen.com



DEEP SEA MINERALS

EXPLORATION, EXPLOITATION, RESOURCES, TECHNOLOGY, ENVIRONMENT

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Worldwide exploration for deep sea minerals – a status report

HARALD BREKKE, NORWEGIAN PETROLEUM DIRECTORATE, **PEDRO MADUREIRA**, UNIVERSTIY OF ÉVORA

The world oceans contain three types of seabed minerals, polymetallic nodules, polymetallic crusts, and polymetallic sulphides. Deposits of these minerals may represent resources of economic interest as well as forming in place habitats to different life forms. These deposits are thus subject to exploration and research both in the international seabed area (the Area) and in the continental shelf areas of coastal states. In the Area, these resources are managed by the International Seabed Authority (ISA) on behalf of humankind in accordance with the UN Convention on the Law of the Sea. The managment includes the organization of contracts and monitoring of activities regarding exploration and exploitation in the Area. So far, no exploitation has taken place in the Area while exploration under ISA has been going on for more than 20 years.

After ISA's regulations for the exploration for nodules came in place in 2000, the first exploration contracts were signed by seven government agencies called the "Pioneer Investors". Renewed interest for contracts started in 2010 after the regulations for the exploration for crusts and sulphides were adopted, resulting in 31 currently active, commercial exploration contracts in the Area. This by far exceeds the level of such activity on the continental shelf of the world coastal states.

A contract for exploration under ISA is based on an approved plan work, which is designed to both assess the resources and characterize the environment of the contract area. This requires the acquisition of data and information from the seabed and adjacent water column. Such acquisition involves marine, ship-based operations and activities. The key activities are those needed to map and sample the seabed and subsurface. Mapping involves the acquisition of geophysical and bathymetric data, videos, and photos using instruments and sensors that are towed or mounted on underwater robots (AUVs and ROVs). Sampling of the seabed and subsurface is done by grabs, corers, dredge, ROVs, and core drilling by ship or seabed rigs. Moreover, ISA contracts also include the testing of exploitation technology as part of the exploration activity. Testing of technology may involve the testing of separate components only, or full test mining.

The ISA regulations divide the exploration activities into two categories: those activities that may be performed without an environmental impact assessment (EIA), and those that require such an assessment prior to commencement. The division into the two categories is based on the scale of physical disturbance of the seabed and adjacent water column caused by the activity in question. Thus, activities like testing of mining components or large-scale sampling will require an EIA. In such cases, the regulations require the preparation of an environmental impact statement (EIS) that includes the descriptions of measures to mitigate hazards and risks, identified by the EIA, and an appropriate monitoring program. These regulations reflect the precautionary approach in exploration under ISA. A recent example of testing exploitation technology in the Area in accordance with these regulations, was performed by the contractors GSR and BGR in May this year who performed two tests of the nodule collector Patania II within their respective contract areas in the Clarion-Clipperton Zone.

So far, only a few coastal states (e.g. Papua New Guinea, Japan, Cook Islands and Norway) have initiated deep sea mineral exploration activities on their the continental shelf that may compare with the ISA activity in the Area.

The State of the Art in SMS Exploration

GEORGY CHERKASHOV, INSTITUTE FOR GEOLOGY AND MINERAL RESOURCES OF THE OCEAN,
ULRICH SCHWARZ-SCHAMPERA, INTERNATIONAL SEABED AUTHORITY

Marine scientific research on hydrothermal systems has been going on for more than 40 years, starting immediately after their discovery in 1977.

SMS exploration was legally commenced after the **International Seabed Authority** (ISA) issued a regulation in 2010 for the global oceans outside national jurisdiction defining the 'Area' and signed the first exploration contract in 2011.

Hydrothermal systems occur in oceanic spreading and rift zones along both **mid-ocean ridges** (MOR) and subduction-related arc systems. While ocean arc systems generally occur in national territories, all contract areas with the ISA are situated within slow and ultraslow spreading MORs, which are regarded beneficial for base metal sulfide enrichments due to enhanced tectonic activity, reduced magmatic influx but steady heat supply and rejuvenation, and stable, long-term hydrothermal activity.

Slow rates at oceanic spreading centers determine specific methods for the identification and exploration of SMS deposits.

In general, the exploration methodology and data collection is based on the regional geological control and potential mineral endowment for SMS deposits along a distinct ridge segment and the adoption of onshore exploration experiences from volcanic-hosted massive sulfide deposits as fossil equivalents to present-day SMS deposits. Traditionally, marine exploration surveys for SMS deposits develop from regional to detailed stages to identify the potential ore zones of a few hundred meters in diameter. The regional work begins with ship-borne, deep-towed and autonomous multibeam echosounder mapping and the creation and compilation of bathymetric maps.

Based on these map compilations, the next step of exploration involves the identification of characteristic structures which potentially control the occurrence of SMS deposits.

The structural pattern of mid-ocean ridge tectonics in areas of reduced magmatic activity is critical for the definition of prospecting areas as is the long-term structural and magmatic stability for enhanced metal sulfide enrichments. It has been recognized that key structures are represented by axis-oblique, tectonic features of oceanic core complexes (i.e., structural megamullions), which are increasingly identified and regarded typical for slow and ultraslow spreading ridges, and larger-scale off-axis volcanic complexes, particularly associated with a larger regional plume framework and periods of structural ridge recombination. With the identification of these prime exploration target areas, further work is associated with the search for volcanic, sedimentary and geochemical anomalies that form around massive sulfide occurrences both, at the stage of their formation (active venting of hydrothermal fluids) and after the termination of hydrothermal activity (inactive hydrothermal fields). In the first case, physical oceanographic characteristics of the near-bottom water column are surveyed as well as volcanic and sediment textures on the seabed, in the second case, potential physical fields (electric and magnetic) and their anomalies as well as the composition of the bottom sediments surrounding the hydrothermal fields are studied.

Lessons learned from their fossil VMS equivalents on land indicate that only a very few sulfide occurrences within larger rift-related volcanic successions enriched enough base metal sulfides over time to represent actual feasible ore deposits.

As a consequence, any discovery of sulfide occurrences requires detailed assessments to determine its lateral horizontal extension, boundaries and morphology using deep-towed or autonomous high-resolution echo sounder and side-scan sonar as well as video systems. The identification of the vertical extension and first resource assessments, necessary for the identification of the most prospecting resource drilling positions, are carried out using electromagnetic methods.

Reliable reserve assessments for feasibility considerations and orebody and ore-type identification (pyrite versus base metal sulfides, precious metal endowment and distribution) require drilling.

A ship-based Derrick-type drilling system require specialized vessels typically used in the oil and gas industry but also for scientific purposes (e.g., IODP with JOIDES Resolution and D/V Chikyu). Remotely operated lander-type seafloor drilling rigs are used successfully for scientific purposes and can be deployed from multipurpose vessels to reduce the costs of the operation.

Geological settings, distribution, and resource potential of SMS occurrences at slow-spreading ridges

SVEN PETERSEN, ANNA KRÄTSCHELL, GEOMAR - HELMHOLTZ-ZENTRUM FÜR OZEANFORSCHUNG KIEL

Seafloor hydrothermal systems or seafloor massive sulfides (SMS) have become a target of increased global exploration activity due to their presumed resource potential.

Recent investigations have shown that these occurrences are more variable than previously thought and that this variability is not necessarily reflected in analogous volcanogenic massive sulfide deposits preserved in the ancient rock record.

The geological setting has profound impacts on water depth, source rocks, permeability, vent fluid chemistry and hence on the geochemical composition and mineralogy of the sulfides deposited at or below the seafloor. Spreading rate tends to be one of the major factors affecting the accumulation, distribution, and ultimately the resource potential of seafloor massive sulfides at spreading centers.

To date, over 415 hydrothermal occurrences hosting massive sulfides or of sufficiently high vent fluid temperature to carry sulfides to the near-subseafloor are known. Most of these occurrences are, however, hydrothermally active and tend to be in an early stage of development and are therefore commonly quite small. Additionally, they commonly host chemosynthetic faunal communities that will likely receive strong protection by the regulation of mining activities.

Hence, inactive and/or extinct sites, that have gone through a full life cycle of metal deposition, where hydrothermal activity has ceased, and where associated high-temperature vent communities have disappeared, are seen as the more reasonable mining target. These inactive systems, however, lack the prominent water column signature and are more difficult to locate. Many more extinct sites are considered to be located at even greater distance to the neovolcanic zone increasing the areas that needs to be explored to several million km².

Over the past years considerable effort has focused in exploring ultra-slow- and slow-spreading mid-ocean ridges (five out of seven exploration licenses with the International Seabed Authority), but also slow-spreading segments within back-arc basins or in extensional zones have been explored (Okinawa Trough, Mariana Trough, Lau Basin). The main reason for the intense exploration in these areas is the favorable metal content (**Cu, Au**) and size of many of the documented occurrences at slow-spreading ridges (German et al., 2016).

Due to the overall increased tectonic activity at slow-spreading ridges when compared to the magmatically robust fast-spreading ridges, many of the SMS occurrences that formed at slower spreading rates are associated with deep-reaching faults that are commonly located at some distance to the neovolcanic zone. Here, tectonic forces may even expose rocks of lower crustal or mantle origin (core complexes) and allow interaction of hydrothermal fluids with these source rocks.

The presence of such large-scale faulting has been suggested to be responsible for long-lived and even periodic hydrothermal activity at some sites, possibly explaining why most of the large known SMS occurrences are located at slow-spreading ridges (Hannington et al., 2011). This includes a number of vent fields, such as the TAG and Semyenov vent fields on the Mid-Atlantic Ridge, that contain a number of individual large vent sites or mounds, each of which could be considered a possible mining target (Graber et al., 2020). A concentration of the sulfide tonnage into smaller areas seems to be more common at slow-spreading ridges when compared to their faster equivalents.

Based on published geochemical analyses of SMS occurrences globally, an enrichment of **copper, gold** and other trace metals is apparent in many of the sites associated with slower spreading rates, especially those associated with the exposure of lower crustal and mantle rocks. Additionally, slow- and ultra-slow spreading ridges are a major portion of the global ridge system (36% and 24% of the global ridge length; Fig. 1) that is still under-explored, thereby representing a large permissive area.

The true resource potential of SMS occurrences, however, cannot really be estimated as only a handful of the sites has been drilled at all, and even fewer have been drilled to the basement and/or with a drill-spacing that would allow a proper resource assessment.

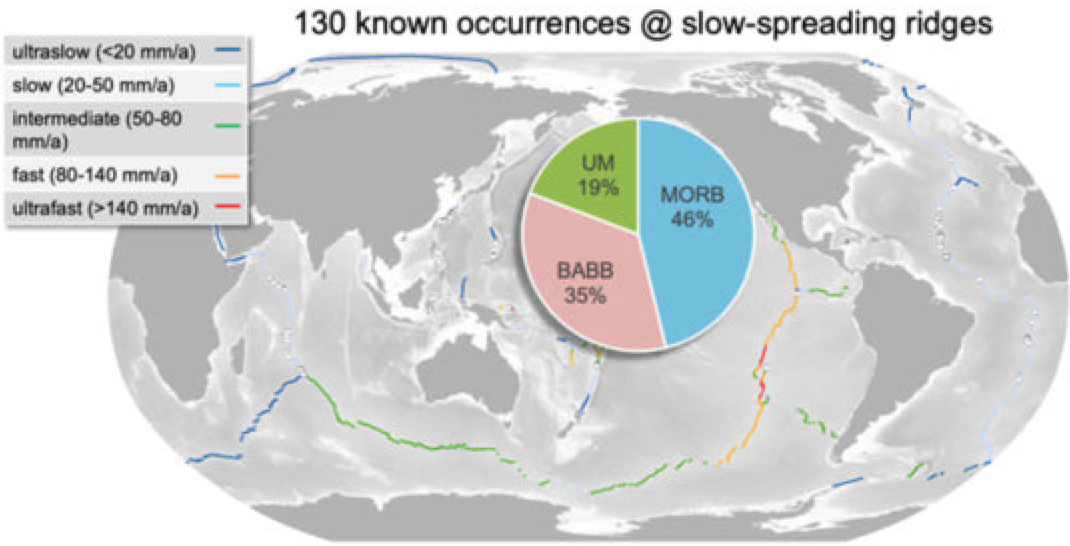

Figure I: Global distribution of seafloor massive sulfide (SMS) occurrences at slow-spreading ridge and association with major source rock lithologies (BABB = Back-arc basin basalt; MORB = Mid-ocean ridge basalt; UM = ultramafic rocks).

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State-of-the-art Knowledge of the TAG System, Atlantic Ocean

BRAMLEY J MURTON, NATIONAL OCEANOGRAPHY CENTRE, UK

Seafloor massive sulphide deposits (SMS) provide a potential resource of base metals including **copper** and **zinc**, as well as more critical metals such as **cobalt**, **selenium** and **gold**.

Formed through hydrothermal activity in which jets of super-heated sulphide-saturated fluids vent from the seafloor and precipitate deposits of sulphide of various sizes and compositions, SMS are considered as modern analogous of ancient volcanogenic massive sulphide deposits that have formed since Archean times.

Although more than 600 SMS are known today, their economic potential is poorly known.

Estimates (made in 2011) based on known SMS occurrences suggest modern hydrothermally active sites account globally for at least 650 million tons (Mt) of massive sulphides, containing 10 Mt of Cu, 29 Mt of Zn, 1 Mt of Pb, 33 million kg Ag, and 750 thousand kg Au. These volumetric calculations are based on the surface expression and densities of the SMS deposits and include only a cursory estimate of any sub-surface stockwork.

Bulk geochemical data suggest modern SMS deposits have a median grade of 3 wt.% **Cu**, 9 wt.% **Zn**, 2 g/t **Au** and 100 g/t **Ag**.

However, these mainly report easily recoverable, surface grab-samples from high-temperature sulphide chimney and related talus and hence they do not represent the average composition of an entire deposit, which is three-dimensional and subject to internal processes such as recrystallisation and metal redistribution.

To address the uncertainty surrounding the full structure and composition of SMS, it is necessary to identify methods that assess the deposits in their true three-dimensionality. This requires both direct sampling and remote sensing of the structures at and below the seafloor.

TAG

The TAG (Trans-Atlantic Geotraverse) hydrothermal field, situated in the axial valley of the slow-spreading Mid-Atlantic Ridge due west of the Canary Islands, is one of the largest and best-studied extinct seafloor massive sulphide (eSMS) deposits formed at a slow spreading ridge in the world.

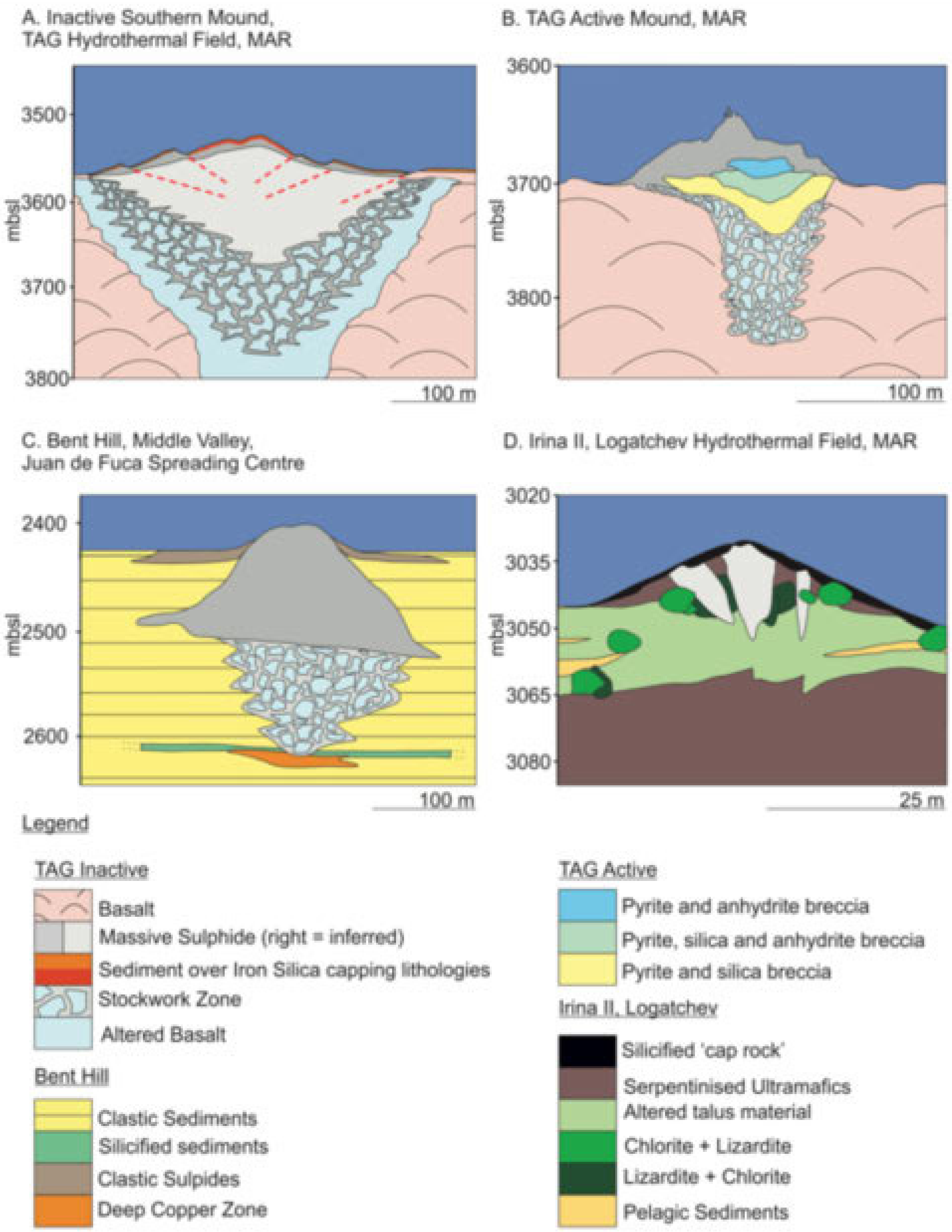
During the EU-funded Blue Mining project, during the summer of 2016, several surveys were conducted at the **TAG hydrothermal field**, a volcano-tectonically driven system located at 26°09'N 49°20'W on the slow-spreading Mid-Atlantic Ridge. There, we focused on the structure and composition of several hydrothermally extinct SMS deposits (**eSMS**) forming mounds up to 300 m in diameter and tens of metres high.

The relevance of the TAG area to the Norwegian Mid-Ocean Ridge sector is that it shares many of the structures and driving forces that are expected for the Mohns Ridge. As such, it provides a cases study of the challenges surrounding the exploration and assessment of SMS deposits on slow-spreading ridges.

In this presentation, I will summarize the results of our work at the TAG field and bring together **surface geology, seafloor drilling, seismic and electromagnetic imaging** of the sub-seafloor to yield a new model for eSMS deposits at slow-spreading ridges.

The take-home message is that eSMS deposits differ from active hydrothermal deposits, they may have a substantially greater volume (by a factor of 3) of sulphide at depth (compared with their surface expression), and that eSMS pose some challenging lithologies for mining.

Much more remains to be done to develop techniques to reliably assess eSMS deposits, especially their sub-seafloor composition. Finally, not all eSMS are the same, and different geological settings and lithological hosts may offer other resource opportunities.



Cartoon showing the state of knowledge for SMS deposits from several different settings, where sub-seafloor investigations have been made.

The "Blue Mining" consortium, active from February 2014 to January 2018, consisted of 19 large industry and research organisations on various maritime fields of expertise. The goal was to develop solutions that will bring sustainable deep sea mining a big step closer. The project addresses all aspects of the value chain, from resource discovery to resource assessment and from exploitation technologies to the legal and regulatory framework.
The final report is available here.

Controls on the genesis and composition of ferromanganese crusts in the global ocean

JAMES R. HEIN

1. Introduction

The transition from a global hydrocarbon economy to a green-energy economy and the rapidly growing middle class in developing countries are driving the need for considerable new sources of critical materials, and deep-ocean minerals has been proposed to potentially fulfill that need (e.g., Hein et al., 2013; Sharma, 2017). Critical materials in ferromanganese crusts include cobalt, manganese molybdenum, nickel, vanadium, niobium, the 14 rare earth elements plus yttrium, and the very rare metals tellurium, scandium, and platinum. Many of these metals are needed for the batteries that will power electric vehicles and turbines that will power wind, tidal, and wave generators (Hein et al., 2013). The concentrations of these elements vary locally, regionally, and globally and it is essential to know what controls the variation in grade, as a guide for exploration.

Ferromanganese crusts (AKA FeMn crusts, manganese crusts, cobalt-rich crusts, polymetallic crusts) are essentially two-dimensional deposits forming pavements on seamounts and ridges where rocks are exposed, at water depths of about 800-7000 m throughout the global ocean (Fig. 1). All deep-ocean FeMn crusts considered here are hydrogenetic, that is, all elements are derived from ambient ocean water. The area considered to host FeMn crusts of greatest economic interest is the equatorial north Pacific Ocean (Fig. 1), identified by Hein et al. (2009) and named the prime crust zone (PCZ; Hein et al., 2013). This PCZ features thick, metal-rich crusts, distributed over large regions. The dominant control on crust thickness is the age of the edifice on which the crusts grow. The longer time that a crust grows, the thicker it can get, although gravity-movement processes can destroy crusts, which will then begin to grow again.

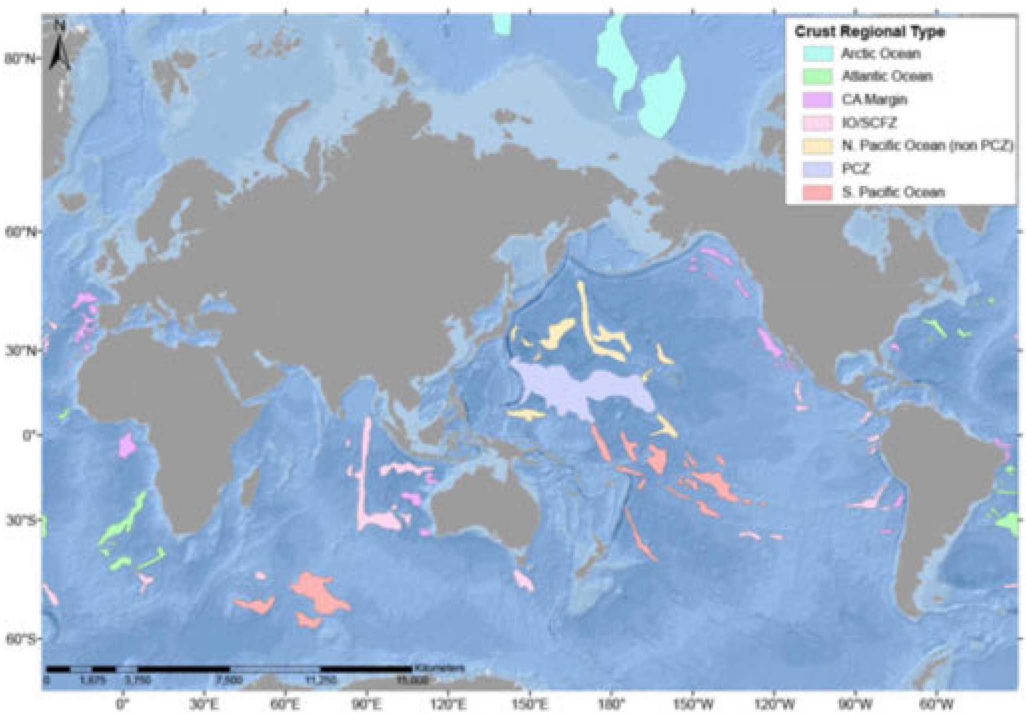


Figure 1. Global crust prospective regions showing distribution of the 7 regional types (Mizell et al., in press). IO/SCFZ = Indian Ocean/Spreading Center Fracture Zone; PCZ = Prime Crust Zone. Base map was created by Esri, Garmin, GEBCO, NOAA NGDC, and others and is shown in WGS 84 / PDC Mercator projection.

2. Controls on Chemical Composition of FeMn Crusts

Local, regional, and global variations in FeMn crusts chemical compositions are controlled by many factors. The most widespread factors include the concentration of dissolved phases of elements in ocean water; water depth; the oxygen content of the ocean water and the presence of an oxygen-minimum zone (OMZ) locally--which is related to primary productivity; proximity to continents or volcanic arcs; and proximity to hydrothermal systems (Hein et al., 2000; Mizell et al. 2020; Josso et al., 2021).

The concentration of oxygen, metals, and other elements in ocean water change with water depth for several reasons: One reason is that water masses at different depths originate in different parts of the ocean and have different compositions, for example Antarctic abyssal water is relatively oxygen rich. Another reason that metal contents can change with depth is the dissolution of carbonate minerals in the water column, which not only releases calcium and magnesium, but also releases iron that can be taken-up by the FeMn crusts. This process is most important near the calcite compensation depth (CCD) where the dissolution of calcite (foraminifera and nano-plankton) is equal to its supply—below this depth carbonate sediments do not accumulate. Iron generally increases in crusts with water depth, which has been related to this process of iron release during carbonate dissolution (e.g., Halbach and Puteanus, 1984; Halbach et al., 2017), as well as an increase in pH that results from higher carbonate ion concentration in ocean water that can facilitate Fe(II) oxidation (King, 1988; Mizell et al., 2020), and deep sources of iron (Horner et al., 2015); iron enrichment dilutes the contents of other metals of potential economic value.

An OMZ forms when plankton die and sink through the water column where this organic matter oxidizes and depletes the ocean water in oxygen to various degrees. The water-depth range and degree of depletion of oxygen depend on the intensity of the primary productivity in surface waters, which in turn varies due to changes in regional and global climates and oceanography. Formation of an OMZ is important because low-oxygen ocean water acts as a reservoir for dissolved Mn and associated metals (such as cobalt, nickel, phosphorus, molybdenum, zinc, tellurium, etc.). In the open ocean, such as in the central Pacific, the OMZ is generally weak, and the most oxidized form of manganese (MnO_2) prevails in FeMn crusts, along with the elements associated with the Mn (see below). However, along continental margins where upwelling and primary productivity are strong, the FeMn crusts are composed of less-oxidized manganese minerals, which changes the predominant metals associated with those minerals (e.g., Conrad et al., 2017). These continental-margin FeMn crusts are also enriched in Fe relative to open-ocean crusts and this is true throughout the global ocean. In fact, Atlantic and Indian Ocean crusts in general are more like Pacific continental-margin crusts in composition, with a Fe/Mn ratio >1 (Benites et al., 2020; Marino et al., 2017; Muiños et al., 2013; Yeo et al., 2019; Josso et al., 2021). This high Fe/Mn is characteristic of FeMn crusts from the Atlantic and Indian Oceans since they are much smaller than the Pacific Ocean with closer proximity to the surrounding continents—this is also especially true of FeMn crusts formed in the Arctic Ocean where extensive continental shelves supply huge amounts of Fe to ocean water which is incorporated into the crusts (Hein et al., 2017; Konstantinova et al., 2017). Moreover, silicon, aluminum, potassium, chromium, and other aluminosilicate-hosted elements are enriched in continent-proximal crusts due to input of detritus from the continents.

FeMn crusts that form near hydrothermal systems may acquire some metals from that source. A continuum occurs between purely hydrogenetic and hydrothermal crusts. When hydrothermal fluids exit the ocean floor, FeMn crusts become predominantly hydrogenetic within a short distance from the diffuse-flow low-temperature sites. In general, the hydrothermal component in FeMn crusts is regionally small, and has been estimated to be <30% for crusts forming in the central Atlantic Ocean (Bury, 1989). This metal input is typically dominated by iron, thereby increasing the Fe/Mn ratio and decreasing the metal contents of economic interest. FeMn crusts that form in the Atlantic Ocean have a higher hydrothermal component than open-ocean crusts formed in the Pacific Ocean. Moreover, the Indian Ocean topography is dominated by three hydrothermal spreading ridges, and consequently, Indian Ocean FeMn crusts have the highest hydrothermal component of any region in the global ocean, again, especially increasing iron contents (Hein et al., 2016).

In rare cases, diagenetic input from redox cycling in nearby sediment may supply metals to bottom water that are then added to the metal complement of the crusts as they form (Hein et al., 2012; 2017). Thick crusts may show a latter-stage diagenetic mineralization by carbonate fluorapatite (CFA) that affects only the older layers (Cretaceous to early Miocene)—this process, called phosphatization, records global changes in ocean circulation and other environmental conditions (Hein et al., 1993). It has been generally considered that phosphatization may change the chemical composition of FeMn crusts with some metals gained and others lost. This does seem to be true for the precious metal platinum, which always has the highest content in phosphatized parts of crusts (Koschinsky et al., 2020). However, Josso et al. (2021) concluded that changes in metal fluxes from ocean water is the primary control on variations in metal contents in NE Atlantic crusts rather than secondary phosphatization. An exception to phosphatization occurring only in the older parts of thicker crusts is at Rio Grande Rise in the SW Atlantic Ocean where even the Miocene-Pliocene parts of thin crusts can be extensively phosphatized (Benites et al., 2020).

3. Arctic Ocean

Amerasia Basin FeMn crusts are the best studied crusts in the Arctic Ocean (Hein et al., 2017; Konstantinova et al., 2017). These FeMn crusts are atypical compared to crusts from elsewhere in the global ocean and reflect the unique characteristics of the Arctic Ocean. These crusts share many characteristics with crusts from Lomonosov Ridge in the central Arctic Ocean and those within the Norwegian EEZ, although these later crusts likely have a hydrothermal component due to their proximity to hydrothermal sites. Amerasia Basin crusts have generally low contents of manganese and cobalt and high contents of continental detritus (silicon, aluminum, potassium, etc.) and iron, with the highest Fe/Mn ratios found for hydrogenetic FeMn crusts. The crusts are uniquely high in the very rare metal scandium, as are the Lomonosov Ridge and Norwegian EEZ crusts. About half of the scandium is hosted in continental detritus contained in the crusts and half sorbed onto the framework oxide phases reflecting the high concentrations of dissolved scandium in the bottom ocean water (Hein et al., 2017). The Amerasia Basin crusts also have atypically high contents of arsenic, lithium, mercury, and vanadium compared to crusts from elsewhere in the global ocean.

4. Mineralogical Controls on FeMn Crust Compositions

Mn oxide (MnO_2) and Fe oxyhydroxide (FeOOH) comprise the framework components of FeMn crusts and most other elements are acquired by those two main components via sorption, oxidation, and other mineral surface processes (Koschinsky and Hein, 2003). Generally, elements that form positive ions or complexes dissolved in ocean water sorb onto the negatively charged surface of the MnO_2 (e.g., cobalt, nickel, zinc, barium, thallium) and negatively charged and neutral complexes in ocean water are sorbed onto the FeOOH surface (e.g., Titanium, zirconium, chromium, hafnium, thorium, tungsten). Surface oxidation of the sorbed metal will prevent desorption of the metal and further concentrate it (e.g., cobalt, thallium, platinum). These general chemical processes can be overcome during co-precipitation of metals along with the Mn and Fe minerals, for example tellurium and molybdenum form negative complexes in ocean water and based on the electrochemical model should sorb onto the FeOOH, but instead they coprecipitate with MnO_2 (e.g., Kashiwabara, et al., 2014; Mizell et al., 2020).

5. Terrestrial-dominant and deep-ocean-dominant critical metals

A conservative estimate is that 930 billion dry tonnes of FeMn crusts and 210 billion dry tonnes of manganese nodules exist in the global deep ocean (Mizell et al., in press). Based on those tonnages and mean contained metal contents that incorporate genetic types and regional influences, contained metal tonnages can be calculated. The global FeMn crust and nodule contained metal tonnages compared to the world terrestrial identified metal resource indicates metals that are predominantly found in deep-ocean FeMn deposits and those occurring predominantly in terrestrial deposits. Metals predominantly found in deep-ocean crusts plus nodules include tellurium, cobalt, manganese, yttrium, thallium, titanium, molybdenum, scandium, tungsten, vanadium, antimony, zirconium, thorium, niobium, arsenic, and nickel (listed in decreasing magnitude), whereas terrestrial dominant critical materials include copper, lithium, bismuth, and the 14 rare earth elements (Mizell et al., in press). This evaluation must be viewed in the light that deep-ocean and terrestrial deposits are not calculated using the same methods and that non-identified terrestrial resource are not included in the reported inventories.

If deep-ocean mining follows the evolution of off-shore production of petroleum, we can expect that about 30-40% of the demand for critical metals will come from deep-ocean mines by about 2065.

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The Metals Company – Responsibly Sourcing Battery Metals to Address Looming Critical Shortage for EV Supply Chain

ANTHONY O'SULLIVAN, THE METALS COMPANY

The Metals Company is targeting development of a new, scalable source of EV battery metals in the form of polymetallic nodules found on the seafloor in the Pacific Ocean. The estimated resource in the company's NORI and TOML exploration areas of 1.6 billion tonnes of nodules contains sufficient nickel, copper, cobalt and manganese to supply around a quarter of the global passenger car fleet. The development of this resource would offer an abundant, low-cost supply of critical raw materials for EV batteries and wiring, with a lower lifecycle ESG impact than conventional terrestrial mining. Developing this critical raw materials supply is essential to the transition from internal combustion engines to EVs, which faces the following risks:

- A multi-decade long slump in discovery and decade long lack of development of new world class metal deposits which is widely expected to lead to shortages in and increased ESG impacts from developing lower quality resources for key metals such as nickel and copper from 2024-2025 onwards;
- Rising raw materials prices risk undermining EV manufacturers' efforts to drive down the cost of EV batteries necessary for mass adoption;
- Existing metals supply comes at a steep cost to people and planet, leading to vast deforestation in some of the most biodiverse areas on the planet, generating the world's largest industrial waste stream and gigatons of emissions, poisoning ecosystems and people's health, and potential labor exploitation including child labor.

Techno-economic and life-cycle-analysis (LCA) studies have been completed for the collection, transportation and processing of nodules to produce battery nickel and cobalt sulfate powders, copper cathode, manganese silicate feedstock for manganese alloy production and fertilizer-grade ammonium sulfate. Measured, Indicated and Inferred resources have been defined to the most exacting SK 1300 and NI 43 -101 international reporting standards.

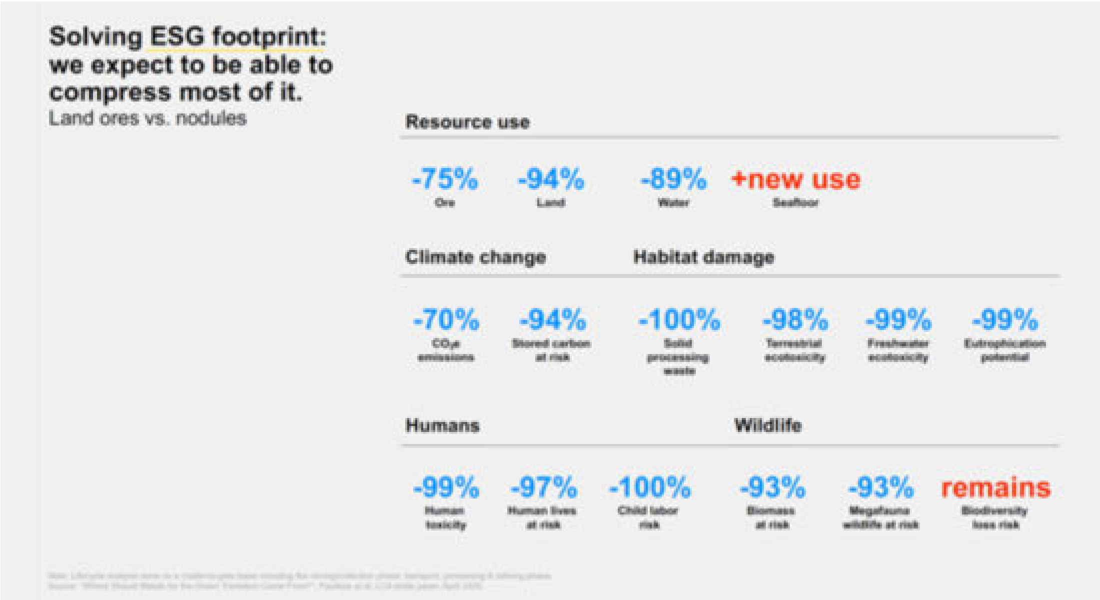
An offshore collection system is being developed in partnership with Allseas SA, which comprises a tracked hydraulic collector with subsea nodule separator, airlift riser supported by a dynamically positioned vessel. An onshore processing flow-sheet has been developed involving zero-waste hybrid pyrometallurgical smelting and hydrometallurgical refining by TMC and leading process development group Hatch.

One of the largest integrated seafloor to surface environmental baseline study programs is in progress, involving in excess of 100 individual studies, supported by leading scientists from world renowned institutions: University of Hawaii, National History Museum and National Oceanographic Center to name a few. Full environmental LCA from cradle to battery precursor producer gate has been completed which compares the ESG impact of sourcing battery metal from deep sea polymetalic nodules vs existing terrestrial supply, demonstrating significantly improved outcomes for nearly all ESG categories as out lined in the figure below (*next page*).

TMC has plans to complete prefeasibility and environmental impact assessment studies by mid-2023 involving;

- Offshore collector test and environmental monitoring campaigns to technically demonstrate the collection system and to provide critical environmental impact assessment data.
- Onshore pyrometallurgical and hydrometallurgical processing pilot testwork on a 70 tonne nodule sample collected in 2019 from the NORI area to demonstrate the Zero Waste flow sheet and to provide critical design data for development of commercial facilities.
- Environmental baseline studies and environmental impact assessments and preparation of an environmental impact study.

The exciting part about metals is that unlike fossil fuels, they are recyclable. The daunting part is that our transition off fossil fuels is very metal intensive, and we need to build up enough inventory to live off recycled metals.



The magnitude of the environmental, social and economic costs of getting all this metal from conventional sources is only now starting to sink in. There are no perfect solutions to this issue, but we are confident that by using polymetallic nodules we can dramatically reduce the social and environmental impacts of battery metal production while we build up global inventories and recycling capacity.

ISA's Regional Environmental Management Planning with a Focus on the Progress Made in the Area of the Northern Mid-Atlantic Ridge

WANFEI QIU, INTERNATIONAL SEABED AUTHORITY

Regional Environmental Management Plans (REMPs) are developed to support informed decision-making that balances resource development with the protection of the marine environment in the International Seabed Area (the "Area").

Such REMPs are adopted by the Council of the International Seabed Authority (ISA) on recommendations from the Legal and Technical Commission. The first REMP in the Area was adopted for the Clarion-Clipperton Zone in 2012 and includes the establishment of a network of nine areas of particular environmental interest (APEIs), which are protected from future exploitation activities.

Building on this experience, progress has been made in developing REMPs in other priority regions, including the northern Mid-Atlantic Ridge, through a series of expert workshops convened by ISA.

Key results from the expert workshops for the northern Mid-Atlantic Ridge include the scientific tools and approaches for environmental management at a regional scale, suggestions for management measures, as well as priorities for monitoring and research. The results from the expert workshops provided the key elements for the Legal and Technical Commission to formulate the REMP for the Area of the northern Mid-Atlantic Ridge.

The Ethics of Deep Sea Mining

SIRI GRANUM CARSON, NTNU OCEANS, ESPEN DYRNES STABELL, DEPARTMENT OF PHILOSOPHY AND RELIGIOUS STUDIES

Deep sea mining (DSM) involves extracting mineral deposits from the ocean floor at great depths – a form of mining which is still at a very preliminary stage and where the scientific and technological uncertainties are plentiful. The potential environmental, social and economic impacts of DSM can be addressed empirically by natural sciences such as marine biology, geology and ecology, as well as by social sciences and economics, or by a combination of these sciences. How to assess or evaluate the results of these scientific studies, however, is very much an ethical question. For example, if the marine biologist finds that certain species may be endangered by a mining project, questions of the following form arise: Can the expected benefits to humans from mining justify endangering the species? How should we consider the relation between the value of the species and the value of human welfare in this case? Does the act of causing a species to go extinct violate important moral principles? Similarly, if a combination of geotechnical and economic studies indicates that a mining operation may show a significant profit, questions arise as to how these calculations should be balanced against the environmental damage that the operations may cause. These questions cannot be answered by the sciences themselves; ethical reflection is needed in order to guide policies and regulations. In this presentation, an overview of central ethical issues will be given and the potential implications that these issues may have for the overall assessment of DSM will be discussed.

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Are we in too deep?

FREDRIK MYHRE, WWF-NORWAY

We are currently facing the biggest challenges in the history of mankind. Our planet is in the middle of both a climate crisis and a nature crisis – and we need to tackle both issues – at the same time. And the one can only be solved by also solving the other.

Can deep-sea minerals be the answer to some our problems, or will the hunt for the rare metals of the deep cause even more distress to an already troubled ocean?

To answer this, we need to understand more about how little we actually know about the ocean.

Today, only around 5 percent of the ocean is already explored. The deep-sea is especially scarcely mapped and poorly understood. There is literally an ocean of knowledge to be learned out there. Yet, we do know a great deal already. For instance, 95 percent of all the known living areas on Planet Earth are in the ocean. And the rich algae blooms and the flourishing kelp forests of this blue element daily provide us with 50 to 80 percent of the oxygen we need. We also know that the deeper parts of this element hold endemic life, a life that simply does not exists in other places on earth. A life that very well may be crucial to the ecosystem that we know as the deep sea. And the deep sea can hold many of the key roles for the greater ocean ecosystem – an ecosystem that both life in the ocean and life on land depends on.

We also know that the ocean floor in the deep sea is one of the biggest carbon storages in the world. Recent studies looking at the effects of the world's bottom trawling show that disturbing this carbon, and thereby releasing it from the seabed sediment into the water, can have significant negative effects on the ocean ecosystem and increase ocean acidification. A more acid ocean is not good news for neither all the marine animals depending on building their skeletons of calcium carbonate, nor the fight against human-made climate change. A more acid ocean will reduce its potential for uptake of greenhouse gases from the atmosphere – and thereby have a negative climate effect for the whole of the planet.

The deep ocean is one of our planet's last true wildernesses. Still, quite untouched by human hands and with a biodiversity richness that can even outcompete the most blooming and dense rainforests on land – at least so far.

There is now a dark cloud of sediments threatening the life down in the abyss. Increased interest for the minerals on the ocean floor, which quickly could change the faith of the animals living there – and possibly also alter entire ecosystem functions which the deep provides for the greater ocean, maybe for all generations to come.

Marine researchers are crying out: We do not have enough knowledge to say that deep-sea mining can be done in an environmentally sustainable manner. In fact, they state quite the opposite – that a mining industry may very well destroy important biodiversity in the deep and even its ecosystem functions. The high-level panel for a sustainable ocean economy also said in their report of December 2020 that "Until the need for, and potential consequences of, deep-sea mining are better understood, the concept is conceptually difficult to align with the definition of a sustainable ocean economy and raises various environmental, legal and governance challenges, as well as possible conflicts with the UN Sustainable Development Goals.".

In other words, we are nowhere near having good enough knowledge about life in the deep and what it means for the rest of the ocean system. This needs to be mapped out and understood thoroughly before even thinking of starting up a mining industry in the deep. It couldn't have been said any clearer. And gaining this knowledge will take time – quite a lot of time. That is why we need to see a global moratorium for deep-sea mining become a reality, to do the research the future our mankind depends on.

The ocean is truly our planet's most important life-support system. Humans need it to be intact and functioning if it is to provide us and future generations to come with all the necessary ecosystem services that we need. Services such as energy to harvest, food to eat and even oxygen to breathe.

I would like to end with a quote from a wiser man than I'll ever be:

"Mining the deep sea could create a devastating series of impacts that threaten the processes that are critical to the health and function of our oceans. Fauna & Flora International is calling on global governments to put in place a moratorium on all deep-sea mining – a call I wholeheartedly support. The idea that we should be considering the destruction of these places and the multitude of species they support – before we have even understood them and the role they play in the health of our planet – is beyond reason."

Sir David Attenborough

Can the Environmental Challenges with Deep Sea Minerals be Solved by Better Mining Technologies?

JENS LAUGESEN[1], SEBASTIAN ERNS VOLKMANN[2], ØYVIND FJUKMOEN[1]

1 DNV

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Introduction

Due to the green shift and the energy transition, there is an increasing interest in deep-sea minerals.

At the same time there is a strong concern about the environmental impacts that deep-sea mining may cause, while the environmental impact and the ecosystem functioning are still under investigation.

The current situation is that no full-scale commercial mining has taken place and there is therefore limited information concerning the environmental impacts. In addition there is still only limited knowledge about the biological life at large water depths (2 000 – 6 000 m water depth) where deep-sea mining is planned to take place.

Due to that The International Seabed Authority's (ISA) Mining Code for international waters (The Area) is expected to be in place in the near future and that several countries are also preparing for obtaining licenses to mine in national waters there is an ongoing development of technologies for deep-sea mining.

The main environmental challenges that have been identified are related to:

- Direct impacts by sediment disturbance, compaction, and removal of hard substrate and life,
- Indirect impacts by generation and re-sedimentation of particle-laden sediment plumes,
- Discharges to water (for example return water from the mining vessel),
- Others, like thermal pollution, light pollution, noise and vibrations (from the mining activity and the support vessel)

We will here concentrate on the first three bullet points; direct impacts through the mining process on the seabed habitat and sediment disturbance, indirect impacts through re-sedimentation of particle-laden plumes from the collector and return-water discharge from the mining vessel. All these impacts may lead to habitat loss, fragmentation, and degradation.

An interesting question is if the technologies that are now being developed can solve the environmental challenges completely or partly.

Assumed impacts from deep-sea mining

There is a substantial difference between the present technologies for mining of manganese nodules and mining of massive sulphides and cobalt-rich crusts. Not only are the technologies different, but also the environment in which they are located, the ecosystem and habitat as well as the spatial extent of the living and non-living resources.

The mining of manganese nodules is most comparable to potato harvesting, where potato-sized nodules lying loosely on or in the top sediment layer of the seabed are collected over vast areas of the abyssal plains. Mining of massive sulphides and cobalt-rich crusts is much more local and requires cutting processes and technologies to loosen the material before the sulphides/crusts can be removed.

There could also be impacts from activities related site preparation before the mining, such as flattening rough terrain to make it accessible for the mining tools.

It is clear that any type of deep-sea mining will have an impact on the seabed due to that material (ore) will be removed and that the seabed therefore will be changed after the operation.

Possible technical measures to reduce the environmental impact from seabed mining

There are several possible technical measures to reduce the environmental impact from deep-sea mining, for example:

- Vehicles for deep-sea mining are moving on or over the seabed compacting the seafloor, removing nodules and habitat and generate sediment-laden plumes. An alternative could be slow-moving tools with minimal contact with the seabed.

Figure 1: Example of auger dredger with a retractable visor which closes around the auger when dredging to prevent particles from spreading. Source: www.dredgeyard.com

- The mining equipment could be housed to limit the spreading of sediment during operation. Such equipment is for example also used in dredging operations, see Figure 1.
- Nodule collection technologies that only penetrate the top nodule-rich layer (approx. 5 cm) in order to reduce the amount of sediment entering the collector.
- Technologies and methods to separate sediment and nodules at the seabed before lifting them up to the mining vessel, and discharge again into the deep-sea water column can be further developed so that discharges are minimised
- Modelling the operation and plume (considering subsea current speeds and directions, soil properties, and operational data among other) helps optimize processes, plans and mining routes to reduce the spreading range and the thickness of the overlapping sediments.

Restoration of the seabed

A question that has been raised is if it is possible to restore the seabed after a deep-sea mining operation.

For example, artificial nodules could be placed on the seabed where the original nodules have been removed, see Figure 2. The artificial nodules might help to provide additional suitable habitats for fauna to occupy when the original habitat has been removed.

Research has indicated that the recolonization of the artificial nodules in the deep-sea seems to be a very slow process that might take decades or even more, and the growth of natural nodules is only a few millimetres per million years. This makes restoration projects very complicated, as it will take a very long time for natural restoration to take place and to be able to conclude whether the restoration measures are working. The United Nations Convention on the Law of the Sea (UNCLOS), states that precautionary measures must be taken (article 194), but such measures will often be in in contrast to the contractors goal to make the deep-sea mining profitable.

For hydrothermal vents (massive sulphides) some studies have shown that it may be possible to recreate new habitats by drilling holes to lead the fluid flow away from the vent and allow for vent fauna to recolonise the newly created sites. However, the duration of such measures is uncertain.

Due to that restoration is very complicated, the best and most efficient method is probably to ensure that areas are set aside that are protected and remain unaffected by extraction activities. This can for example be ensured by leaving a certain proportion of the mineral resource intact or by leaving specific vulnerable areas that are protected for extraction activities.

Conclusion

The environmental challenges with deep-sea minerals cannot be solved only by having better mining

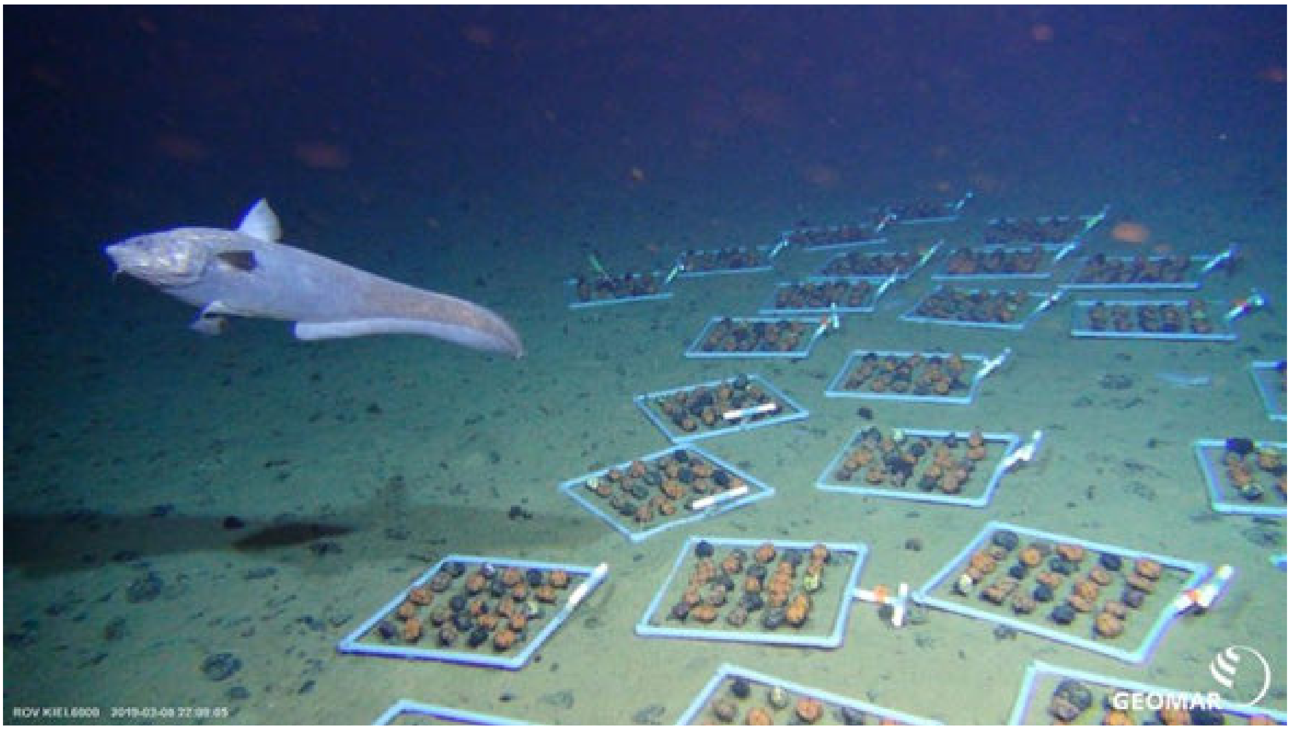

Figure 2: Frames from NIOZ with natural and artificial nodules deployed in the Clarion-Clipperton Zone. Photo: ROV team/ GEOMAR (2019).

technologies. There are also other important factors that need to be taken into consideration like restoration and protection of specific vulnerable areas from extraction activities. Reducing the area consumption and footprint through technical, operational, legal or other (restrictive) measures or thresholds will be crucial to maintain a healthy ocean ecosystem.

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A precautionary approach to developing nodule collector technology

KRIS DE BRUYNE, GLOBAL SEA MINERAL RESOURCES NV

Figure 1 - PATII during deployment (2020)

Global Sea Mineral Resources NV (GSR) holds an exploration contract with the International Seabed Authority (ISA) established under UNLOS, to explore for polymetallic nodules on the seafloor of the Clarion Clipperton Zone (CCZ) in the Pacific Ocean. (ISA, 2012)

The basis of GSR's research and development (R&D) strategy was developed in 2013 following a desktop study which defined an integrated concept of operation. By performing this integrated study, it was possible to identify all systems and related sub-systems, and define an overall architectural diagram. A key component of the deep seabed mining system is the Seafloor Nodule Collector (SNC).

The SNC has a significant influence on the overall operational environmental impact and on the achievable production rate, two criteria that are critical in developing a responsible mining operation. Additionally, given commercial deep-seabed mining operations are unprecedented, the SNC is the sub-system involving the highest number of information and knowledge gaps, such as the environmental impacts and effects, its response to soil characteristics, trafficability and nodule collection methodology.

Hence, from all the systems and sub-systems identified, GSR decided to focus its first efforts on the SNC system and more specifically on a pre-prototype of a SNC. This feasibility study, called ProCat (derived from "Prototype Caterpillar") extended from 2015 to 2021 and consisted of a step-by-step approach and culminated in the design, building and testing of a pre-prototype SNC, called Patania II (PATII):

- **ProCat#1 [2015 – 2017]:** Separate parallel testing of nodule collection system and propulsion system (TSTD Patania I). ProCat#1 was successfully completed in September 2017.
- **ProCat#2 [2018 –2021]:** The knowledge acquired during the first phase was applied in this second phase. The nodule collection system and propulsion system were integrated into the design of a Pre-Prototype SNC called Patania II. This vehicle was used for pilot mining trials in Q2 2019 and Q2 2021 in the GSR exploration license area.

With regard to the 2021 offshore test campaign, GSR defined several objectives which were mostly focused on the technical performances of PATII and the monitoring of the environmental response.

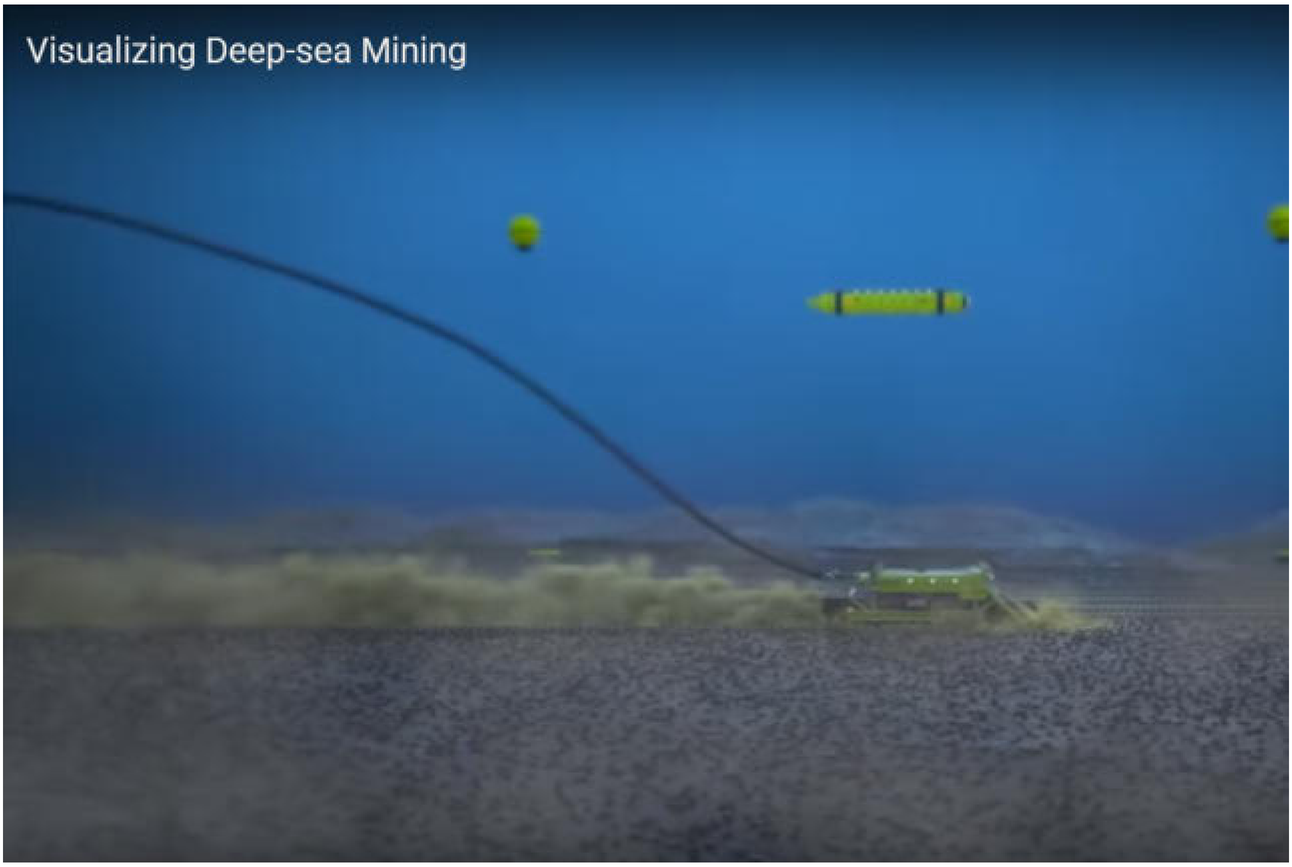
Firstly, the technologies and different working principles developed during ProCat#1 needed to be validated and optimized in situ. Purpose-built measurement equipment was installed on PATII that provided insight into the functioning of the collection system and how it influences its surrounding environment. Secondly, the trials with PATII were a major opportunity to improve the understanding of the impact and effects of deep seabed mining. Two field trials were conducted in the GSR and BGR license areas. The potential geophysical, biogeochemical, and biological effects were monitored from a second ship (M/V Island Pride) involving an equipment spread consisting of ROVs and AUVs (for far field sediment plume monitoring), among others. Beside the far field sediment plume monitoring, also the source term and near field effects have been studied. The size, concentration and behavior of the suspended sediment generated by PATII was measured during different operational scenarios. The results will lead to an optimized design of a discharge system and an optimized mining pattern to minimize the environmental impacts.

With the successful ProCat program, GSR's solution for responsible deep seabed mining has taken a giant leap forward. From a technological, operational, and environmental perspective, there is sufficient confidence to proceed to the next phase, the System Integration Phase (SIP). The SIP will culminate in a System Integration Test (SIT), whereby a commercial scale Seabed Nodule Collector, Patania III, and Vertical Transport System (VTS), including all necessary auxiliary (deck) equipment, will be integrated and tested in the CCZ. With regard to the SIT, GSR will continue to advocate a step-by-step development strategy using the Best Available Technologies, in collaboration with world-leading experts, scientists and universities, while simultaneously adhering to all the relevant environmental considerations.

GSR remains committed to responsible deep-sea research and technology development, one step at a time.

Study de-mystifies sediment plumes

THOMAS PEACOCK, MIT



Visualization of "collector plume" when mining polymetallic nodules. Illustration: MIT

Central to understanding the environmental challenges concerning deep-sea mining of polymetallic nodules is the extent of sediment plumes caused by mining and discharge.

Oceanographers at MIT, the Scripps Institution of Oceanography, and elsewhere have developed a model that makes realistic predictions of how a sediment plume generated by mining operations would be transported through the ocean.

This model predicts the size, concentration, and evolution of sediment plumes under various marine and mining conditions. These predictions, the researchers say, can now be used by biologists and environmental regulators to gage whether and to what extent such plumes would impact surrounding sea life, according to a study published in Nature Communications: Earth and Environment and reported by Jennifer Chu, Massachusetts Institute of Technology in phys.org.

"Our study is the first of its kind on these midwater plumes and can be a major contributor to international discussion and the development of regulations over the next two years," says **Thomas Peacock**, professor of mechanical engineering at MIT.

The reason for conducting such studies is the potential value of potato-sized nodules layered with minerals accumulated over millions of years. In the deep oceans, and in particular in the Clarion Clipperton Fracture Zone (CCFZ), these polymetallic nodules are estimated to contain vast resources of nickel, cobalt, copper and manganese, as well as titanium, molybdenum, zirconium and rare earth elements (REE).

According to phys.org, such deep-sea-mining schemes propose sending down tractor-sized vehicles to vacuum up nodules and send them to surface, where a ship would clean them and discharge any unwanted sediment back into the ocean. But the impacts of deep-sea mining – such as the effect of discharged sediment on marine ecosystems and how these impacts compare to traditional land-based mining – are currently unknown.

Deep-sea mining for polymetallic nodules will generate two types of plumes. First, there is the "**collector plume**s" that vehicles generate on the seafloor as they drive around mining nodules 4-6000 meters below the surface, and second, "**midwater plumes**" that are discharged through pipes that descend 1,000 meters or more into the ocean's aphotic zone, where sunlight rarely penetrates.

The recently published study focused on the midwater plume and how the sediment would disperse once discharged from a pipe.

To shed light on what happens to the sediments in the plume, Peacock and colleagues conducted six experiments off the coast of Southern California. What they discovered was that the sediment, when initially pumped out of a pipe, was a highly turbulent cloud of suspended particles that mixed rapidly with the surrounding ocean water.

"There was speculation this sediment would form large aggregates in the plume that would settle relatively quickly to the deep ocean," **Peacock** says. "But we found the discharge is so turbulent that it breaks the sediment up into its finest constituent pieces, and thereafter it becomes dilute so quickly that the sediment then doesn't have a chance to stick together," according to phys.org.

Jennifer Chu reports that "the researchers have developed formulae to calculate the scale of a plume depending on a given environmental threshold. For instance, if regulators determine that a certain concentration of sediments could be detrimental to surrounding sea life, the formula can be used to calculate how far a plume above that concentration would extend, and what volume of ocean water would be impacted over the course of a 20-year nodule mining operation".

Halfdan Carstens,
for expronews.com

Visualizing deep-sea mining and sediment plumes:
https://www.youtube.com/watch?v=LwqIj3nOODA&t=108s

Updating the Unknown

STEINAR L. ELLEFMO, NTNU

Our society demands minerals.

The minerals must be supplied through the execution of a holistic mineral resource management (MRM) approach where multiple sources are assessed and included. From 2012 the Norwegian University of Science and Technology (NTNU) and Nordic Ocean Resources AS, with support from Equinor ASA, reviewed the knowledge about seabed mineral resources in Norway and assessed its potential, focusing on seafloor massive sulphides (SMS) along a section of the Mid-Atlantic Ridge that are inside Norwegian jurisdiction, specifically the Mohns and the Knipovich ridges (Ellefmo et al., 2019).

Given bathymetric data, and the thereof derived morphostructural elements and modelled in-situ rock stresses, a total of 16 permissive tracts or so-called favourable areas were defined. These formed the basis for a probabilistic mineral resource potential assessment (play analysis) using methods that draws on procedures incorporated in the assessment of oil and gas resource evaluations in Norway and globally for onshore deposits (Singer and Menzie, 2010).

The assessment a documented an expected **Cu-** and **Zn**-tonnage of about **7 million tonnes** with an upside potential of about **20 million tonnes**. The large differences between the upside and the expected value underline the large associated quantified uncertainty. The estimates are validated against other and similar assessments (Cathles, 2015; Hannington, 2013; Singer, 2014) and the probabilistic output (the min and the max) spans the results given in the cited resources.

Since the majority of the work presented in (Ellefmo et al., 2019) was executed, a number of research

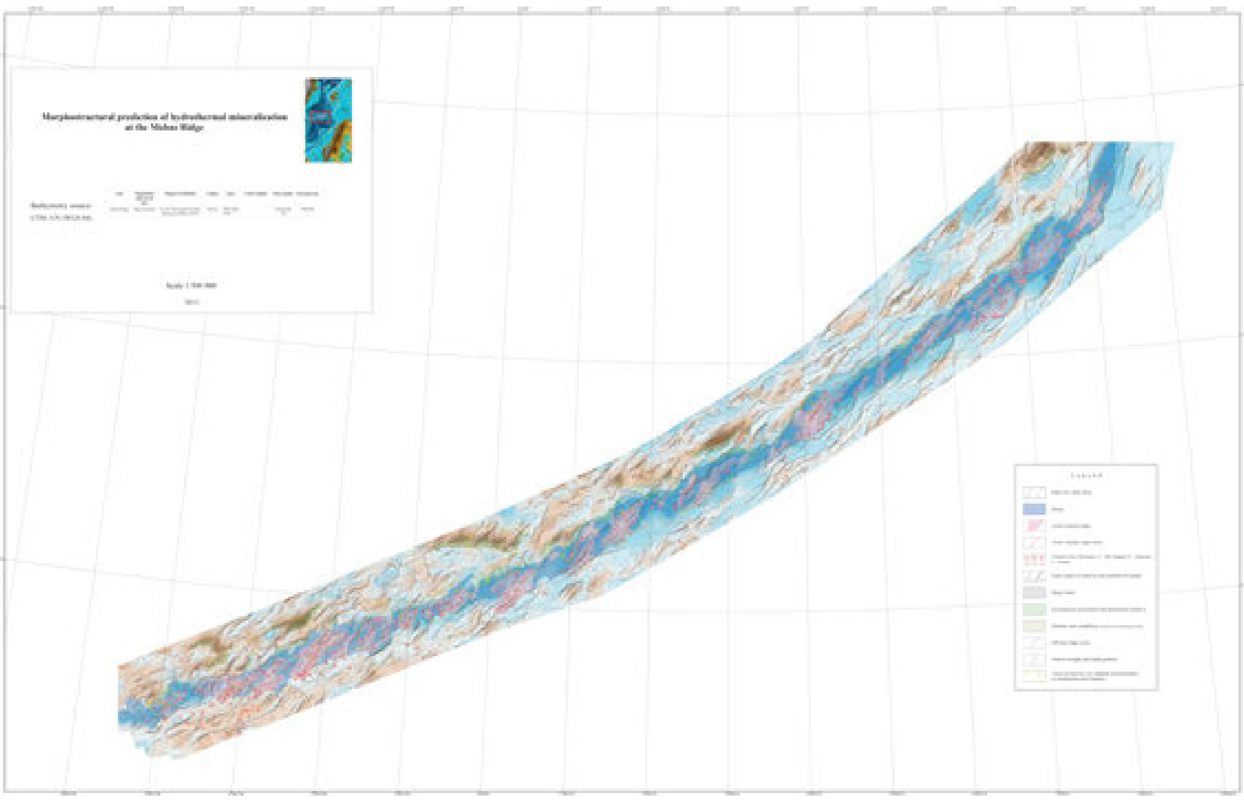


Figure 1 Identified morphostructural elements along the Mohns Ridge and associated permissive tracts. Source: (Ellefmo et al., 2019)

cruises have been completed along relevant sections of the Mid-Atlantic Ridge (for example NPD, 2018). New sites of interests have been found and new high resolution bathymetric data has been collected. Some of these data have been made publicly available and will in this presentation be sought incorporated into the marine mineral resource potential assessment framework already developed.

The play analysis includes a two-layer incorporation of uncertainty.

Firstly, the answer to questions like "how many sites of interest?", "how large are they?" and "what are their grades?" are answered by applying the probabilistic approach where distributions are used as input, not deterministic, single values. Relying on the principle that the past is the key to the present, the parametrization of the statistical distributions is made based on onshore ancient analogues, samples from recent sites of interest and sound geological knowledge. Combined, this leads to what is considered an unbiased assessment of what the grade and the size (measured in tonnage) undiscovered sites of interest might have and how many undiscovered sites of interests there might be inside the permissive tracts. These answers assumes basically that we have complete knowledge and that it is known that the sites of interests are there. This is not known.

Secondly, to accommodate for this lack of knowledge, the second layer of uncertainty is incorporated as a "risk"; a probability that the factors like metal and heat source, migration paths that facilitate hydrothermal flow, some trapping mechanism and a recipient or some sort of reservoir necessary to form a deposit has not been effective. This is done both on a play and on a site of interest or prospect (segment) level. Based on recent research (Gehrmann et al., 2019; Graber et al., 2020; Grant et al., 2018; Hölz et al., 2019; Juliani and Ellefmo, 2019; Murton et al., 2019) and cruise activities both the risks and the uncertainty will be updated.

The presentation will discuss the applied methodology, the incorporation of new data and how their links to the assessment results and delineate future activities.

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Assessing the Resource Potential of Cobalt-Rich Crusts at a Mining-Site Scale: Lessons from MarineE-Tech

PIERRE JOSSO, BRITISH GEOLOGICAL SURVEY, ISOBEL YEO, SARAH HOWARTH, PAUL LUSTY, BRAMLEY MURTON

Deep oceanic ferromanganese (Fe-Mn) crusts are of particular interest because of their high concentrations in a range of metals of increasing economic importance for the energy transition such as Mn, Co, Te, REY, Pt, Ni and Cu [1]. They form condensed deposit of oxide layers at the seawater-rock interface, accumulating at the extremely slow rate of a few mm/Ma under low sedimentation rate and seawater oxidizing conditions. As such, Fe-Mn crusts are ubiquitous in the world ocean and have been forming intermittently since the Late Cretaceous [2]. Owing to the large variety of geological, oceanographic and climatic parameters influencing the distribution, preservation and metal endowment of the deposits at the regional scale and through time, the determination of exploration models, deposit characterisation and resource estimates at the mining site scale remain a complex task.

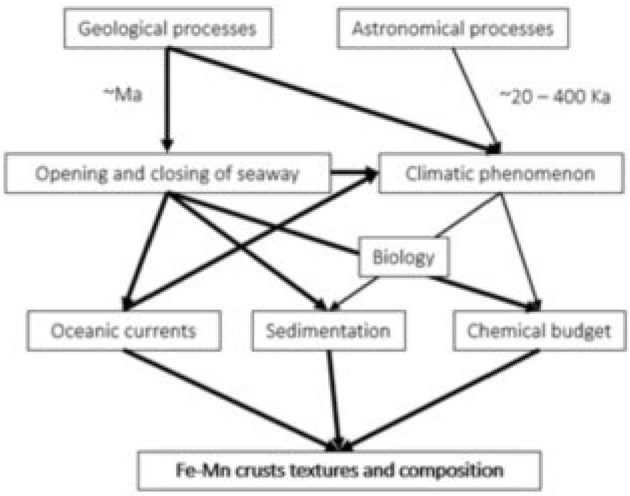

Figure 1: Relationship of parameters influencing the composition of Fe-Mn crusts

In 2016, the UK-led MarineE-Tech project investigated Fe-Mn crust deposits from Tropic Seamount, a 120 Ma volcanic edifice situated 450 km off the coast of West Africa at the southern end of the Saharan Seamount Chain (SSP). A holistic approach involving oceanography, geophysics, geology, and biology allowed for a macro- and micro-scale investigation of the seamount environment and associated Fe-Mn crust deposits between the abyssal plain and the flat summit of Tropic Seamount located around 1000 mbsl. During a 6 weeks mission, a large panel of operations were conducted in this natural laboratory including (i) mooring deployments to record oceanic currents direction and intensity at various depths, (ii) CTDs for water masses properties, (iii) AUV high-resolution mapping and geophysics data acquisition, complemented by (iv) 22 ROV dives for ground-truthing and collection of geological and biological samples. In total, 400 were recovered and 120 were analysed for whole rock geochemistry.

Using detailed mapping of seafloor outcrop combined to AUV side-scan sonar we were able to map in high-resolution the distribution of encrusted areas of the summit of Tropic Seamount [3]. We find that just over 35% of the summit is covered by ferromanganese crust, with the rest variably covered by plains of mobile sediment. The steep flanks of the seamount largely expose thick ferromanganese crust both in situ and as debris flows. The strongest currents are located on the seamount's upper-flanks, central eastern limb, and summit as a result of tidal energy dispersion, which impact the degree of preservation of the deposit [3]. Least eroded and actively forming Fe-Mn crusts are observed below 2000 mbsl where current speeds rarely exceed 0.2 m/s whilst summital deposit are actively eroding as a result of mobile sediment patches acting as abrasive agent.

While the surface textures yield a snap-shot of current factors controlling growth and erosion, the FeMn crusts record a history of accretion of over 75 Ma with many periods of growth interruptions [2]. By constructing a multi-proxy age model and coupling that with high-resolution, stratigraphic, textural and geochemical investigation of a 15 cm-long core, we

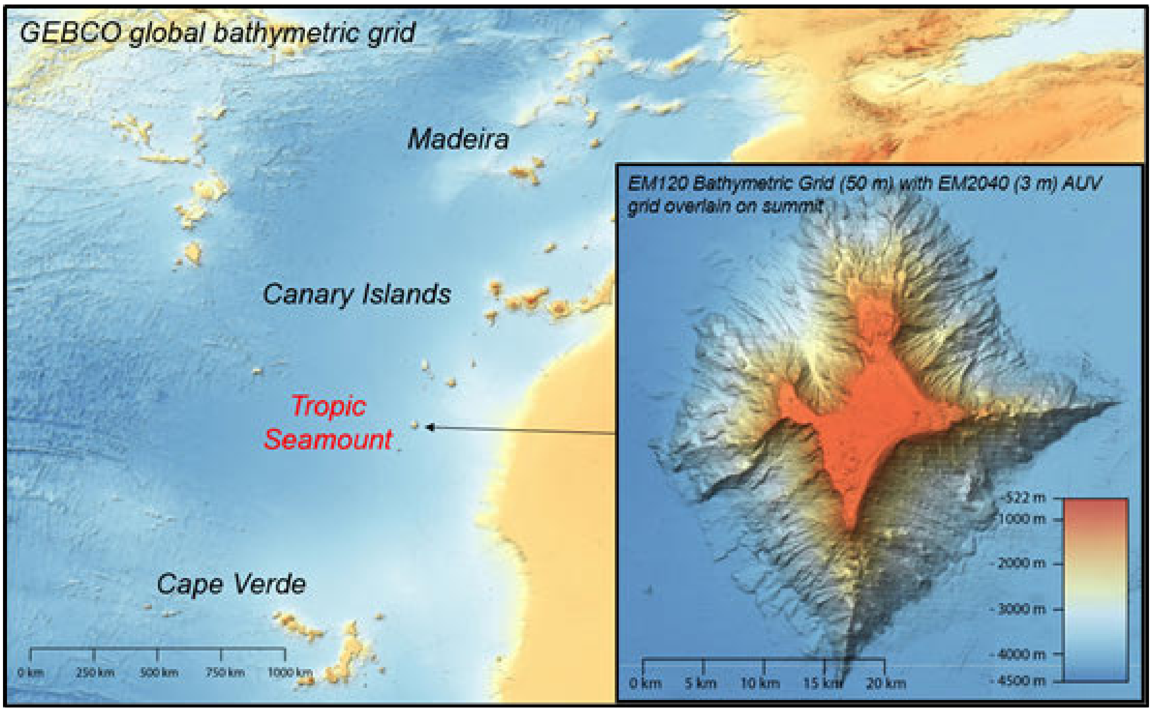

Figure 2: Regional setting of Tropic Seamount

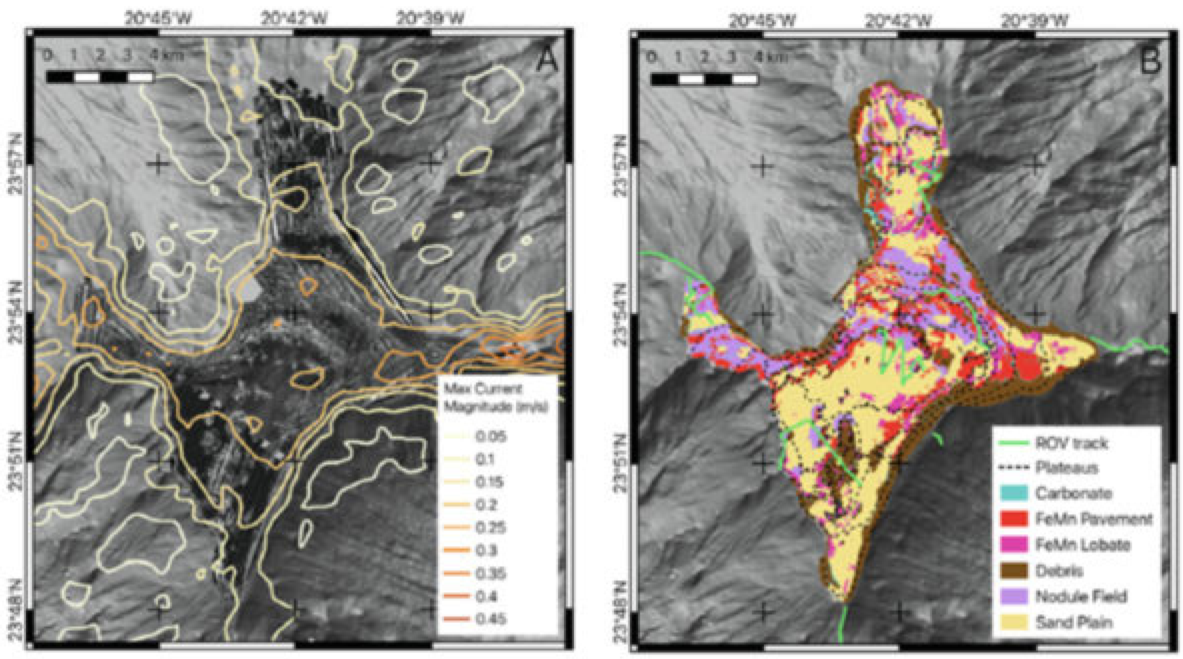

Figure 3: A) Sidescan sonar data of the summit collected by AutoSub6000, mosaicked at 2 m, overlaid on the EM120 bathymetry of Tropic seamount gridded at 100 m. Maximum current magnitudes are shown by the contours. (B) Geological map of the surface outcrop at Tropic Seamount [2]

are able to reconstruct the prevailing oceanographic conditions during formation [2, 4]. We find textural stratigraphic coherence between Tropic Seamount and Pacific Fe-Mn crusts formed since the Late Cretaceous, highlighting that global oceanic and climatic phenomena exert first order controls on crust development and their geochemistry [4].

Detailed stratigraphic work on selected samples and bulk geochemical analysis allow to investigate Fe-Mn crust geochemical variability spatially in relation to water depth (1000 – 4000 mbsl) and through time. Bulk analyses of the top 10 mm demonstrate the control of dissolved metal content in the water column on deposit concentration at various depth, with notably higher Co-Te content in shallower deposits [5]. Consistent trends in stratigraphic profiles from samples from the summit and flank of Tropic Seamount highlight that a similar influence was present throughout the last 75 Ma despite 3-5 fold concentration changes over time [6]. We observe that older crust layers are usually richer in Pt and Te whilst the Co content continuously increase stratigraphically [6].

This complex 4-dimensionl geochemical variability coupled to small-scale pattern of erosion/accretion controlled by local seabed morphology, current energy and turbidity explain in part the difficulty to predict accurately Fe-Mn crust resources based on low sample densities. Nevertheless, preliminary resource assessment of the summit region of Tropic Seamount suggests a mineral potential of 17 kt Co, 9 kt Ni, 165 t Te and 0.8 t Pt.

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Critical Minerals – what is the problem?

KAREN HANGHØY, BRITISH GEOLOGICAL SURVEY

Raw materials are important for society in general, and for the transition to a green economy in particular. They are key for achieving the goals set out in COP21 and several of the United Nations Sustainable Development Goals, for implementing the European 2030 Agenda for Sustainable Development and for the European Resource Efficiency Flagship. Metals, minerals and materials and their sustainable supply and consumption are essential in the move towards a Circular Economy as laid out in the new EU Circular Economy roadmap.

When a mineral is both essential in use and subject to supply risk it is considered critical. Emerging energy and mobility technologies create a strong demand for certain raw materials, and some of these are critical raw materials where demand will dramatically exceed current production in the next 10-15 years. Limited access to these materials might negatively impact the transition, and reduce the competitiveness of European actors downstream.

Almost all research and other initiatives regarding critical raw materials are aiming at substitution, new materials and technologies, new methods to produce critical raw materials from non-conventional sources, and exploration activities. However, this seems to have not significantly improved the criticality situation. To meet the raw material challenge of the energy transition, we need diverse solutions for the sustainable extraction, processing and use/repairing/recycling of raw materials from both primary and secondary sources.

For the extractive industry, the two main barriers to increase CRM production are probably that criticality and large scale investments are disconnected and the political and public resistance to see projects with negative environmental impact. Both are related to the timescales of extractive projects and the limited understanding of the complexity of the environmental impact.

Responsible Sourcing and Responsible Stewardship of Critical Raw Materials

FRANCES WALL, UNIVERSITY OF EXETER

Many of us buy fairtrade coffee, tea or bananas, but how many of us think about the origin of the raw materials in our manufactured goods? The long and complex supply chains in, for example, cars and electronic devices mean that responsible sourcing schemes are less well developed than in areas where it is easy to make a connection between the product and the source. Responsible sourcing is, however, becoming an increasingly important consideration for critical raw materials, and perhaps especially so for the raw materials required for low carbon technologies such as electric cars and renewable energy devices.

Diversifying supply, an important strategy to overcome the dangers of criticality, is also an opportunity for suppliers to gain a business advantage with their responsible sourcing credentials. Numerous schemes are now available. Examples include the Initiative for Responsible Mining Assurance (IRMA) that certifies individual mine sites, schemes related to particular metals such as the Copper Mark, the Cobalt Industry Responsible Assessment Framework (CIRAF), conflict minerals regulations, and product-related schemes such as the Global Battery Alliance Battery Passport. Finland has implemented a national scheme of responsible mining. Along with these schemes come techniques of supply chain assurance that range from paper trails to distributed ledger technologies.

Life Cycle Assessment (LCA) is a particularly useful technique for linking mining to the value chain. It 'talks the same language' as the manufacturers and helps link into circular economy systems and responsible metals stewardship. The Rare Earth Industry Association is an example of where a comprehensive life cycle inventory for LCA is being developed to aid responsible sourcing.

The direct drivers for responsible sourcing include the requirements of manufacturers and also the environmental, social and governance agenda of investors. More indirectly but equally importantly though, it is public attention to high profile issues and their pressure on manufacturers that has accelerated the adoption of responsible sourcing schemes. It has often been single high profile issues such as conflict minerals ('blood diamonds and 'coltan') or child labour (cobalt) that have driven change rather than the overall concept of responsible sourcing.

Responsible sourcing is very relevant to deep sea mining. Consideration needs to be given to developing robust tests of environmental credentials using LCA, engaging with operators of schemes for the relevant metals, and perhaps most of all, listening to, and addressing, the single high profile issue of marine biodiversity that is in the headlines at the moment.

Acknowledgement:
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GeoERA-MINDeSEA project database and cartography of European seabed mineral deposits

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MINDeSEA[1] (Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials) is a GeoERA ("Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe") funded project by Horizon 2020. GeoERA Raw Materials projects represent a first stage to take our share of responsibility and expertise to ensure responsible sourcing from domestic sources, including the offshore mineral resources. Covering 15,000,000 km², the pan-European seas represent a promising new frontier for the exploration of mineral resources. The GeoERA-MINDeSEA consortium, a cooperative network of 12 Geological Surveys and Marine Institutes, is facing this exploration challenge. 691 seabed mineral occurrences are described in the MINDeSEA database, GIS cartographies, publications and reports, containing valuable information on geology, geohabitats, metallogeny, critical raw materials prospectivity and mineral potential. Five types of mineral deposits are investigated, including seafloor massive sulphides and hydrothermal mineralization (153 occurrences), ferromanganese crusts (141 occurrences), phosphorites (12 occurrences), polymetallic nodules (296 occurrences) and placers (89 occurrences). The database contains geochemical and mineralogical data of 1106 individual samples. Many of the deposits exhibit a polymetallic nature that include one or more battery metals such as cobalt, lithium, manganese, tellurium, nickel, rare earth elements, copper, and other strategic and critical metals. These deposits are being explored using cutting-edge technologies both onboard ship and at labs, as well as in seabed mineral occurrences under the jurisdiction of European coastal states, all of which may provide an alternative sustainable resource to land-based mineral deposits. Maps on the seafloor mineral occurrences (Fig. 1) and their metallogeny (Fig. 2) for energy-critical elements are being produced for the first time to support European climate actions and growth strategies. The MINDeSEA dataset compiles data reported for 23 European countries and adjacent international waters beyond national jurisdictions; in 14 marine regions surrounding the European continent from the Arctic Ocean to Macaronesia (includes the Arctic and Atlantic

[1] This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166.

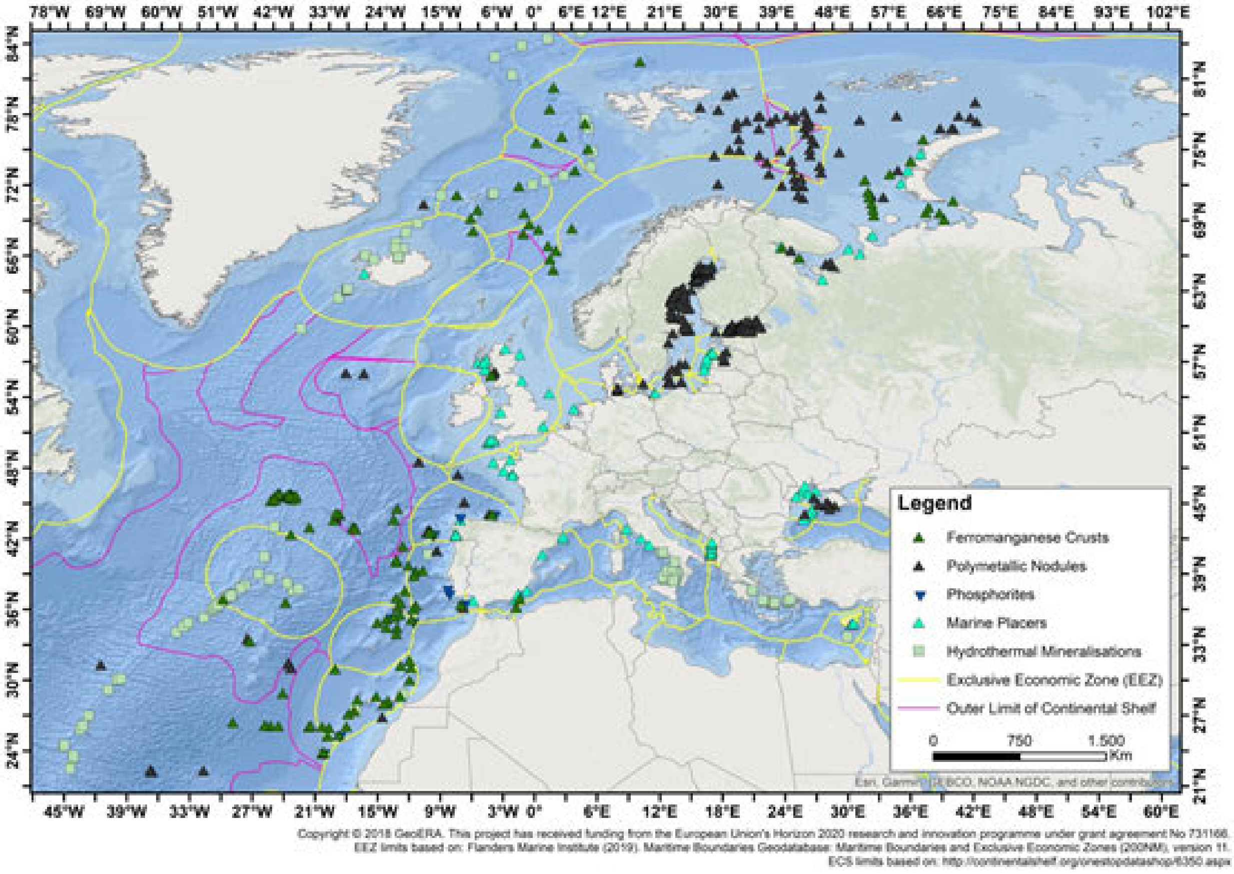


Figure 1: pan-European map of seabed mineral occurences. MINDeSEA compilation, June 2021.

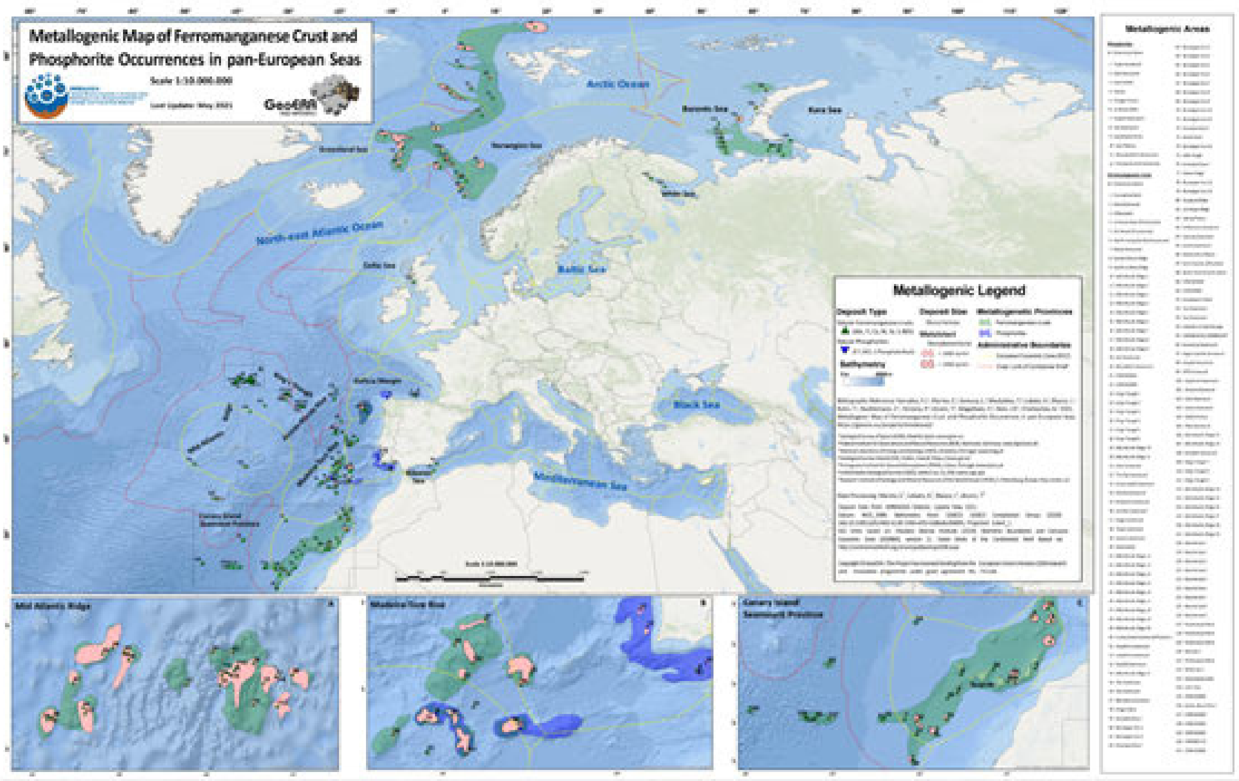


Figure 2: Metallogenic map of Fe-Mn crusts and phosphorites; crusts and phosphorite occurrences in European marine regions. MINDeSEA compilation, June 2021.

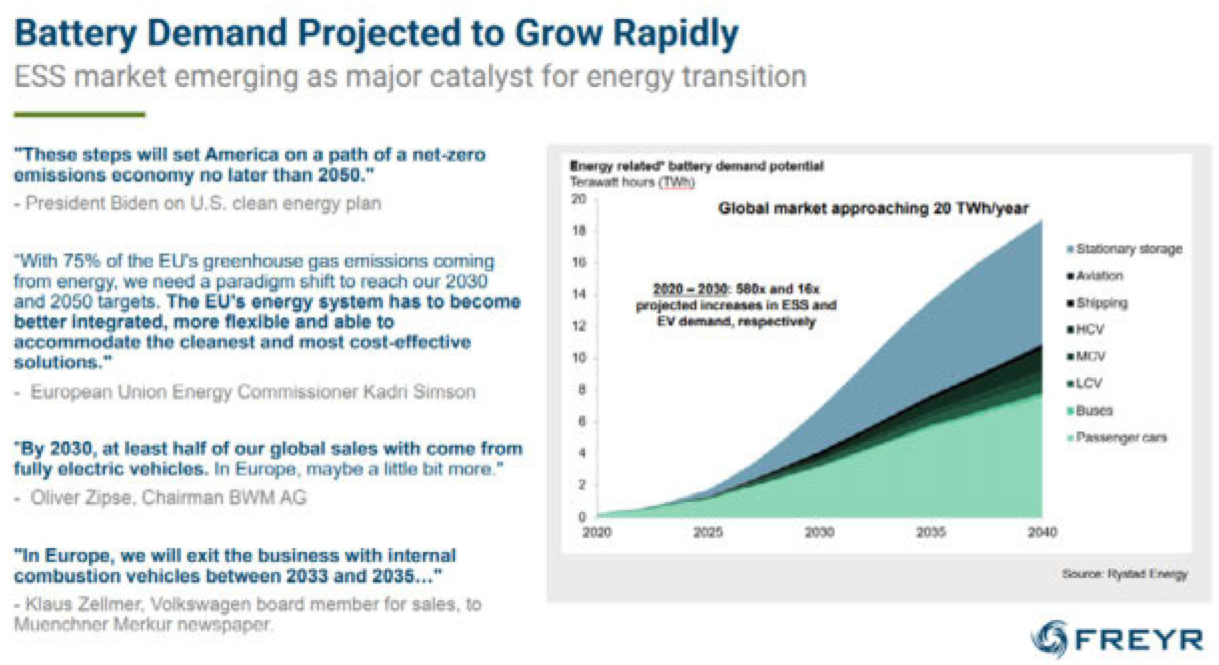
oceans, the Mediterranean, Baltic, and Black seas); at a scale 1:250.000 or more detailed for the spatial resolution; containing 20 elements included in the EC 2020 list of CRM (Sb, Ba, Bi, Co, F, Ga, Ge, HREEs, In, LREEs, Mg, Nb, PGMs, Phosphate rock, P, Sc, Si, Ta, W, V); and other 12 strategic elements (Fe, Mn, Ti, Cu, Ni, Zn, Pb, Li, Au, Ag, Th, U). The studies on the metallogenesis of European seafloor mineral resources include (1) metallogenic maps of submarine mineral occurrences scale 1:10.000.000; (2) a compilation of major seafloor mineral deposit models; (3) a series of metallogenic provinces and descriptions; (4) location map of submarine mineral occurrences; (5) a database on seabed mineral occurrences; (6) vocabularies and (7) references material.

An enormous challenge in terms of research, expertise information, technological innovation, environmental protection, spatial planning and social license is facing the European and international research and sustainable development plans. The GeoERA raw materials projects are sharing and harmonizing databases, outlining on land and seabed areas for new mineral deposits. MINDeSEA is identifying areas for sustainable development and information to support decision-making on management and Marine Spatial Planning in pan-European seas as part of its core actions.

INSPIRE-compliant harmonised MINDeSEA datasets and maps will be public and free accessible in the "EuroGeoSurveys" European Geological Data Infrastructure (EGDI) portal (http://www.europe-geology.eu/). The GeoERA portal (https://geoera.eu/), dedicated website (https://geoeramindesea.wixsite.com/mindesea) and Social Media (https://twitter.com/MINDeSEA) provide more detailed information about the project MINDeSEA.

FREYR Battery – decarbonizing all energy and transport systems

TOM EINAR JENSEN, FREYR



FREYR will be at the forefront of the energy transition both within Norway, and the wider world, and has a clear interest in locally sourced raw materials for its key battery components, both in terms of security of supply, and also the ability to transform these raw materials domestically using zero carbon energy as a benefit to the wider environment

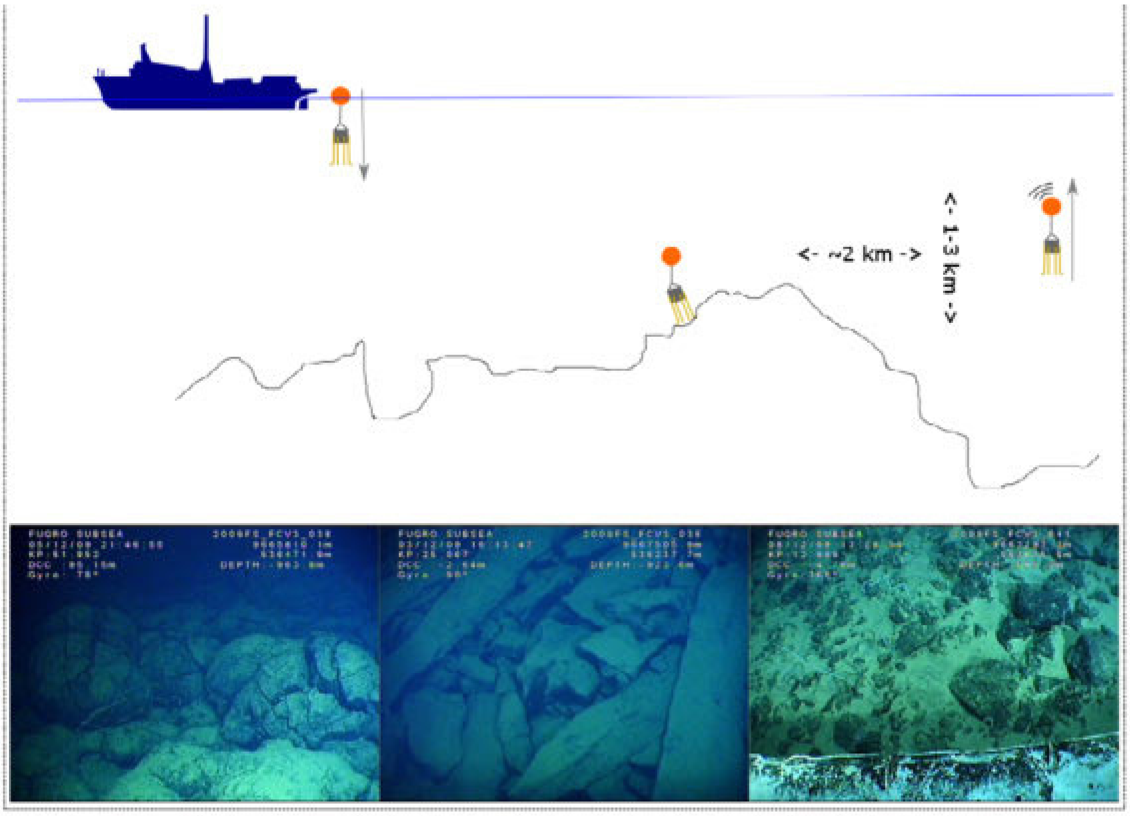
The projections of global demand for batteries are growing by the month and the latest update projects is close to 7 TWh by 2030 and close to 20 TWh by 2040. Todays' demand is around 0,35 TWh. This will require a total rethink of supply chains, use of energy and not the least recycling of materials. Batteries will have to be part of a circular economy as we see being discussed in the EU Battery Directive review.

In a long-term perspective, we believe that some deep-sea mining could be part of the value chain for batteries. FREYR fully supports the continued, careful and diligent study of the impact of deep-sea mining on marine and land-based ecosystems and believes that once this impact is fully understood and mitigated, the development of these resources could be a strategic priority for Norway.

Norway is in a unique position to exploit these deep-sea deposits, having a skill set and work force familiar with operating in these extreme environments, whilst adhering to strict environmental and safety guidelines. It is also believed that should deep sea mining become environmentally and economically feasible, that it will enable the petro-driven economy in certain areas to transition towards the fully sustainable future which Norway is moving toward.

Key Challenges, and Some Potential Solutions in SMS Exploration

GEORGY CHERKASHOV, INSTITUTE FOR GEOLOGY AND MINERAL RESOURCES OF THE OCEAN, **JOHN PARIANOS,** COOK ISLANDS SEABED MINERAL AUTHORITY



With reference back to ancient terranes, as well as to evolving models of seafloor massive sulfide (SMS) formation, experience on the Mid-Atlantic Ridge and in arc-back arc basins in Tonga and Papua New Guinea indicates two key types of technical challenges facing current explorers.

1. discovery challenges relate to the compact size of deposits against the immensity of the ocean floor search space and the likelihood that some deposits will be at least shallowly buried. This is compounded by a high rate of 'false positives' i.e. seafloor massive sulfide occurrences of very limited size, low grade or both.
2. exploration cost challenges relate to the high logistical costs (i.e. crewed support vessel and long steaming distances) needed to support any testing, delineation or evaluation stages, including necessary turnover of the abovementioned false positives.

Common solutions to both challenge types will likely include:

1. improved economies of scale via efficiency at sea, i.e, larger surveys using higher rates of survey and sampling per fixed unit cost (nominally day rate of the expedition vessel(s)). Work to date by Polar Expedition in the Russian Mid Atlantic Ridge International Seabed Authority contract area includes relatively inexpensive but very systematic towed side-scan survey and TV grab sampling programs.
2. adoption of new technology that promotes the first point. This includes improved AUV sensor packages, and cheaper scout drilling platforms.

It is clear that innovation in this emerging industry is spawning a host of new potential solutions. From the authors experience, some examples specific to each key challenge type may then include:

1. with regards to discovery, grid surface sediment geochemistry can complement regional geological interpretation (e.g. from multibeam echosounder data) and geophysics (e.g. from surface or extensive near seabed magnetic and self-potential surveys). The samplers are ideally inexpensive, autonomous and able to be managed efficiently off smaller less expensive expedition vessels (even blue water fishing vessels). They need to be able to collect consistently and effectively off a wide range of seabed surface types (e.g. pillow basalts versus seabed clay-oozes verses volcaniclastics), with effective reduction if not elimination of sources of cross contamination. The v3.1 "Jumping Spider" samplers are tested and designed for this type of application;
2. with regards to exploration cost, the biggest issue facing the industry today is cost-effective drill sampling. This includes both scout drilling (testing numerous targets to determine which have prospects for development) and resource definition drilling (systematic sampling of a newly discovered deposit to demonstrate value for development). In SMS systems both types of drilling struggle to collect good quality samples for a variety of technical and geological reasons. An alternative approach, in at least some cases, may be to analyse the sidewalls of the hole in-situ rather than spend valuable time trying to collect good quality samples. Pros of such an approach include likely more rapid cheaper operations (= more holes) and better primary sample (in terms of analysed volume and sample quality). Cons of such an approach may include calibration issues associated with in-situ analysis, likely more limited elemental spectrum for such field based analysers and industry acceptance of the results. Prompt gamma neutron activation analysis has been demonstrated to work, down hole, submerged, and on massive copper sulfide samples. A program is currently underway to build a tool capable of being deployed onto SMS systems.

Lessons Learned from 14 years of Seafloor Massive Sulfide Exploration - Geophysical Approaches

LUCY MACGREGOR, MATTHEW KOWALCZYK, PETER KOWALCZYK, OFG MULTIPHYSICS

Introduction

The accelerating electrification of the world and the transition to clean energy sources is putting pressure on onshore supplies of metals. This demand coupled with negative social impacts of onshore mining is driving a growing interest in the development of offshore mining. Seafloor Massive Sulfides (SMS) are one type of marine mineral deposit currently being explored for and characterized as a potential source as they often have high concentrations of metals. These SMS deposits are precipitated from hydrothermal systems at mid-ocean ridges and back-arc spreading centres, sedimented rifts, and on- and off-axis volcanos and seamounts. Typically found in water 1 to 4 km deep they are usually only a few hundred metres wide and tens of meters deep. Generally, they form in clusters, some with seafloor expressions, while others are buried.

Effective mineral exploration programs, whether terrestrial or marine, revolve around robust and efficient mapping campaigns. Thousands of square kilometres are searched to find each SMS site which may only occupy a few hundred square metres. The SMS sites of most commercial interest are inactive and can potentially be mined with less environmental impact, however these relict sites can also be sedimented over making them even harder to find. The difficulty in finding and then characterising SMS deposits, active and inactive, further highlights the need for a methodical multiphysics approach to each exploration effort.

The ultimate goal of a commercial SMS exploration program is to reach a decision to invest in a mining system. This requires knowledge of the size, grade, geometry, mineralogy of a deposit and environment surrounding it with enough certainty so that the risk of failing is quantifiable and acceptably small. Supporting two dozen SMS exploration campaigns over 14 years has given OFG the opportunity to evaluate and develop a multiphysics approach to SMS exploration and site characterization that

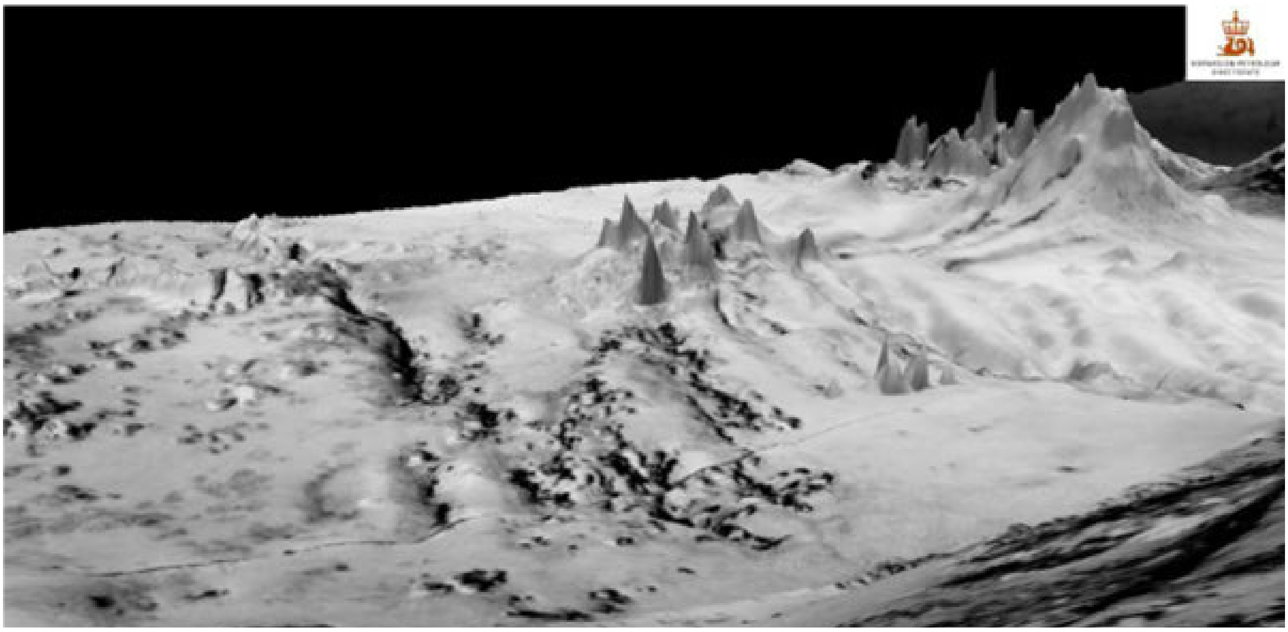


Figure 1: SAS imagery laid over MBES bathymetry acquired with OFG AUV "Chercheur". (Source http://www.npd.no/en/news/News/2018/New-deep-sea-mineral-deposits/)

provides critical information as part of this overall program. Technologies presented herein form the basis for best practice and standardized methods for seafloor mineral geophysical exploration.

Acoustic surveying

Acoustic methods are one of the most effective approaches for discovering SMS deposits. Surface vessel hull mounted multibeam echosounders (MBES) allow for the rapid survey of large areas to identify seafloor morphology likely to host SMS deposits, and in some cases can directly identify areas with mounds or chimneys. Once sites have been identified, AUVs can be deployed to acquire high resolution bathymetry and sonar imagery to map with extremely high resolution to identify mount and chimney structures. For example, AUV mounted synthetic aperture sonar (SAS) can produce seafloor imagery at a resolution of 4cm x4cm across several hundred metres. Figure 1 shows an example of AUV SAS data draped on AUV MBES data acquired with the OFG AUV "Chercheur" in 2018 as part of an NPD SMS exploration campaign. AUV sub-bottom profiler (SBP) data can also provide information on structure in the shallow sub-surface to depths of a few tens of metres.

Magnetic surveying

Large mineralised systems usually have large signatures. However, the magnetic signatures of SMS deposits can be highly variable. For example, in volcanic rock hosted settings, SMS sites are typically associated with areas of low magnetisation, due to the hydrothermal alteration and destruction of magnetite. Within ultramafic hosted systems the serpentinization of peridotite the formation of magnetite, results in increased magnetisation of the sub-surface. AUV SMS surveys designed for MBES and SAS/SSS acquisition typically flow in a pattern that is amenable to magnetic mapping and subsequently inversion to give a 3D distribution of the sub-surface magnetization. Figure 2 shows an example from the Solwara-1 SMS deposit in Papua New Guinea. The green surface encloses an area of low magnetic susceptibility, resulting from the destruction of magnetite in the sub-surface by the active hydrothermal system in the area. The surface expression of this deposit supports this interpretation.

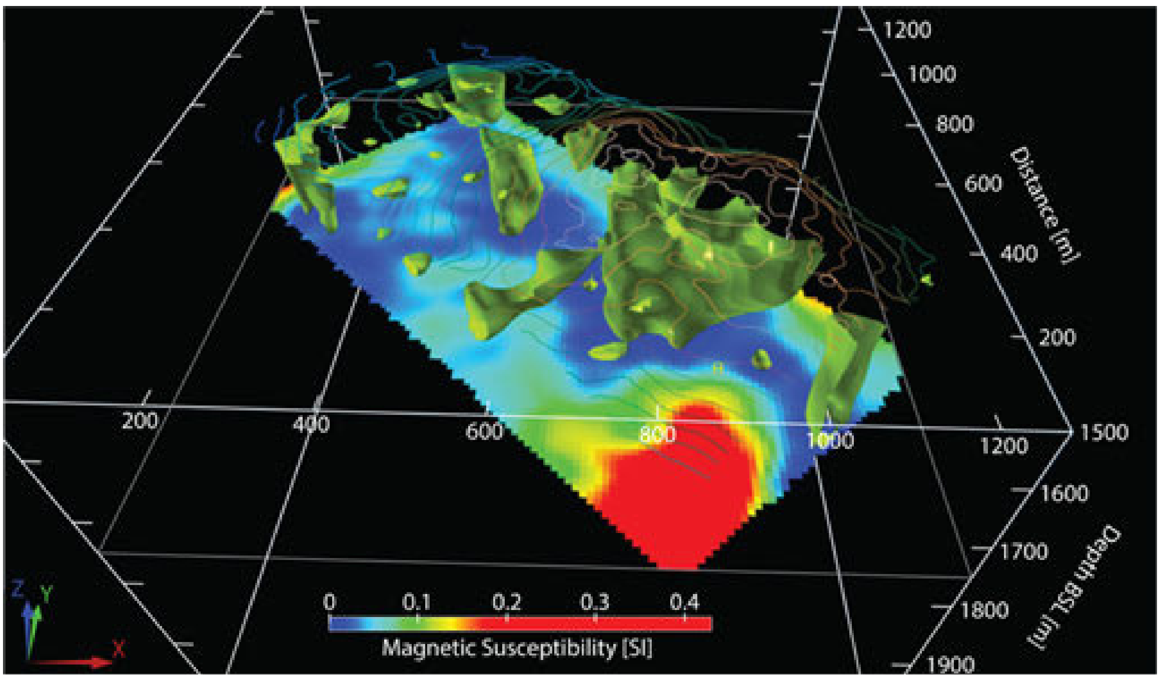


Figure 2: 3D Inversion of magnetic field data acquired with magnetometer mounted on an AUV over the Solwara-1 SMS deposit. The green surface encloses an area of low magnetic susceptibility associated with magnetite destruction in the active hydrothermal system. Contour lines show seafloor bathymetry. Magnetic data courtesy Tivey et al., Woods Hole Oceanographic Institute.

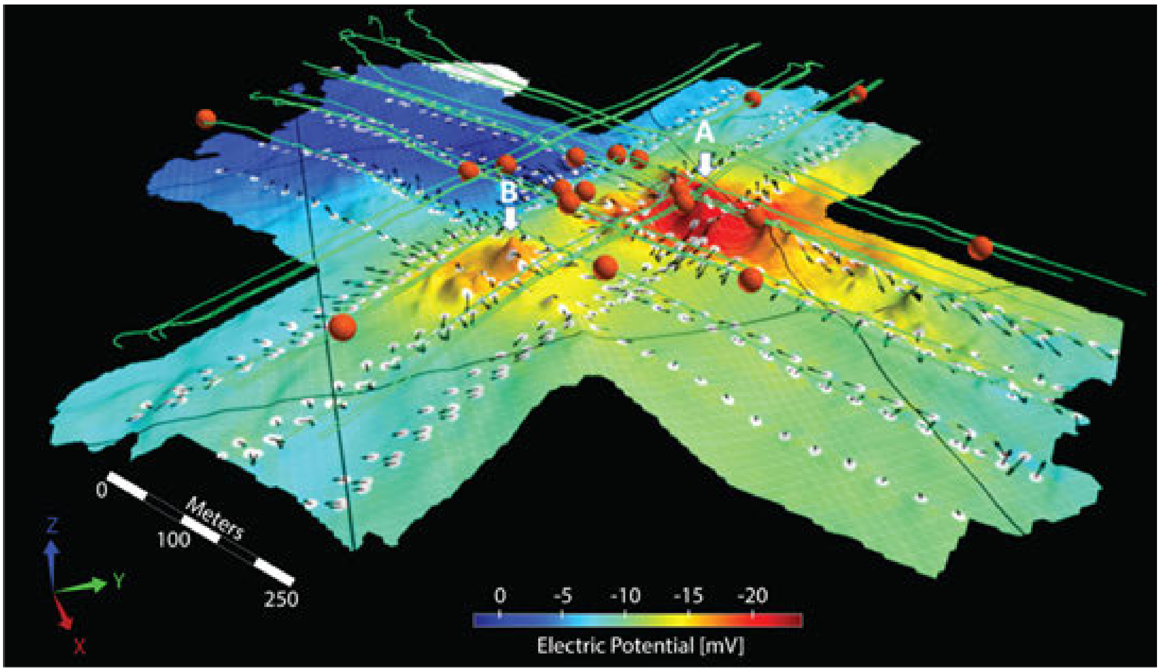


Figure 3: Self potential anomalies draped over seafloor bathymetry. The electric fields measured at the AUV are shown by the arrows (length scaled by amplitude), whilst the colours show magnitude of the self-potential (figure reproduced from Constable et al., 2017). Orange balls show the position of geochemical anomalies in the water column.

Electrical surveying

Measurements of electric fields provides valuable information An AUV can be equipped with an electric field sensor system for either passive self-potential (SP) measurements or controlled source electromagnetic (CSEM) data collection.

SP methods have been used for nearly two hundred years to study ore bodies. Offshore studies have traditionally used a deep-towed electric field receiver. However, in the water depths typical of SMS deposits, tow speeds are low and so data acquisition is inefficient. AUV mounted electric field sensors allows for efficient acquisition of electric field data over SMS deposits which can be used to recover the SP data.

An example of SP data showing three anomalies from the Iheya area of the Okinawa Trough, offshore Japan, is shown in Figure 3 (Constable et al., 2017). The anomalies are coincident with seafloor mounds observed in the MBES bathymetry.

Controlled source electromagnetic (CSEM) data can also be acquired from an AUV. An active electrical transmitter is required, either towed from a vessel or deployed to the seafloor. Figure 4 shows an example using deployed underwater electromagnetic source instruments transmitting signals received at the AUV electric field sensors (Constable et al., 2017). Figure 4 shows the inversion of the electric field data resulting in a 3D conductivity model of the subsurface. The high conductivity zone connecting the mounts and extending to the East is interpreted as a region of mineralization in the sub-surface.

Gravity

Seafloor gravity measurements allow tonnage estimates to be calculated with is important not only for resource estimation but for mining engineers planning resource extraction. ROV and AUV ocean bottom gravity (OBG) systems have been developed, deployed and demonstrated on SMS sites. Well designed OBG surveys can be used to estimate tonnages of a deposit and to limit expensive and wasteful over-drilling of a deposit that may consume the value of the deposit while trying to establish its grade and tonnage.

Multiphysics interpretation

An integrated model that brings all of this geophysical information together allows for a more complete understanding of the deposits and leads to insights and interpretations that are not apparent

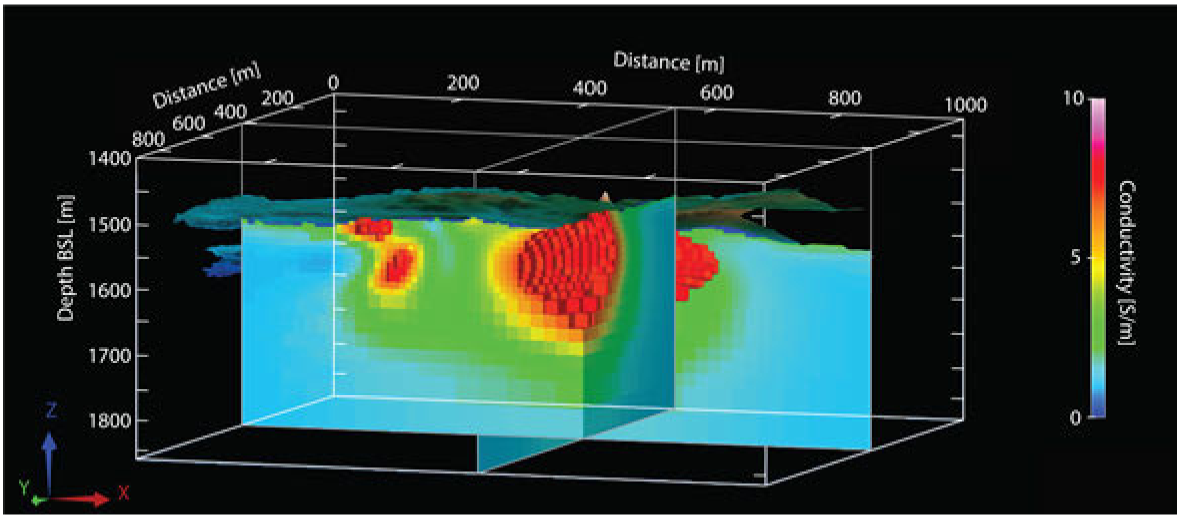


Figure 4: two images of the sub-seafloor conductivity structure resulting from 3D inversion of the CSEM data acquired. The high conductivity (red) area is indicative of the presence of mineralisation in the seafloor.

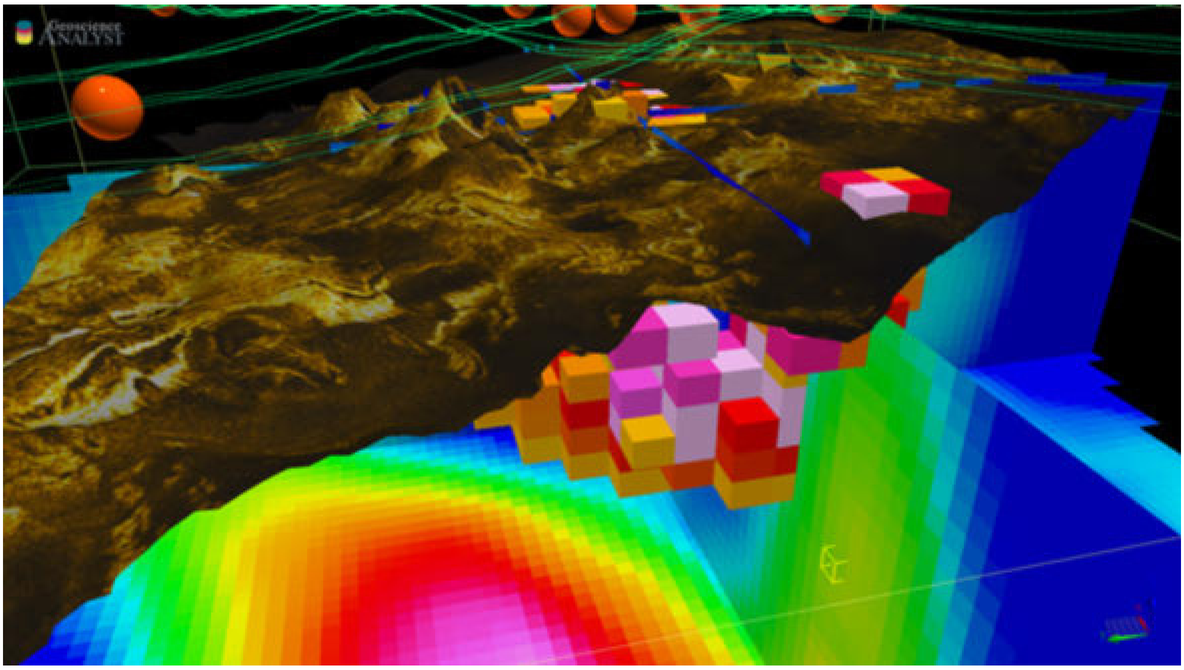


Figure 5: Combining the rich multiphysics dataset acquired allows a more complete understanding the hydrothermal system and sub-surface mineralization to be developed. Shown here, AUV data acquired in a single dive and integrated into a 3D model: sidescan sonar, MBES, SBP, 3D conductivity inversion model, water chemistry, 3D magnetic inversion model

with disparate or incomplete data sets. An example is shown in Figure 5 of a rich multiphysics AUV data set collected at Iheya, Japan.

Acknowledgements

The data in Figure 5 at Iheya was acquired by OFG in collaboration with Fukada Salvage and Marine Works Co. Ltd, and the Marine EM Laboratory at Scripps Institution of Oceanography.

Geophysical Solutions to Efficient Marine Mineral Exploration

DAG HELLAND-HANSEN, FRIEDER ROTH, HANS ROGER JENSEN, EMGS

According to the International Energy Agency (IEA), the on-going energy transition will require a significant increase in metallic mineral supply to upscale the electric infrastructure, the production of battery capacity and manufacturing of solar panels and wind turbines. The demand for metallic minerals is forecasted by IEA to multiply by more than 6 times on the way to path "net zero 2050".

Most of the current metallic mineral supply is from onshore paleo volcanic geological settings. The high-grade deposits are becoming depleted, and new sources of minerals are needed to support the Energy Transition.

Some of the black smokers building up Seabed Massive Sulfide (SMS) deposits along modern day ocean spreading are rich in copper, zinc and to a lesser extent rare earth minerals. The current active smokers have a thriving pristine ecosystem which should be protected from human interference. However, SMS deposited by now extinct smokers are being considered as potential supply sources for minerals by governments.

The SMS deposits discovered to date are at the seabed in ultra-deep water. Each deposit is normally relatively small from around 50 meter up a 1000 for the large ones, relative to the vast ocean bottom areas in question approximately 18000 km2 for the Mohns Ridge as an example. The SMS deposits vary in both mineral content and volume and only a few of the many "extinct" SMS deposits are expected to have valuable metallic minerals in large enough quantities to be of commercial interest for offshore mineral excavation. Hence geophysical techniques are a necessity to cost-effectively search for and identify potential SMS prospects for sampling and shallow drilling. Following a successful drilling campaign geophysical techniques will be key to further appraise the deposit in a cost-efficient manner.

EMGS believes that its cutting-edge EM technology developed for the oil and gas industry may be an important tool in the exploration for marine minerals (in combination with seismic and other acoustic measurements). We are looking to address the mineral exploration challenge at different stages in the exploration process with a suite of tools and methods.

Regional mapping and understanding of marine mineral plays

In this context EMGS propose to use our current proprietary CSEM/MT technology to arrive at superior images of the sub-surface allowing geoscientist to define areas likely to be plays for marine minerals by understanding the present and past volcanic processes and hence identify areas/plays that has the better potential to contain SMS deposits with commercial quantity

EMGS has already acquired two EM surveys together with the Norwegian University of Science and Technology (NTNU) as part of the ATLAB consortium

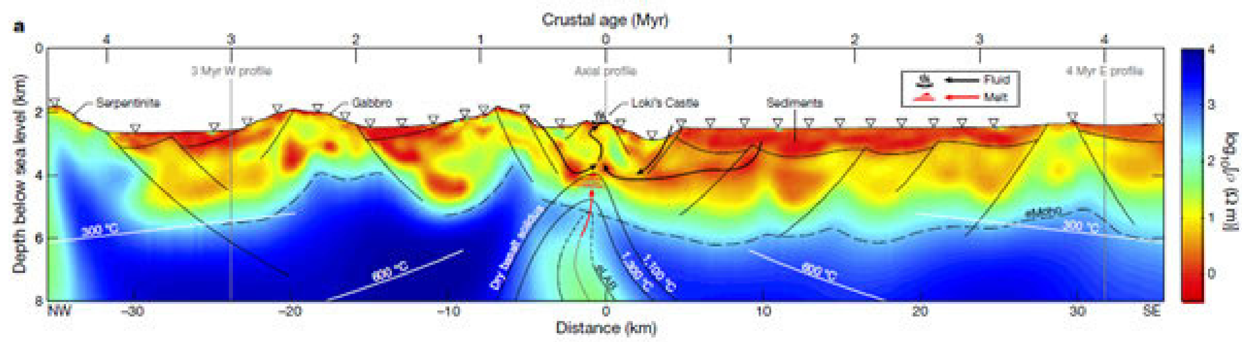
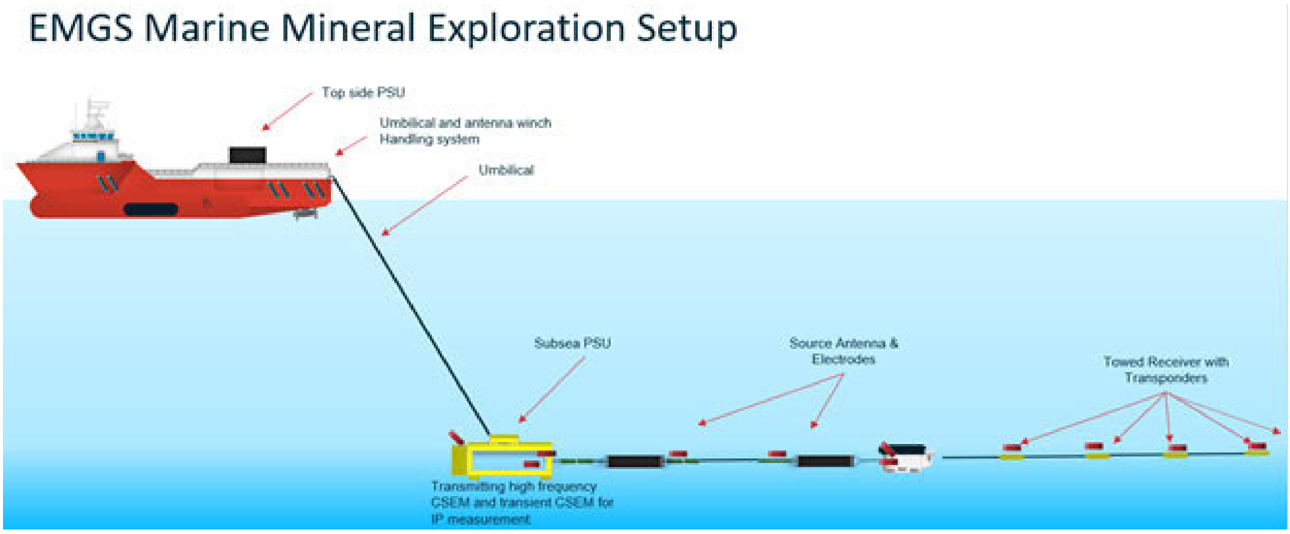


Figure 1: Results of CSEM and MT joint inversion of data acquired near Lokis Castle at the Mohns Ridge in the Norwegian Sea (Johansen, S. E.; Panzner, M.; Mittet, R.; Amundsen, H. E.; Lim, A.; Vik, E.; Landrø, M. & Arntsen, B.; Deep electrical imaging of the ultraslow-spreading Mohns Ridge Nature, Nature Publishing Group, 2019 , 567 , 379)



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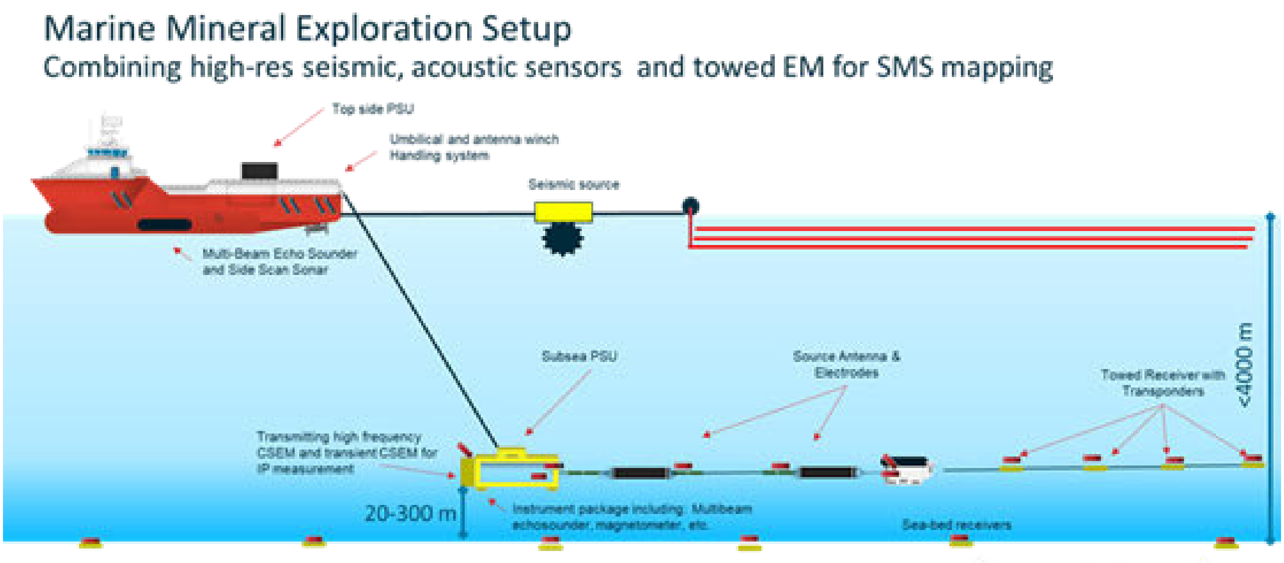
to improve the understanding of tectonic and magmatic processes that lead to the formation of marine minerals at the spreading ridges, see figure below

Play, lead and prospect maturation

With the geologic knowledge from regional geophysical lines, the geoscientist can map areas based upon multibeam and/or seismic datasets and with geologic knowledge of the SMS forming processes zoom into smaller regional areas which are likely to contain SMS with potential deposits of valuable minerals. The mineral composition of the SMS leads should then be quantified, spatial distribution mapped, and volumetrics estimate in the process maturing leads to drillable SMS prospects.

Academic work by GEOMAR has demonstrated that CSEM methods can discriminate mineral type and content in SMS at the seabed (Gehrman et al,



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Marine Mineral Exploration with Controlled Source Electromagnetics at the TAG Hydrothermal Field, 26°NMid-Atlantic Ridge, Geophysical Research Letters 2019). A combination of electrical conductivity and chargeability allows the discrimination of primarily iron rich SMS deposits from SMS deposits with larger content of valuable metallic minerals.

Enabling cost-efficient mapping that allows such discrimination is crucial to this stage of the exploration process. EMGS is planning a modification of our current system which will allow for such shallow sub-surface geophysical mapping. We are developing a prototype to be ready for a 2022 pilot survey over know accumulation in the North Atlantic mid-ocean ridge. The system based upon our proprietary EM source will be a towed system including a measure-while-towing system allowing for direct scanning of promising SMS deposits.

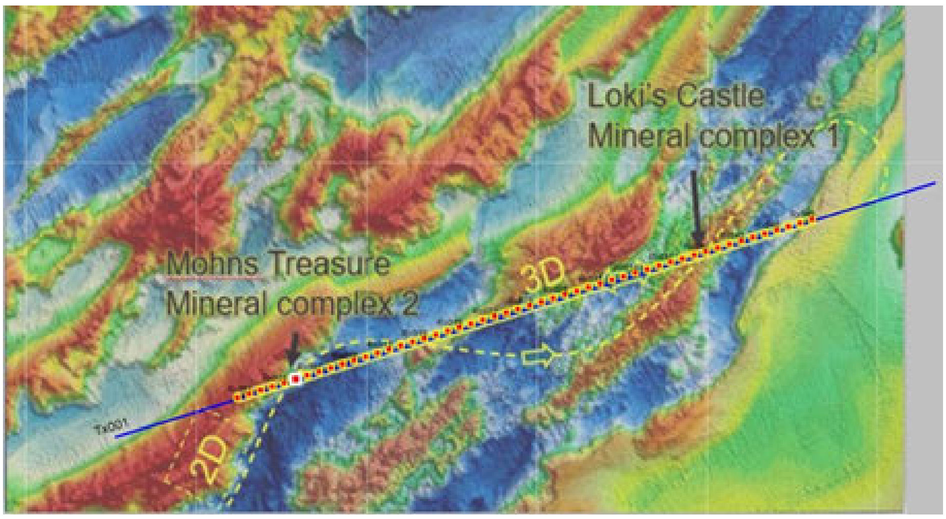
Appraisal stage

Commercial marine mining is feasible if a SMS has a high base-metal and/or gold grade and are of sufficient volume, hence given a successful drilling/sampling campaign an appraisal stage requires improved spatial and grade mapping to evaluate suitability for commercial excavation, EMGS will at this stage propose a dense 3D EM and high-resolution seismic surveys.

EMGS platform for multi-geophysical simultaneous acquisition

The Atlantic Guardian vessel itself allows mounting multibeam, and other acoustic measurements underneath the vessel and or on the source. Furthermore, since the EM cable is towed close to seabed, a seismic source and cable can be operated at the sea surface to acquire high-res seismic simultaneously. This set-up with simultaneous acquisition will allow us a cost-effective solution to a acquire a multi-geophysical survey, furthermore, including a measurement-while-towing of the key EM components will allow to scan SMS areas for the EM signals associated with high content of valuable mineral deposits. A next step following this set-up would be to use AUV's on either side of the towed EM cable to further optimize a 3D EM acquisition.

NTNU suggests an expansion of their ATLAB consortium to include a marine mineral geophysical test based upon the Atlantic Guardian platform as depicted in the figure across mapped and sampled SMS. In addition, the program will be expanded to acquire more regional lines for better regional understanding of the development of the mid-Atlantic ridge. The shallow seabed survey will be in conjunction with the TGS technology test program they are promoting as part of a complete technology test and the area is depicted in the figure below.



Find the Needle without Disturbing the Haystack: High Resolution 3D Geophysical Characterization of Deep-Sea Minerals

ALLAN MCKAY, PGS

The cost-effective and sustainable exploration for deep-sea minerals will require the use of non-invasive methods to ensure that both the prospectivity and sustainability of future exploitation can be assessed with minimal impact on the environment. Regardless of the type of mineral deposit then vast areas of the deep ocean need to be explored to find commercial quantities of marine minerals that can potentially be exploited. However, when we consider Sea-floor Massive Sulphide deposits (SMS) then it will most likely be in-active sites that can be an exploitable resource. SMS deposits at in-active sites are also likely to be buried under a veneer of soft sediment. Therefore, remote sensing methods such as geophysics will be crucial as both a regional and site-specific exploration tool. Whilst exploration for deep-sea minerals has been undertaken for some time the exploration workflow will need to be scaled up to enable efficient operations. Indeed, it is likely that exploration will proceed in a similar fashion to oil and gas exploration with the early phase comprising large scale reconnaissance surveying to identify sweet spots of relatively high prospectivity and low environmental sensitivity. Thereafter more focused surveying and monitoring will be required to characterize given sites in more detail.

The foregoing considerations indicate the need to be able to acquire rich data sets to be able to determine both the geophysical and geochemical characteristics over wide areas. No single measurement or datatype can provide all of the information required about e.g., the water column, sea-floor and

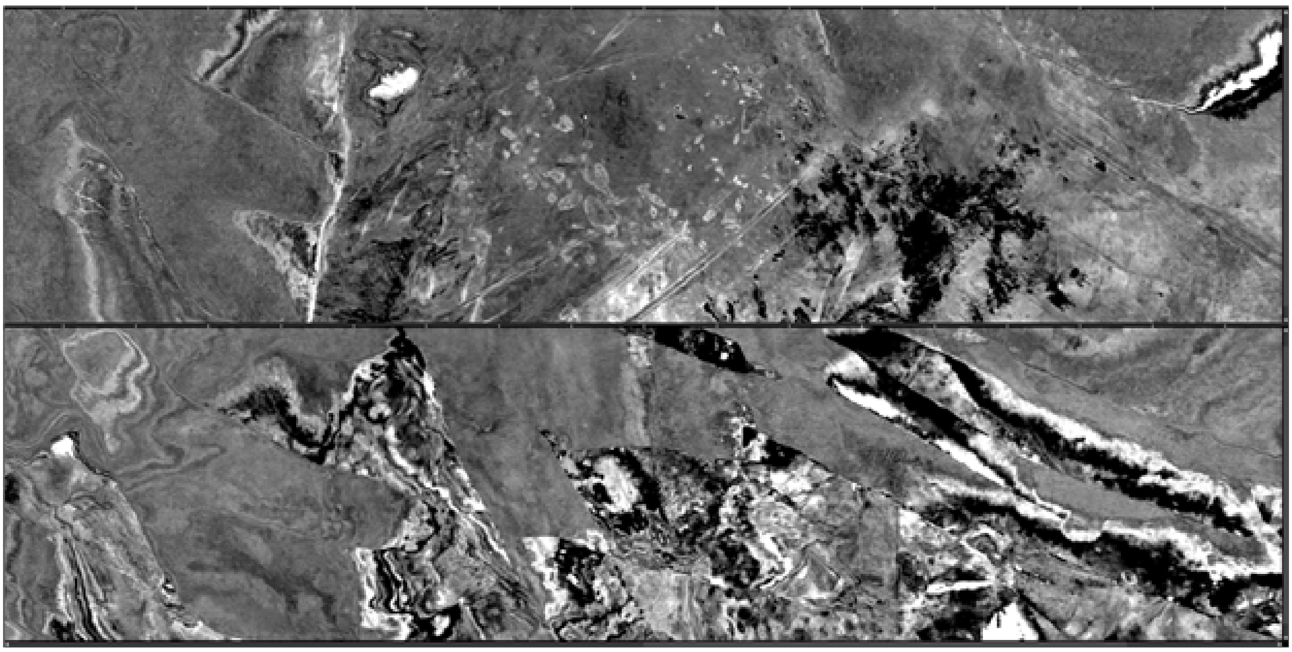


Figure: Illustrative seismic images from PGS' novel, tailored seismic acquisition, and imaging configuration that be scaled for the near-surface high resolution 3D studies of interest in deep sea minerals. The areal dimensions of the depth slices – approx. 10 m (upper) and 60 m (lower) below the sea-bottom - are 21.9 km x 5.3 km, with individual bin dimensions of 6.25 x 6.25 m.

sub-surface therefore a multi-physics approach is required; see for example MacGregor et al. 2021 who shows that Autonomous Underwater Vehicles (AUVs) are an ideal sensor platform to enable acquisition of a suite of geophysical (e.g. acoustic, magnetic and electric) and geochemical data. However, AUV enabled data acquisition alone may be too slow and in-efficient to enable large-scale early phase exploration although the development and adoption of long-endurance AUVs, and ability to operate swarms of AUVs, represent an obvious efficiency enabler.

What have we learned and developed in the oil and gas industry that can be help cross the chasm between site specific and regional surveying, mapping, and characterization? Recent advances in marine seismic acquisition have enabled quality - i.e., 3D data resolution – to be maximized without sacrificing efficiency; see for example Widmaier et al. 2021 and the Figure below. This kind of approach provides a good example of a method developed in the oil and gas industry - to image and characterize the acoustic and elastic properties of the deeper sub-surface – that can be modified and scaled to focus on being able to characterize the shallow sub-surface in water depths ranging from e.g., 1 to 6 km. In addition, we recently undertook a combined sparse ocean bottom node and 3D high resolution GeoStreamer seismic survey covering nearly 4000 square kilometers clearly highlighting the ability to efficiently combine different marine geophysical operations that could be adapted to enable both surface vessel and AUV operations. In addition, recent advances in seismic imaging (e.g., Yang et al. 2021) and data interpretation (e.g. Ruiz et al. 2021) indicate the potential for efficient, tailored, data-based methods to characterize subsurface properties at scale.

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Synthesis of Offshore Robotics, Multi-physics Data and Digital Twin Technologies for Deep-sea Mineral Exploration

ANNA LIM, JOHAN MATTSSON, THORBJØRN REKDAL, TROND CRANTZ, ARGEO

Decades of research studies and offshore cruises have established a solid knowledgebase about different types of deep-sea minerals. Active hydrothermal vent fields, in large due to their geological and biological significance and not least due to the relative simplicity of their identification through water column measurements, have been explored.

Seafloor massive sulfides associated with hydrothermal venting benefit from their size often around 250×250×150m. This is not the case for crusts that can reach similar areal extent but rarely exceed 0.25m in thickness. The third type of mineral, nodules, can be spread even wider, hundreds of kilometers, but constitute covers with inconsistent thickness of 0 to 0.25m. With such range in dimensions and very limited vertical or horizontal extent of the deposits compared to the water depth they can be found at (3,500m on average), water sampling and other sea-surface measurements are no longer efficient in identifying nor resolving these deposits. This scale difference and the geological context of the marine minerals are of paramount importance.

While underwater robotic solutions with Autonomous Underwater Vehicles (AUVs) close to the seafloor address the scale challenge by significantly increasing data resolution, e.g. reaching 5cm-resolution with Hi-SAS surveys, a multi-physics approach becomes critical in addressing the variability of the geological contexts. In addition to acoustic measurements, widely used in the ocean realm, other geophysical methods such as magnetics and electromagnetics play a crucial role in delineation of the deposits and de-risking the sampling and drilling targets.

In recent years, a common exploration methodology has shaped to include the use of various

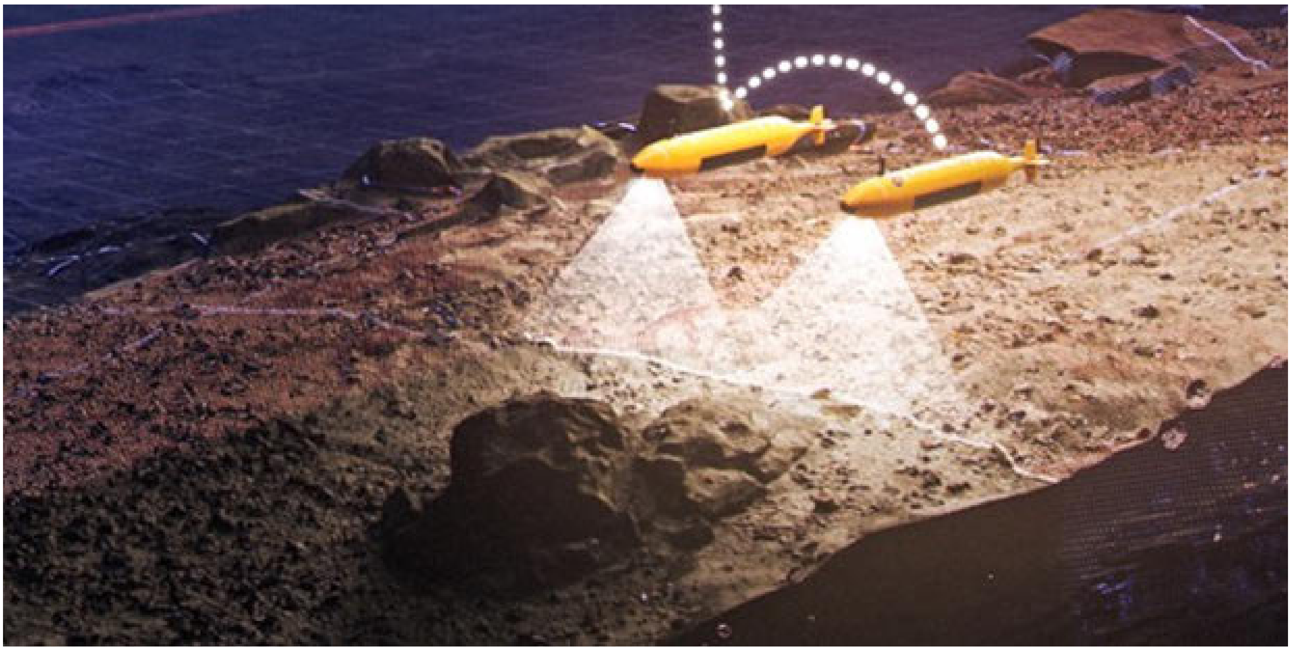

Figure 1. Autonomous deep sea marine mineral exploration surveys using a variety of sensors. Fusion of high-resolution acoustic sonar data with data from a specifically tailored Controlled Source EM (CSEM) system on-board the AUVs enhances the interpretation and classification of the seafloor and near seafloor.

high-frequency sonars together with magnetometer and passive electric field sensors mounted on underwater vehicles. Such setup allows for more confident identification of the deposits, and in some cases provides insight into the deposit's subsurface extent. To further improve both horizontal and vertical delineation of crusts and SMS, Argeo Robotics have developed a new electromagnetic system that can be mounted on several AUVs and considerably improve exploration efficiency and accuracy, figure I.

From an operational perspective, exploration strategies and sensor configurations are also required to be contextualized and thoroughly planned for prior to each survey in accordance with geological context, environmental factors, and many other considerations. This implies that survey planning and data acquisition should be part of the continuous data loop that ensures no data gets lost or underutilized. In the realm of deep and ultra-deep sea, a digital representation (Digital Twin) of the ocean becomes the space where operations are monitored and managed throughout project lifecycles. The ability to investigate changes over time, i.e. use of 4D-data, is readily facilitated in a Digital Twin solution. Moreover, short turnaround times and high-risk environments require real-time overview of project activities to support decision making. This can be satisfied with Argeo's Digital Twin solution, along with the demand for continuous environmental impact monitoring that has already become a voluntary operational standard.

New geophysical measurements in DSM/SMS exploration – the MOHN22 collaboration

BENT KJØLHAMAR[1], ADRIANA RAMIREZ[1], DAG HELLAND-HANSEN[2]

1 TGS

2 EMGS

Executive summary

The critical energy transition metals demand an unprecedented step-up in mining for rare earth metals onshore and when allowed, within the deep marine sea. Due to the limiting environmental and remaining resource factors of onshore mining, the pressure to open areas for deep sea mining is increasing. Benefit and risks must be weighted between onshore and offshore, and if deep sea mining (DSM) can operate safely and under a transparent proof of no harm to life principle, it is our view that this option is clearly the better choice to meet the predicted dramatic demand increase.

Many of the geophysical and geochemical tools developed for the oil and gas offshore industry still lack proper field test on sulfide complex (SMS) bodies. We propose to make a large consortium of mixed commercial interested parties, public research funds, and academic institutions to perform a large scaled geophysical test program on the known SMS's at the Mohn's Ridge in 2022: To offer a broad suite of measurements that will give us the best knowledge and value for the participants.

A licensing round is proposed for 2023, and hence time is short to find the most cost-effective tools for seabed mineral mapping. The challenges are to locate SMS's, prove extinct, quantify mineral type and content prior to a volumetric assessment and predict areas with probable commercial deposits, prior to this round.

The consortium is proposed to constitute of the following geophysical tools: Deca SA SIM source streamer 3D, Deep tow EM, High resolution short and dense streamer like P-Cable, and Coil tube drilling with new wireline logging tools and sidewall coring + in well DAS VSP seismic. This is a joint venture, with help from EMGS, Halliburton, University of Tromsø and Bergen beside TGS.

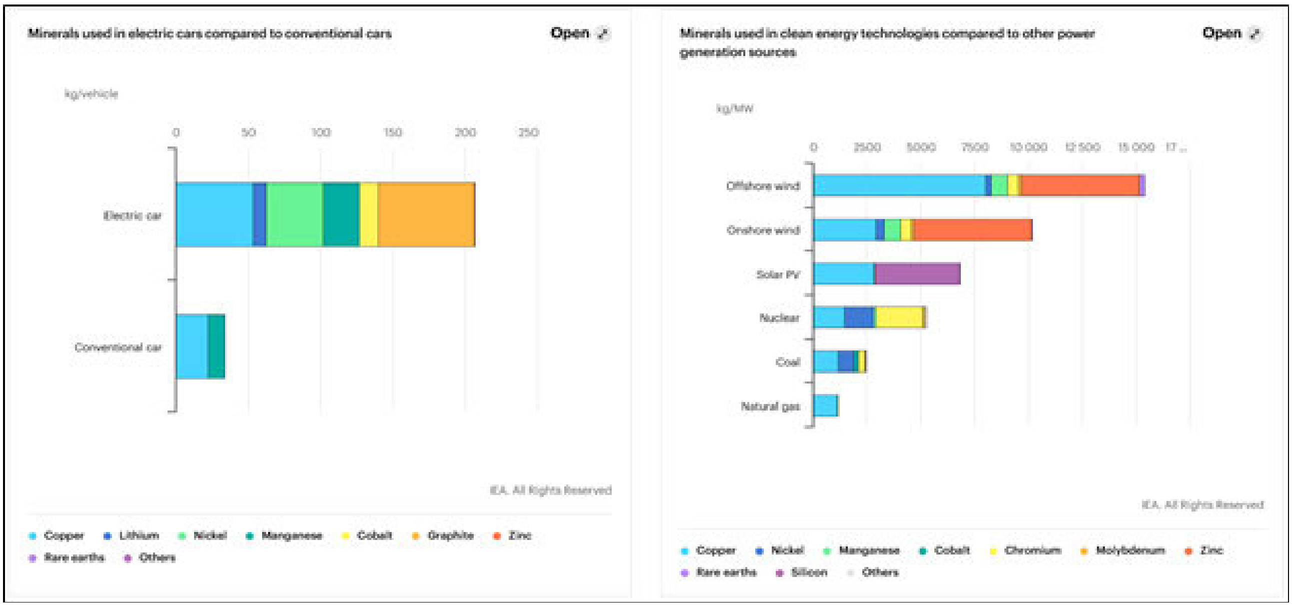

Figure 1 left: Type and volume of rare metals in an electric car compared to a conventional. Right: Use of metals within the renewable energy sector (wind and solar) compared to nuclear and fossil energy (IEA, Flagship Report – May 2021).

Introduction

IEA recently reported a desperate future shortage of critical energy transition metals, given the green energy market is allowed to grow as predicted within the two-degree-trajectory by 2050 (IEA, Flagship Report – May 2021). Wind and solar, electrical cars and batteries for energy storage will create a growth demand of cobalt as an example, between 6- and 30-times todays production. Although an increase in secondary recycled minerals and increased recovery from existing mineral mines are expected a large increase in primary mineral resources are expected within the 2-degree scenarios energy transition.

The increased demand can be met by onshore exploration and excavation for low-grade mineral deposits, or the mineral industry can “step offshore” to explore and excavate probable large high-grade minerals deposits in an analogy to the oil and gas business some 50 years ago, there are pros and cons with both. The already scrutinized global onshore mining is currently all diesel-driven and mines on steadily leaner ore, and predominantly within the developing countries in Africa and South America. Mining 6-30 times today’s levels in 2040 onshore will mean large increase in the land area used for mining, increased risk of soil and water pollution where people live. Furthermore, this will be a large climate gas emissions challenge that counter the purpose of building renewable energy facilities or electric cars. Since much of the metal processing industry is situated where coal power is used, like in China, Russia or in the US, this is not helping matters.

The offshore mining, with the potential to take on all the expected growth and more, is not sanctioned

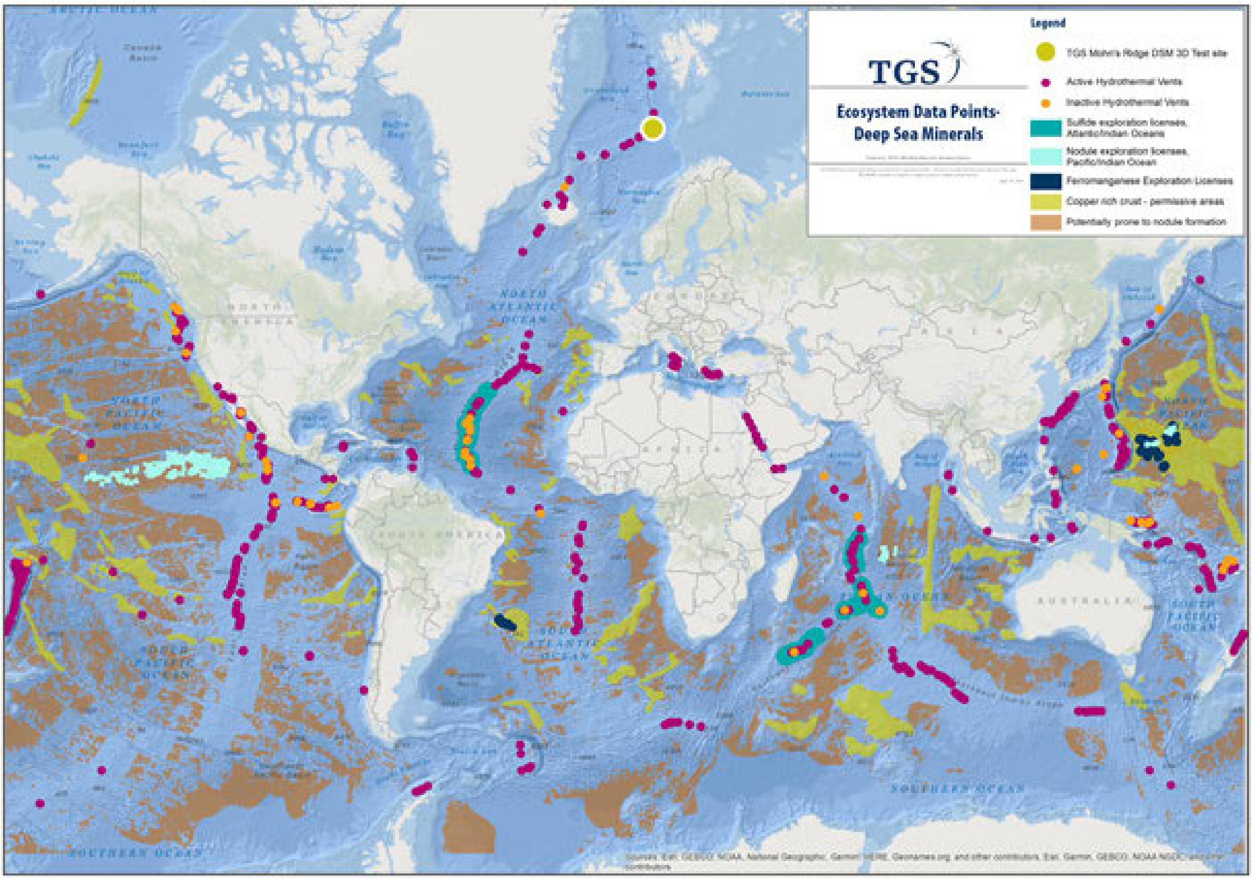

Figure 2 shows the DSM resources mapped per today and the current international exploration licenses in turquoise and light blue. The sulfide complexes discussed here is marked with orange dots for inactive or extinct complexes and purple dots for active ones (https\\dsm.tgs.ai, in press). As seen, there are much less inactive SMS’s found than active ones per today, but logically since the average active life of a complex is expected to be a few thousands of years, it should be more inactive orange dots on our map.

yet and mostly due to serious environmental risks attached. In exploitation these risks should be dealt with doing thorough mapping and follow a transparent proof of no harm to life principle. Beside these serious risk mitigation issues, offshore mining should be the better choice in most other facets. The envisioned production technology would have a smaller total production equipment mass per ton ore produced, thereof have much less carbon footprint especially if renewable sources of energy or decarbonized fuels are used. Furthermore, the predicted richer ore means less energy used in the refinement and processing. If deep sea mining (DSM) can operate safely and under a transparent proof of no harm to life principle, it will in our eyes be the clearly better choice to tackle the coming dramatic demand increase. Finally, securing sufficient offshore mineral resources for the Green Transition from politically stable areas and also easier to guard production and export from human conflicts and other terrestrial interruptions offshore is a clear benefit to the global community.

Academia has for decades studied deep sea mineral deposits but have been limited by funding to test many of the latest seabed and sub surface technologies from the offshore oil and gas industry. Before large scale DSM exploration and exploitation take place, scientific expeditions funded by a consortia of industry partners and public funds should happen to test out the most cost-effective measurement for each stage in the exploration phase. I will in the following focus on the sulfide complexes or so-called SMS's and the exploration tools we propose to test here.

We expect based on published material that the SMS's in question are newly extinct (past million years), vary in mineral grade, are relatively small (100-300m in diameter), and typically discos shaped bodies, and it may be far between each on a dramatically rugged ocean floor (Ref UiB). Also, vertically slanted mineralized bodies along fault planes and fractures are also described. The economically interesting part is the center core of each SMS where copper and cobalt ore are likely enriched. These might not be more than a few tens of meter wide and 20-60m deep (Ref TAG). In the vast ocean, this is a very small target for most ship track based geophysical measurements, at least for the cost-effective ones. The area of interest is huge, as an example the prospective Mohn's ridge has a core prospective area of 20 000km^2 based upon exploring for SMS's from the last 1 million years of ocean floor spreading. To do a proper first order evaluation of this area and with small and scarcely distributed SMS's in mind, we need cost effective 3D tools. After they are found we can use many dense 3D or 2D measurements and drilling to establish ore grade and local extent of the ores.

Methods

We have based on our experience with high resolution 3D seismic data for oil and gas proposed this as a starting point and the regional baseline database. We regard ship track Multi-Beam (like Mareano, 2019 EM304), any 2D based measurements including UAV based measurements to either be too ineffective measurements or too costly for regional size datasets (in the order of 20-200 000km^2). As shown in figure 3 we therefor suggest testing on known SMS's in 2022; high resolution 3D streamer seismic, seafloor sampling and ROV footage, deep-tow EM+ P-Cable, AUV based measurements and finally coil-tube drilling with new WLL tools and optical fiber DAS VSP seismic imaging. This is the most cost-efficient way we see SMS exploration prior to mining development. We will not mention AUV based measurements here since this is thoroughly tested and used by NPD, operated by OFG. All of the mentioned technologies for 2022 testing needs per today's permit regulations to be non-profit scientific led cruises in close collaboration with NPD and academia. Data will be made available to contributing commercial sponsors, universities and scientific papers is required to be published.

High Resolution, large vessel 3D streamer seismic is proposed as an initial exploration tool for SMS bodies. The first challenge is to find good candidates before doing more local and areal expensive measurements. In recent years the processed seismic has increased cross line data density first with more streamers, then utilizing more seismic sources. In the fall of 2020 TGS performed a 2D test with a 12-streamer 3D vessel (Polarcus Adira), utilizing 5-gun strings with two separated sources per string, fired semi-simultaneously with small dither periods of 0-50ms, set up in a seismic apparition mode (Ref Adriana). This Deca source line was processed by Apparition Geoservices and compared to overlapping AM20 Penta source 3D production data in the outer Møre Basin in the Norwegian Sea. Furthermore, a small

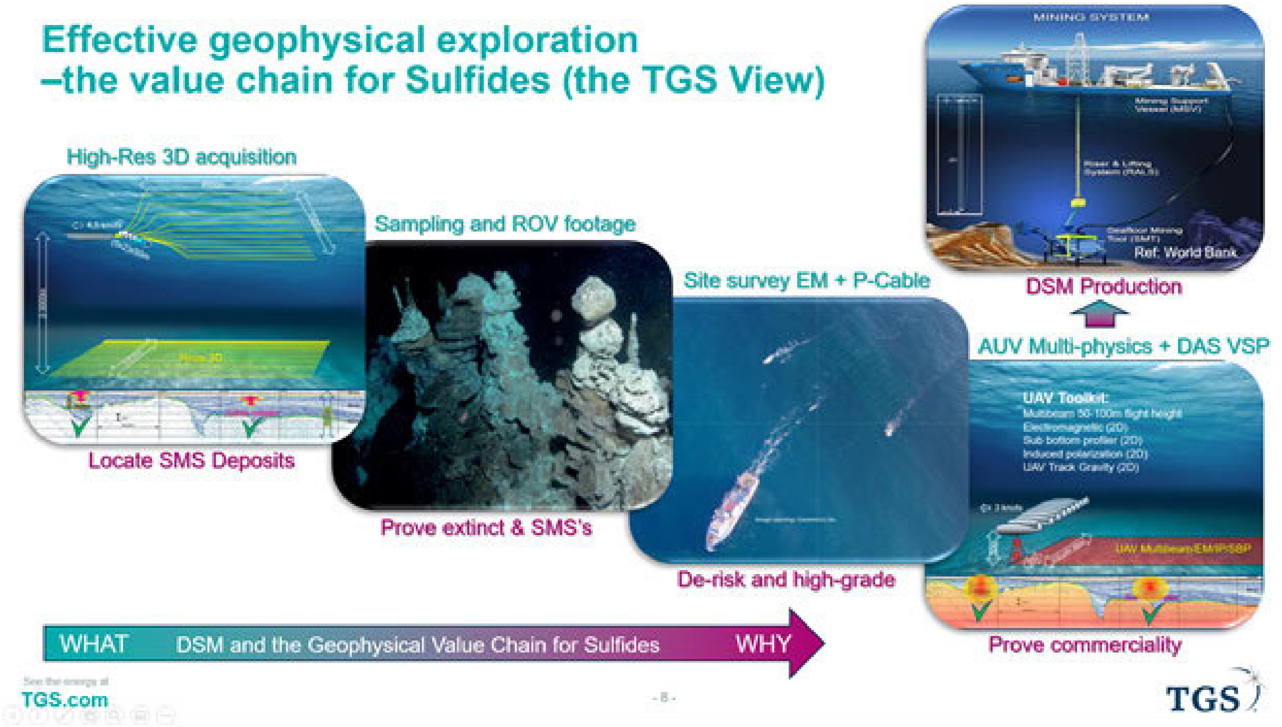

Figure 3 shows TGS's view on the per today optimal geophysical value chain for SMS exploration prior to any field tests at the Mohn's Ridge proposed for 2022. This view is based on cost-effectivity learned from different exploration phases within offshore oil and gas. In addition to the reported physical properties and sizes of SMS bodies based on scientific measurements.

3D volume with 80 crosslines (from 12 streamers) was made from this single sail line and the purpose of this test was to estimate what overlap we need when we are to acquire 3D with focus on the seafloor and a few tens of milliseconds below. Early indications are that we probably can save 20% of acquisition time directly by overlapping the spread, sail-line by sail-line only 30% rather than the 50% standard. This is also a part of the 2022 test plan. The intended purpose of this 3D seismic dataset is to basically find the SMS's and do first order de risking of ore volumes.

Seafloor sampling and ROV footage is not a part of our 2022 test plan since this has been done extensively by academia for decades. Although we do recommend doing this for a commercial exploration multi-client offering prior to or after DSM licensing rounds like planned for the Mohn's Ridge. Having the proof of a real SMS body and that it is indeed an extinct complex by video footage should be valuable data prior to the round applications and a chance to state to the wider public, in a transparent way, that this SMS should not be harm to local macro-life. Furthermore, micro biological analysis of the drop cores can both give valuable scientific data and be further de risking based on the no harm to life principle.

High resolution short and dense streamer 3D data like P-Cable and deep tow EM data acquisition is proposed by EMGS and TGS, thus the EM part is now a sub-set for the larger scope Atlab consortium (EMGS, NTNU, UiT and other academic/authority/commercial partners TBA. Hansen, D. et. Al. this conference). Since the towing speed of the deep tow EM source and receiver system will be around 3 knots and the umbilical and ropes for the deep tow EM are diving steeply behind the vessel, it's feasible to add a light high resolution short streamer seismic 3D system (P-Cable or similar) to undertake a simultaneous seismic and EM acquisition, resulting in a cost effective system combining measurements of acoustic and electro-magnetic (including IP) properties to depict SMS geometry, mineral type and content. The typical sail line distance for P-Cable is 75m and which also suits well for the EM measurements generating a

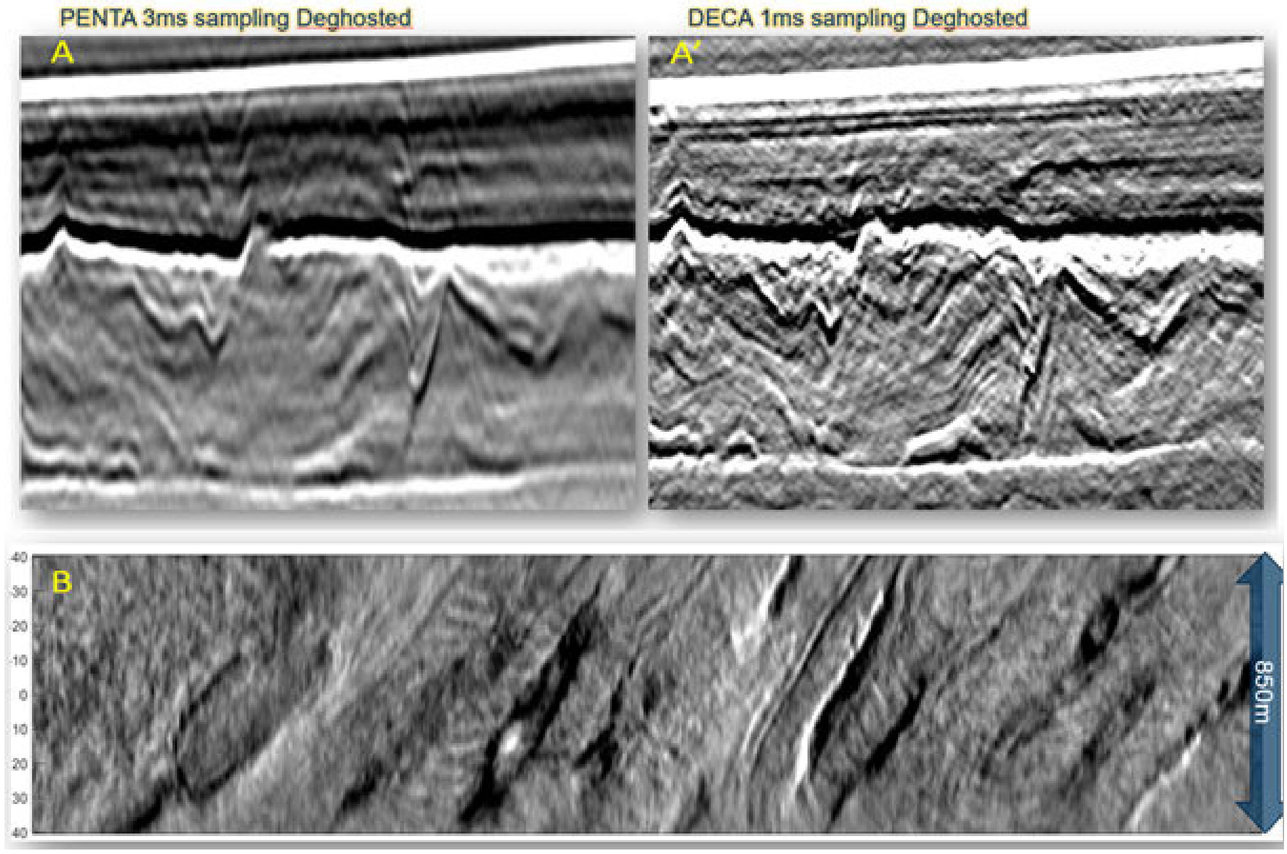

Figure show results from AM2O Lab where a Deca source test was performed over AM2O Penta source 3D streamer seismic. A-A' show the difference in resolution between the Deca source test A' processed at 1ms vertical sampling versus a production 3D line processed at 3ms. The Displays are a few tens of milliseconds below the seafloor (white reflector in the top of A-A'. The processing was done by Apparition Geoservices in Zürich. Another test in AM2O Lab was to create a 3D volume using one sail line with 12 streamers and the Deca source to create an 80-crossline narrow 3D volume. The aim for this test is to evaluate what overlap is needed in future 3D acquisition when the seafloor and 10ms below is the sole interest. Early indication is that 30% overlap gives sufficient horizontal resolution. Furthermore, we can observe small structures simulating SMS bodies within this volume, features down to 15-20m in the vertical sections can be interpreted. Expected commercial sized SMS bodies of 100-300m in horizontal diameter should then be well within range.

dense 2D EM dataset that can be 3D modeled. These technologies are not cost-effective in the SMS identification phase, however the towed EM system will be fitted to provide a measuring while towing system to enable scanning the EM properties of various identified SMS from seismic and or multibeam seabed data. The most interesting SMS's can then be matured by smaller 3D EM/high-res surveys.

TGS and VBPR have tested P-Cable in water depths down to 2000m in the Norwegian Sea (HR15) and the resolution and data quality in these depths is unmatched. We typically see a doubling of spatial and vertical resolution compared to modern 2ms sampled de-ghosted 3D data.

Coil Tube drilling using a new wireline logging tool and vertical in-well optical cable DAS VSP seismic is proposed as the last and probably the commercially most important dataset prior to SMS mining. NPD used coil tube drilling on SMS's at the Mohn's Ridge in 2020 operated by Halliburton, where they cored the entire well section. Halliburton and Technip now propose a more efficient way to drill SMS's with a combination of side wall cores and a newly developed wireline logging tool identifying specific metals with regard of presence and intensity or volume. Early 2021 TGS and Halliburton joint ventured on in-well DAS VSP acquisition and processing. One of the future products proposed is DAS VSP seismic for SMS. Already, Halliburton's drilling tools have an optical cable that can be used for this purpose. Our goal is to do a test of the new logging tool and the DAS VSP seismic at the Mohn's ridge the next years.

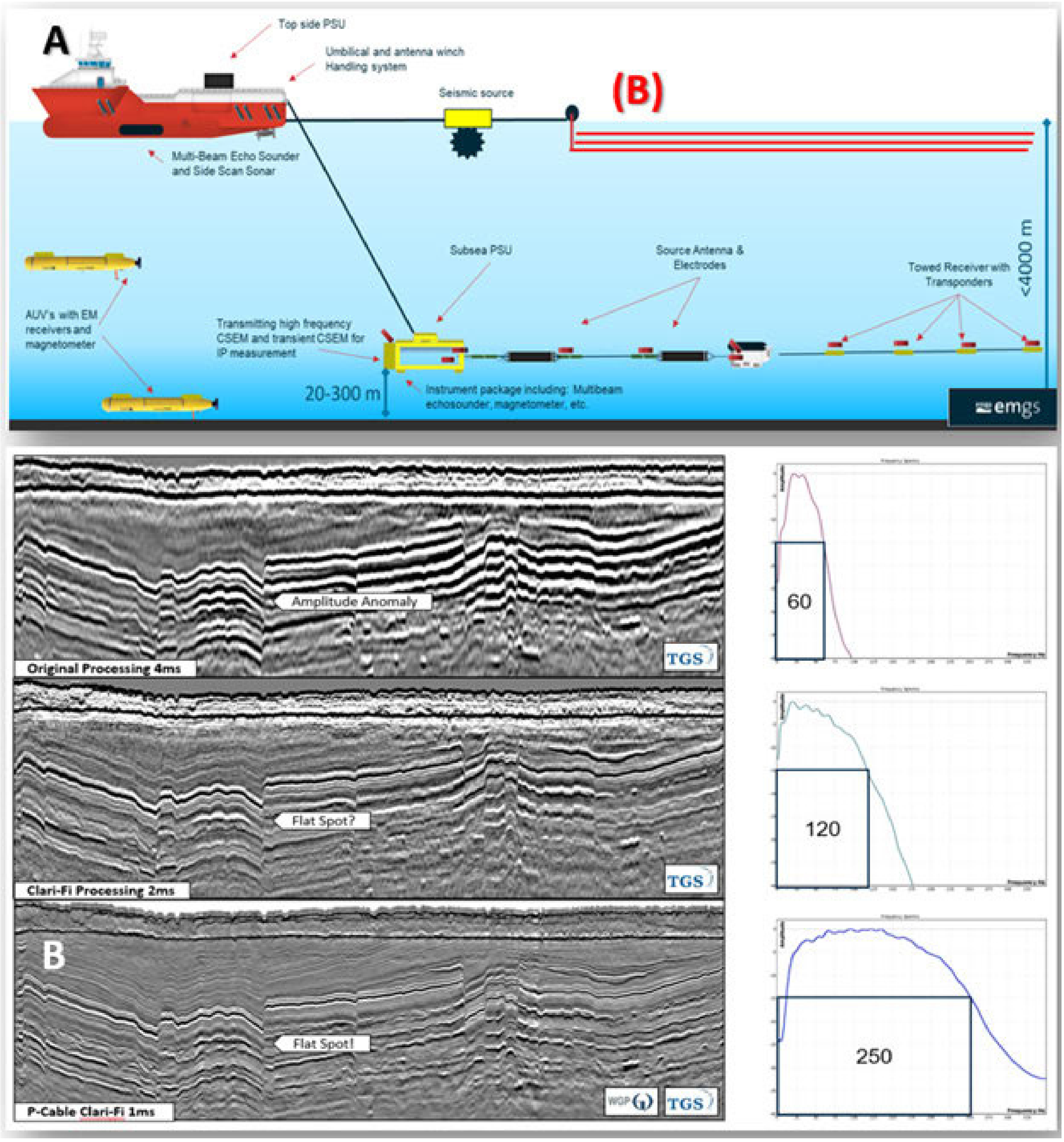

Figure shows the proposed acquisition setup of combined deep tow EM (A, EMGS) and high resolution short, dense 3D like P-Cable below (B, TGS). In addition, two AUV's flying on the sides with EM+ gravimetric tool and there are plans to equip the EM source module with multi-beam echosounder and another gravimetric tool. Panel B shows the difference in seismic resolution between 4ms sampled ghosted conventional 3D data versus 2ms de-ghosted conventional 3D data versus at the bottom 1ms de-ghosted P-Cable in the Barents Sea. Typically, we see a quadruple increase in resolution over vintage ghosted 3D seismic. Similar results are found at ~2000m water depths on the HR15 P-Cable survey.

Geodynamic Models, Hydrothermal Vents and Metal System Analysis

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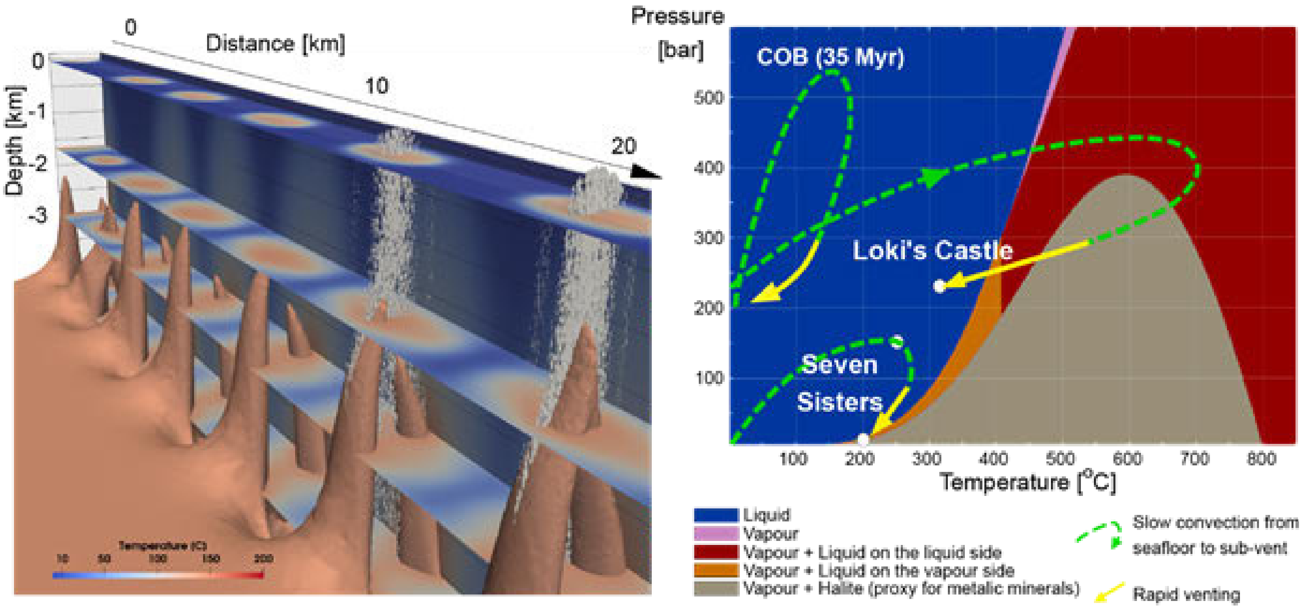


(Left) Hydrothermal convection model for an (actual) off-ridge transform, showing temperature and fluid flow (small arrows). (Right) PT loops extracted from the convection models compared to data from Loke Castle (Petersen et al., 2010) and Seven Sisters (Marques et al., 2020). Data er plotted onto a 2D-static seawater phase diagram. Metals will deposit in vents where PT loops have entered the solid mineral field. Note that the combined model suggest that metals will only deposit (near the surface) in one of these vent-systems.

After decades of hydrocarbon exploration, the main risk still resides in pre-drill predictions of hydrocarbon volumes and phase. Understanding the **Ultimate Recoverable Resources** (URR) involves investigations of where hydrocarbons form, move and accumulate, in short petroleum system analysis (PSA).

Accurate estimates of the URR of marine minerals/metals, should involve some form of **Metal System Analysis** (MSA), with similarities to PSA.

Both starts with geodynamic analysis, and then narrows into predictive models of where metals move and deposit from regional to prospect-scale. For vents (active or 'dead'), the building blocks of MSA are similar to PSA: Lithology/rheology, pressure, temperature, stress, time, phase of the fluid/vapor/solid. Also, the goal is the same: Where are the conduits and deposits?

The upsides of MSA are reflected in the economics and environmental impact of accurate forecasting. The exercise itself has relatively low cost and no environmental impact. As exploration escalates into surveying and sampling MSA will iteratively improve and be the tool for further work and benchmarking.

Here we illustrate how geodynamic and hydrothermal flow analyses contribute to MSA by combining North Atlantic-scale 3D thermal models (Schmid et al., 2021) and intermediate scale hydrothermal-chemical convection models (figure). We study the time-evolving pressure-temperature (PT) path of specific vent sites along regional short-lived hot (ridges) and long-lived cold (transforms) structures. The PT-paths of these convection cells are mapped into equations of state (phase) calculations (Driesner and Heinrich, 2007), using halite as a proxy for metallic minerals (e.g. chalcopyrite, (Guo et al., 2020)). The calculations show where minerals form sub-vent before rapidly being vented ('spit') out.

The locations of vent sites result from an interplay of geodynamics and hydrothermal convection. Fully coupled, lithosphere-scale mechanical (SmartTectonics) models show the complex geodynamic state of the mid-ocean (Mohn) ridge is. The stress state depends on the overall spreading velocity, magma supply, mechanical properties, and the presence of faults (Howell et al., 2019).

There are multiple scientific, environmental and exploration outcomes of these models. For example, will the vents carry metals, and if so, will they deposit under the vent/surface, or flow into ocean, and if so, in what form?

Presently MSA cannot accurately predict where metals will deposit, but we can begin to predict where they will not deposit. Future developments will refine this approach, guide exploration and limit the environmental impact of surveying and exploring.

Financing Options for Exploration of Marine Minerals

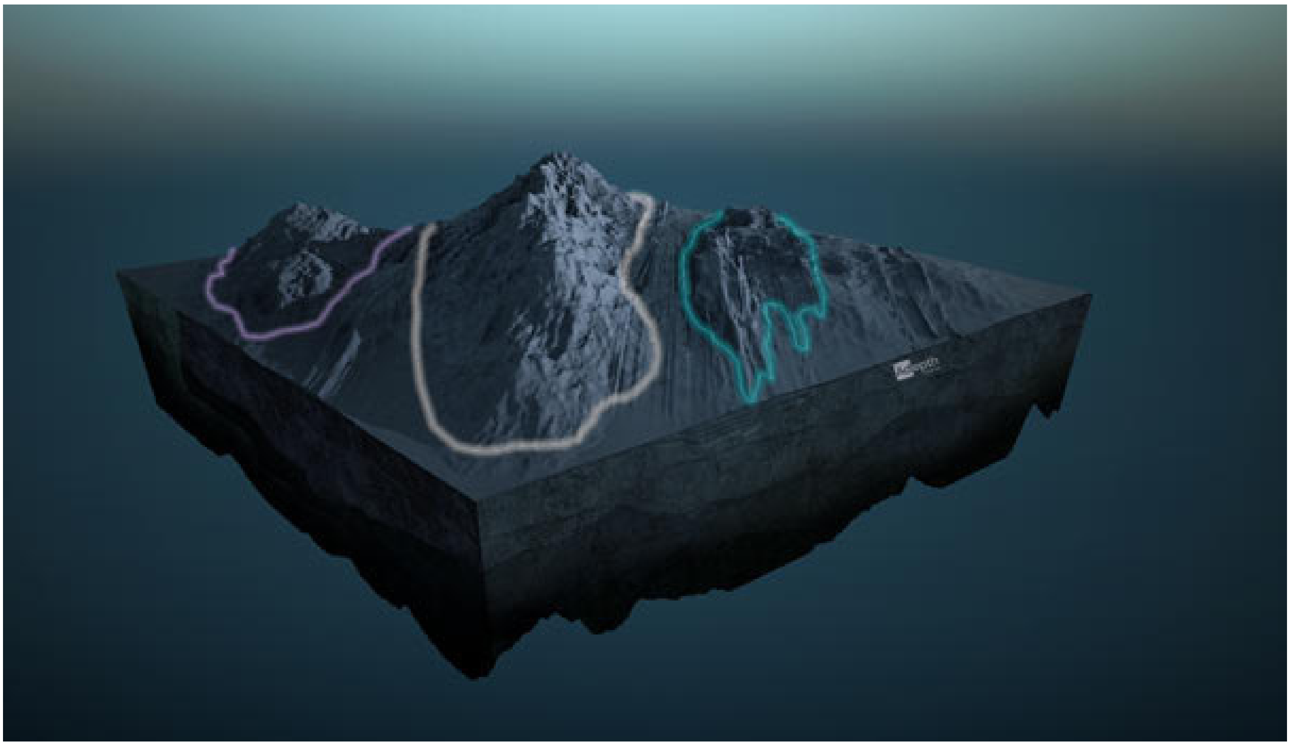
ANDREAS STRAND, ØYSTEIN VAAGEN, FEARNLEY SECURITIES

Fearnley Securities (part of the Astrup Fearnley Group) has advised and helped leading Deep Sea Mineral companies raise attractively priced growth capital from both industrial players and financial investors. During our presentation we will talk about how companies can attract investors given the early stage of the Deep Sea Mineral sector and what we have learned from raising capital for the leading Deep Sea Minerals companies globally.

Furthermore, we will go through our valuation framework and explain the financial upside potential we see in the Deep Sea Mineral industry, while lastly highlighting how the few publicly listed companies are priced today and how pricing has developed since their IPOs.

Unlocking the Potential in the Deep Ocean

ANETTE BROCH MATHISEN TVEDT, ADEPTH MINERALS



A growing demand for critical minerals to support a green energy shift (as outlined in the International Energy Agency 2021 report "The Role of Critical Minerals in Clean Energy Transitions") has led to the global exploration for marine minerals. Adepth Minerals is currently focused in on actively contributing towards a sustainable and successful exploration of deep-sea minerals. Adepth Minerals is a competent, data-driven, and innovative deep sea minerals exploration and production company with focus on the Norwegian shelf. As a highly data-driven organization, Adepth aims is to explore for the sought-after materials in an environmentally responsible manner utilizing all data available in the smartest way possible.

To develop our exploration concepts we need more data, and thereby we need to take part in developing exploration technology that will provide better, more cost-effective technology and methodology for data collection for seabed mineral exploration. We aim to develop deep-water core drilling equipment, mapping, and environmental monitoring technology that can be used simultaneously for detailed subseafloor mapping of marine minerals.

Key to reducing our environmental footprint is our exploration strategy that will use all available data to rapidly eliminate non-prospective areas and focus in on the anticipated soccer field sized deposit locations. Integral to our elimination process is our focus on lower-impact resource regions such as extinct hydrothermal deposits. Our exploration strategy automatically assigns all active hydrothermal fields as non-prospective, and we will work with scientist to determine appropriate buffer-zones around active hydrothermal fields.

The integration of data is key and ensuring we obtain geological and ecological information from the subsurface of hydrothermal sulfide deposits and manganese crusts, will help us ensure that we can perform exploration and extraction of deep-sea minerals minimizing our environmental footprint and reducing emissions.

Green Minerals – Enabling the Green Shift

STÅLE MONSTAD, GREEN MINERALS

The green shift is hungry for raw materials due to the ever-increasing electrification of the society. The forecast inadequacy between supply and demand will lead to commodity market stress and the subsequent delays in green policies objectives (Paulikas et al., 2020). Among the commodities at hand, copper and battery metals e.g., cobalt and nickel are in focus. The main challenge now is to build the primary stock of metals up to such a level that the economy is satisfied. The question is where should these metals come from? In land-based mining the ore grades are decreasing, and we are moving towards mining of waste. New sources of copper, cobalt and other metals have been discovered as marine minerals deposits within Norwegian waters. Norway has the necessary technology and experience to extract the marine deposits. Together with a favourable geological setting and a solid political framework we are in a very good position to start this industry.

Within Norwegian waters we have evidence that we have rich resources of Seafloor massive sulphides and Manganese crusts, both with metal grades relative richer to other locations worldwide (NPD 2020). There is no better place to start this industry adventure than in Norway as we have a regulatory framework and 60 years of technical experience with offshore operations from the Oil and Gas industry.

Green Minerals was established November 2020 and listed on Euronext Growth since March 2021 as the first listed marine minerals company in Norway and the only one globally at the time of listing. Green Minerals' mission is to deliver the resources needed for the green shift to the market in a sustainable and responsible manner.

Many uncertainties remain regarding the environmental impact of seafloor mining. Because of the limited footprint of Seafloor massive sulphides deposits compared to other types of marine mineral's deposits, Green Minerals focuses on the exploration and mineral production from extinct and inactive sulphide deposits.

Our philosophy is to:

- Prioritise the production from larger deposits in order to minimise the habitat destruction i.e., minimising the "ecological capital expenses (CAPEX)"
- Ensuring that the largest portion of the deposits are mined by understanding "value" as a metric not limited to an economical value for a project but finding synergies through several projects
- Ensuring that environmental constraints are understood and integrated in operational strategies and procedures.

To become a global leader within of the marine minerals industry, Green Minerals focuses on establishing a benchmark model within the Norwegian jurisdiction which can be exported as a best practice to international areas. The Company is already discussing with international authorities as part of this plan.

Green Minerals believe in a capital light approach, and it has entered into agreements with several companies that have a proven record within this nascent marine mineral industry. This strategy will help us keep our capital costs low and leave us to focus on what we do best, which is managing the overall value chain encompassing exploration, production and logistics.

Several studies (Rystad 2020, Ellefsmo et al,. 2019) indicate that the marine minerals industry has a massive social economic upside and a significant potential, nationally and globally.

Green Minerals will be one of the leading pioneers ensuring this industry gets off the ground. We have now positioned ourselves as one of the leading companies in Norway and we are looking forward to being given the responsibility to exploit the marine minerals in the most sustainable way possible, nationally and internationally.

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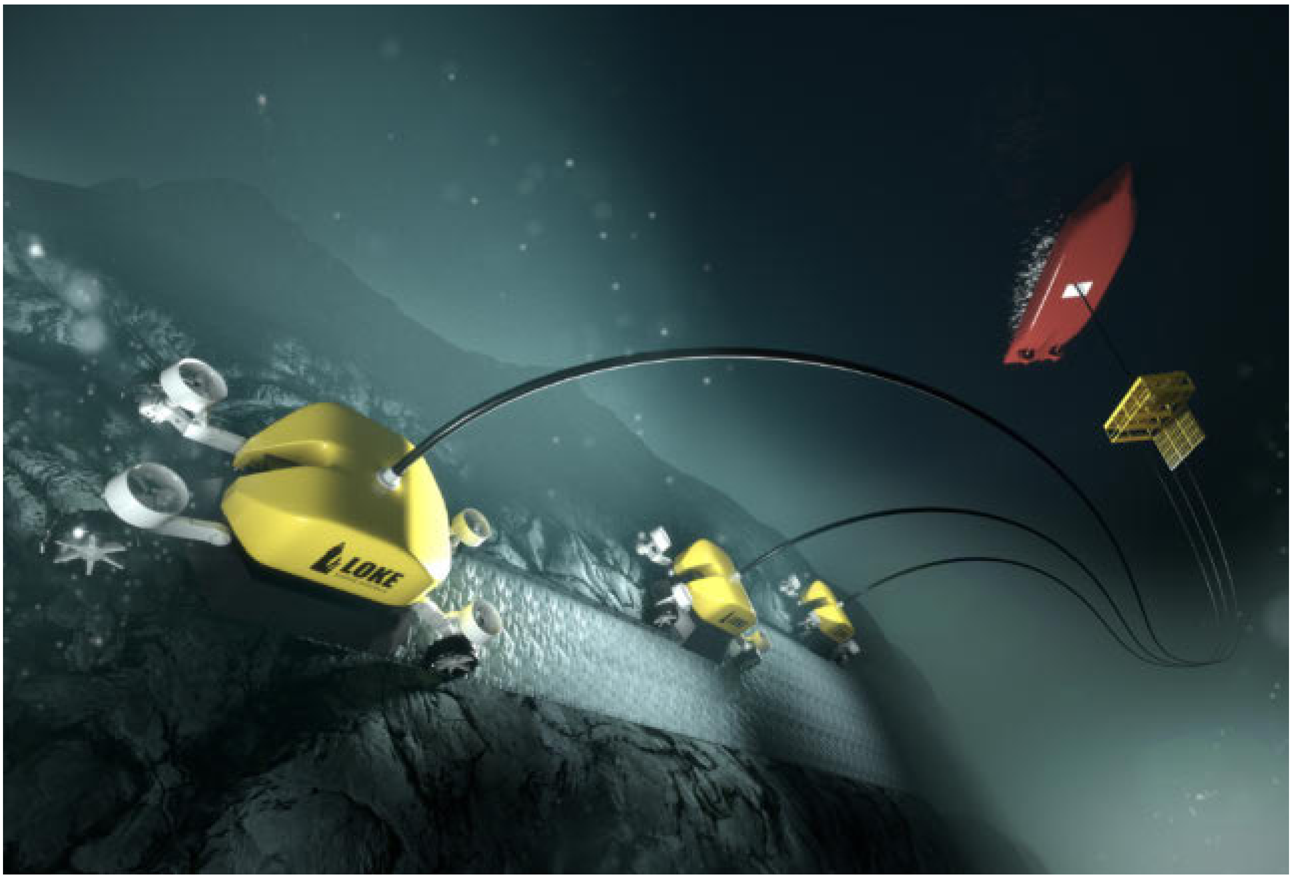
Loke Marine Minerals – A front runner in Marine Mineral exploration and production

WALTER SOGNNES, LOKE MARINE MINERALS



Loke Marine Minerals was established in 2019 by experienced offshore energy leaders and entrepreneurs to become an international leading marine mineral company.

In August 2021 Loke Marine Minerals completed a private placement of equity which will enable the company to fund further development of enabling technologies. Together with our partners Loke Marine Minerals will leverage its E&P and subsea technology experience to develop breakthrough proprietary technology for both exploration and production of marine minerals.

Loke is implementing the most ambitious environmental plan in the mining industry, building on the framework and track-record of the oil and gas industry in Norway over the past decades.

The process of opening for exploration and production of marine minerals within Norwegian Exclusive Economic Zone is ongoing with a final decision expected in 2023. Loke will be ready to apply for a license on Norwegian EEZ in 2023.

In the meantime, we will focus on securing licenses within the International Sea Authorities (ISA) jurisdiction. Standing on the shoulders of 50 years of Norwegian oil and gas industry, Loke will be a fast mover internationally. We have already developed enabling technology for excavation of manganese crust. This is a breakthrough technology which puts Loke in a pole position for mining of manganese crust.

Our unique manganese crust mining tool is founded on our knowledge and experience from the Oil & Gas industry. We are basing it on ROV technology where tool weight is compensated with buoyancy. By having a common center of gravity and buoyancy, the tool is neutral also in pitch & roll and we can then work on any surface – both vertical and horizontal.

The terrain on seamounts can be very uneven – meaning it will be impossible to use large machines.

However, by using technology from the autonomous vehicle industry, we can use several smaller machines in formation and having them operate as one larger machine and thereby obtain sufficient volume and Recovery Rate of Manganese Crust. This tool is just the first of many enabling technologies Loke will be developing together with Technip FMC and our other partners.

When we develop technology our highest priority and key focus is minimum environmental impact. This is in our DNA, and we understand the challenges with ultra-deep waters.

We see a large cross-over from the oil and gas industry to the marine mineral industry. For us it is obvious that the marine mineral industry needs the experience and technology from deep water oil and gas industry. This is the best way to ensure that marine minerals are extracted with lowest possible environmental impact. The oil and gas industry has used decades mastering harsh environment and ultra-deep waters. There is a unique potential for the oil and gas industry to use this experience to be a frontrunner in developing this new industry. Not only in Norway but also internationally. Norwegian oil and gas industry can become a global industry leader as we are on many segments within the offshore oil and gas industry.

There is no doubt that large amount of minerals is needed for the green energy transition. The IEA report - **The Role of Critical Minerals in clean energy transition (2021)** – clearly states this. Current terrestrial reserves are not sufficient. Already within a few years demand will exceed supply for several of the critical minerals. You cannot embrace the IEA report – **Net Zero by 2050** (2021) - and use this as an argument against the oil and gas industry and at the same time ignore IEA's mineral report. These two are connected. You can have one without the other.

POSTERS

Seabed Mineral Services

THE VERTICAL APPROACH

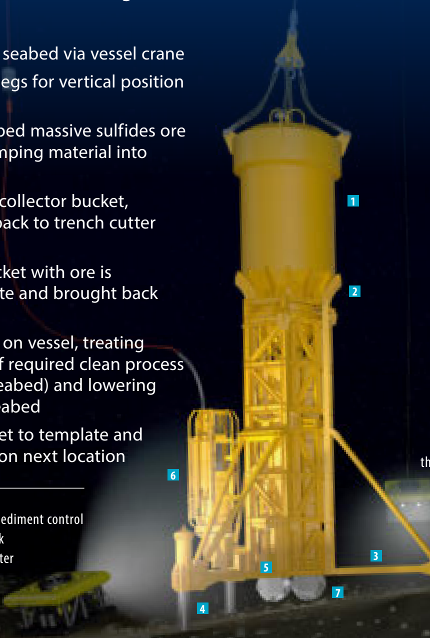
Sustainable Exploration and Exploitation of Mineral Resources in the Deep-Sea

THE TECHNICAL CONCEPT

Using trench cutter technology for vertical seabed massive sulfide sampling and / or mining

Procedure

- Lowering sampling unit to seabed via vessel crane
- Leveling of template with legs for vertical position of trench cutter
- Cutting and sizing the seabed massive sulfides ore with trench cutter and pumping material into collector bucket
- Separation process within collector bucket, process water is pumped back to trench cutter (closed circuit)
- After cutting, collector bucket with ore is disconnected from template and brought back to vessel via crane
- Emptying collector bucket on vessel, treating remaining process water (if required clean process water is brought back to seabed) and lowering collector bucket back to seabed
- Connecting collector bucket to template and positioning sampling unit on next location



1 Collector bucket
2 Adapter for collector
3 Template
4 Template legs
5 Collar for sediment control
6 Power pack
7 Trench cutter

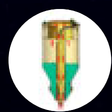
FOCUS ON SUSTAINABILITY

Minimizing footprint of the operation in all aspects

Separation process

Water with ore cuttings feeding into collector bucket

Solids setting



Surplus water overflowing through lamella thickener and returning to cutter

- In-situ separation of ore cuttings and process water at seabed and reuse of treated water at trench cutter
  - No mixture of seabed water with surface water
  - Minimizing quantity of water used for process
- Electrically driven pump and cutter
  - Reducing risks of oil pollution
- Selective and precise vertical cutting with one tool only
  - Small footprint on seabed, possibility to preserve sensitive areas
- Collar around cutter wheels
  - Minimizing formation of sediment plumes
  - Reducing noise emissions from cutting process
- Closed process water circuit and discontinuous ore transport via lifting collector bucket to vessel
  - Energy savings because no return of process water to seabed required

JOINT VENTURE BETWEEN BAUER AND HARREN & PARTNER

Target: Combination of established technologies for minimizing risks and keeping costs down

HARREN & PARTNER

BAUER MASCHINEN

HARREN & PARTNER

- Founded in Bremen in 1989, a privately owned maritime services conglomerate
- Core competence is to manage complex maritime projects and deliver a wide range of high-end services to a global client base
- The H&P fleet currently consists of 85 units – heavy lift carriers, bulkers, tankers, dock ships, container vessels, tugs, barges and offshore vessels
- 22 offices in 19 countries, 270 colleagues ashore and 2,900 at sea – 47 different nationalities working as one team
- Existing technologies and assets

Contact: h.felderhoff@hp-shipping.de

BAUER MASCHINEN GMBH

- Is one of the three segments of the BAUER Group
- The BAUER Group employs over 10,000 people and, with more than 110 subsidiaries, operates in around 70 countries worldwide
- Designer and manufacturer of specialist foundation equipment since the 1970s and 37 years of experience with trench cutter technology
- Trench cutters are typically used for in-situ construction of reinforced concrete walls and cutting depths of > 250 m have been reached
- Besides construction equipment, BAUER Maschinen GmbH also has experience with various offshore applications

Contact: leonhard.weixler@bauer.de

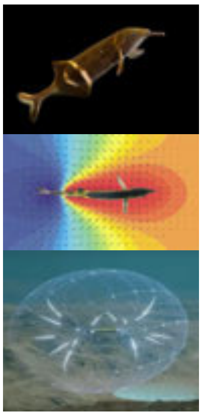
SUBSEA ELECTRIC SENSE

a biomimicry technology for Deep Sea Minerals localisation & characterization

ELWAVE

BERGEN 19-21 OCT 2021 NCS EXPLORATION DEEP SEA MINERALS

Inspired by Nature

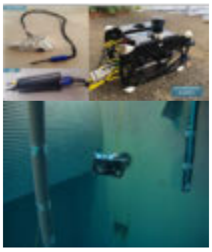


Electric sense is a perception mode used by weakly electric fishes leaving in tropical murky waters in which vision and acoustic perception are inefficient. Thus, natural evolution has led to an electromagnetic adapted new perception mode, the "electric sense".

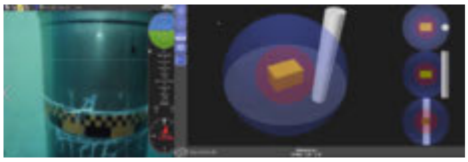
These fishes generate a very low electromagnetic field, harmless for the fauna and the flora, in their vicinity ("electric bubble"). The obstacles penetrating in this bubble perturbate the electromagnetic field and the fishes perceive, thanks to electroreceptors on their skin, these perturbations. By analysing these perturbations, the fishes locate and characterize the objects and obtain a 360° real-time "electric image" of their environment.

The biorobotics laboratory of the top French academic "Mines-Telecom Atlantique Institute" has worked since 2005 to develop sensors based on the "electric sense". ELWAVE has been created in 2018 on the basis of these academic results and has developed the 'BLUESENSE' proprietary technology, reproducing this perception mode.

Localization by Electric sense

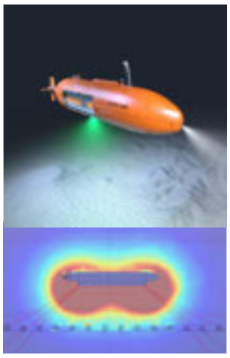


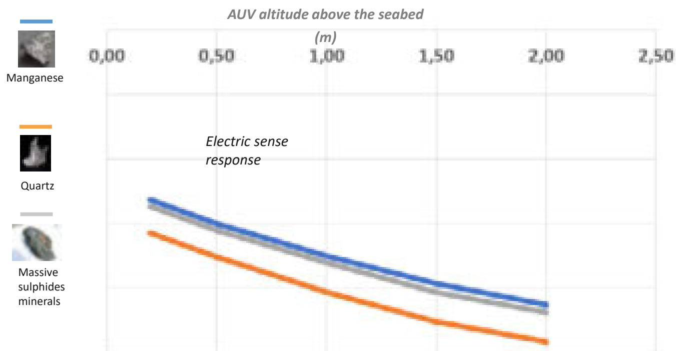
- An electrodes octopus is fitted on the vehicle. Connected to the electronic POD, the embedded algorithm will command and control the dipoles interrogation strategy to detect, localize and define the size and shape of the detected objects.
- Sea trials conducted at IFREMER pool test in 2020 demonstrated a decimetric 3D positioning accuracy.



- The maximum detection range is now going to be extended to 5 times the ROV/AUV size. This performance can be pushed further for specific vehicle designs.

Deep Sea Minerals characterization by Electric Sense



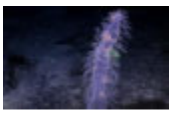


This simulation assesses the minerals identification capabilities of the Electric Sense.

Considering the conductivities of Manganese (7.10^5 S/m), Quartz (1.10^{-4}S/m) and Massive Sulphide Minerals (1.10^2S/m), we observe different Electric responses above the detection threshold of Elwave system, proving its capability to discriminate in between the seafloor components.

Electric Sense benefits for Deep Sea Minerals operations

✓SOFT & CONTACT LESS



Only 1W electric field generated is expected to be harmless to most deep-sea life

✓SMART ROBOTIC EXPLORATION

Embedded processing and analysis Electric sense algorithms could allow smart vehicles to adapt their mission according to the observed ressources (even buried)

✓SMART ROBOTIC EXPLOITATION

Electric Sense can be used to focus the harvest operation, as an ant- collision & swarm navigation system

Towards mineral system modeling
Resource assessments and process understanding at the TAG hydrothermal field

Lars Rüpke, Zhikui Guo, Sven Petersen

GEOMAR

Background

Meeting the UN sustainability goals and engaging in the energy transition will require sustained and even increased primary mining for the foreseeable future. Electrifying transport and switching to renewable power generation all involve more metals than conventual cars and power stations (Fig. 1). This has and will continue to result in increased metal production, so far coming only from terrestrial mines.

Does this mean we are running out of metals, or that there is a supply shortage? No. A recent paper analyzing reserves to production ratios shows that these ratios have remain fairly constant for the past 30 years (Jowitt et al., 2021); miners appear to be able to increase reserves as production is ramped up. Still, a societal debate is needed from where and at what environmental impacts we will source our future raw materials and what the role of seabed resources could be in that equation. This poster shows pathways towards resource assessment and mineral system modeling using the TAG hydrothermal field as an example in order to provide background information that may help in the discussion.

Figure 1a: UN sustainable development goals as outlines in 2015

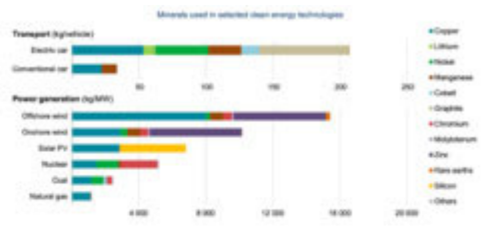


Figure 1b: International Energy Agency report 2021.

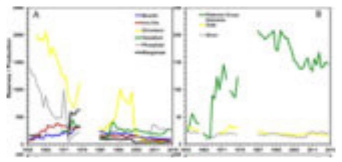


Figure 1c: taken from Jowitt et al. (2021), reserve/production ratios shows no major change over past 30 yrs.

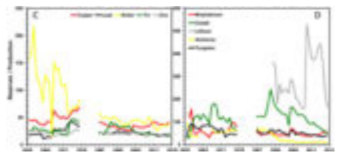


Figure 1d taken from Jowitt et al. (2021), reserve/production ratios shows no major change over past 30 yrs.

Seabed mineral resources

The seafloor host vast amounts of natural resources including manganese nodules, cobalt-rich crust, and massive sulfides. This poster focusses on massive sulfides in the oceans' neovolcanic zones and how we can quantify their abundance and resource potential.

Box 1: Types of seafloor mineral resources

Nodules

- 34 billion tons in the CCZ alone
- form on sedimented deep sea plains (3,000 – 6,500 m)
- growth rate: <5 – 20 mm/mio years
- contain Mn + Fe; plus **Cu + Ni + Co,** plus trace metals incl. REE
- 2D resource

Crusts

- resource potential also huge
- grow on flanks of old seamounts
- growth rate:
  1-5 mm / mio years
- highest **Co + Ni** at depths: 800 – 2,500 m
- elevated REE
- 2D occurrences

Sulfides

- at divergent volcanic plate boundaries
- depth: 300 – 5000m
- growth rate: 100's to 1000's tonnes / year
- **Cu + Zn + Au + Ag**
- regional and local chemical variability
- **~600 Mt, 3D resource**

Bottom-up: how much massive sulfide in the neovolcanic zones?

Given the sparsity of seafloor observations, robust and reliable prediction on the ocean's massive sulfide endowment are not possible. To bracket the likely amounts, we here review results of two different approaches. A bottom-up approach that evaluates the amount of metal possibly mobilized by high temperature fluid flow, and a top-down approach that extrapolates from known accumulations using statistical methods. First we look at the bottom-up approach first formulated by Cathles, (2010):

Reasoning:

- within the neovolcanic zone, high temperature fluid flow must "remove" the heat necessary to cool the crust from ~1200°C down to ~350°C and to crystallize 6km thick basaltic magma to make the crust.
- hydrothermal flow models arrive at the average scaling that 1 kg of hydrothermal fluid is needed to cool 1 kg of basaltic rock.
- this, combined with the average spreading rate in the oceans, allows computing the high temperature fluid flux needed to make 1 new square meter of seafloor.
- to relate this to massive sulfide (or metal) accumulation rates, an average metal concentration in those high-T fluids and a deposition efficiency (approx. 3%) is needed.
- with these rough values, a "copper flux" of 0.3-1.2 Kg Cu per m^2 of new seafloor can be computed
  - note that the value given in the publication is 9.8 to 41.9 kg m^{-2}, which then needs to be multiplied with the "deposition efficiency" of 3% to get copper in massive sulfides.
- this value can be seen as an upper bound.

Top-down: how much massive sulfide in the neovolcanic zones?

An alternative complementary approach is to start with how much massive sulfide has been found in the neovolcanic zones and to use statistical methods to extrapolate. This method has been used by Hannington et al. (2010) and details can be found there.

Reasoning:

- starting point is the likely number of massive sulfide accumulations in the oceans. The likely number of active sites (approx. 1000) is a good proxy.
- Careful analysis of known accumulations allows formulating a probabilistic tonnage model, plotted as the red line in Fig. 2b. Note how submarine accumulations are much smaller than terrestrial VMS deposits.
- Monte-Carlo-type sampling of this tonnage-distribution curve with the likely amount of deposits results in the distribution shown in Fig. 2c. Just as in Hannington et al. (2010), the prediction is about 600 Mt massive sulfide in the neovolcanic zones (containing about 30 Mt of Cu plus Zn, or 1 year global metal production).
- Making assumptions about the width of the neovolcanic zone and the average spreading rate allows to also compute a "copper flux" of 0.034 Kg Cu per m^2 of new seafloor using the top-down approach.
- Note that the value in the original paper is 0.34 Kg Cu per m^2 but that refers to the concentrated flux into 1/10 of the neovolcanic zone width.
- This 10-40 times differences can be taken as evidence that
  - the total amount of massive sulfide in the neovolcanic zone is relatively small with respect terrestrial sources (based on the currently available data)
  - locally, however, accumulations could be significant if the "right" geological conditions exists to accumulate a large fraction of the metal mobilized by high temperature fluid flow.

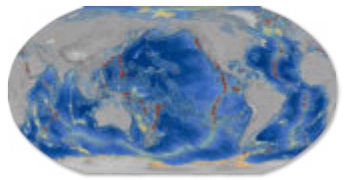


Figure 2a: Distribution of known hydrothermal vent sites (Petersen et al., 2016)

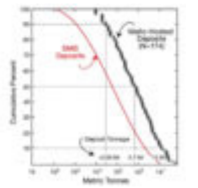


Figure 2b: Tonnage model for submarine massive sulfides (SMS); taken from Hannington et al., 2010.

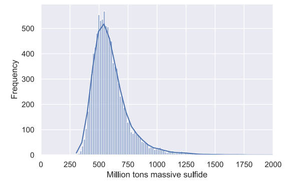


Figure 2c: Random sampling with the number of likely accumulations of the distribution shown in Fig. 2b results in a mean global value of approx. 600 Mt of massive sulfide.

How to make a prolific mineral system? The TAG hydrothermal field

Submarine massive sulfide deposits on slow spreading ridges seem to be larger and longer-lived than deposits at fast-spreading ridges, likely due to more pronounced tectonic faulting creating stable preferential fluid pathways. The active TAG hydrothermal mound on the Mid-Atlantic Ridge is a type example being located on the hanging wall of a detachment fault. It has formed through distinct episodes lasting 10s to 100s of years of high-temperature fluid discharge throughout at least the last 50,000 years and contains about 2.7 Mt of massive sulfide. Yet, the mechanisms that control the episodic behavior, keep the fluid pathways intact, and sustain the observed high heat flux of up to 1800 MW remain poorly understood. Here, based on the joint interpretation of hydrothermal flow observations and findings of 3-D flow modeling, we show that TAG can be explained by episodic magmatic intrusions into the footwall of a highly permeable detachment surface. Each intrusion drives a three-dimensional circulation system in which the flow directions are reversed with respect to previous ideas in that recharge occurs along the detachment and discharge is sub-vertical along intersecting tectonic faults in the hanging wall.

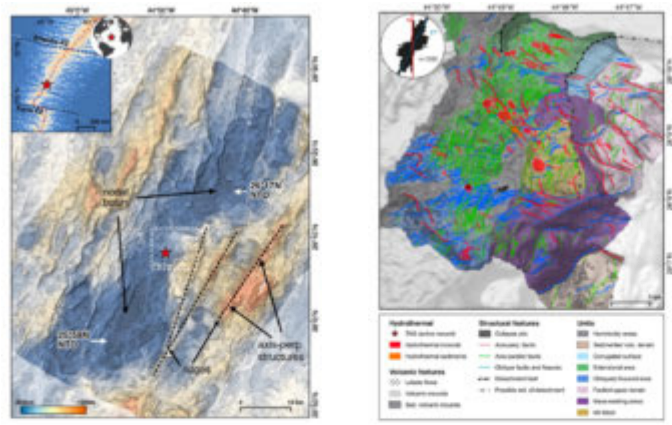


Figure 3: Figures from Graber et al., 2020 showing the structural elements of the TAG segment and the location of known massive sulfide accumulations. Those accumulations, including the active TAG mound, are located at the intersection of two sets of cross-cutting normal faults in the hanging wall of the presumed detachment.

This complex structural configuration of the TAG segment raises important questions about the hydrological regime as well as the maximum circulation depth of hydrothermal fluids and which critical combination of hydro-tectono-magmatic processes resulted in the accumulation of approx. 2.7Mt of sulfides at the TAG mound. To address this question we use a 3-D hydrothermal flow model instructed by multiple geophysical and geological data sets including:

- 2D/3D tomography
- gravity, magnetic, and controlled-source EM
- AUV bathymetry
- fluid chemistry
- seafloor sampling

A TAG geomodel: Scenario testing

Based on the available data, we test scenarios in which the repeated magmatic intrusions into the footwall of the detachment drive phases of hydrothermal circulation. The guiding assumption is that recharge is channelized along the detachment surface and that discharge is channelized along the intersecting normal faults identified in the high resolution bathymetric data.

The exact location of the heat source driving the current phase of activity is unfortunately poorly constrained and was not identified in recent seismic surveys. The existing 3D tomography (Zhao et al., 2012) did reveal a low velocity zone and a zone of inverted velocity gradients in the footwall, we take those anomalies as proxies to the likely heat source.

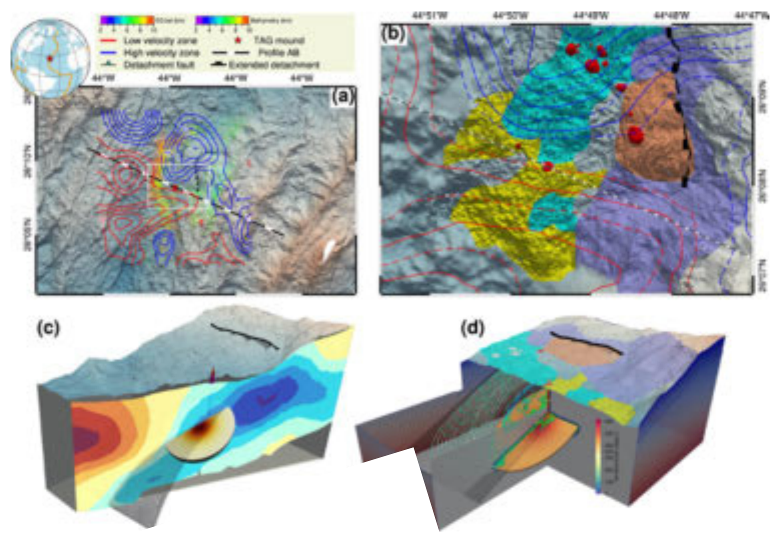
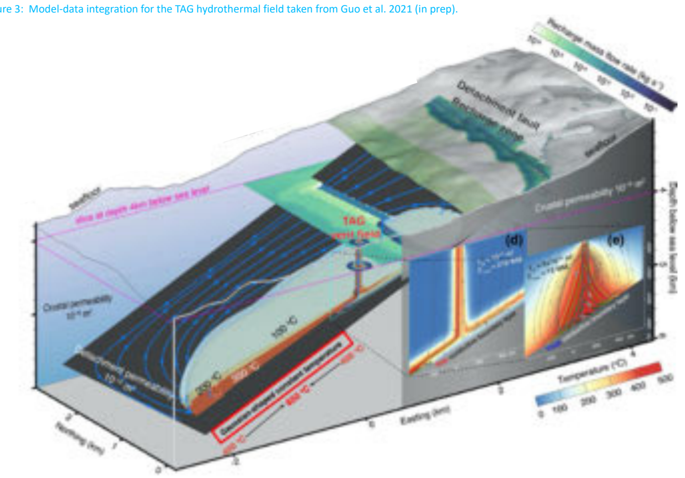


Figure 3: Model-data integration for the TAG hydrothermal field taken from Guo et al. 2021 (in prep).



A revised flow model for the TAG hydrothermal field

We have performed many 2-D and 3-D numerical simulations to assess the likely flow solution and to evaluate which model parameters result in model predictions most consistent with the available data. Based on this analysis we propose that:

- hydrothermal circulation beneath the TAG segment is driven by episodic magmatic intrusions into the detachment footwall
- the exact location of that intrusion determines if discharge occurs only at the TAG mound or also at other sites
- matching the model to the observed high heat flux requires the intrusion to be located close to the highly permeable detachment surface
- recharge flow is mainly occurring along the detachment surface; discharge flow is channelized along the intersecting normal faults
- key to accumulating the observed amounts of massive sulfide is the re-activation of the discharge pathways along the intersection normal faults, so that massive sulfides can be accumulated throughout multiple phases of hydrothermal activity
- these features may be a guide to the critical combination of geological parameters required to make a prolific mineral system at slow-spreading ridges.

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Deep-sea electric and magnetic surveys over active and inactive basalt-hosted hydrothermal sites of the TAG Segment (26°, MAR): An optimal combination for seafloor massive sulfide exploration

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Abstract

A GEOMAR (Kiel, Germany) research team has developed a passive electric field acquisition system for Autonomous Underwater Vehicles (AUVs) to optimize seafloor massive sulfides exploration. This sensor was made of two perpendicular and horizontal pairs of electrodes, and was successfully tested over active basalt-hosted hydrothermal site TAG (26°N, Mid-Atlantic Ridge) and several inactive sites in its vicinity. The resulting data underline the efficiency of combining deep-sea electric and magnetic measurements for searching for active and inactive hydrothermal vent fields. With these datasets, it becomes possible to determine the geological nature of the targets and to constrain the characteristics of fluid circulation at depth without involving costly and invasive underwater tools such as Remotely Operated Vehicles or even manned submersibles to collect samples. Data analysis also revealed that AUV attitude variations induce distortions of the electric signal. These distortions start prevailing for dives at altitudes higher than 90 m above the seafloor, as the distance between the AUV becomes too important to guarantee that the signal produced by the geological target still dominates. To improve the acquisition system and reduce the overall noise, we discuss solutions that limit the impact of such attitude variations. These solutions consist of minor adjustments, such as masts at AUVs stern to tow damping electrodes arrays. In such configurations, we believe that deep-sea passive electric measurements combined with high-resolution magnetic measurements can become a highly efficient seafloor exploration tool, including for sulfide deposits associated with inactive hydrothermal systems.

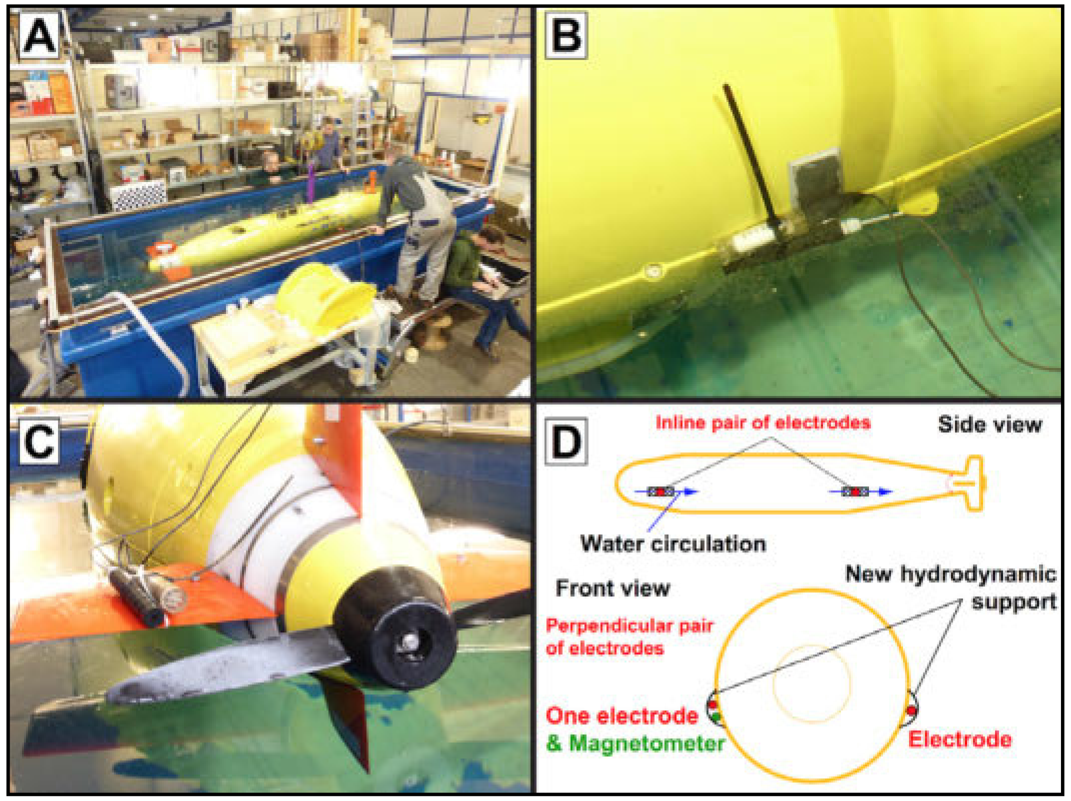

Fig. 1: (A) AUV Abyss in its seawater basin at GEOMAR (Kiel, Germany) during the testing phase of the electrodes. (B) Front electrode mounted to the side of the AUV. (C) Back electrode. The electrode is located on its initial testing position near the AUV propellor. It was later relocated at 1.50 m from the stern, next to the AUV engine. (D) Electrodes configuration. (E) Results of the acquisition system static test in a basin filled with seawater (inline pair of electrodes). The electrodes measure variations of the ambient electric field whereas the AUV engine speeds up. Some limited noise appears when the engine starts, however the peaks on the electric signal are not correlated with variations of the AUV engine speed and likely result from external perturbations in the warehouse hosting the basin. Overall the noise produced by the AUV is of the order of 0.04 mV (i.e., 0.025 mV/m with a 1.60 m spacing between the electrodes). Even if this is not completely negligible, it remains significantly lower than the amplitudes measured over the different hydrothermal targets (of the order of 0.8 mV over TAG, i.e., 0.5 mV/m).

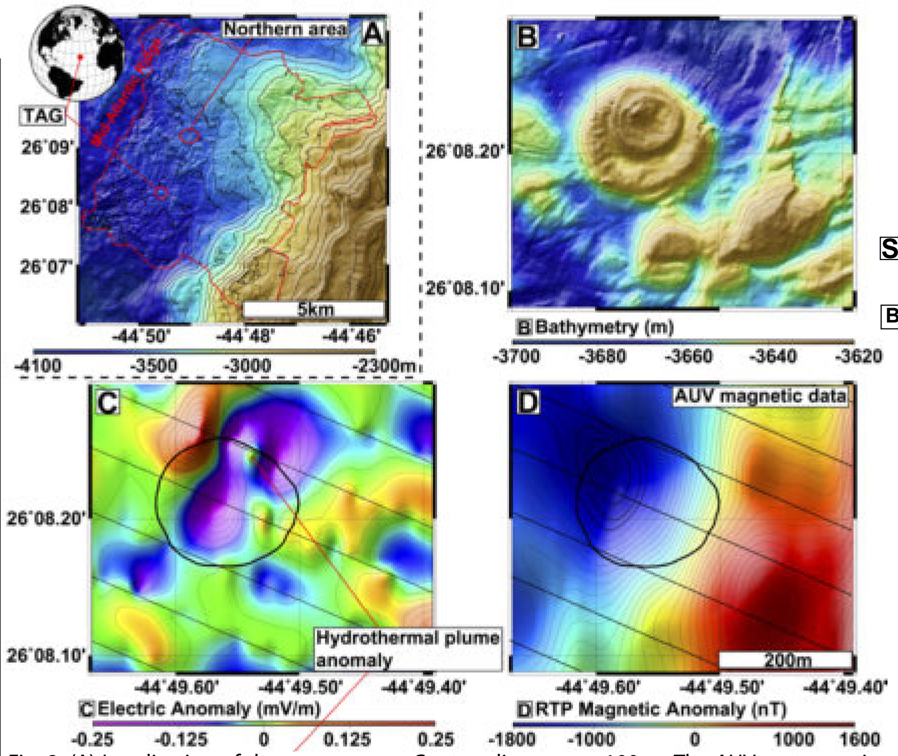

Fig. 2: (A) Localization of the survey areas. Contour lines every 100 m. The AUV route spacing was 100 m. (B) High-resolution bathymetry in the vicinity of hydrothermal site TAG. Contour lines every 10 m. (C) Bimodal electric anomaly from the inline pair over site TAG and seawater temperature along the AUV route. The temperature rise is correlated with the local electric anomaly high. Contour lines every 0.05 mV/m. (D) Magnetic anomaly over site TAG. Contour lines every 100 nT. On both C and D, the black contour line delineates the active TAG mound, and the black parallel lines mark the AUV routes. (E) Characteristics of hydrothermal activity at TAG deduced from our combined magnetic and electric datasets. Hydrothermal fluids rise with a non-vertical angle from the NW and the plume is dispersed in a preferential NE direction.

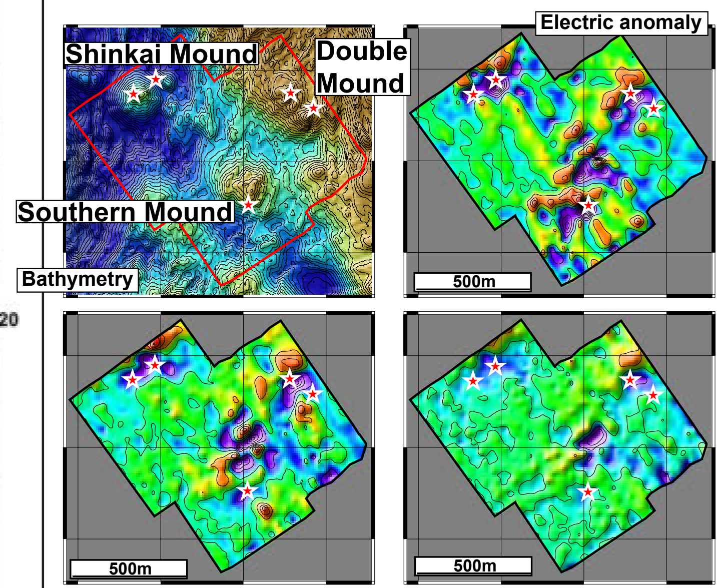

Fig. 4: Clockwise from top left: High-resolution bathymetry of the northern mounds area; Electric data collected by the AUV Abyss at low altitude (on average 35 m) above the seafloor; Electric data collected at the intermediate AUV altitude dive (on average 60 m above the seafloor); Electric data collected at the highest AUV altitude (on average 90m above the seafloor). The inactive hydrothermal vent fields retain a measurable electric anomaly on all dives, however the background noise starts prevailing on the highest altitude data, suggesting that any dive at a higher altitude would become less reliable in terms of inactive SMS exploration. For these three dives, the line spacing was 50 m.

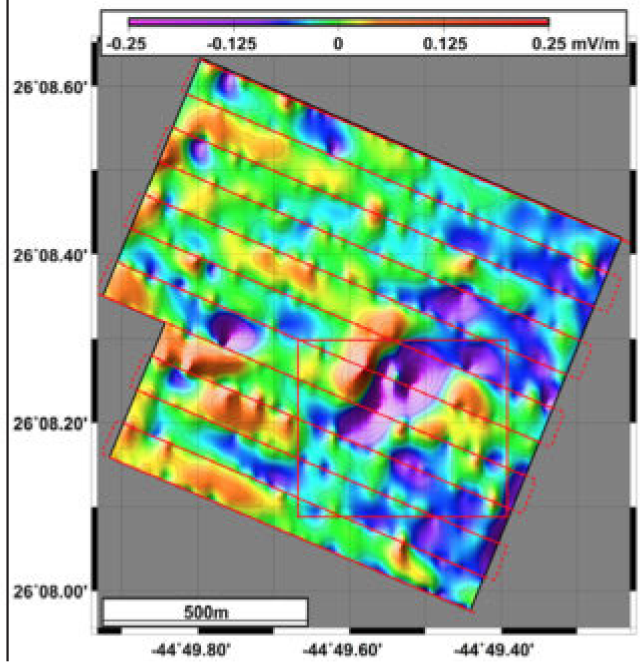

Fig. 3: Electric anomalies over an extended area around the hydrothermal site TAG. The red rectangle delineates the limits of Fig. 2A. Contour lines every 0.05 mV/m.

Even if the hydrothermal site TAG remains associated with the dominant signal, the passive electric data are clearly not devoid of noise, suggesting that improvements can be done on the design of the data acquisition system.

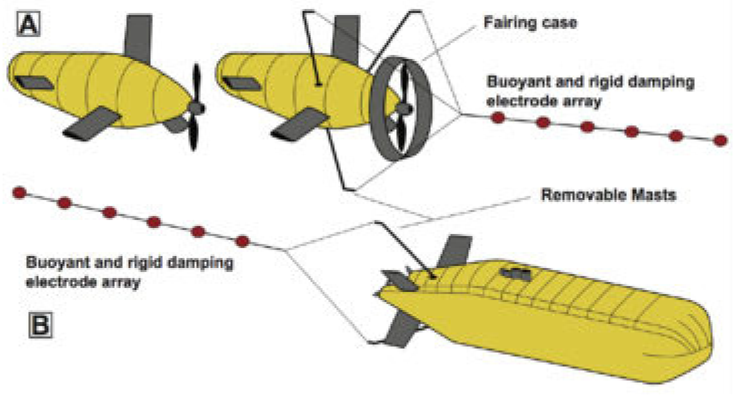

Fig. 5: (A) Representation of the envisioned engineering adjustments on a typical torpedo-shaped AUV. Two or three removable masts could be installed at the stern of AUVs equipped with a single, central propeller. A light fairing case protects the sticks, securing the electrode array from the propeller. The general balance of the AUVs is preserved by the symmetry of the installation and a rigid, neutrally buoyant damping array of electrodes can be attached to reduce signal distortion. (B) Same as (A) but with another widely-used type of AUVs. In this second case, only two masts are needed to attach an array of electrodes at its stern.

Mineral paragenesis and fluid inclusion studies in active submarine hydrothermal systems: Implications for mineral exploration and environmental risk assessment

Sabina Strmic Palinkas[1,2], Rolf B. Pesersen[2], Håvard H. Stubseid[2], Carly Faber[1], Fredrik Sahlström[1], Marie Wold[2]

[1] UiT The Arctic University of Norway, Department of Geosciences, Tromsø, Norway
[2] University of Bergen, Department of Earth Science, Centre for Deep Sea Research, Bergen, Norway

INTRODUCTION

Although active submarine hydrothermal systems do not represent a primary target for mineral exploitation, they give a direct insight into ore-forming processes and may provide valuable information for sustainable and environmentally responsible mineral exploration and exploitation both in deep-sea and on-land conditions.

In particular, understanding the hydrothermal transport mechanism of target commodities is essential for development of successful exploration strategies, while the knowledge about the element composition of ore and gangue mineral phases provides a key input for the estimation of mineral resources and the assessment of environmental risks during and after the exploitation phase.

A mineralogical and geochemical diversity of active hydrothermal vent fields located along the Mohns Ridge of the Arctic Mid-Ocean Ridges (Fig. 1, Table 1) makes this area a unique natural laboratory for studies of submarine hydrothermal systems and associated ore-forming processes.

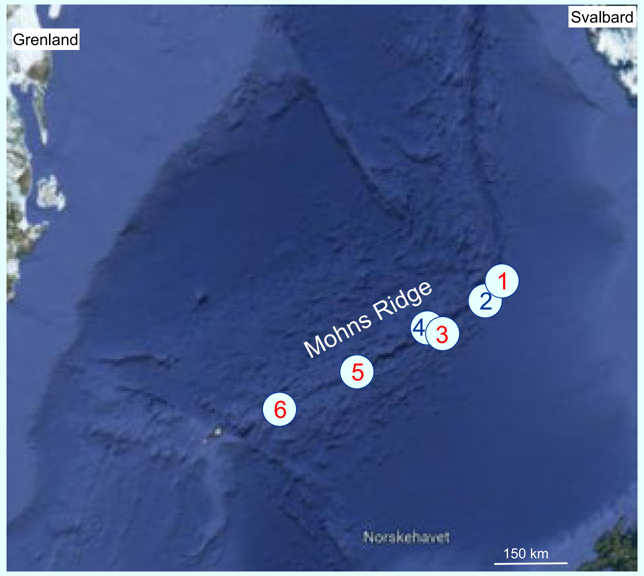

Figure 1. Position of the selected active vent fields (red) and sulphide deposits (blue) along the Mohns Ridge, the Arctic Mid-Ocean Ridges.

Table 1. Overview of the selected active vent fields and sulphide deposits along the Mohns Ridge. Their positions are marked in Figure 1.

Vent field	Depth	Host lithology	Mineralisation
1 - Loki's Castle	~2300 m	Basalt-hosted, sediment influenced	Pb, Zn, Cu, Au, Brt + Hg, Tl, Cd,…
2 - Mohns Treasure	~2600 m	Basalt-hosted	Au, Ag
3 - Fåvne	~3000 m	Basalt-hosted, ultramafic rock influenced	Cu, Co vs. Zn
4 - Gnitahei	~2700 m	Basalt-hosted, sub-seafloor mineralization	Au ± Ag
5 - Æegir	~2400 m	Basalt-hosted	Cu, Zn
6 - Soria Moria	~700 m	Basalt-hosted	Zn, Brt

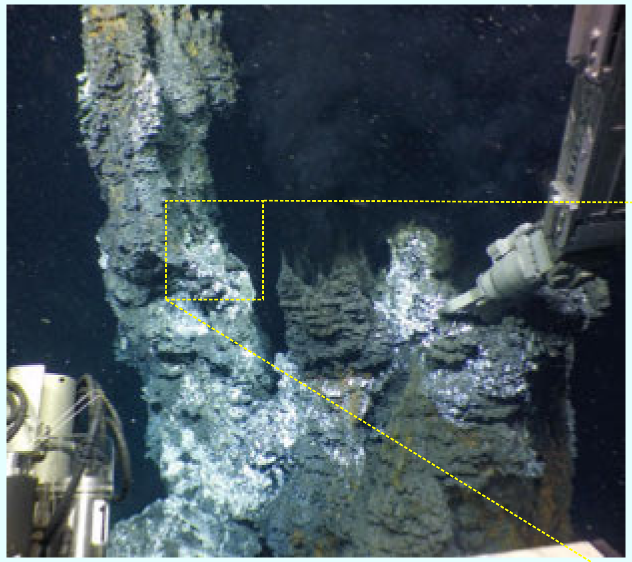

Figure 2. An active chimney at the Loki's Castle Hydrothermal Vent Field, the Arctic Mid-Ocean Ridges.

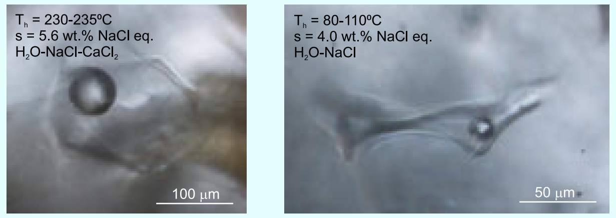

Figure 3. Fluid inclusions hosted by silica in the active chimney at the Loki's Castle Hydrothermal Vent Field, the Arctic Mid-Ocean Ridges. A) Fluid inclusions in the inner portion of the chimneys are characterized by eutectic temperatures around -52°C indicating a H_2O-NaCl-$CaCl_2$ solution. The final ice melting temperature at -3.5°C reflects the fluid salinity around 5.6 wt.% NaCl eq. Homogenization into the liquid phase is recorded in the temperature interval between 230 and 235°C; B) Fluid inclusions in the outer portion of the chimneys have eutectic temperatures around -21°C suggesting a H2O-NaCl system. The final ice melting temperature at -3.5°C corresponds to the fluid salinity of 4.0 wt.% NaCl eq. Homogenization temperature ranges between 80 and 110°C.

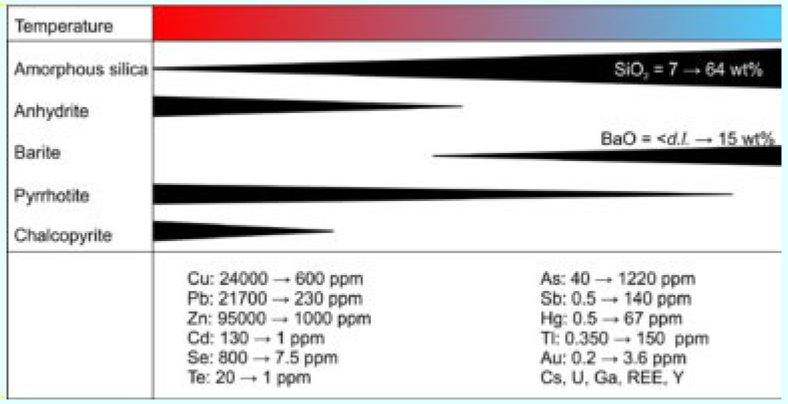

Figure 4. Paragenetic sequence of the Loki's Castle Hydrothermal Vent Field indicates that the deposition of metals is predominantly controlled by temperature and salinity of hydrothermal fluids. The increase in the pH value of ore-bearing fluids due to mixing with seawater may also reduce metal mobility.

The main sulphide phase is pyrrhotite, associated with minor amounts of pyrite. The high-temperature portion of the mineral paragenesis consists of base-metal sulphides, anhydrite and minor amounts of silica species and shows an enrichment in Cu, Pb, Zn, Cd, Se and Te. In contrast, the low-temperature paragenesis is predominantly composed of silica species and barite accompanied with variable amounts of sulphides and sulphosalts and contains elevated concentrations of Au, As, Sb, Hg and Tl.

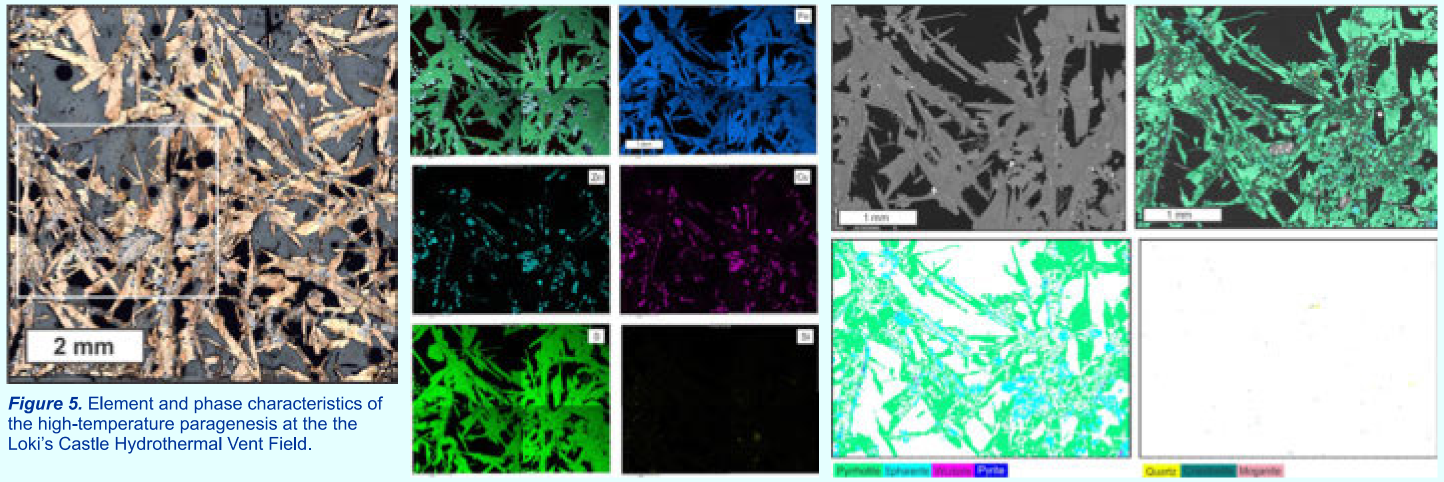

Figure 5. Element and phase characteristics of the high-temperature paragenesis at the the Loki's Castle Hydrothermal Vent Field.

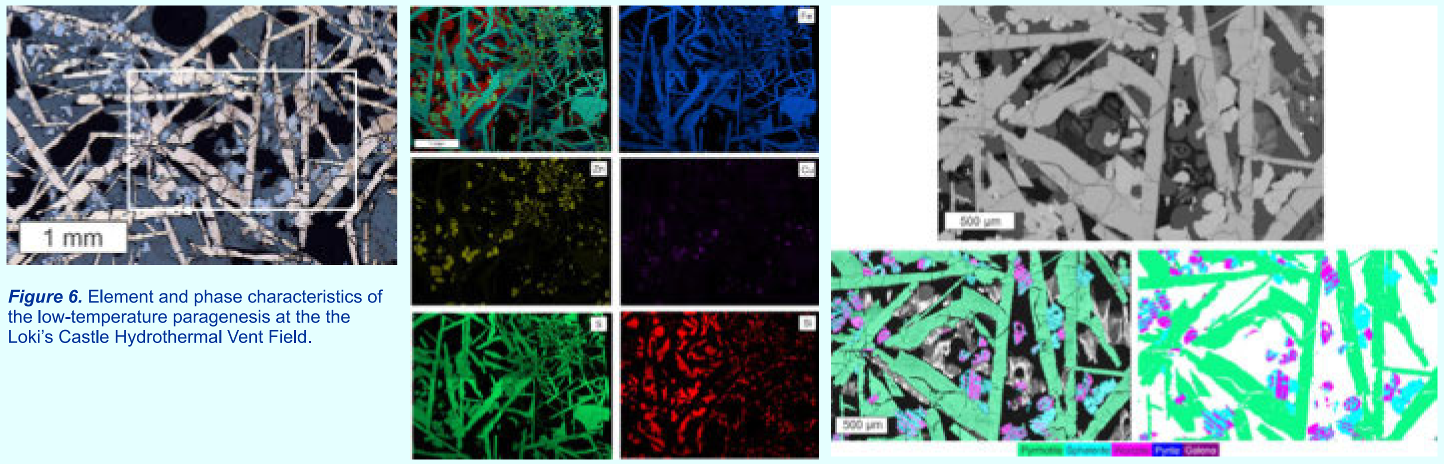

Figure 6. Element and phase characteristics of the low-temperature paragenesis at the the Loki's Castle Hydrothermal Vent Field.

Table 2. Element composition of main sulphide phases in the the Loki's Castle Hydrothermal Vent Field, the Arctic Mid-Ocean Ridges

	Isocubanite	Pyrrhotite	Sphalerite	Pyrite
Cu (ppm)	m.e.	1600 - 4400	150 - 470	< 1500
Zn (ppm)	17300 - 23800	< d.l.	m.e.	< 40
Mn (ppm)	150 - 290	< d.l.	1900 - 2500	< 310
Co (ppm)	70 - 150	30 - 100	100 - 150	< d.l.
Se (ppm)	280 - 780	200 - 1500	230 - 450	50 - 570
Ag (ppm)	40 - 70	< d.l.	0.4 – 0.7	< 5
Cd (ppm)	70 - 150	< d.l.	2100 -2500	< d.l.
Bi (ppm)	< 1	<370	< d.l.	< d.l.

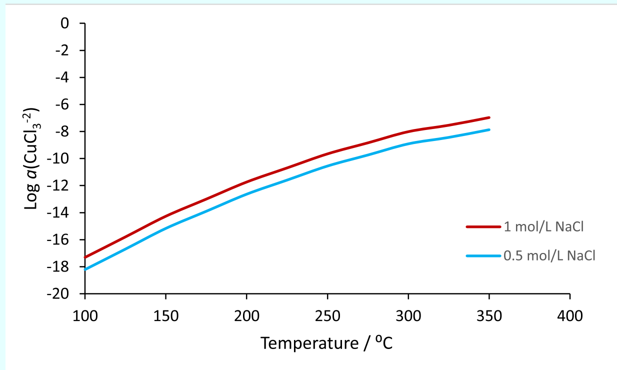

Figure 7. Thermodynamic modelling, based on fluid inclusion and mineral chemistry data, reveals that base metals and Tl were transported in forms of metal-chloride complexes. Gold was transported as Au-bisulphide complex, and hydroxide complexes were responsible for hydrothermal transport of As and Sb.

The diagram illustrate the effect of cooling and dilution of the Cu-bearing fluid due to infiltration of cold seawater.

Detecting seafloor massive sulfide deposits along the Mohns Ridge using self-potential methods

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[1]Department of Earth Science, The Centre for Deep Sea Research, University of Bergen, Bergen, Norway

Introduction

Exploring for marine minerals is becoming a major part of the green shift due to the increasing demand for base metals. Remote sensing plays an integral part as a tool for detection of mineral deposits such as manganese crust and seafloor massive sulfides, the latter being the focus of this study.

For economic exploitation, seafloor massive sulfide deposits in regions with inactive vents are of most interest due to environmental concerns. However, inactive seafloor massive sulfide deposits are harder to locate as they do not produce a detectable plume signature in the water column. Here we present self-potential data used to locate seafloor massive sulfides.

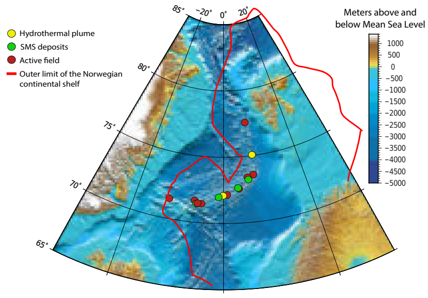


Figure 1: Map of the Arctic Mid-Ocean Ridges showing the location of active (red) and extinct (green) vent fields in the Norwegian-Greenland Sea. Locations of Hydrothermal fields taken from Pedersen et al., 2010 and 2016.

Seafloor massive sulfide depostis – active versus inactive

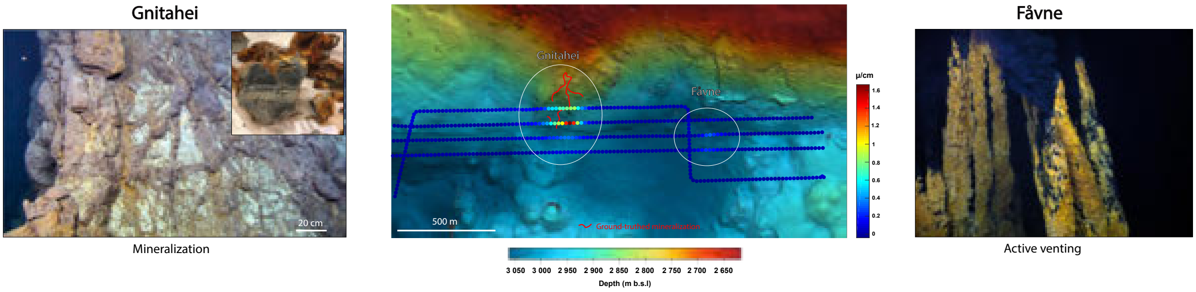
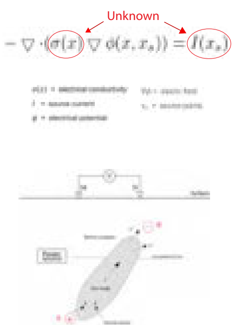


Figure 2: Self-potential data (magnitude of x, y, z components) collected at Gnitahei and Fåvne with ground-truthing superimposed on bathymetric map. Measurements showing an anomaly of both a hydrothermally active and inactive seafloor massive sulfide deposit.

Self-potential – proven to be a efficient method to detect hydrothermal deposits

The self-potential can be used yo detect naturally occurring electric voltages, which may be produced by electrically conductive mineral deposits, such as massive sulfides.



$$-\nabla\cdot(\sigma(x)\nabla\phi(x,x_s)) = I(x_s)$$

For self-potential, this function has both an unknown current density (I) and a unknown electrical conductivity (σ(x)). The two unknowns makes self potential a fairly complicated method in terms of understanding its physics compared to other active methods such as seismic or resistivity methods, with less unknown parameters.

Figure 3: Sketch illustrating Sato and Mooney's classical "geobattery" model for ore bodies. This figure illustrates gradients in redox potentials in the surroundings of the ore body. Figure modified from Revil & Jardani (2013).

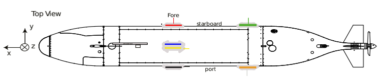


Figure 4: Sketch of an example of how self-potential data can be collected using a Autonomous Underwater Vehicle (AUV) equipped with electrodes. Self-potential data were collected by the Norwegian Petroleum Directorate (NPD) in 2018, 2019 and 2021 using the Ocean Floor Geophysics (OFG) iCP system.

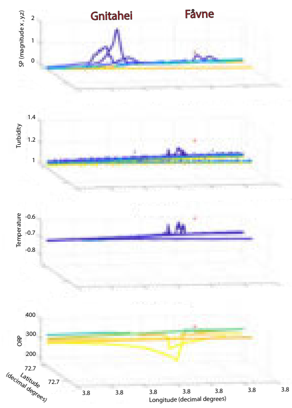


Figure 5: Self-potential, turbidity, temperature and ORP data collected at Gnitahei and Fåvne. This self-potential dataset were used to locate Gnitahei in 2019, as there were no other sensor signal anomalies.

Acknowledgements

The Norwegian Petroleum Directorate (NPD) is thanked for suporting the first author's PhD and for collecting most of the datasets used in this study.

NORWEGIAN PETROLEUM DIRECTORATE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ABSTRACTS

Exploring Norwegian Waters

October 19-21 2021

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GeoERA-MINDeSEA project database and cartography of European seabed mineral deposits

Javier González, T. Medialdea, H. Schiellerup, I. Zananiri, P. Ferreira, L. Somoza, X. Monteys, T. Alcorn, E. Marino, A. Lobato, T. Kuhn, J. Nyberg, V. Magalhaes, R. Lunar, B. Maliuk, J.R. Hein, G. Cherkashov and the MINDeSEA Team

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CSIC
Consejo Superior de Investigaciones Científicas
Instituto Geológico y Minero de España

GeoERA RAW MATERIALS

MINDeSEA
Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

GeoERA RAW MATERIALS

MINDeSEA Consortium (12 partners)

Project Lead

Instituto Geológico y Minero de España

WP Leads

Instituto Geológico y Minero de España

GEOLOGICAL SURVEY OF NORWAY - NGU -

LNEG Laboratório Nacional de Energia e Geologia

H·S·G·M·E

Geological Survey Suirbhéireacht Gheolaíochta Ireland | Éireann

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GeoERA RAW MATERIALS

8 work packages:

- Management
- Dissemination
- Hydrothermal sulphides
- Fe-Mn crust, phosphorites & CRM
- Placers
- Polymetallic nodules
- Exploration
- GIP-P link

MINDeSEA

Digital Products at:

https://geoera.eu/projects/mindesea2/

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GeoERA RAW MATERIALS

Characterising the European deposit types and their CRM

1- Hydrothermal mineralisations
2- Co-rich Ferromanganese Crusts
3- Phosphorites
4- Polymetallic Nodules
5- Marine Placer deposits

Pan-European seabed minerals

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GeoERA RAW MATERIALS

Using cutting-edge technologies

- ✓ On board
- ✓ At Labs

EPMA, BGR Hannover

LA-ICP-MS, Leibniz Un. Hannover

ROV LUSO 6000, EMEPC

ROV ISIS 6000, NOC

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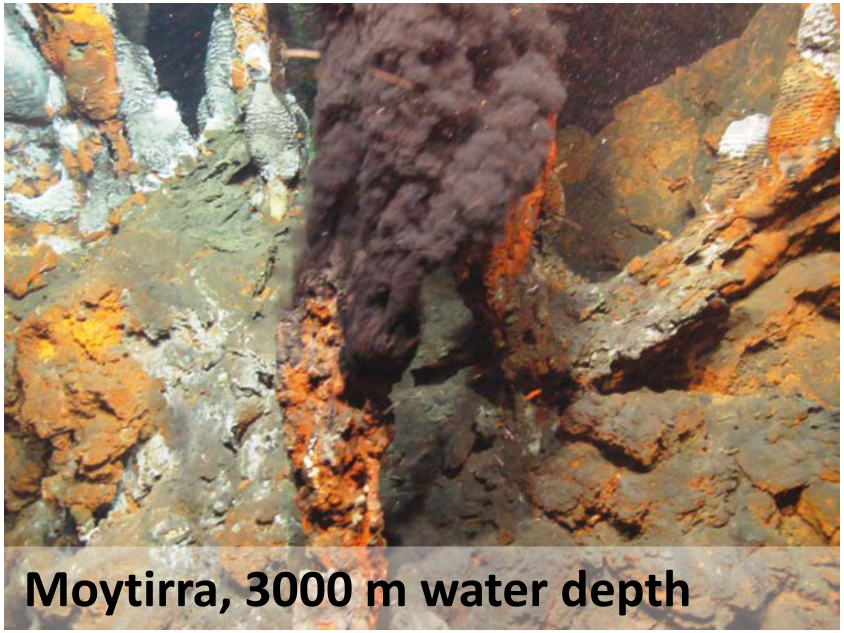

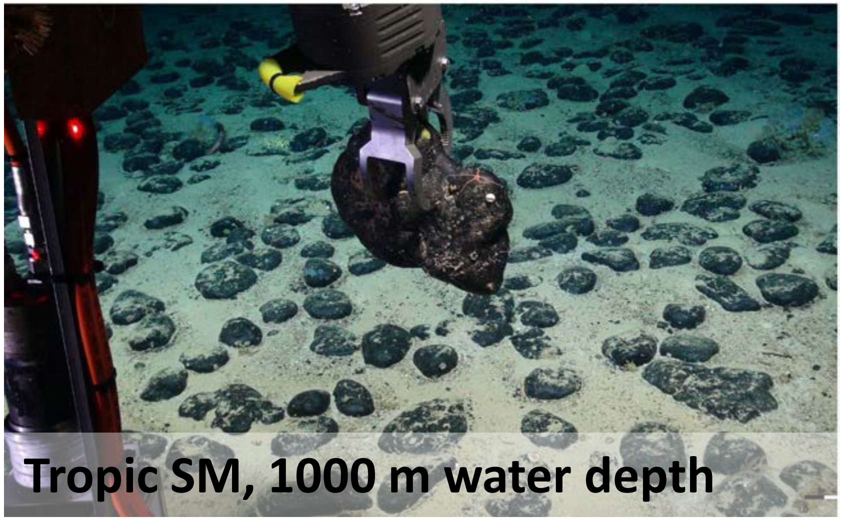

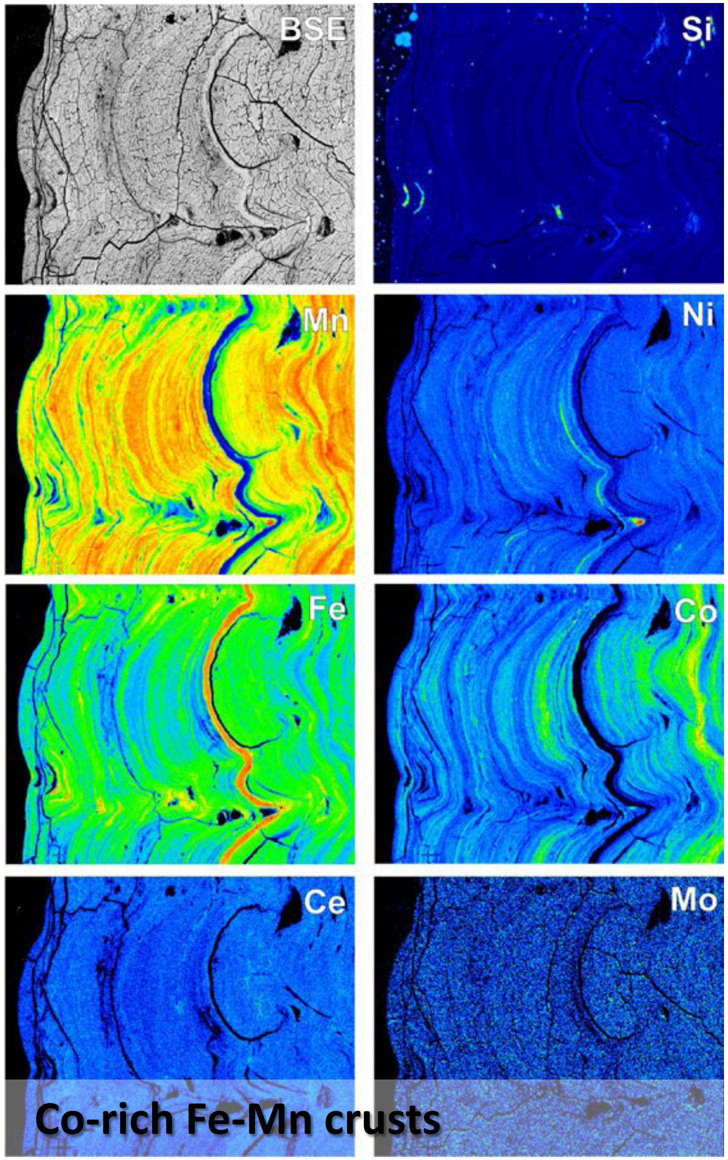

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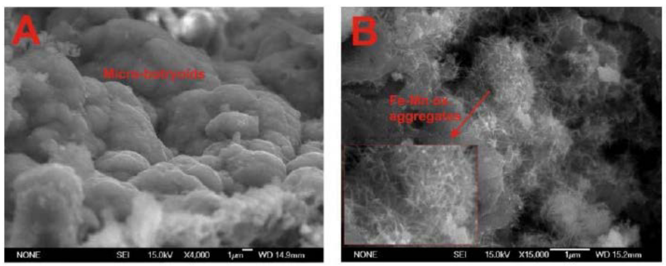
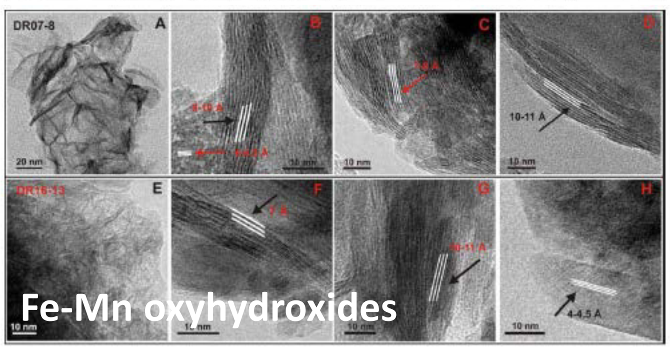
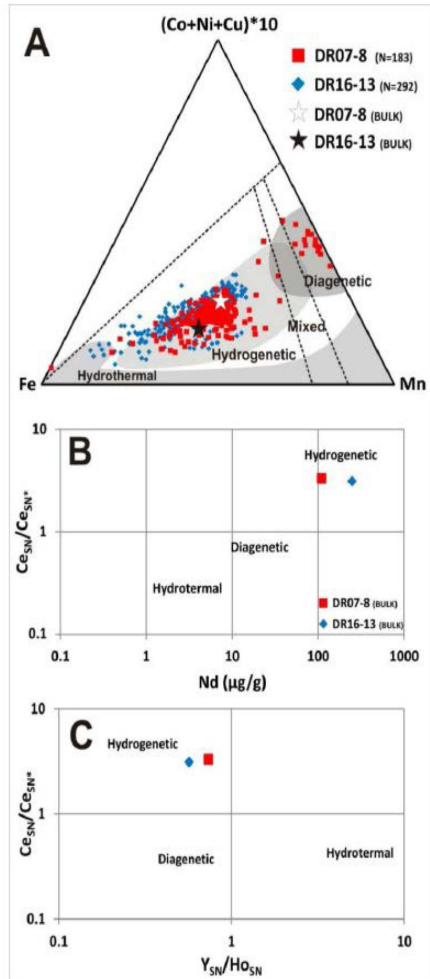
GeoERA RAW MATERIALS

Identifying the principal metallogenic provinces

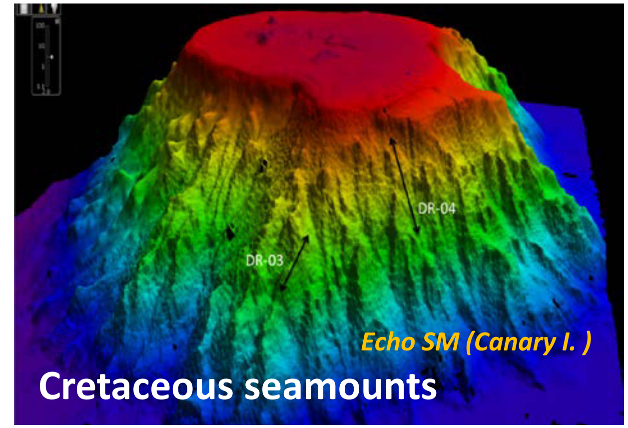
- ✓ Mineral assemblages
- ✓ Areas of distribution
- ✓ Epochs of formation
- ✓ Genetic models

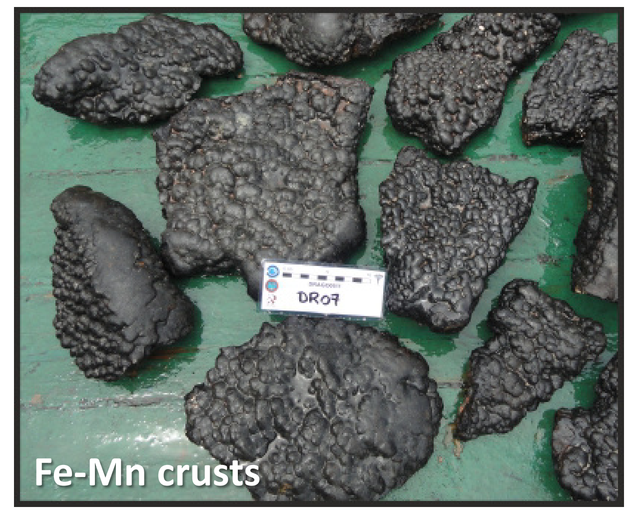






Genesis





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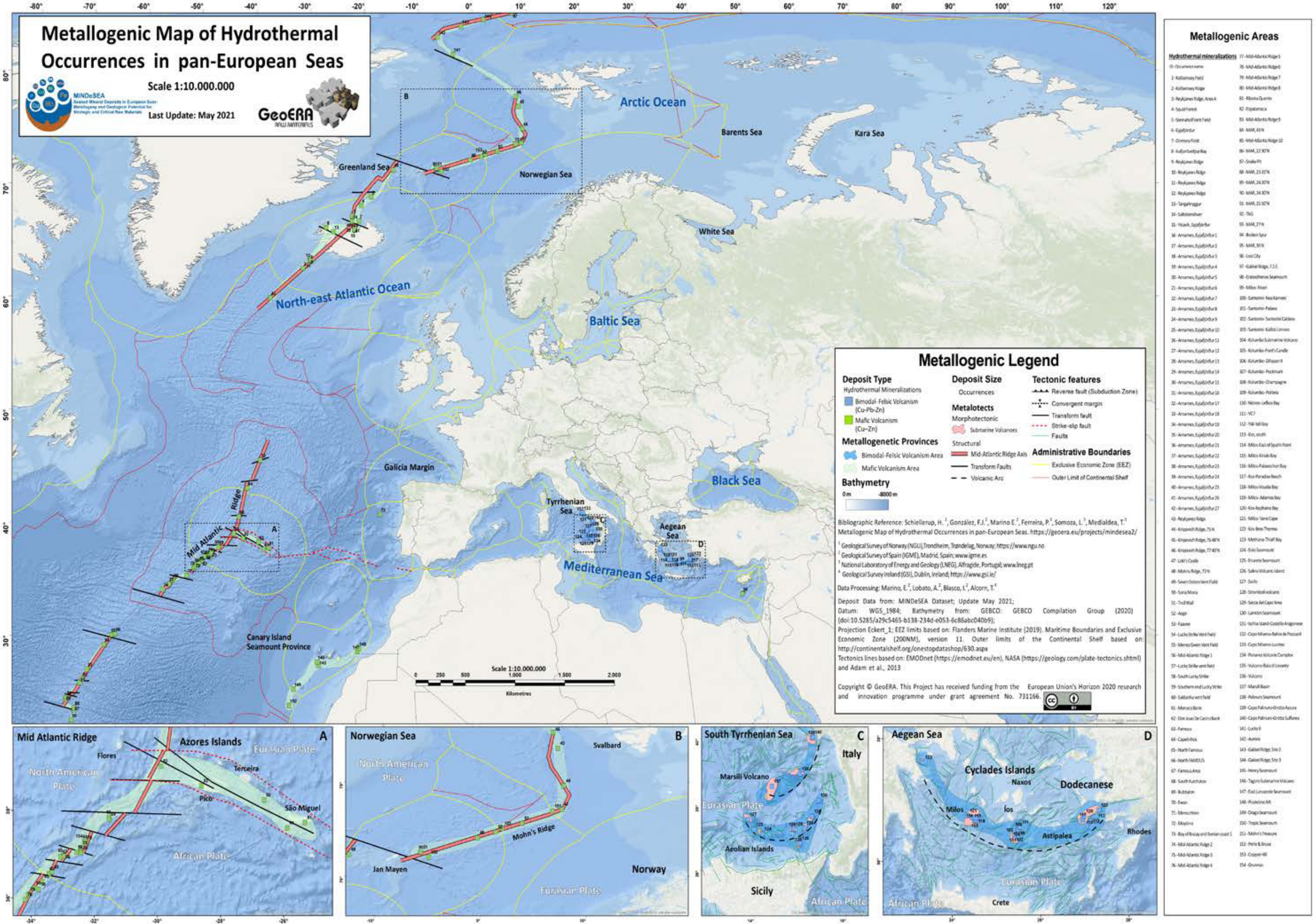

Metallogenic Map of Hydrothermal Occurrences in pan-European Seas
Scale 1:10.000.000
Last Update: May 2021
MINDeSEA
GeoERA
Arctic Ocean
Barents Sea
Kara Sea
Greenland Sea
Norwegian Sea
White Sea
North-east Atlantic Ocean
Baltic Sea
Galicia Margin
Black Sea
Tyrrhenian Sea
Aegean Sea
Mediterranean Sea
Mid Atlantic Ridge
Canary Island Seamount Province
Metallogenic Legend
Deposit Type
Hydrothermal Mineralizations
Bimodal- Felsic Volcanism (Cu-Pb-Zn)
Mafic Volcanism (Cu-Zn)
Metallogenetic Provinces
Bimodal-Felsic Volcanism Area
Mafic Volcanism Area
Bathymetry
0 m -8000 m
Deposit Size
Occurrences
Metalotects
Morphotectonic
Submarine Volcanoes
Structural
Mid-Atlantic Ridge Axis
Transform Faults
Volcanic Arc
Tectonic features
Reverse fault (Subduction Zone)
Convergent margin
Transform fault
Strike-slip fault
Faults
Administrative Boundaries
Exclusive Economic Zone (EEZ)
Outer Limit of Continental Shelf
Bibliographic Reference: Schiellerup, H. 1, González, F.J. 2, Marino E. 2, Ferreira, P. 3, Somoza, L. 3, Medialdea, T. 3 Metallogenic Map of Hydrothermal Occurrences in pan-European Seas. https://geoera.eu/projects/mindesea2/
1 Geological Survey of Norway (NGU), Trondheim, Trøndelag, Norway; https://www.ngu.no
2 Geological Survey of Spain (IGME), Madrid, Spain; www.igme.es
3 National Laboratory of Energy and Geology (LNEG), Alfragide, Portugal; www.lneg.pt
4 Geological Survey Ireland (GSI), Dublin, Ireland; https://www.gsi.ie/
Data Processing: Marino, E. 2, Lobato, A. 2, Blasco, I. 2, Alcorn, T. 4
Deposit Data from: MINDeSEA Dataset; Update May 2021;
Datum: WGS_1984; Bathymetry from: GEBCO: GEBCO Compilation Group (2020) (doi:10.5285/a29c5465-b138-234d-e053-6c86abc040b9);
Projection Eckert_1; EEZ limits based on: Flanders Marine Institute (2019). Maritime Boundaries and Exclusive Economic Zone (200NM), version 11. Outer limits of the Continental Shelf based on: http://continentalshelf.org/onestopdatashop/630.aspx
Tectonics lines based on: EMODnet (https://emodnet.eu/en), NASA (https://geology.com/plate-tectonics.shtml) and Adam et al., 2013
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Scale 1:10.000.000
Kilometres
Metallogenic Areas
Mid Atlantic Ridge
Azores Islands
Flores
Terceira
Pico
São Miguel
North American Plate
Eurasian Plate
African Plate
A
Norwegian Sea
Svalbard
Jan Mayen
Mohn's Ridge
Norway
B
South Tyrrhenian Sea
Italy
Marsili Volcano
Aeolian Islands
Sicily
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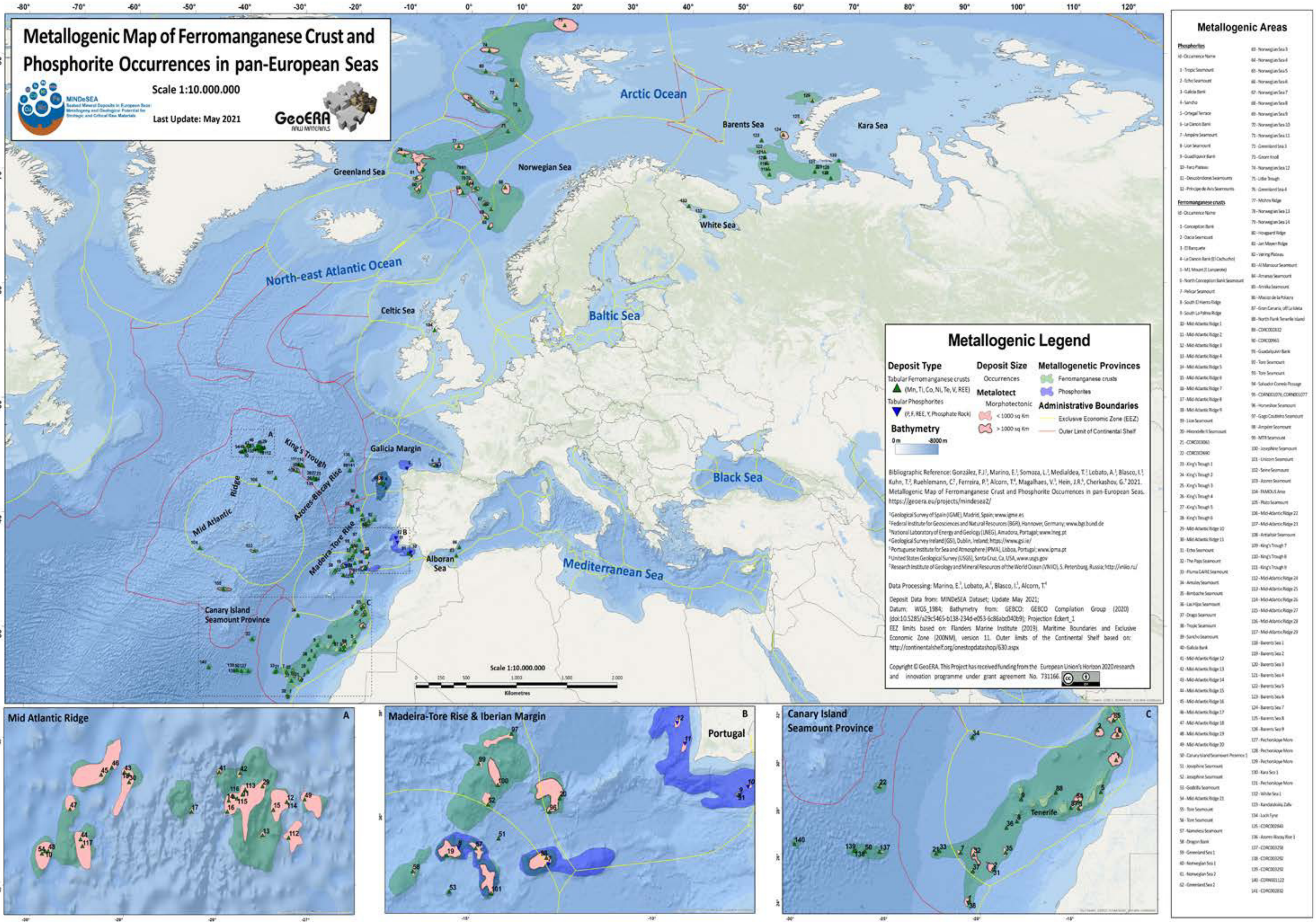
Astipalea
Rhodes
Crete
D


Metallogenic Map of Ferromanganese Crust and Phosphorite Occurrences in pan-European Seas
Scale 1:10.000.000
Last Update: May 2021
MINDeSEA
GeoERA
Arctic Ocean
Barents Sea
Kara Sea
Greenland Sea
Norwegian Sea
White Sea
North-east Atlantic Ocean
Celtic Sea
Baltic Sea
Galicia Margin
King's Trough
Azores-Biscay Rise
Mid Atlantic Ridge
Madeira-Tore Rise
Alboran Sea
Mediterranean Sea
Black Sea
Canary Island Seamount Province
Metallogenic Legend
Deposit Type
Tabular Ferromanganese crusts (Mn, Ti, Co, Ni, Te, V, REE)
Tabular Phosphorites (P, F, REE, Y, Phosphate Rock)
Bathymetry
0 m
-8000 m
Deposit Size
Occurrences
Metalotect
Morphotectonic
< 1000 sq Km
> 1000 sq Km
Metallogenetic Provinces
Ferromanganese crusts
Phosphorites
Administrative Boundaries
Exclusive Economic Zone (EEZ)
Outer Limit of Continental Shelf
Bibliographic Reference: González, F.J.[1], Marino, E.[1], Somoza, L.[1], Medialdea, T.[1], Lobato, A.[1], Blasco, I.[1], Kuhn, T.[2], Ruehlemann, C.[2], Ferreira, P.[3], Alcorn, T.[4], Magalhaes, V.[5], Hein, J.R.[6], Cherkashov, G.[7] 2021. Metallogenic Map of Ferromanganese Crust and Phosphorite Occurrences in pan-European Seas. https://geoera.eu/projects/mindesea2/
Data Processing: Marino, E.[1], Lobato, A.[1], Blasco, I.[1], Alcorn, T.[4]
Deposit Data from: MINDeSEA Dataset; Update May 2021;
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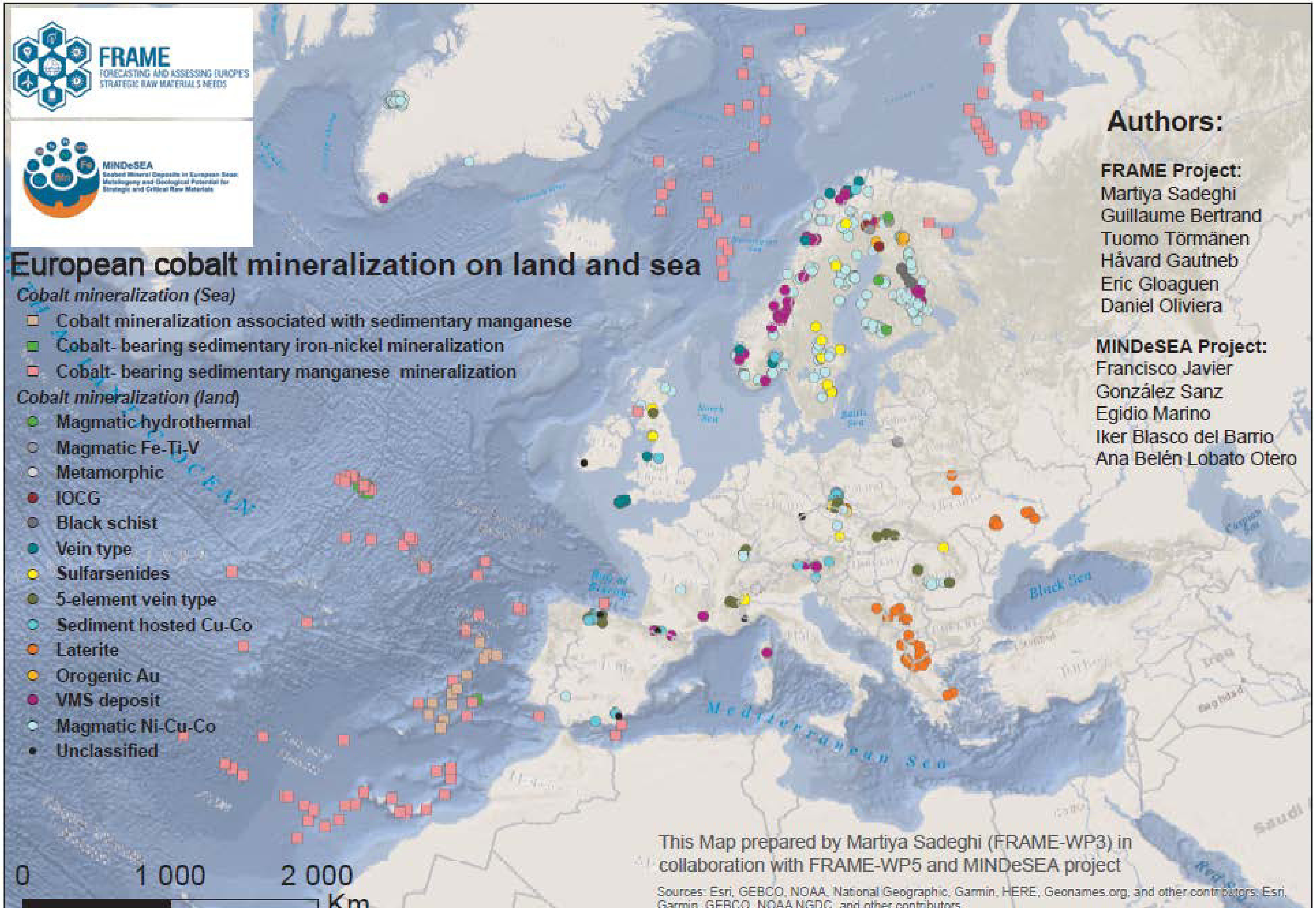
Scale 1:10.000.000
Kilometres
Mid Atlantic Ridge
Madeira-Tore Rise & Iberian Margin
Portugal
Canary Island Seamount Province
Tenerife
Metallogenic Areas

GeoERA projects cooperation: onshore-offshore

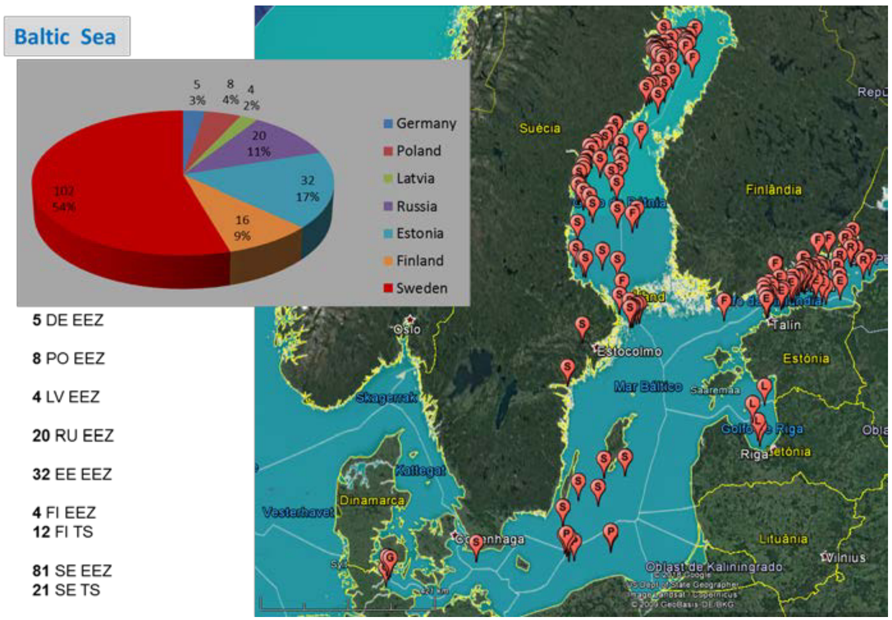


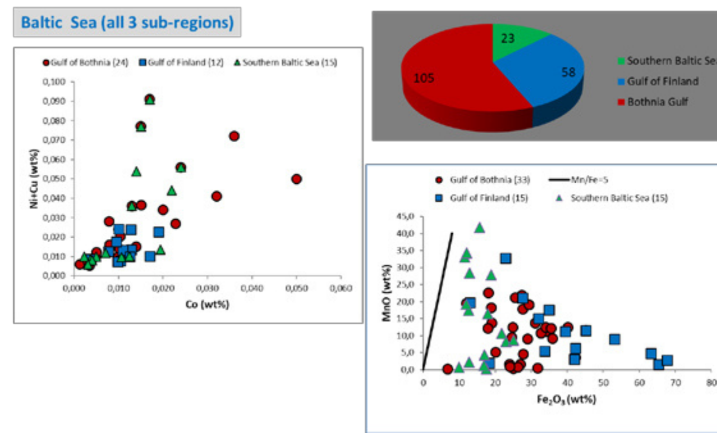
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

Demonstrating the efficiency of the case study results

- ✓ Offshore minerals exploration
- ✓ Critical metals assessment

Areas: Baltic, Mediterranean and Atlantic





This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

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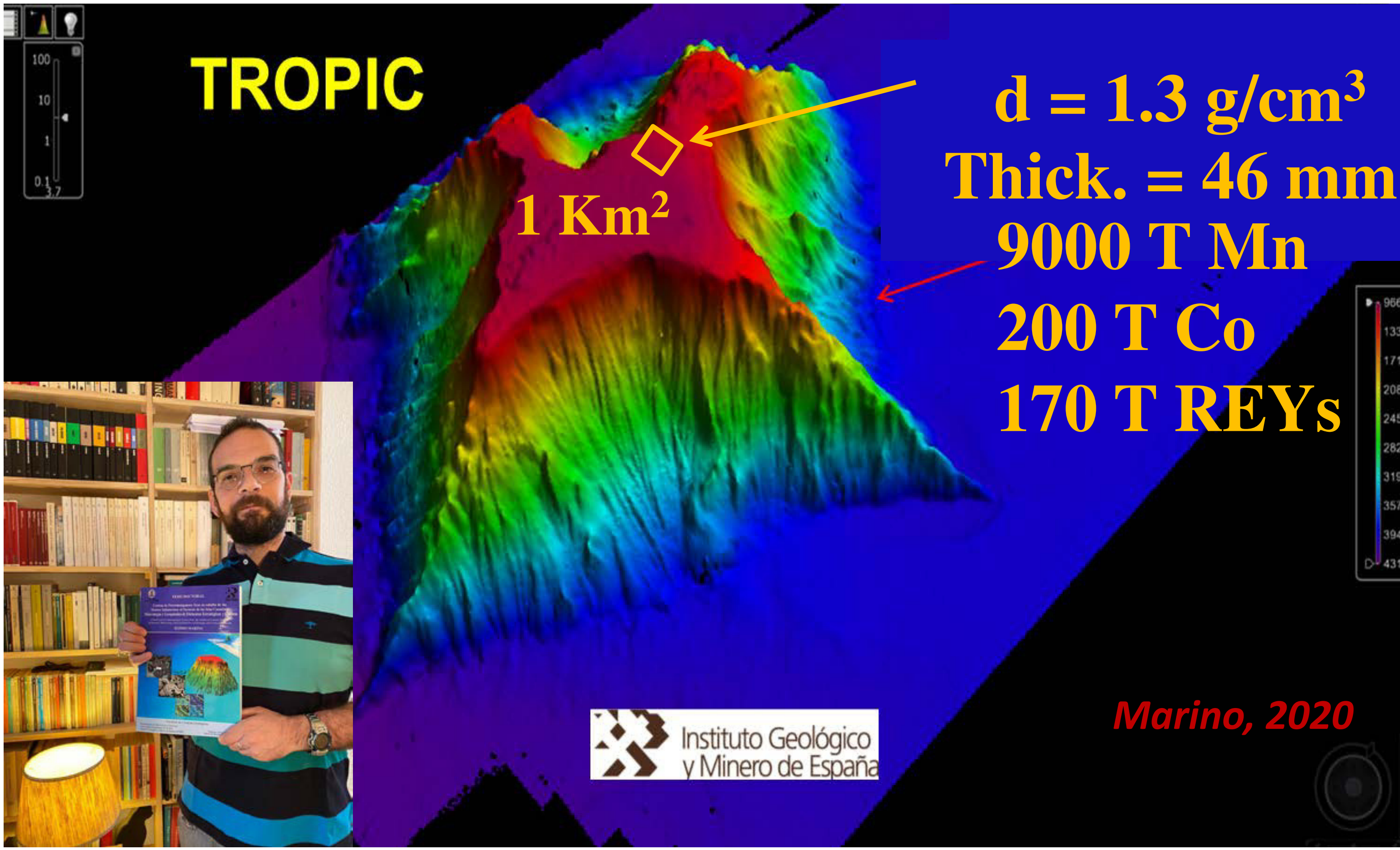
Assesment to Policy Makers

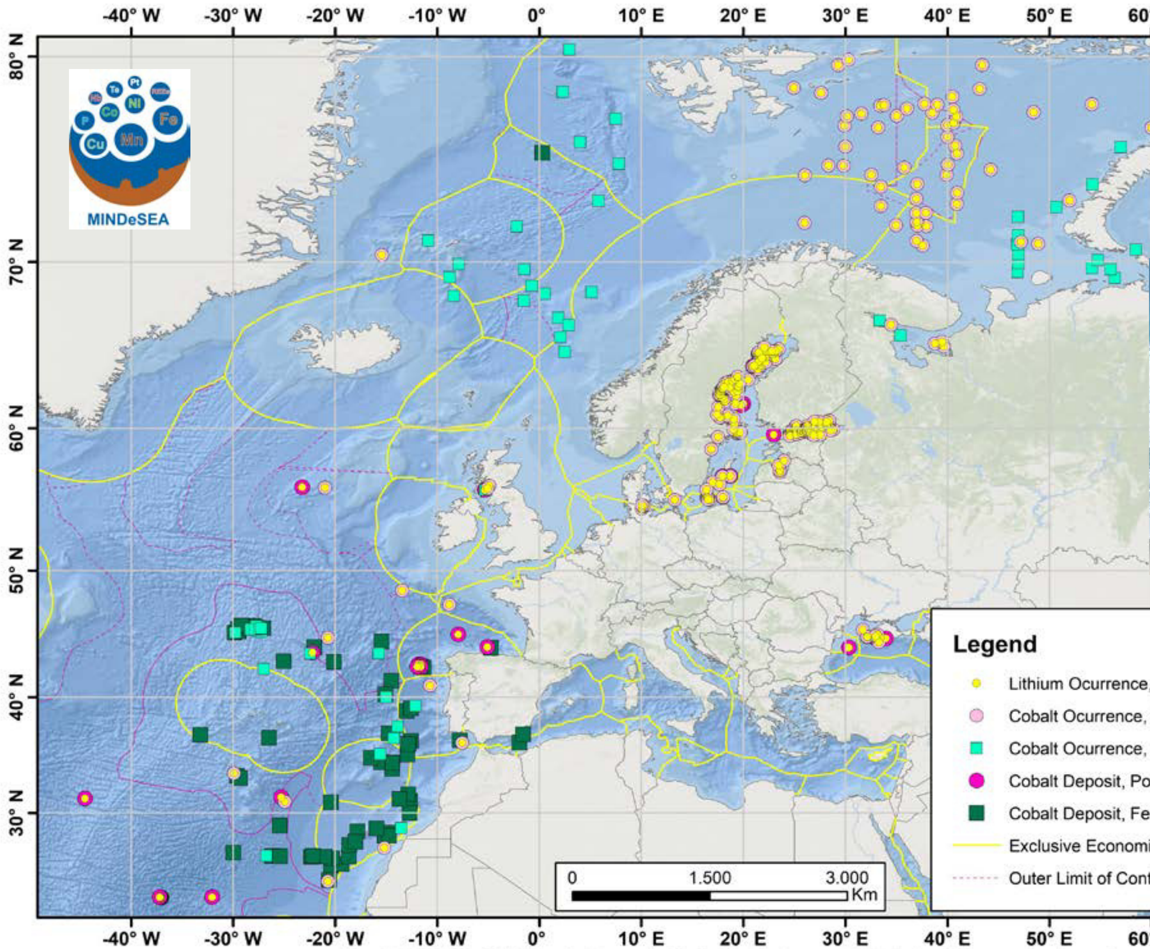
✓ **Tropic Seamount (Canary Island Seamount Province)**



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

Supporting EC and outreach activities

✓ **Pan-European map of Energy-critical elements Co and Li**



EEZ limits based on: Flanders Marine Institute (2019). Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11.
ECS limits based on: http://continentalshelf.org/onestopdatashop/6350.aspx

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Analysing present-day exploration and exploitation status

✓ **Regulation, legislation, environmental impacts, exploitation and future directions**


D6-6: Present-day status of regulation, legislation and exploitation of placer deposits

MINDeSEA

Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials

MINDeSEA

Deliverable 5.5: WP5 Literature review report on present-day status of regulation, legislation and exploitation of placer deposits, with emphasis on the impact of a pan-European research approach

WP5 leader: Hellenic Survey of Geology & Mineral Exploration (HSGME) - Greece		
	Address: 1 Spirou Loui str. Olympic Village 13677 Acharnae Attica Greece	Telephone: +30 213 133 7000 +30 213 133 7194 (I.Zananiri) Email: izananiri@igme.gr
WP5 HSGME Team: Dr. Irene Zananiri (scientific responsible) Vaggelis Zimianitis – Marilza Thomadaki – Nikolaos Georgakopoulos		

This work has been supported by the European Union's Horizon 2020 research and innovation programme, GeoERA (Grant Agreement N° 731166, project GeoE.171.001).

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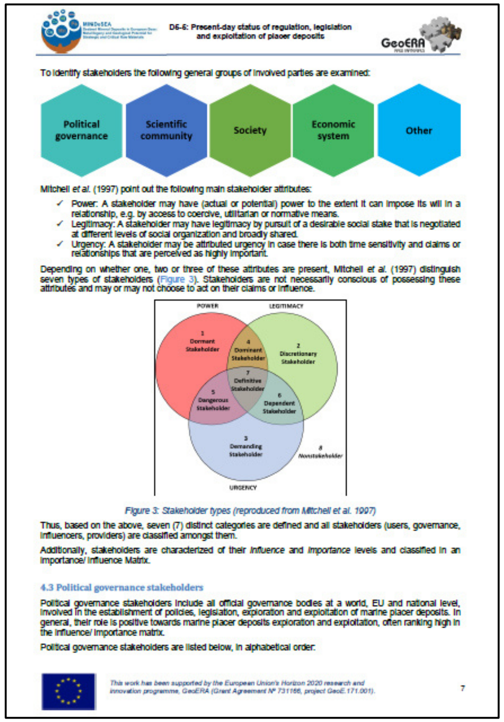
D6-6: Present-day status of regulation, legislation and exploitation of placer deposits

To identify stakeholders the following general groups of involved parties are examined:

Mitchell et al. (1997) point out the following main stakeholder attributes:

- ✓ Power: A stakeholder may have (actual or potential) power to the extent it can impose its will in a relationship, e.g. by access to coercive, utilitarian or normative means.
- ✓ Legitimacy: A stakeholder may have legitimacy by pursuit of a desirable social stake that is negotiated at different levels of social organization and broadly shared.
- ✓ Urgency: A stakeholder may be attributed urgency in case there is both time sensitivity and claims or relationships that are perceived as highly important.

Depending on whether one, two or three of these attributes are present, Mitchell et al. (1997) distinguish seven types of stakeholders (Figure 3). Stakeholders are not necessarily conscious of possessing these attributes and may or may not choose to act on their claims or influence.

Figure 3: Stakeholder types (reproduced from Mitchell et al. 1997)

Thus, based on the above, seven (7) distinct categories are defined and all stakeholders (users, governance, influencers, providers) are classified amongst them.

Additionally, stakeholders are characterized of their influence and importance levels and classified in an importance/ influence Matrix.

4.3 Political governance stakeholders

Political governance stakeholders include all official governance bodies at a world, EU and national level, involved in the establishment of policies, legislation, exploration and exploitation of marine placer deposits. In general, their role is positive towards marine placer deposits exploration and exploitation, often ranking high in the influence/ importance matrix.

Political governance stakeholders are listed below, in alphabetical order.

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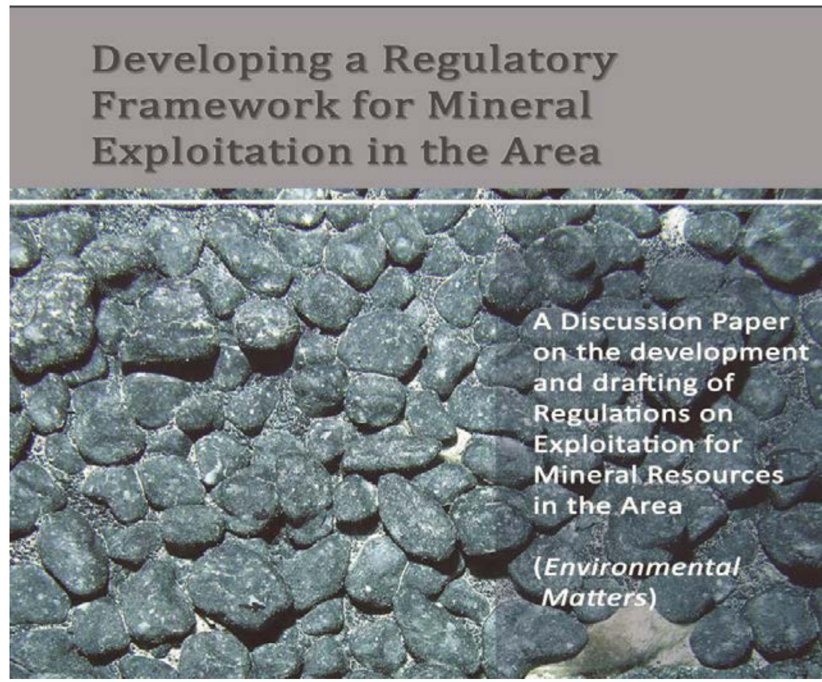
7



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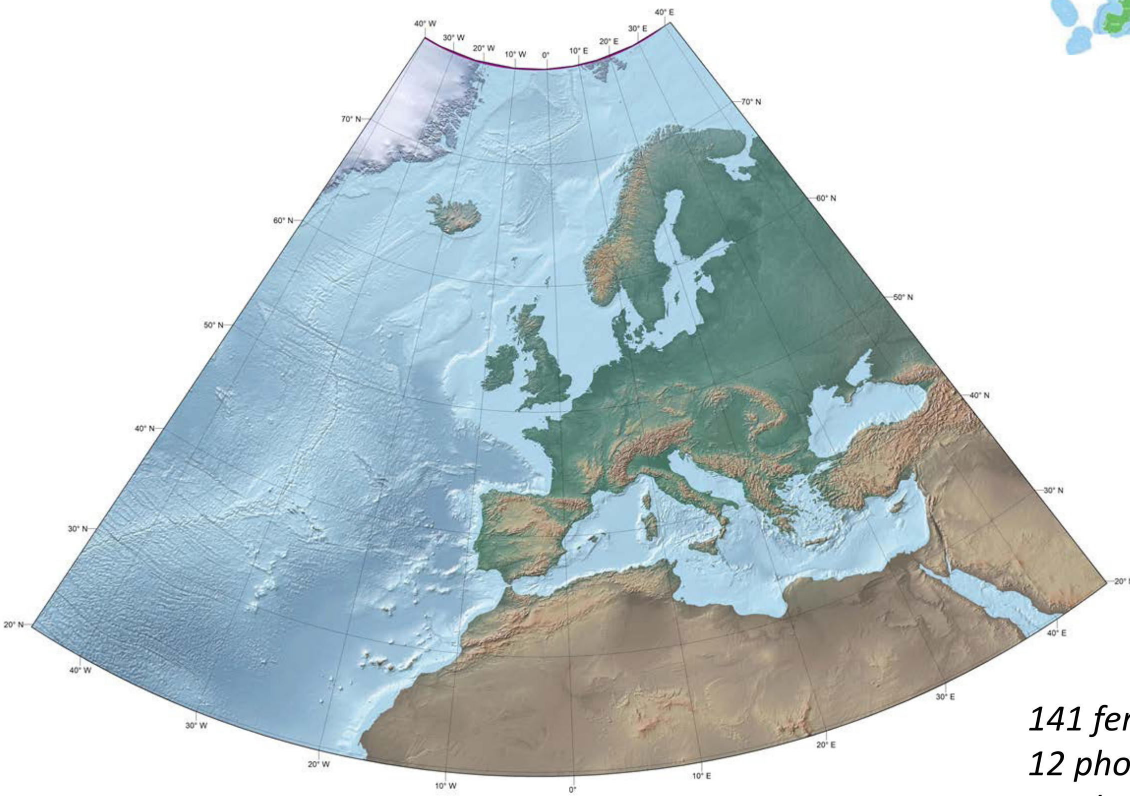
Developing harmonized mineral maps and datasets

- ✓ **Geological Survey Organizations datasets**
- ✓ **Mineral potential and prospectivity maps**



23 European countries

14 marine regions

Scale 1:250.000

23 CRM
5 deposit types

691 occurrences

141 ferromanganese crusts; 89 marine placers; 12 phosphorites; 296 polymetallic nodules; 153 hydrothermal mineralisation

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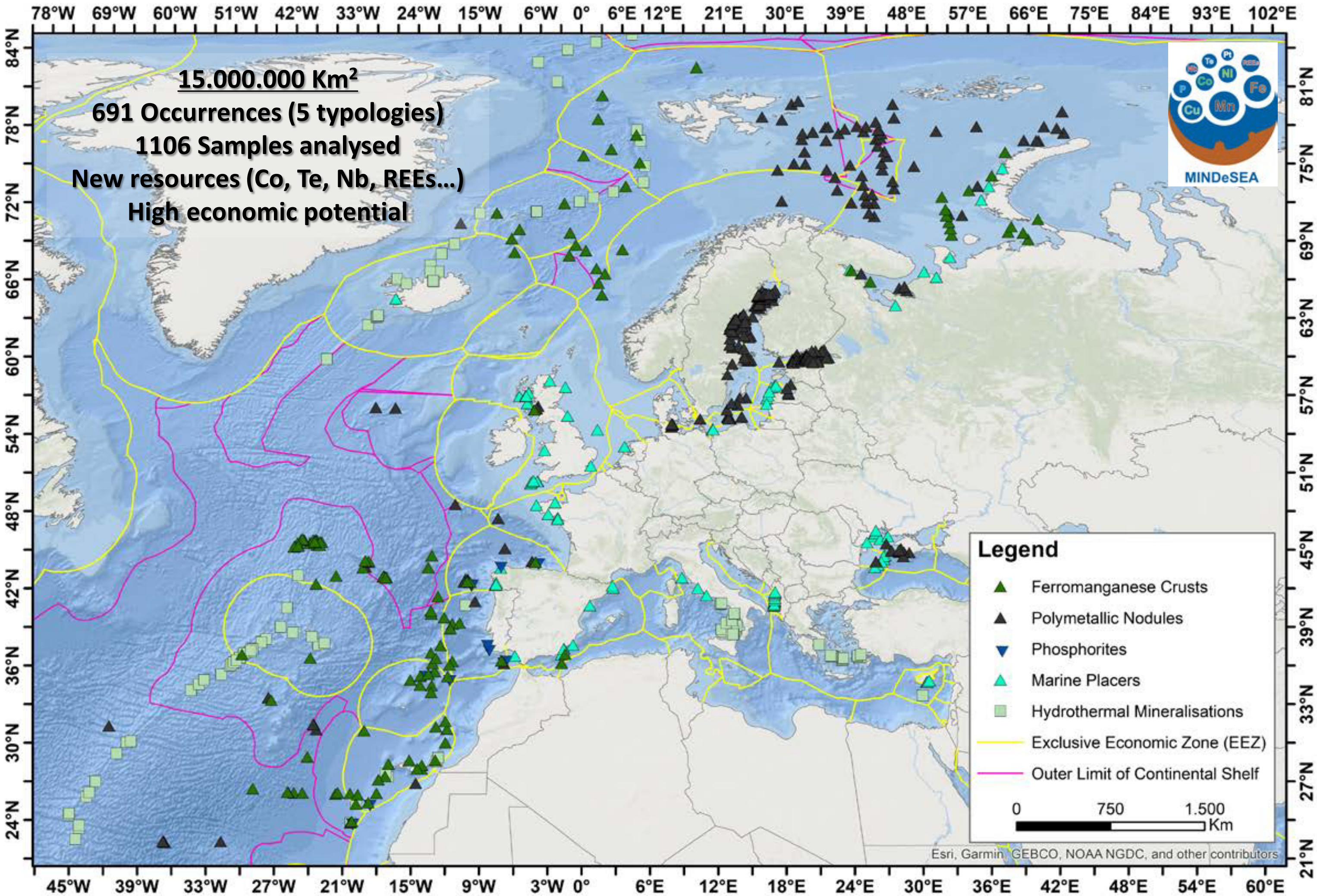
pan-European research approach for seabed mineral deposits



EEZ limits based on: Flanders Marine Institute (2019). Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11.
ECS limits based on: http://continentalshelf.org/onestopdatashop/6350.aspx

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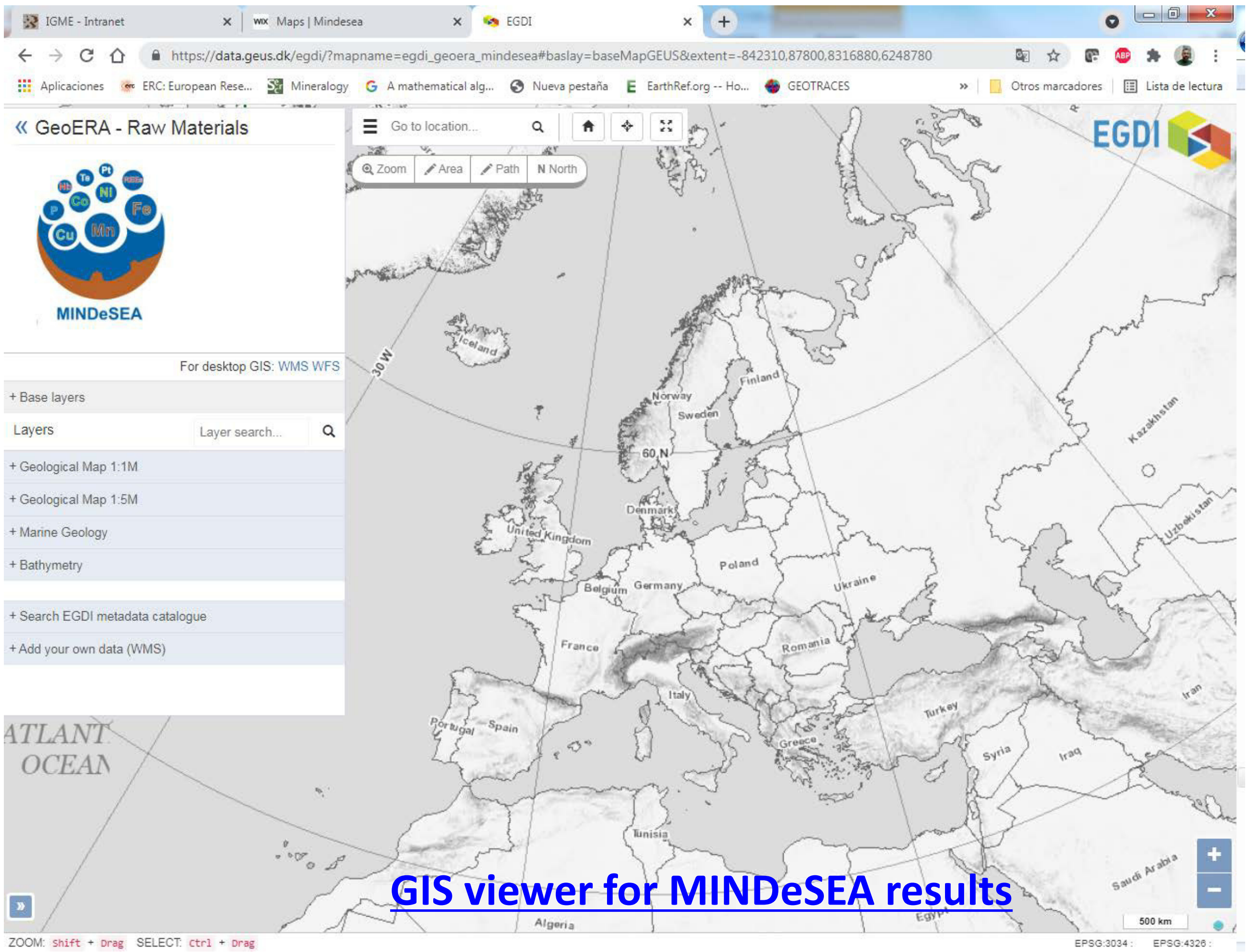
European Geological data Infrastructure (EGDI)

http://www.europe-geology.eu/



GIS viewer for MINDeSEA results

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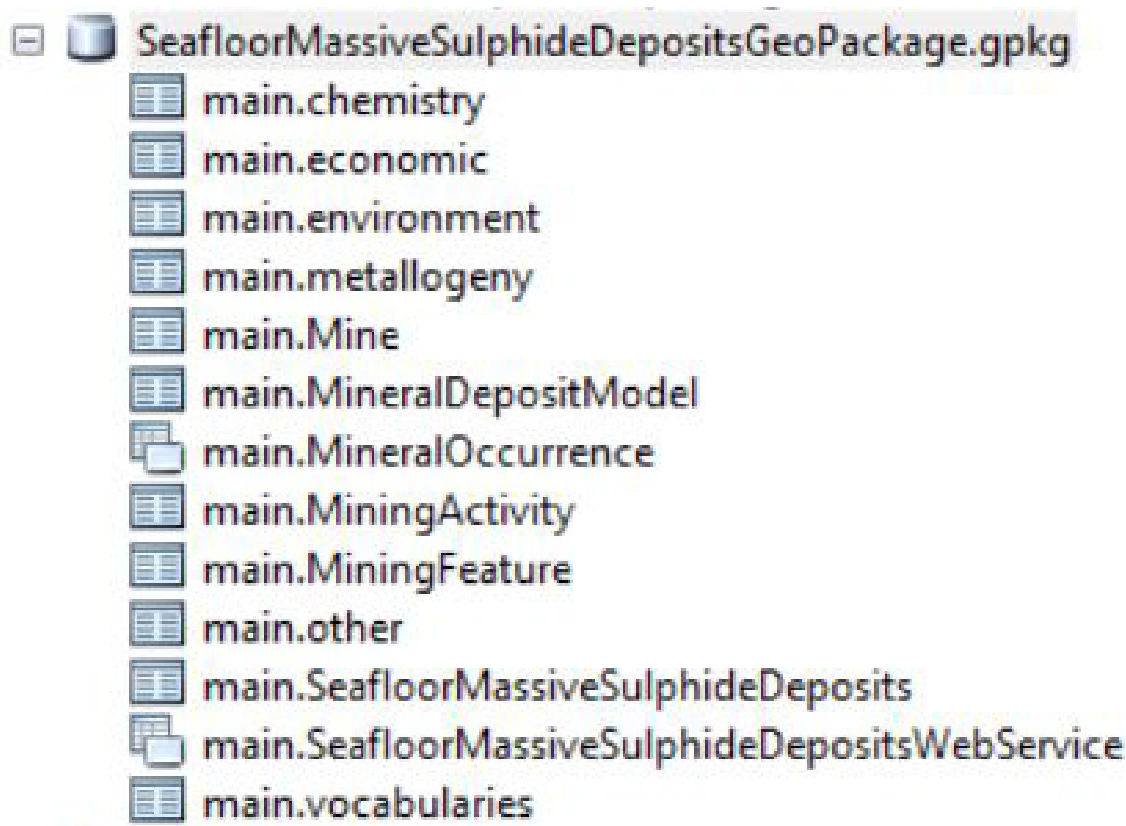

Alcorn et al., 2021

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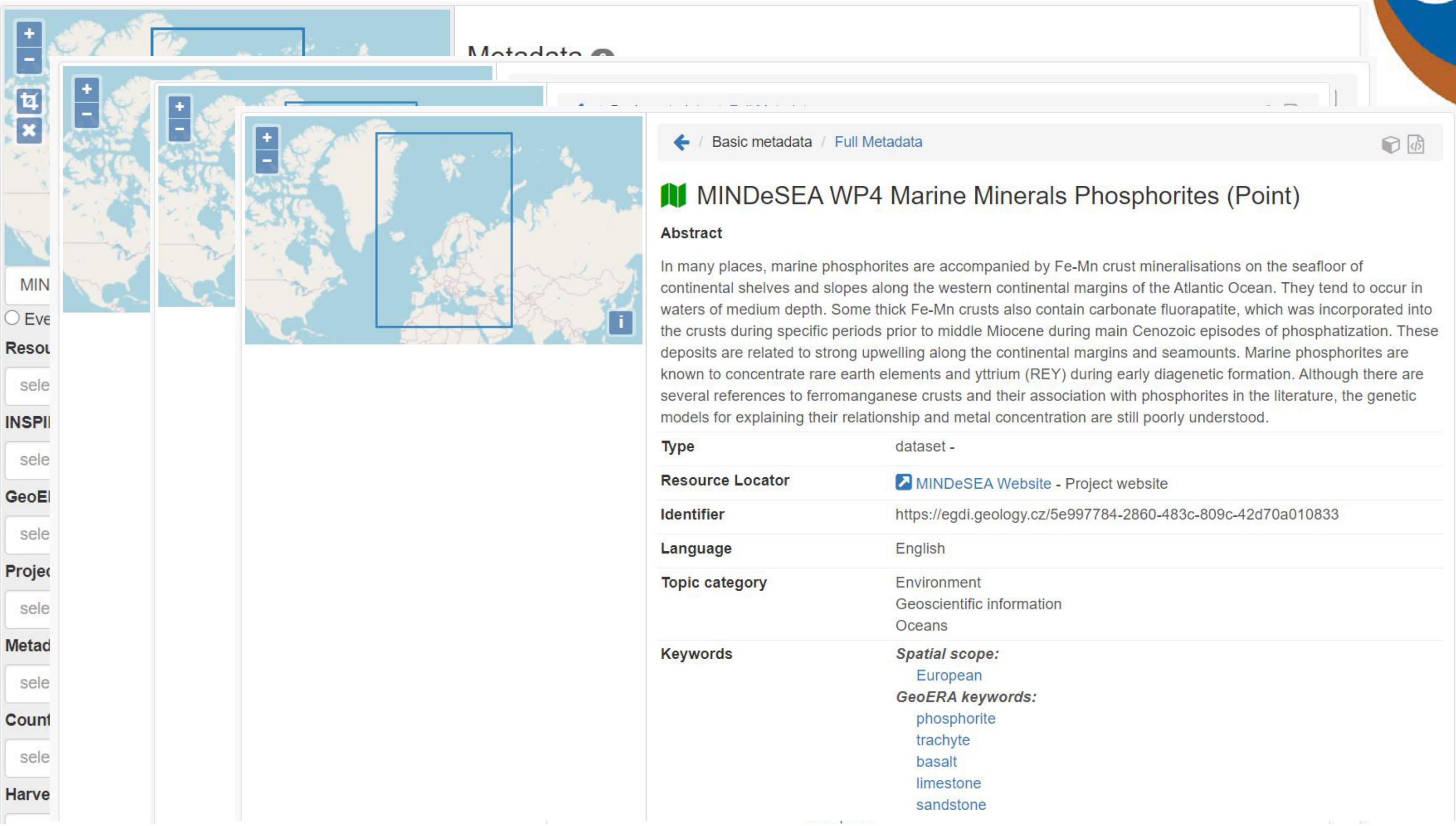
Metadata



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

Seabed mineral deposits potential for Critical Raw Materials

✓ **Assesment to EC** (DG- GROW, MARE)

Sustainable development
Energy transition
Environmental protection and spatial planning

Mapping critical and strategic raw materials in European seas
<u>Maps for 14 CRM (Co, Li, REE, Te, Ni, V, Sb, PGE, Au, Ag, Ti, P, Mn, Cu)</u>
5 deposit types (hydrothermal, ferromanganese crusts, phosphates, placers and polymetallic nodules)
Geochemistry :
- **Mean content**
- **N samples**
- **Range of contents**

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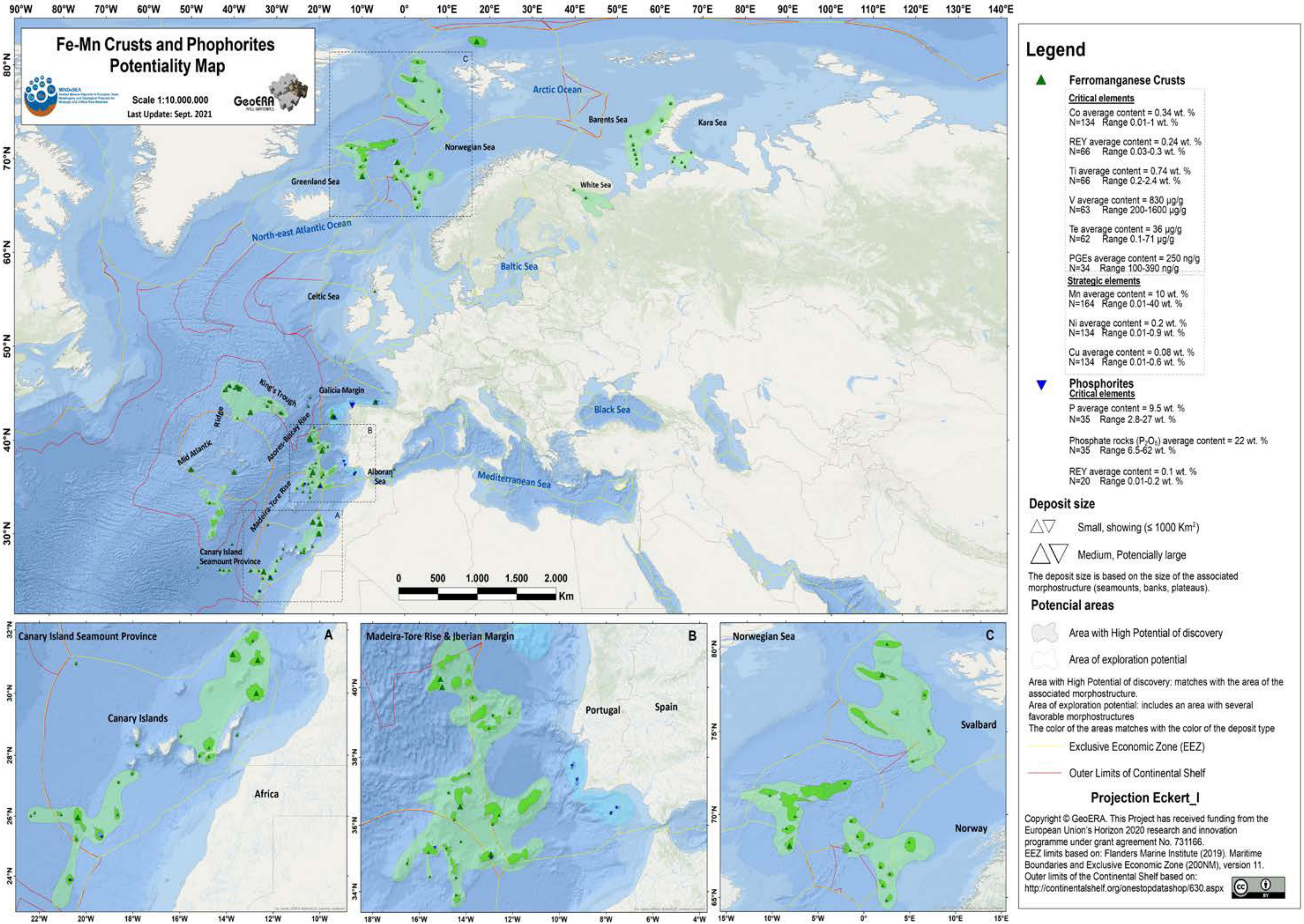
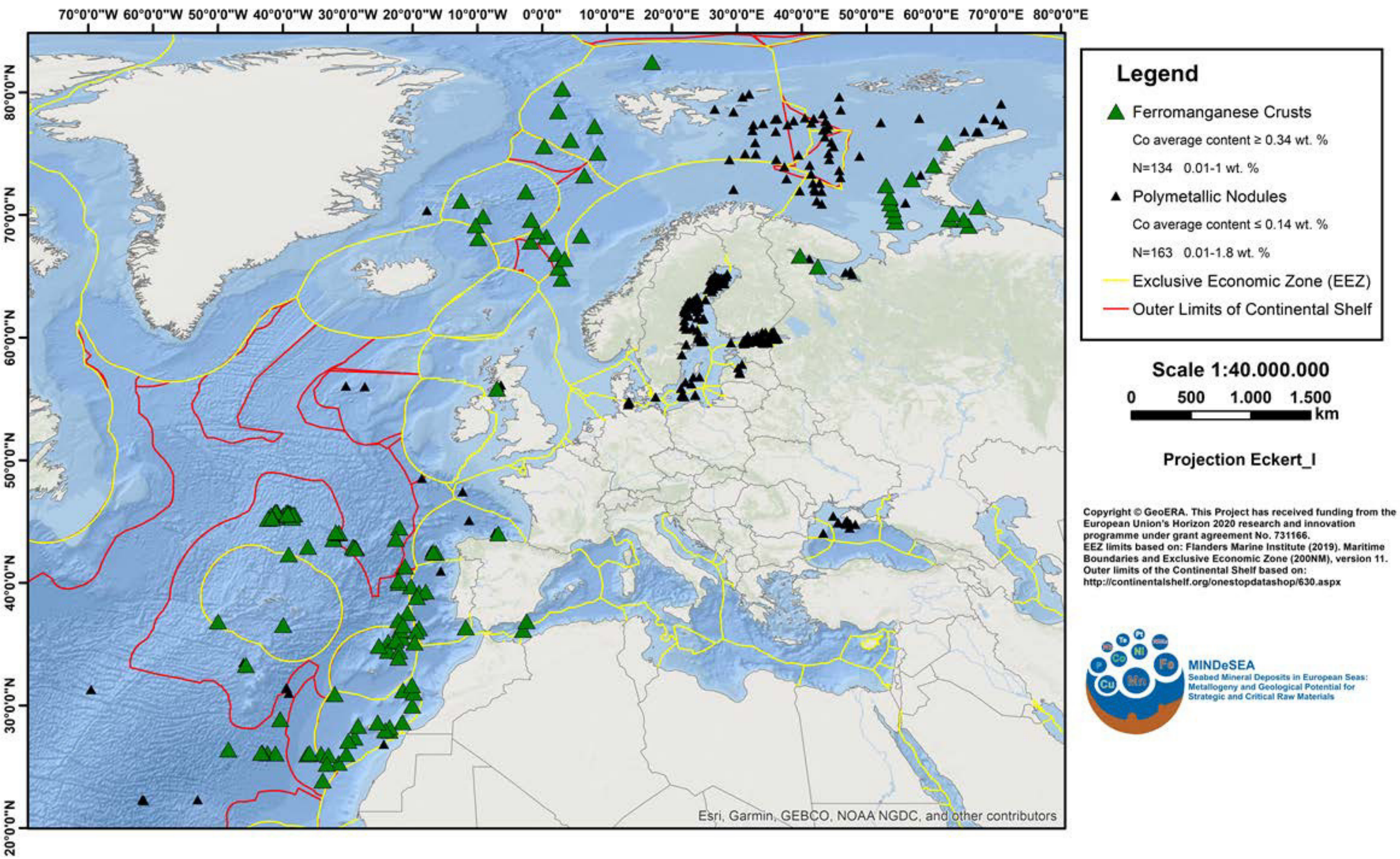

Fe-Mn Crusts and Phophorites
Potentiality Map
Scale 1:10.000.000
Last Update: Sept. 2021
GeoERA
Arctic Ocean
Barents Sea
Kara Sea
Norwegian Sea
Greenland Sea
White Sea
North-east Atlantic Ocean
Baltic Sea
Celtic Sea
King's Trough
Galicia Margin
Mid Atlantic Ridge
Azores-Biscay Rise
Madeira-Tore Rise
Alboran Sea
Mediterranean Sea
Black Sea
Canary Island Seamount Province
0 500 1.000 1.500 2.000 Km
Canary Island Seamount Province A
Canary Islands
Africa
Madeira-Tore Rise & Iberian Margin B
Portugal
Spain
Norwegian Sea C
Svalbard
Norway
Legend
Ferromanganese Crusts
Critical elements
Co average content = 0.34 wt. % N=134 Range 0.01-1 wt. %
REY average content = 0.24 wt. % N=66 Range 0.03-0.3 wt. %
Ti average content = 0.74 wt. % N=66 Range 0.2-2.4 wt. %
V average content = 830 µg/g N=63 Range 200-1600 µg/g
Te average content = 36 µg/g N=62 Range 0.1-71 µg/g
PGEs average content = 250 ng/g N=34 Range 100-390 ng/g
Strategic elements
Mn average content = 10 wt. % N=164 Range 0.01-40 wt. %
Ni average content = 0.2 wt. % N=134 Range 0.01-0.9 wt. %
Cu average content = 0.08 wt. % N=134 Range 0.01-0.6 wt. %
Phosphorites
Critical elements
P average content = 9.5 wt. % N=35 Range 2.8-27 wt. %
Phosphate rocks (P_2O_5) average content = 22 wt. % N=35 Range 6.5-62 wt. %
REY average content = 0.1 wt. % N=20 Range 0.01-0.2 wt. %
Deposit size
Small, showing (≤ 1000 Km^2)
Medium, Potencially large
The deposit size is based on the size of the associated morphostructure (seamounts, banks, plateaus).
Potencial areas
Area with High Potential of discovery
Area of exploration potential
Area with High Potential of discovery: matches with the area of the associated morphostructure.
Area of exploration potential: includes an area with several favorable morphostructures
The color of the areas matches with the color of the deposit type
Exclusive Economic Zone (EEZ)
Outer Limits of Continental Shelf
Projection Eckert_I
Copyright © GeoERA. This Project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.
EEZ limits based on: Flanders Marine Institute (2019). Maritime Boundaries and Exclusive Economic Zone (200NM), version 11.
Outer limits of the Continental Shelf based on: http://continentalshelf.org/onestopdatashop/630.aspx

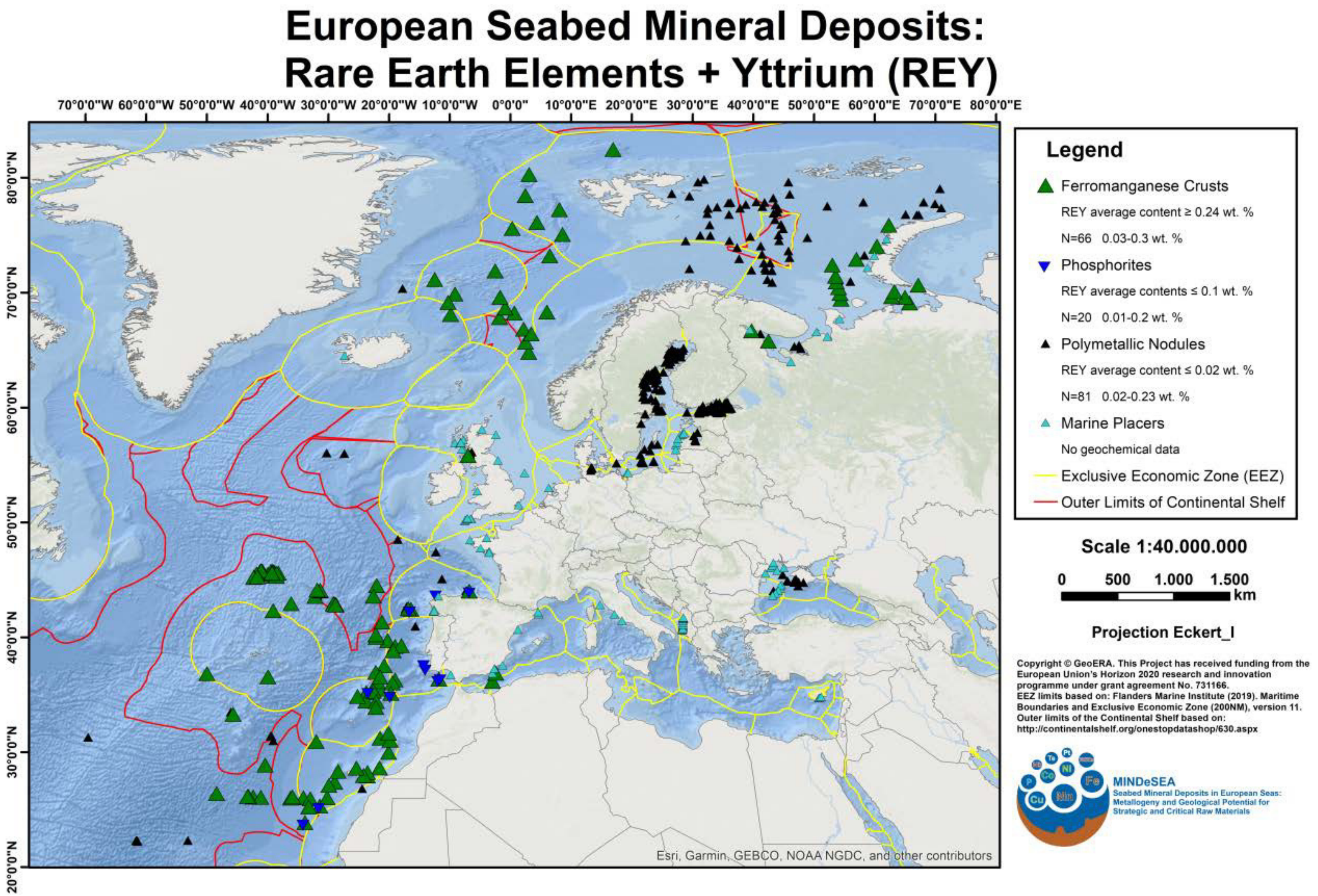
Energy-critical elements

European Seabed Mineral Deposits: Cobalt (Co)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

High-technology elements



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MINDeSEA findings published in SCI journals:

https://geoeramindesea.wixsite.com/mindesea/publications

F.J. González, et al. Marine Geology 430 (2020) 106333

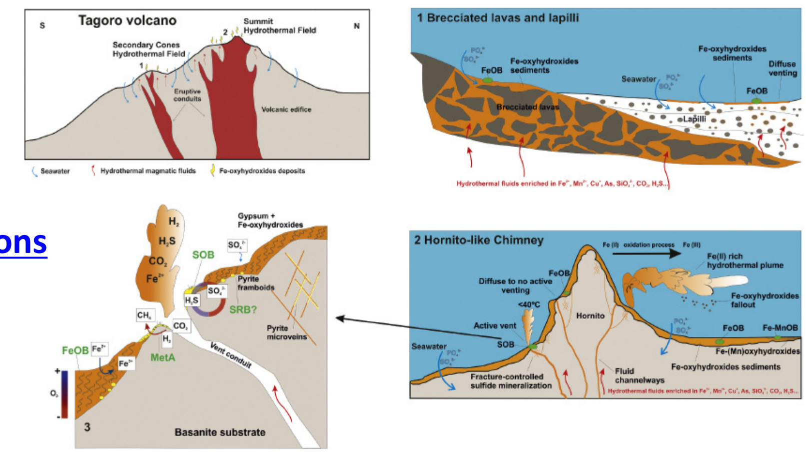
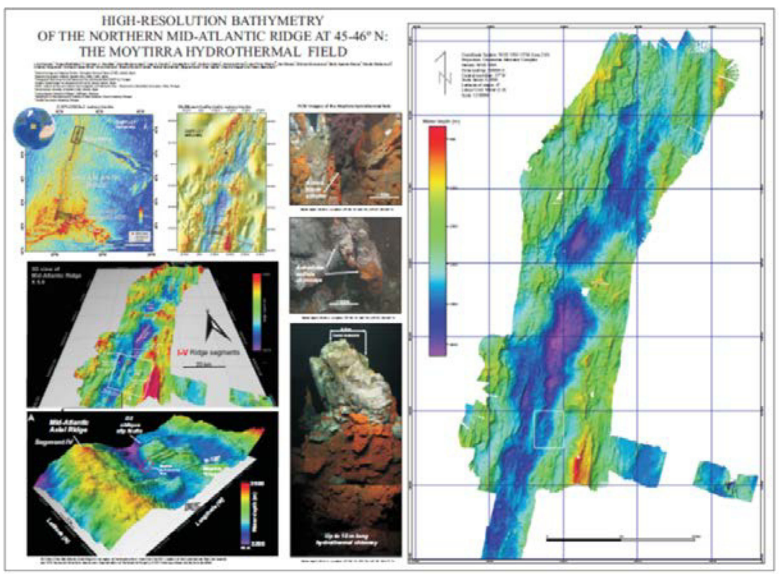


Fig. 13. Schematic model, not to scale, showing geologic setting and formation of Tagoro volcano hydrothermal deposits: (1) Secondary cones hydrothermal field with development of microbial-mediated Fe-oxyhydroxide mineralization on brecciated lavas and lapilli; (2) Summit hydrothermal field with mineralization on a hornito-like chimney; formation temperatures for the Fe-oxyhydroxide sediments are inferred to have varied below 40 °C; a host of elements (e.g., Fe, Si, P, Mn, As, Cu, Mo) were derived from leaching of basanite basement, sorbed from seawater, and to a lesser extent, magmatic fluids; Fe(II)-rich hydrothermal plumes allowed for the precipitation of Fe-Si-(Mn) mineralized sediments far away the vent sites; breakdown of the volcanic rock due to lava cooling or seismicity allowed for the precipitation of sulfides (pyrite ± chalcopyrite) from the hydrothermal fluids; (3): diversity of metabolic processes carried out by microorganisms related to diffuse venting. FeOB = iron-oxidizing bacteria, MetA = methanogenic archaea, SOB = sulfur-oxidizing bacteria, SRB = sulfate reducing bacteria.

González et al., 2020



Somoza et al., 2020, 2021

Minerals 2019, 9, 439

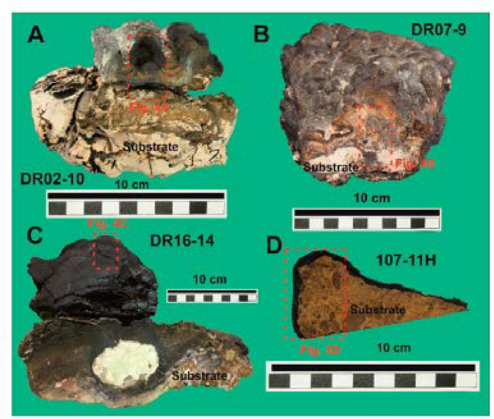


Figure 2. Image of selected Fe-Mn crust samples for this study. (A) Crust DR02-10 was dredged from Echo Sm., (B) crust DR07-9 from The Paps Sm., (C) DR16-14 and (D) 107-11H from Tropic Sm. Red discontinuous squares mark the areas where thin sections were taken for further investigations (Figure 4).

5

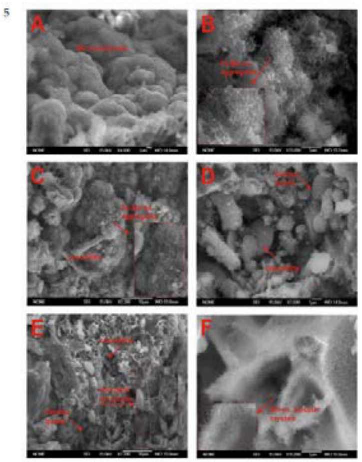


Figure 6. SEM photomicrography. (A) Micro-botryoidal morphology (B,C) Acicular micro aggregates of Fe-Mn minerals forming rounded shapes and sometimes covering other minerals or bioclasts (F). (C,D) Detrital grains, coccoliths and (F) Biological tubular structure identified crossing through the Fe-Mn oxides.

Marino et al., 2018, 2019

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Thank You!

MINDeSEA Team members at Geominero Museum (IGME-CSIC), Madrid

Instituto Geológico y Minero de España