MINDeSEA

Seabed Mineral Deposits in European Seas: The metal potential of hydrothermal mineral deposits in European waters

Deliverable 3.4

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The current report provides an assessment of the prospectivity and supply potential of hydrothermal mineral deposits; seabed massive sulphides and hydrothermal crusts, within the European waters. The report is based on the findings reported in deliverable 3.3 on the metallogenic setting of exhalative sulphide deposits and the data compiled through the project.	
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D 3.4 THE METAL POTENTIAL OF HYDROTHERMAL MINERAL DEPOSITS IN EUROPEAN WATERS

SUMMARY

GeoERA is a Co-Fund ERA-NET action under Horizon 2020, towards **"Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe"**. The main objective is to contribute to the optimal use and management of the subsurface.

The project **"Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials" (MINDeSEA)** was designed within the scope of the GeoERA Raw Materials Theme (Grant Agreement Nº 731166, project GeoE.171.001), and relies on the collaboration between eight GeoERA Partners and four Non-Funded Organizations with common interest in the exploration for, and investigation of, seafloor mineral deposits.

This document is a deliverable of the MINDeSEA Work Package 3 (WP3); "Seafloor Hydrothermal Deposits", led by the Geological Survey of Norway (NGU). The mineralisations discussed in this document are exhalative polymetallic mineral accumulations formed at or beneath the seabed through hydrothermal activity. The aim of MINDeSEA WP3 is to update and compile existing data on marine sulphides in European waters, including their mineralogy and geochemistry, with contained base, noble, and special metals.

The current report uses the MINDeSEA data compilation, along with existing knowledge on the geology of seabed hydrothermal deposits and their land locked counterparts, the volcanogenic massive sulphide deposits, to give a summary of the exploration potential for base and critical metals in seabed hydrothermal deposits. The report includes a metallogenic map of hydrothermal deposits in European waters and reviews the potential for base, noble, and critical minerals in the European deposits. For further details on the deposits and the collected data, please see MINDeSEA deliverable 3.3.

The seafloor setting is immature as an exploration target, and there is currently insufficient data to assess the metal potential, at least for hydrothermal sulphides. Mapping and characterisation should continue, and technologies for seafloor and subseafloor characterisation should be further developed. The setting has an economic potential with copper, zinc and gold as the main drivers, and a strategic relevance with a supply potential for a range of critical companion metals. All collected data on European seafloor mineralisations are accessible through the EGDI information platform (http://www.europe-geology.eu/).

For an introduction to the European Green Deal, the European Blue Economy and Critical Raw Materials, with regards to potential mineral deposits hosted by the marine environment, please see González et al. 2021.

ROV "Luso" image of sulphide-anhydrite chimneys in Moytirra hydrothermal field (NE Atlantic Ocean). EXPLOSEA 2019 Expedition. Photo: IGME.

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1. INTRODUCTION

GeoERA is a Co-Fund ERA-NET action under Horizon 2020, towards "Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe". The main objective is to contribute to the optimal use and management of the subsurface.

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For strategic evaluation of the European resource potential, and in particular for Europe's ability to improve its resilience towards supply shortages in critical and other necessary raw materials, the land-sea boundary is becoming increasingly irrelevant. Whereas almost all metals and minerals through history have been produced from mining operations on land, the quest for defining mineable targets in the oceans is continuously intensifying. As marine targets are slowly being identified and delineated, it is important to include both marine and onshore mineral potentials and identified resources in the European mineral resource inventory. One of the prime goals of GeoERA and MINDeSEA is therefore to expand and complement the European Geological Data Infrastructure (EGDI) with marine mineral resource information, for politicians, strategists, authorities, and stakeholders to make as informed analyses and decisions as possible. Some databases on marine mineral resources and vent sites do exist today and have provided important base data to the MINDeSEA library. It is, however, of the utmost importance to build a unified mineral resource database for all European resources, whether on land or on the seabed, for clever decision making.

The current report presents a metallogenic map of hydrothermal deposits in European waters. It also uses the MINDeSEA data compilation, along with existing knowledge on the geology of seabed hydrothermal deposits and their land locked counterparts, the volcanogenic massive sulphide deposits, to give a summary of the exploration potential for base, noble, and critical metals in European deposits. For an overview of the geology of seabed hydrothermal deposits, their tectonic settings, and details on the individual deposits, please refer to the MINDeSEA deliverable 3.3 (Schiellerup et al. 2021)

2. EXPLORATION POTENTIAL FOR SEA FLOOR HYDROTHERMAL DEPOSITS

Seafloor hydrothermal deposits, most notably expressed as seafloor massive sulphides (SMS), are modern volcanogenic equivalents of onshore (fossil) deposits of volcanogenic massive sulphides (VMS). VMS deposits have constituted important mining targets through history in many regions of Europe and around the World, and still provide significant resources of copper, zinc, lead, silver, and gold (Singer, 1995). In general terms, SMS deposits and the exhalative processes leading to their formation, are well known to geologists after millennia of mining metals and sulphur from VMS deposits found on land.

Massive sulphides deposits, whether on land or on the seabed, are strata-bound accumulations of sulphide minerals that precipitated at or near the sea floor in spatial, temporal, and genetic association with contemporaneous volcanism (Franklin et al. 2005). On the sea floor, massive sulphide deposits form as a result of heated seawater interacting with oceanic crust through a convection process driven by magmatic activity at depth. During convection, cold seawater infiltrates the seafloor and percolates through the marine crust to reach depths of several kilometres, where the water is heated to temperatures above 400 °C.

Chemical reactions in the descending sea water will generate a fluid, which is hot, acidic, chemically reduced, and able to leach the surrounding rocks (Petersen et al. 2016; 2018). The resulting fluid will become enriched in metals, sulphur, and silica, and quickly rise to the sea floor where it will be expelled into the water column at a confined vent site. Sulphides, sulphates, silicates, and other minerals are precipitated from the hot vent fluids as they cool or come into contact with cold seawater. The associated metal-rich plumes are called black or white smokers depending on their temperature and metal lode. Most of the metals will disperse into the overlying water column, but the remainder will precipitate to form SMS deposits in the form of chimneys, mounds, and metalliferous sediments on and around the vent site (Petersen et al. 2016; 2018), or form veins or massive units below the surface. Base metal rich seafloor massive sulphide deposits generally form from high-temperature hydrothermal activity at black smoker vent sites located at water depths between < 500 to more than 4000 m.

2.1. The geotectonic environment

Even though the geotectonic environment is only one of a number of controlling factors affecting the mineral and metal content of seabed hydrothermal deposits, it is the tectonic setting that dictates the eventual presence of the hydrothermal mineralisations on a first order basis.

Hydrothermal deposits in European waters can be found in basically three types of geotectonic environments. As described in the MINDeSEA deliverable 3.3 (Schiellerup et al. 2021) and references herein, these are:

- Mid-Ocean Ridges
- Intra-plate hotspots
- Back-arc settings

Figure 1 presents a metallogenic map of the European waters, including also deposits in international waters south of the Azores archipelago. The map may be downloaded from the MINDeSEA website and is also shown in larger size in **Appendix 1**. The map shows the Mid-Atlantic Ridge as the main host for seafloor hydrothermal deposits in Europe. Hydrothermal deposits are found along the Mid-Atlantic Ridge from south of the Azores archipelago, to the Arctic Sea north of Greenland, Fennoscandia, and Russia. Activity is controlled by the divergent plate motion of Eurasia/Africa to the east and North/South America to the west. Plate motion is slow to ultra-slow, which affects the longevity of hydrothermal venting, and has an impact on prospectivity. Both the Azores, Iceland and Jan Mayen islands are subaerial expressions of the activity along the ridge and ridge offsets, and their presence also affect local metal production. **Figure 1** shows that the interaction of the Azores hotspot with the Mid-Atlantic Ridge gives rise to additional activity around the Azores triple point. Iceland remains the only place in the world where a mid-oceanic ridge may be followed above sea level. Deposits along the Mid-Atlantic Ridge are generally hosted by mafic or ultramafic rocks, and prospective areas are defined by neo-volcanic rocks without significant sedimentary cover. Since no reliable size or quality estimates exist for any of the hydrothermal deposits displayed on the map, all records must be considered occurrences, even if occasionally referred to as deposits in the current text.

Intra-plate hotspots are represented by volcanism and vent systems associated with the Canary Archipelago off-shore Northwest Africa (Carracedo et al., 2002; Ancochea, 2004). The Canary Islands form an approximately 400 km long train of volcanic islands on the African plate, generally getting younger from east to west, and reflecting the slow movement of the African plate above the Canary Hotspot. Hydrothermal activity has been recorded both in the eastern (Picoletino Seamount) and western (Tagoro Volcano) part of the island chain. Scattered inactive hydrothermal sites are recorded also south of the Canary Islands, but within the Canary Island Seamount Province (See also Schiellerup et al. 2021 and references herein). Also in the Canary Island Seamount Province, mineralisations are associated with mafic volcanic activity. The Canary Island deposits have a stronger epithermal component than most of the Mid-Atlantic deposits, which is also reflected in their mineral and metal content.

The geodynamics of the Mediterranean Sea is ultimately controlled by the collision of the African and Eurasian tectonic plates, resulting in a complex faulting and subduction pattern involving a number of microplates along the length of the basin. Activity is primarily confined to back-arc settings in the Tyrrhenian and Aegean Seas where roll-back of northwards subducting plates play an important controlling role in terms of vent location and activity (Greve et al., 2014; Alagna et al. 2010). In the back-arc environments of the Mediterranean Sea, deposits tend to be associated with bimodal felsic volcanism. This applies both to the Tyrrhenian and Aegean Seas, and only the Eratosthenes Seamount in the Levantine Basin is considered a mafic host for mineralisations. The Mediterranean deposits are epithermal to volcanogenic massive sulphides, and deposits around the Palinuro Sea Mount, south of Naples in the Tyrrhenian Sea, are considered to result from high sulphidation fluids.

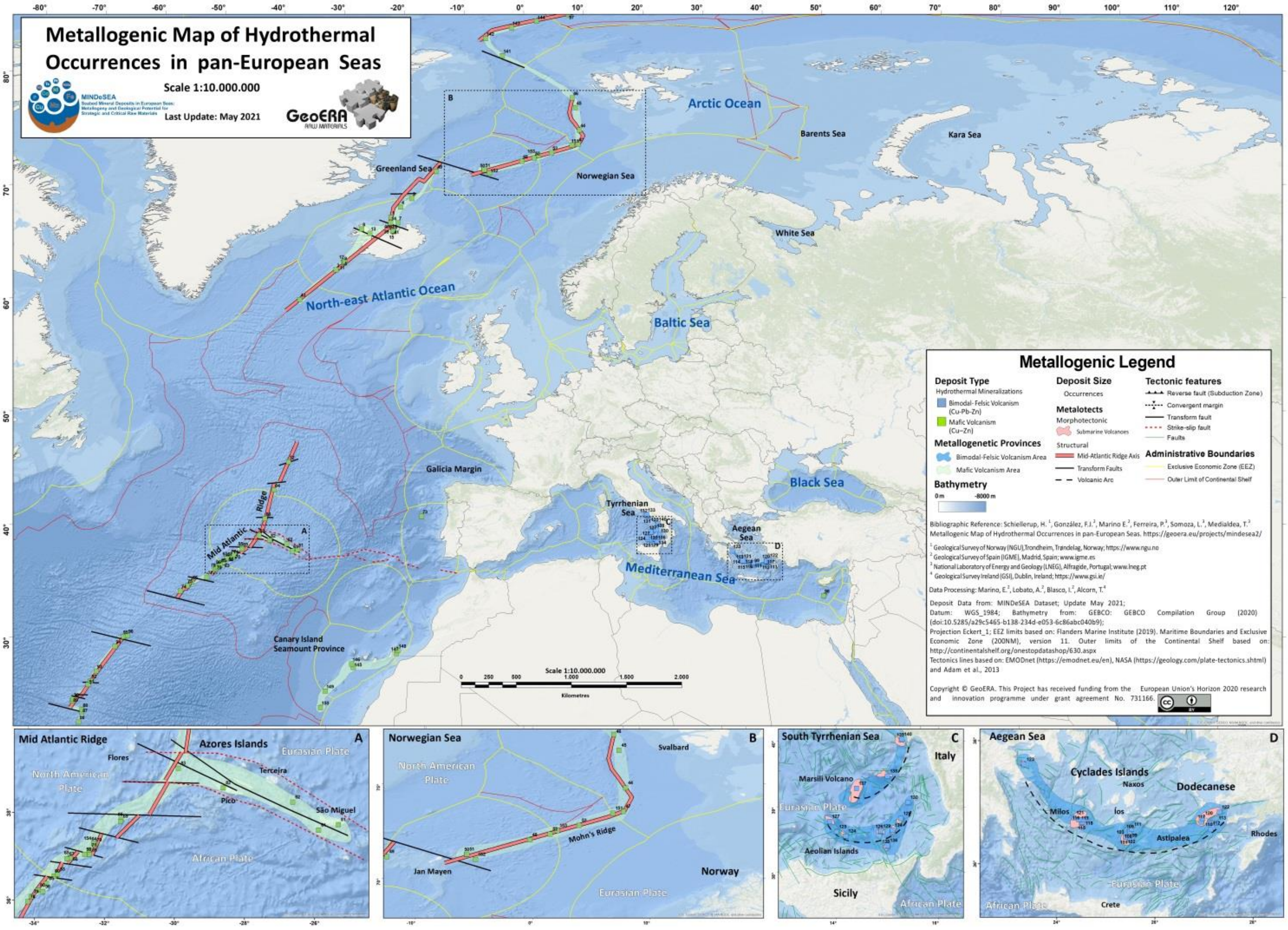

***Figure 1**. Metallogenic map of hydrothermal deposits in European waters. Numbers refer to individual vents and deposits. The full map with further details can be downloaded from the GeoERA-website: https://geoera.eu/projects/mindesea2/*

3. BASE, NOBLE AND SPECIAL METALS IN HYDROTHERMAL DEPOSITS

The geochemistry of massive sulphide deposits depends on a range of factors, including the temperature of the vent systems, as observed in the mineralogical zonations on both deposit, chimney, and hand specimen scales (Hannington et al. 2005). Both spreading rate and structural setting assert control on the leaching and carrying capacity of the hydrothermal system and the chemistry of the hydrothermal fluids. Phase separation processes, such as boiling, cause fractionation of the elemental lode and are also important. The general geochemistry of high-temperature black smoker systems is, however, primarily dependant on the tectonic setting in which they occur (Hannington et al. 2005).

On mid-ocean ridges, hydrothermal fluids dominantly leach mafic or ultramafic substrates, which are the major sources of Fe, Mn, Zn, and Cu in mid-ocean ridge vent fluids (Hannington et al. 2005). The substrate may also influence the content of noble elements, such as gold and silver, and mafic rock hosted metals, such as nickel and cobalt. There are systematic differences between mafic and ultramafic hosted deposits with, for instance, higher copper and gold contents in ultramafic hosted deposits, and higher zinc and lead contents in mafic hosted deposits (Hannington et al. 2005).

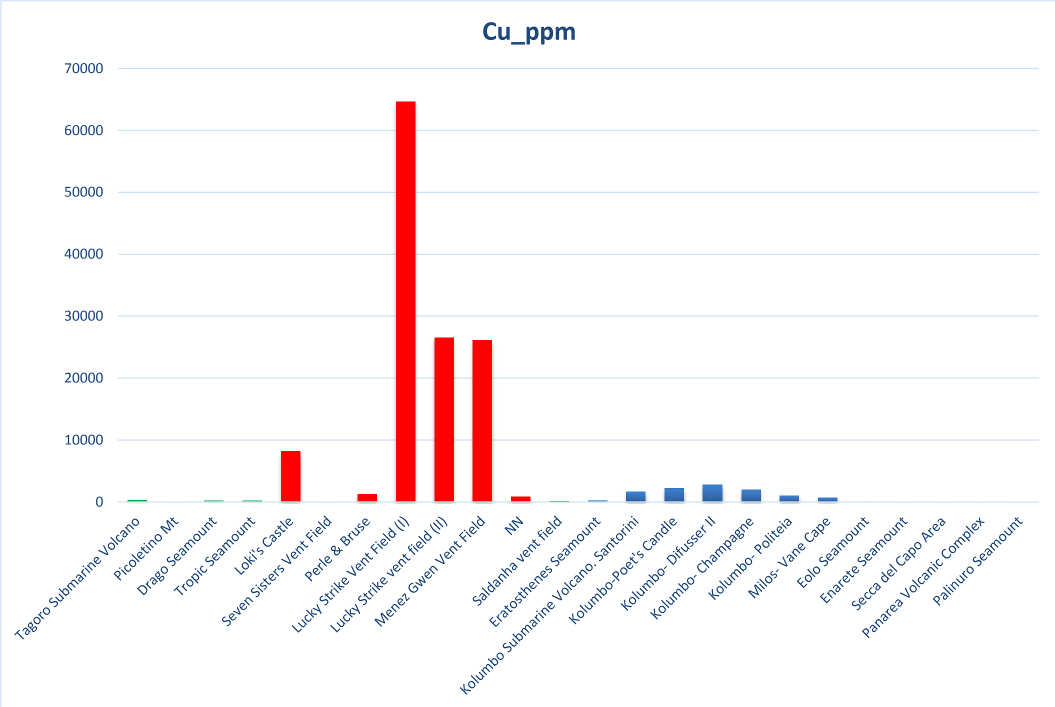

Figure 2. *Average copper concentrations in 25 vent fields in European waters. Intra-plate hotspots in green, mid-ocean ridges in red, and arc/back-arc settings in blue. Data from the MINDeSEA database.*

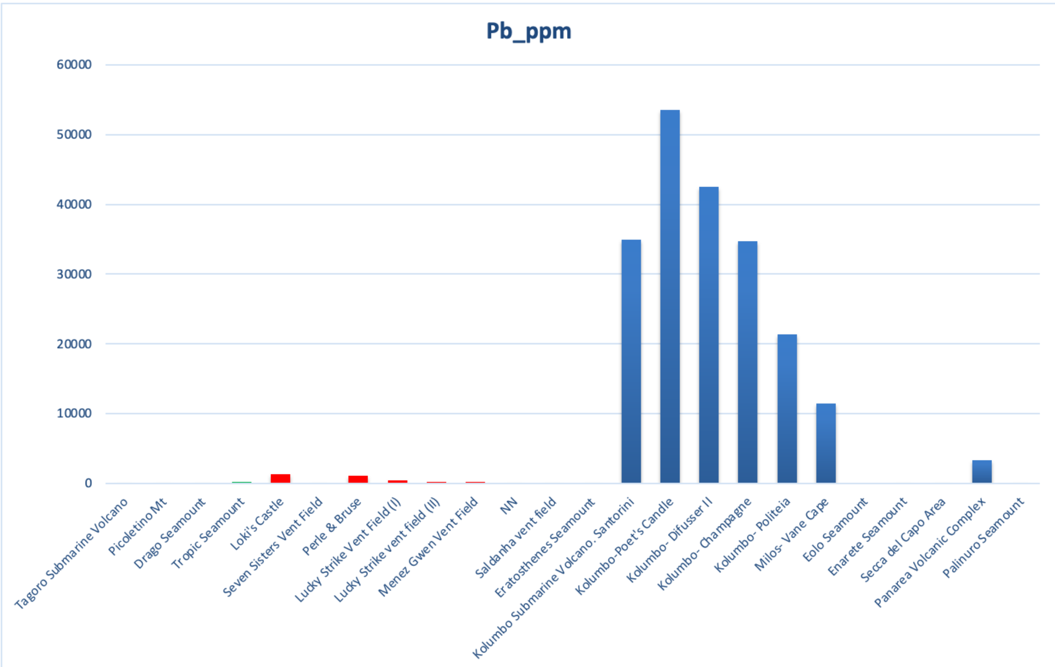

Figure 3. *Average lead concentrations in 25 vent fields in European waters. Intra-plate hotspots in green, mid-ocean ridges in red, and arc/back-arc settings in blue. Data from the MINDeSEA database.*

Deposits in arc and back-arc settings are generally richer in zinc, lead, and silver than deposits in mid ocean ridge settings, but lower in for instance copper (See **Figures 2 and 3**, and Schiellerup et al. (2021). Trace elements, such as antimony, bismuth, cadmium, gallium, germanium, indium, tellurium, and thallium, can be significantly enriched in deposits forming at volcanic arcs (Petersen et al. 2016).

The geochemistry of the seabed hosted massive sulphide deposits is of crucial importance to the possibility for future exploitation. The exhalative deposit type of main current interest in European waters is the high temperature sulphide dominated deposits exsolved from black smoker vents. Copper, zinc, gold, lead, and silver are the major commodities, which should form the base for an economically feasible mining operation on SMS deposits. These deposits are primarily found along the Mid-Atlantic Ridge.

Many of the metals on the current EU criticality list (**Figure 4**) are minor metals which may accompany the base metals into the seabed massive sulphides and add to the value of the deposits. Metals such as gallium, germanium and indium are considered critical in the EU, and are wholly or partly derived as biproducts from zinc ores, such as the land-based volcanogenic VMS deposits. Cobalt may be present in both VMS and SMS deposits, but usually in small amounts and partly hosted by iron sulphides. Marine crusts and nodules remain the primary exploration target for cobalt. However, in spite of a relatively modest economic importance in the seafloor hydrothermal setting, the possible sourcing of critical minor metals from seafloor deposits, may have a major strategic importance.

2020 Critical Raw Materials (new as compared to 2017 in bold)		
Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	**Bauxite**
Fluorspar	Niobium	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	**Strontium**

Figure 4*. The 2020 list of critical raw materials according to the European Commission (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474)*

4. THE SUPPLY POTENTIAL OF HYDROTHERMAL DEPOSITS

Most of the hydrothermal deposits in European waters are located along the Mid-Atlantic Ridge, including the Azores Triple Junction and ridge segments affected by the Icelandic hot spot. Number-wise mid-ocean ridge setting therefore must be considered the most important metallogenic setting of the European seafloor hydrothermal deposits. The sulphide deposits within this setting are all considered mafic (or ultramafic) hosted and are potential sources of copper, zinc, lead, silver, and gold. However, the setting also includes shallow or colder vent systems precipitating mainly anhydrite or barite.

Deposits related to intra-plate hotspots are represented by occurrences in the Canary Island archipelago. These precipitations comprise epithermal deposits, volcanogenic massive sulphide deposits (VMS), and exsolved oxyhydroxides. Their main supply potentials include copper-zinc sulphides, barite, and iron oxyhydroxides.

Apart from the hydrothermally generated iron and manganese crusts found on the Eratosthenes Sea Mount in the Levantine Basin all venting and precipitations in the Mediterranean Sea are related to back-arc spreading, either in the Central and South Tyrrhenian Sea or in the Aegean Sea. These deposits are considered of bimodal to felsic exhalative types, or of epigenetic origin. In both the Aegean and the Tyrrhenian Sea, deposits generally consist of iron and/or manganese with a few occurrences of lead and zinc precipitates around, for instance, the Kolumbo volcano north of Santorini.

The economy of a mining project exploiting a seafloor hydrothermal deposit must rely primarily on the value of its contained base and noble metals, as is the case for any land-locked VMS deposit. High concentrations of gold may contribute significantly to the feasibility of a mining operation, even if copper is the main target. Companion metals, which may be present in smaller amounts, may offer a significant contribution to securing, for instance, European supply chains, but will not influence the feasibility of a mining project. The minor metals, such as indium, gallium, and germanium, even if critical to European industry, are not actually geologically scarce, and even though they may have a strategic importance, they rarely have economic importance. All three metals can substitute for zinc in sphalerite and may potentially be recovered during refinement. However, in a recent study by Mudd (2021) it was stated that Indium often represents less than a percent of the revenue associated with zinc refinery.

Copper, possibly accompanied by gold, make up the primary economic foundation of feasible future mining projects on seafloor hydrothermal mineral deposits. Volumetrically, copper is one of the most important metal commodities in the world today, and through history copper production has generally doubled roughly every 30 years. Demand is likely to continue to surge, to a large extend driven by electrification and decarbonisation of global energy production. There is no geological scarcity of copper, and the global reserve base has always been able to keep up with increasing demand – there is more identified copper available to the world today than at any other time in history (ICGS, 2021). There is, however, a concern that climate actions will require upscaling of copper production at a rate to which the mining industry is not geared. Within this scenario, new and viable business cases may develop in copper mining, also including seafloor hosted deposits.

Of the metals and minerals deemed critical by the European commission in their 2020 assessment, the following five commodities are relevant companion metals or deposits associated with seafloor hydrothermal activity:

Cobalt

> Cobalt is a potential companion metal to both VMS and SMS deposits, but cobalt is mainly extracted from sedimentary copper deposits, magmatic nickel-copper deposits, or lateritic nickel deposits. Very few cobalt-producing mines have cobalt as their primary target. The

metal has received huge attention due to the under-regulated operations and concentrated extraction in DRC. There is no geological shortage of cobalt, even with a strong increase in demand for cobalt for energy storage (USGS, 2021; Mudd, 2021). However, matching demand with production seems to be a current challenge. VMS deposits on land are rarely sourced for cobalt, containing typically a few hundred ppm up to one or two permille of the metal. These figures are also in accordance with the data collected in the MINDeSEA database. The highest cobalt grades are expected where hydrothermal systems interact with ultramafic rocks, typically along ultra-slow spreading ridges. The fairly low Co-grade, and the fact that cobalt resides in multiple host minerals, including Fe-sulphides, is generally a hindrance to the production of Co-concentrates (Gautneb et al., 2020). At the same time, cobalt may be viewed as a profitable target in VMS mine waste. The seafloor is a huge reservoir for cobalt in crusts and nodules, and these deposits are much likelier targets for cobalt-focused exploration and exploitation. These deposits also include hydrothermally generated crusts, where cobalt is ultimately sourced from venting fluids. Seafloor hydrothermal deposits, per se, cannot be considered to impact severely on cobalt production, even if the processing of SMS sulphide ore may provide a sellable cobalt concentrate.

Gallium

Gallium is extracted from either bauxite or zinc ores, and gallium production, with the downstream supply chains, are therefore completely depending on zinc and aluminium refining. With a yearly production of around 300 tons, and estimated resources of around 1 million tons in bauxite alone, Gallium cannot be considered scarce (USGS, 2021). None of the deposits in the MINDeSEA database carry more than 20 ppm Ga, but in a production situation it is the tenor of gallium in sphalerite which will determine the potential for generating gallium-rich concentrates. These data have not been collected.

Germanium and indium

Germanium is, like gallium and indium, considered a minor-value by-product at smelters and refineries (Mudd, 2021). World production is small (130 t, according to USGS, 2021). The global indium production is on the order of 900 t p.a. (USGS, 2021). Both metals are substitute metals which may be recovered from sphalerite, and, as for germanium, zinc-dominated SMS-deposits may represent a source for the metals. There are very limited data on these metals in the MINDeSEA database and the grades tend to be low on sample scale. Again, the mineral chemistry of sphalerite is the determining factor for possible future production of germanium and indium from SMS deposits.

Baryte

Baryte is an industrial mineral used mainly as a weighing agent and heavy filler. It is primarily mined from paleo-oceanic settings in stratabound deposits related to marine exhalative processes. Baryte enrichments are ubiquitous in the seafloor hydrothermal setting where it exsolves from lower temperature fluids, forming gangue, and constitute an indicative component of the SMS and VMS metal and mineral zonation scheme. In the MINDeSEA database, samples are recorded with several tens of percent of barium, indicating the presence of massive or semi-massive baryte in the deposits. Baryte seems particularly prominent in deposits associated with Canary Island intra-plate volcanism, but the formation is temperature controlled and deposits are found in all settings. Baryte is a low-value commodity and the economy of extraction not necessarily sustained even for massive deposits on the seafloor. As for all other critical metals and minerals there is no general geological shortage, but primarily a lack of projects and globally distributed extraction.

5. CONCLUSIONS AND RECOMMENDATIONS

Exhalative deposits have been important mining targets since pre-historic times, and also today these deposits contribute significant amounts of copper, zinc, lead, silver and gold to the global metal consumption. Seafloor hydrothermal or massive sulphide (SMS) deposits are analogues to the terrestrial VMS deposits and may provide opportunities for future metal production, given that mineable deposits are identified, and viable business cases documented. Production from marine hydrothermal deposits may decrease import reliance on for instance copper, and mitigate possible effects of disrupted supply chains affecting European production and industrial development. However, whereas seabed hydrothermal deposits have an inherent potential to provide critical metals for the European market, it is the base metals, copper and zinc, as well as gold which constitute the primary economic assets in these deposits.

The potential for future seabed mining of sulphide-hosted metals is currently not sufficiently resolved, and as an exploration target the setting must be considered immature. Mapping is on-going and progressing, but vast areas remain unmapped and unexplored. In particular sulphide occurrences at inactive vent sites seem to be poorly documented. Whereas many sites with metal sulphides and/or hydrothermal venting have been discovered, very few have been characterised in any detail with respect to size, morphology, mineralogy, and chemistry. Drilling and core extraction is required both to develop individual deposits but also to assess the general metal potential of the seabed setting. So far, only a couple of deposits have been drilled.

Finding and developing mining targets on land and on the seafloor requires geological mapping. Mapping the seafloor is particular challenging, and a different toolbox is required. R&D initiatives directed towards submarine and sub-seafloor characterisation are therefore important. Mapping should be continued in order to further constrain the mineral potential, but also to assess the natural diversity and possible impact of future mining.

However, as marine mineral targets are being more clearly identified, characterised, and delineated, it is important to include the marine mineral potentials and identified resources in the European mineral resource inventories.

The current report outlines the exploration potential for hydrothermal deposits in three main geodynamic settings in European waters:

- Mid-ocean ridge deposits are related to mafic volcanism and hosted by mafic or ultramafic rocks. The most important commodities associated with this setting are copper, zinc and gold. This type of deposit is found in European jurisdictions along the Mid Atlantic Ridge from south of the Azores archipelago to the Arctic Ocean. Slow spreading rate along the ridge tend to favor larger deposits, and there is a potential for discoveries with significant quality and size.
- Intra-plate hotspot-related volcanism drives hydrothermal systems around the Canary Island archipelago. Six different deposits are recorded in the MINDeSEA library representing a large spread in mineralisation characteristics. Mineral deposits include both sulphides,

sulphates and oxyhydroxides but metal content in the deposits investigated so far tend to be low.

- Hydrothermal deposits in arc/back-arc geodynamic settings are found in the Mediterranean Sea. The dominant metal commodities in deposits in the Aeolian, Tyrrhenian, and Aegean Arcs are zinc, lead, and silver, but mineralisations include also sulphates and hydrothermally generated crusts and nodules consisting of iron-manganese oxyhydroxides. The Mediterranean deposits are considered related to bimodal or felsic volcanism.

Several European countries are strongly engaged in locating and surveying for hydrothermal mineralisations on the sea floor under their national jurisdictions, and several more countries are involved in similar exploration in the high seas. Whereas the seabed is currently immature as a mining target, at least for massive sulphides, the understanding of the marine mineral potential is likely to undergo significant improvement during the coming decades. It is also important to acknowledge that better understanding of marine hydrothermal deposits has a clear potential to improve exploration models for equivalent deposits on land.

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7. APPENDIX 1

Metallogenic map of hydrothermal deposits in European waters. The map can be downloaded from the [MINDeSEA project website]