MINDeSEA

Seabed Mineral Deposits in European Seas: Case study for ferromanganese crusts and phosphorites in the Macaronesia area (NE Atlantic Ocean)

MINDeSEA

Deliverable 4.7: Results of the case study

WP4 leader: Geological Survey of Spain (IGME) - Spain		
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D4.7. Case study for ferromanganese crusts and phosphorites in the Macaronesia area (NE Atlantic Ocean)

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"**. Its 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)**, materialized in the frame of the GeoERA Raw Materials Theme (Grant Agreement Nº 731166, project GeoE.171.001), resulted from 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.

This document reports the research and compilations produced by the MINDeSEA partners, led by the Geological Survey of Spain (IGME-Spain). A case study has been proposed for ferromanganese crusts and phosphorites in the Macaronesia area (NE Atlantic Ocean), demonstrating how the case study results can be used in off-shore mineral exploration. A number of seafloor morpho-geological, environmental and socio-economic criteria have been analyzed using GIS tools to produce predictive maps. The final objective of this report is a preliminary identification of areas for responsible resource exploration and extraction; inform policy makers for the management of seabed resources and Marine Spatial Planning design.

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1. INTRODUCTION

Natural resources and raw materials, which are becoming increasingly scarce in land based mining, are important for the development of high-tech and green industries. Advances in technology and sampling methods now allow scientists to map the shape and properties of the seabed in ever more detail. Researchers increasingly explore the use of automated analysis techniques to undertake or assist in the analysis of these datasets. In particular, the availability of high resolution bathymetries, backscatter data, and suites of samples and geochemical datasets, together with oceanographic data, has advanced the ability to assist the development of potential and predictive maps.

Based on the experience over the last ten years in the Central Atlantic, we propose to present a case study which reviews different approaches with a view to initiate thinking on standard ways to associate seabed characteristics with different probabilities for the formation of ferromanganese and phosphorite deposits with economic potential. All of them will improve our ability to develop predicted maps of mineral deposits based on survey data.

This case study will compare different methodologies for producing maps of seabed mineral deposits from acoustic data (high resolution bathymetry and backscatter) and sample data (on site verification, mineralogy and geochemistry). Methods selected for the study will focus on newly emerging techniques that utilise developments in technologies (e.g. multibeam backscatter) and computer processing (GIS tools), enabling faster, reproducible and more objective processing of seabed data.

The case study will be selected in the Macaronesia area, with variable seabed geology that comprises different geomorphic features, sedimentary and mineral deposits and exposed bedrock, representative of those occurring throughout European waters. The benefits this case study will bring are providing empirical evidence on how the new methods could improve minerals mapping (occurring, potential and predictive maps), and the subsequent opportunity to work towards a common understanding across Europe on the use of multibeam-derived data in submarine minerals mapping. The case study will make use of emerging data layers such as the backscatter derived from multibeam echosounder and the more detailed topographical information available from high resolution bathymetry. Derived variables will be calculated from the bathymetry and backscatter data, including e.g. bathymetric position index, slope, size and shape of topographic features and seabed roughness. Ground trothing data from dredge or ROV samples (physical, mineralogical and chemical characteristics) and underwater video and stills will be used to evaluate the accuracy of the resulting maps. In this study we will compare traditional approaches against novel semi-automated approaches. This works desires to continue previous studies started in 2013 that ended with the completion of a Master's thesis and the presentation of the results obtained at international congresses. (Manzanares, 2013; Manzanares et al., 2013)

In this study we will compare traditional approaches based on seabed sampling and video against novel semi-automated approaches. This study aims to develop a protocol for producing potential and predictive maps for ferromanganese crusts and phophorites. Methods proposed to be included in the study, although not exclusively are:

(1) Object-based image analysis (OBIA), which will be used to develop a semi-automated process of map production from multibeam backscatter, bathymetry and their derivative data layers. It is a technique commonly used in terrestrial satellite image analysis, where the image is divided into meaningful objects, based on the spectral and spatial characteristics of the input datasets. The resulting objects can be characterised by their various features, such as layer values (mean, standard deviation, skewness etc.), geometry (extent, shape etc.), texture and many others. The subsequent classification of the objects is based on combinations of these features, where the analyst sets rules according to corresponding values for ground-trothing data.

(2) Predictive modelling, which can be used in conjunction with many methods, including the above, to investigate relationships between substrate types and the various predictive layers and to produce spatial predictions based on these.

Expert and statistical validation of the different map outputs will be undertaken. The results of the case study will be presented in this separate project report and in future peer-reviewed publications.

2. APPROACHES COMPARISON: SAMPLING AND VIDEO VS PREDICTIVE MAPS

Several previous research cruises were made in the study area with different approaches and purpose (See Deliverables D7.2 to D7.4). These cruises resulted in the collection of both several image and video documents and samples obtained by different collection methods (Box cores, Dredges, ROV) (**Fig. 1**). All these data have been collected in the MINDeSEA database as occurrence sites for both Fe-Mn crusts and phophorites.

Figure 1: Sampling thick Fe-Mn crusts on the Tropic Sm during the JC142 cruise. ROV ISIS image.

The result of the multi-criteria analysis show that several favorable areas have been already studied reporting also the presence of thick Fe-Mn crusts rich in several strategic and critical elements (Mn, Co, Ni, Cu, V, Te, REY, etc.) (Koschinsky et al., 1995; Muiños et al., 2013; Muiños 2015; González et al., 2014; 2016; Marino et al., 2017; 2018; 2019; Marino, 2020; Somoza et al., 2021).

In this way is possible to highlight that the automatized predictive map obtained only with physical criteria performed on a low resolution bathymetry allows find the possible interesting areas for the discovery of thick Fe-Mn crusts pavements, covering large seamounts and banks.

3. CASE STUDY: MACARONESIA AREA

The working area chosen for the study is the Central Atlantic Ocean and more specifically, the Macaronesia (**Fig. 2**). This area has been chosen for several reasons: firstly, it is an area with a great interest for Europe as most of it is located within the EEZ of several countries, more over it is a relatively low studied area and finally, the submarine relief of this area presents a great diversity of morphologies, which makes it an area in which is possible to obtain a great variety of results. The Macaronesia area includes the volcanic archipelagos of Canary Islands, Madeira and Azores, in which are present hundreds of seamounts formed in most of the cases by the same volcanic process of the nearest islands. In the area are known several seamounts with a Cretaceous age, growth along several growing phases, and with great surface areas and heights, some of them presenting a flat summit (guyot type) (Hein et al., 2009; Marino et al., 2017; 2018). Between all of them are interesting to be named The Paps, Echo and Tropic seamounts, located in the south of Canary Islands, Lion, Josephine, Ampére and Unicorn seamounts, around Madeira islands, and Atlantis, Hyeres, Irving and Great Meteor, located on the south of Azores islands (MINDeSEA, 2021).

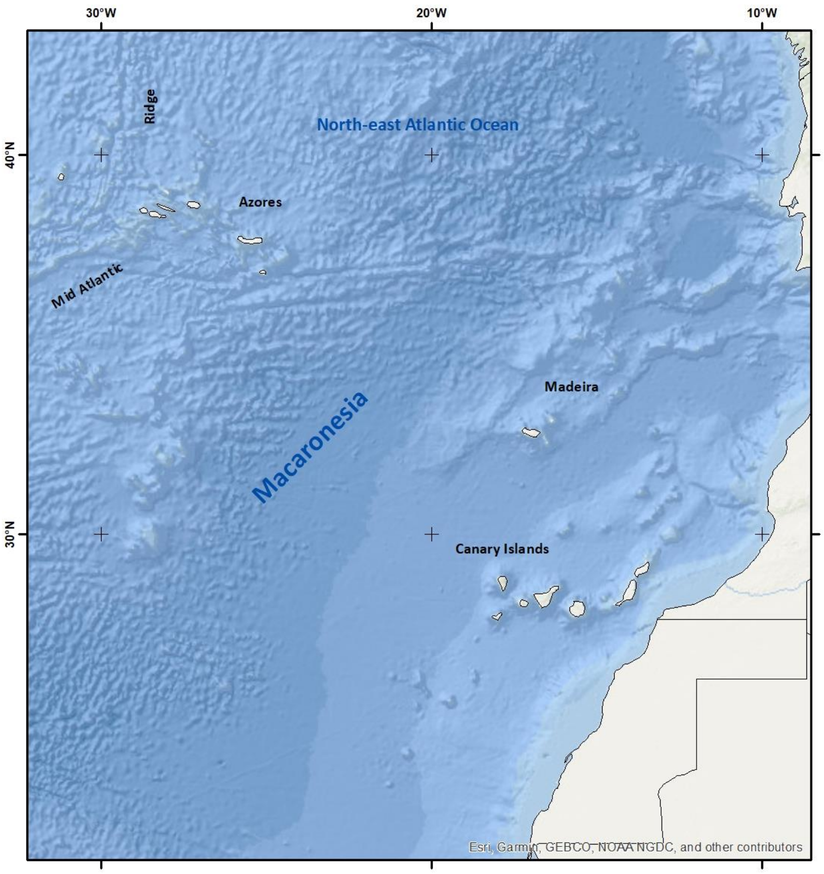

Figure 2: Study area, Macaronesia, comprehending three volcanic archipelagos: Canary Islands, Azores and Madeira.

3.1 The use of predictive maps for Fe-Mn crusts and phosphorites

The predictive map generated for the pan-European seas (see Deliverable D4.3) can be used in order to localize interesting exploration areas within the Macaronesia. The predictive map allowed highlight the presence of different seamounts with a series of processes.

In addition to the predictive map, several other criteria have to be added in order to highlight the better exploration areas in the studied zone.

3.1.1 Highlighting the seamounts and banks

The base cartography was obtained as GIS service (WMS) from GEBCO (General Bathymetric Chart of the Oceans) of 15 arc seconds resolution, approximately 450 m (GEBCO Compilation Group, 2021). This cartography is obtained mainly by altimetric satellites, which are monitored by GPS satellites and ground stations, so that the position of the satellite with respect to a global reference ellipsoid is perfectly known. As can be deduced, regardless of the resolution of the mapping used for the work, the mapping has a medium accuracy due to the media with which it has been obtained, however this type of mapping is homogeneous, so that for global studies it is very suitable (**Fig. 3**). All the physical parameters are based on this bathymetry. The base bathymetry shows several areas with noise generated by a bad processing of the bathymetric data, to solve part of this noise a smooth has been processed on it using the Filter Low analysis. This tool performs traverses a low pass 3-by-3 filter over the raster. This option smooths the entire input raster and reduces the significance of anomalous cells.

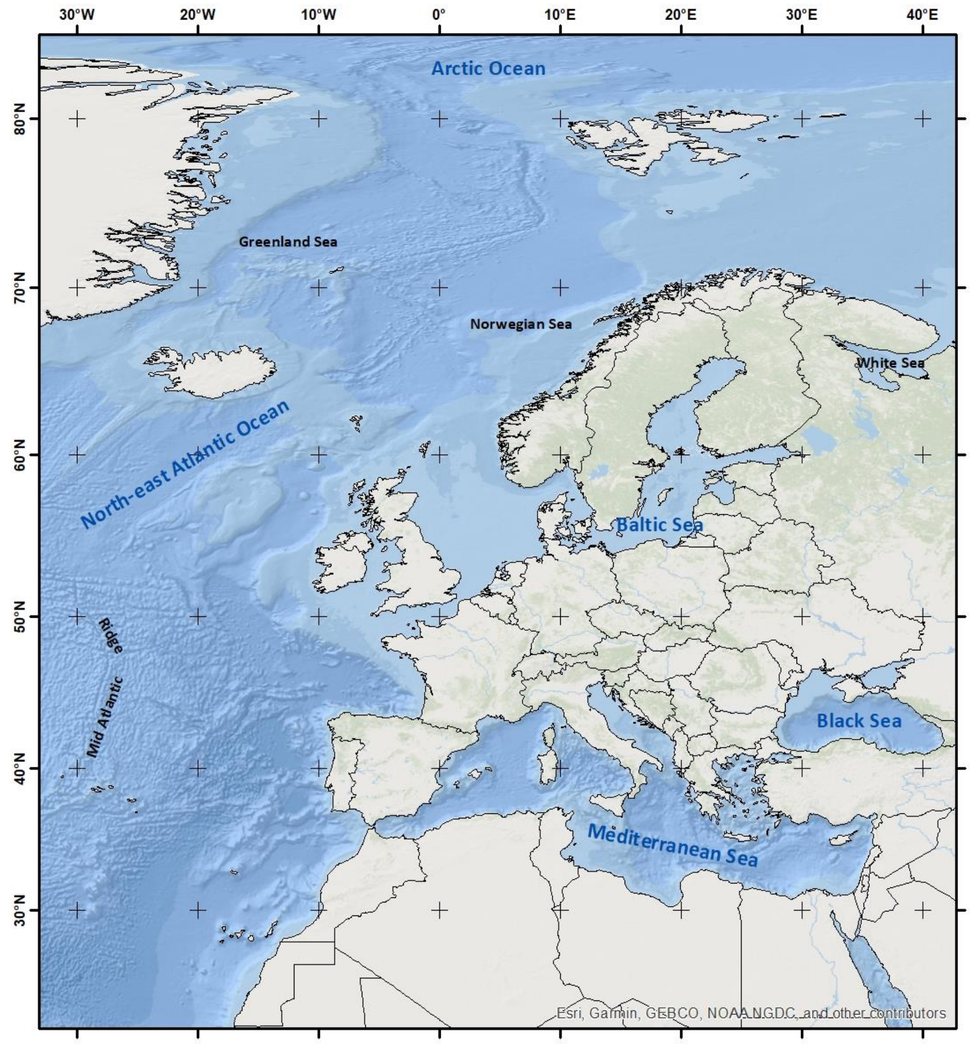

Figure 3: GEBCO bathymetric layer used in the case study.

The first process is to transform the bathymetry to topography (by multiply to -1) so that all the highs, represented by seamounts, are transformed in the lower parts, after this pace the flow direction algorithm is run, this allow highlight were the direction of a possible flow goes and mark all the sinks (represented by the seamounts summits) (**Fig. 4**) (Kitchingman and Lai, 2004; Manzanares et al., 2013).

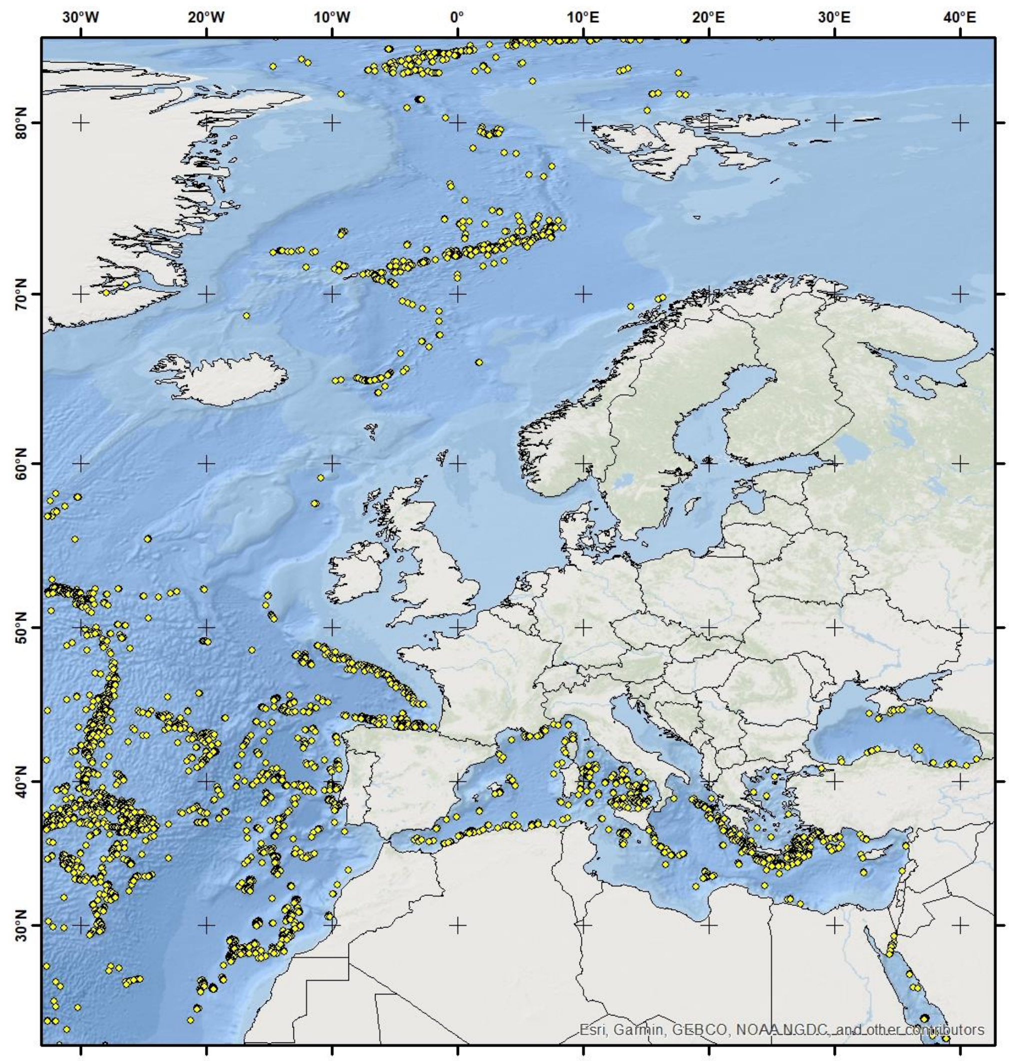

Figure 4: Automatic identification of seamounts and continental shelf scarps using GIS tools.

Once all the sinks are evidenced, to eliminate very small seamounts or bathymetric errors, they are filtered with a depth buffer and a standard deviation buffer so that only seamounts with sufficient height and surface area are evidenced.

3.1.2 Morpho-geological evaluation criteria

After localize the summits four morpho-geological evaluation criteria have been run in order to generate polygons that comply with the majority of them, these parameters are the water depth, the seafloor slope, the age of the oceanic crust and the proximity to the coast. To each parameter was given a values from 1, that represent the better condition to form Fe-Mn crusts, to 3 (**Table 1 and Fig. 5**). This multi-criteria analysis allows localize the marine areas in which are present seamounts, ridges and banks that show the possibility of found thick Fe-Mn crusts with high contents of interesting metals.

Table 1. Multi-criteria evaluation of the better location for Fe-Mn crusts. Depth in meter, slope in degrees, crust age in million years and proximity to coast in nautical miles.

Value	Depth (Z)	Slope (S)	Crust Age (A)	Prox. To coast (D)
1	800 ≤ Z ≤ 4000 m	≤ 10°	≥ 65 Ma	≥ 200 NM
2	200 ≤ Z < 800 m	10 ≤ S ≤ 20°	20 ≤ A ≤ 65 Ma	100 ≤ C ≤ 200 NM
3	Z < 200 & Z > 4000 m	≥ 20°	≤ 20 Ma	≤ 100 NM

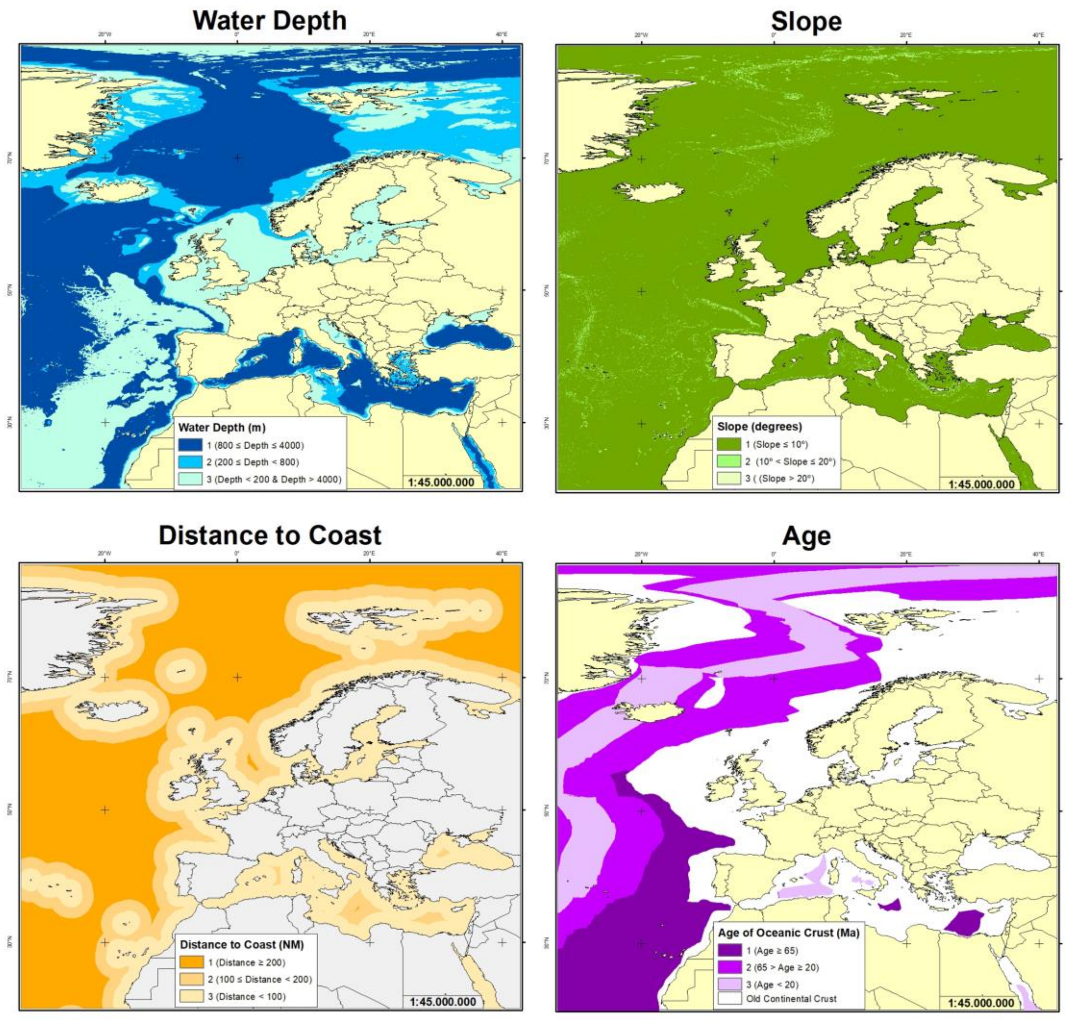

Figure 5: Graphical representation of the evaluation criteria used in the GIS multi-criteria analysis.

With these criteria has been generated a map showing several areas with the increasing possibility of Fe-Mn crust occurrences (**Fig. 6 and Deliverable D4.3 -** Predicitivity map of Fe-Mn crusts and phosphorites).

The analysis of the selected criteria includes as favorable site for the presence of Fe-Mn crusts also large areas of the abyssal planes and areas located relatively near to the Mid Atlantic Ridge (MAR). The first could be a good site for the accumulation of Fe-Mn crusts in those areas in which the substrate is represented by hard rocks and where the bottom currents are strong enough to keep clean the substrate of sediments and/or the sedimentation rate is low enough to allow the slow accumulation of Fe-Mn crusts (eg., current channels). On the other hand, areas located near the MAR and in general any hydrothermal vent, could show the presence of thick Fe-Mn crusts derived from low-temperature hydrothermal fluids. They can show enrichments in specific critical and strategic elements (Li, Mo, Zn, Pb, Cu, or Cr) mostly related to this hydrothermal process with respect to the most typical hydrogenetic Fe-Mn crusts.

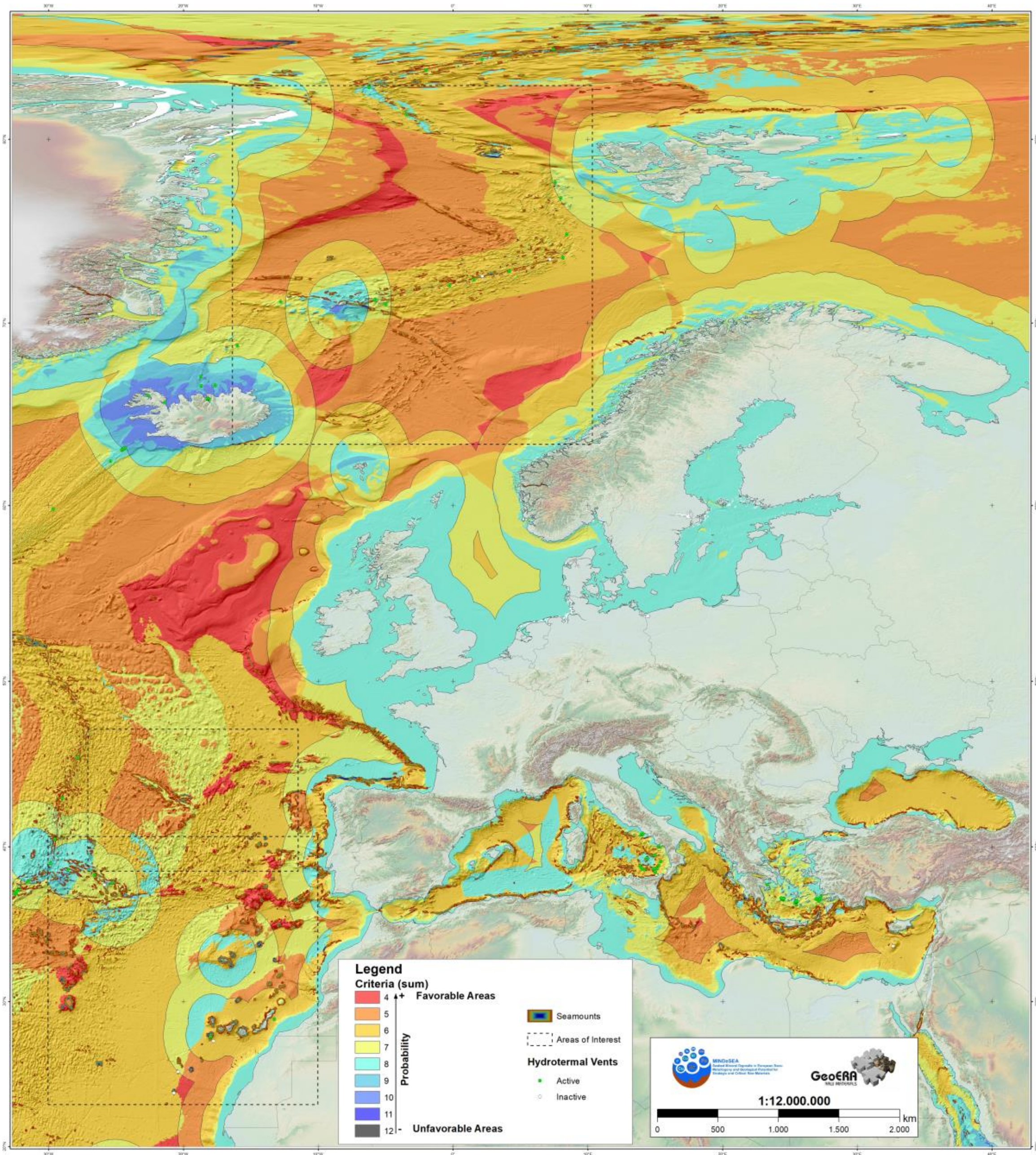

Figure 6: Detail on the predicitivity map for ferromanganese crusts in pan-European seas.

In the MINDeSEA database phosphorite occurrences are located in proximity of the Atlantic Iberian margins and seamounts and banks of the Macaronesia area. They are usually associated with the occurrence of thick Fe-Mn crusts deposits of old substrates. All of these occurrences are related to physicochemical processes that have had effects throughout the Atlantic Ocean and that can be associated with the global phosphatization events also described in the Pacific Ocean (Hein et al., 1993; González et al., 2016; Marino et al., 2017; Marino, 2020).

The methods used to highlight both the presence of seamounts and the better areas for thick and metal-rich Fe-Mn crusts clearly evidence all the seamounts present in the Macaronesia area. These methods perfectly highlight as suitable area for Fe-Mn crusts the seamounts located both in the south of the Canary Islands and around Madeira and Azores archipelagos, in addition the methods evidence as suitable area the Gran Meteor and nearest seamounts (**Fig. 7**).

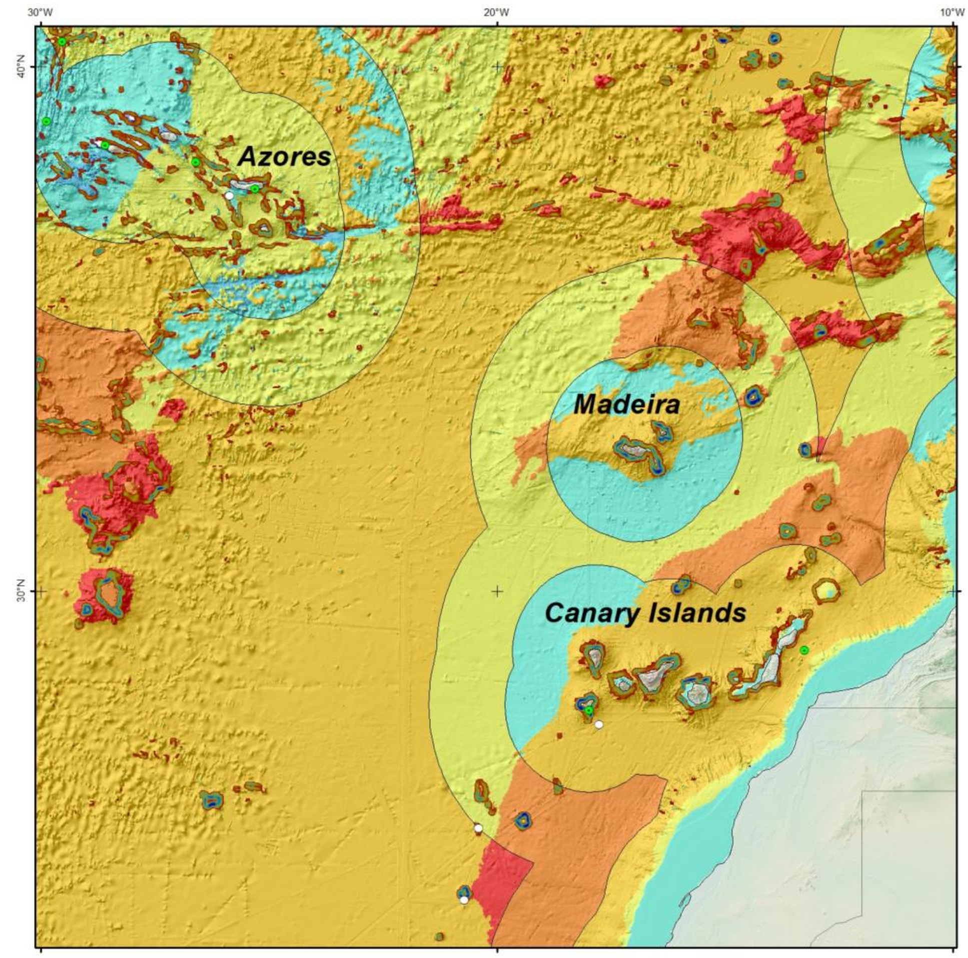

Figure 7: Zoom of the predictivity map in the case study area.

New evaluation criteria have been applied to calculate the different mining potential of the selected area. These criteria take into account the environment and socio-economic component in order to evaluate better place to place a mining site.

3.1.3 Environmental and socioeconomic criteria

The socioeconomic criteria selected take into account several issues essentially to reduce the expenses of the mining project as well as the proximity to coast in order to have less transport costs, the presence of marine protected areas, the depth of the deposit, presence of hydrothermal vents, all of them also linked with the morphology and size of the seamounts (flat summits, summit area, etc.) (**Table 2**).

Table 2. Multi-criteria evaluation of the seamounts with the highest mining potential. Proximity to coast in nautical miles, depth in meter and area in square kilometers.

Value	Proximity to coast (D)	Deposit Depth (Z)	Area (A)
1	D > 350 MN	Z > 2500 m	A < 130 Km^2
2	100 ≤ D ≤ 350 MN	2200 ≤ Z ≤ 2500	130 ≤ A ≤ 500 Km^2
3	D < 100 MN	800 ≤ Z ≤ 2200	A > 500 Km^2

Series of quantitative criteria were chosen to calculate the mining potential and converted into qualitative variables: high potential (value 1), medium (value 2) and low (value 3). The criteria under study in each case were reclassified and a thematic map of mining potential was obtained for each one. With all the criteria studied, a simple average was performed to obtain a total map of mining potential (**Fig. 8**).

- Depth of seamounts: The values were reclassified so that water depths between 800 and 2200 m took value 1, since this is the band in which the ferromanganese crusts present greater richness in metals value 2 for the band of depths between 2200 and 2500 m and value 3 for depths greater than 2500 m.

- Exploitable area: the larger the area, the greater the exploitation and the greater the probability of finding crusts with acceptable thicknesses. Thus, areas larger than 500 km^2 take value 1, those between 130 and 500 take value 2 and those smaller than 130 km^2 take value 3.

- Proximity to the coast from the economic point of view: We will try to choose seamounts that are as close as possible to the coast in order to reduce economic costs in fuel and supply. Thus, the criterion followed was: value 1 for seamounts located less than 200 M from the coast, value 2 for those seamounts located between 200 and 350 M and value 3 for those located more than 350 M.

- Protected areas: In the area of the case of study have been find all the European protected areas in order to verify all the areas in which is forbidden starts any mining activity. The areas are part of the Natura2000 network together with other protected areas chosen by the different countries.

The result of this analysis can be observed in the map in **Figure 8**, in which have been selected the better mining sites of the case of study area and overlapped with the highest potential areas of the predectivity map. In addition to the suitable seamounts the multi-criteria analysis also highlights the presence of steep slopes like the ones presents in volcanic islands (eg., Canary I. and Madeira).

This map shows how the seamounts with the greatest potential are separated from the MAR, even if the area could have a high mining potential due to its proximity to coast and depth essentially in the area located to the north of Azores. Both in the predectivity and mining potential map it can be seen that the location of the seamounts with the greatest mining potential fulfill the theoretical bases, showing the areas with the greatest mining potential located essentially far from the active ridges, where the age of the oceanic crust is greater (>60 Ma), the water depth is usually shallower than in the ridges (800-2500 m), and the distance to the coast is much less than in the center of the Atlantic Ocean (<400 M).

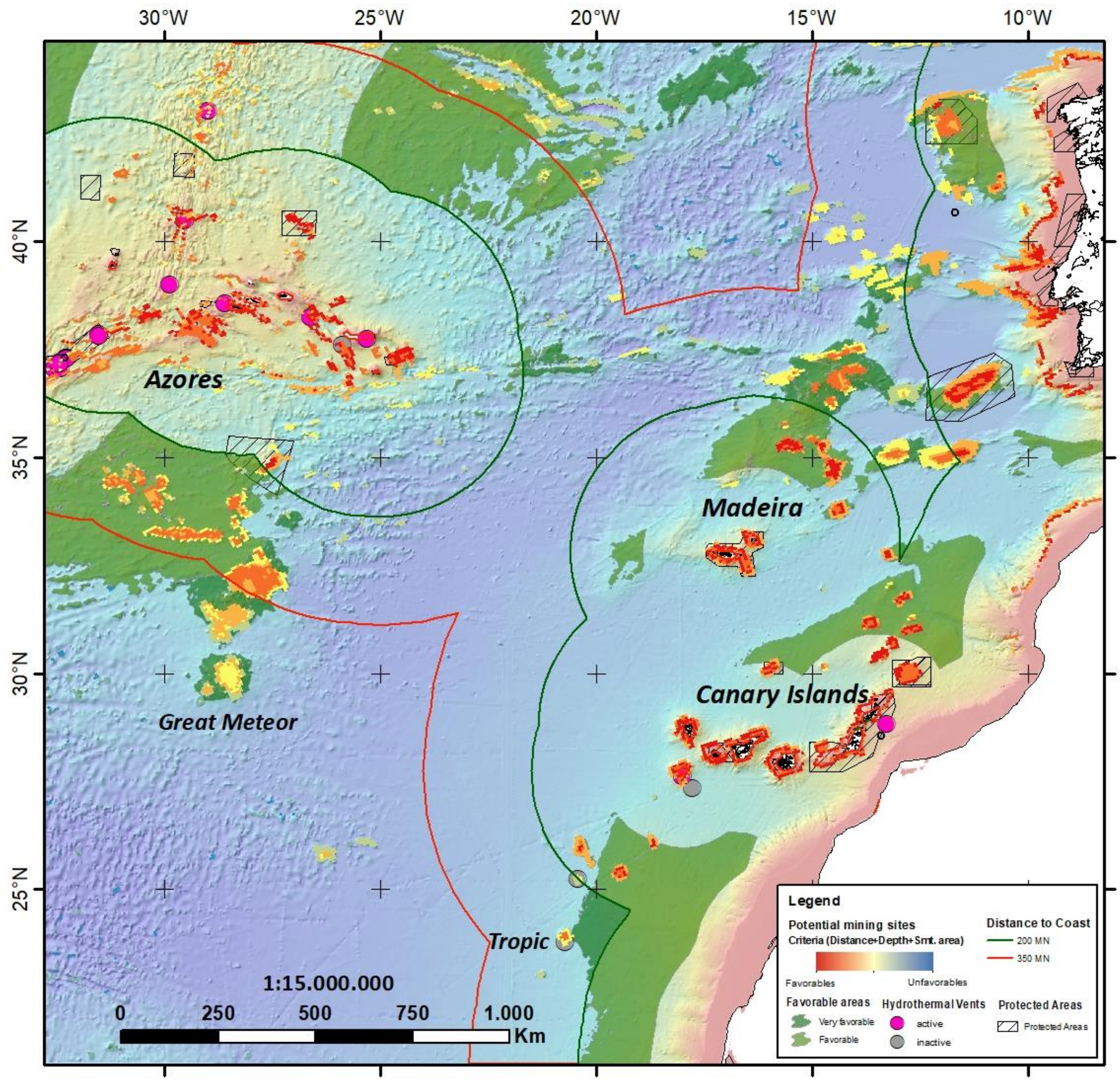

Figure 8: Mining potential Map of the study area overlapped with the areas with the highest potential of Fe-Mn crusts.

The result of this analysis show that in the area of the study case there are several interesting zones suitable for their exploration/mining potential. The area located between Madeira and Portugal, in the Tore-Rise zone, and the area at the south of Azores, comprising the Great Meteor seamount, are the most favorable as mining sites. This is especially due to the size of the different structures localized there and the proximity to the coast. In addition to those, is also worth to highlight the area that comprise the Canary Islands Seamount Province (CISP) and essentially the seamounts located on the south-west of the archipelago. In this area there are several big seamounts, Tropic, The Paps, Echo, etc., and several of them also show a plane summit that is also a good criteria to take into account to plan a mining site (Hein et al., 2009; 2015).

Finally, a hydrometallurgical experiment has been performed on selected samples from the CISP showing a general recovery rates for Co, Ni, Cu, V, Mo and REY reaching 68 % with the maximum represented by Mn, Ni, V and REY (**Table 3**) (Marino et al., 2019; Marino, 2020).

Table 3. Table of tons, recovery rate (RR) and tons recovered of the different valuable elements considered by processing one km2 of Fe-Mn crust from Tropic seamount.

Metal	Tons	RR (%)	Recovery Tons
Mn	$1,14*10^4$	81	9397
Fe	$1,61*10^4$	57	9271
Co	346,84	63	219
Ni	119,6	70	84
Cu	24	50	12
V	59,8	83	50
Mo	29,9	42	13
REY	209,3	81	170

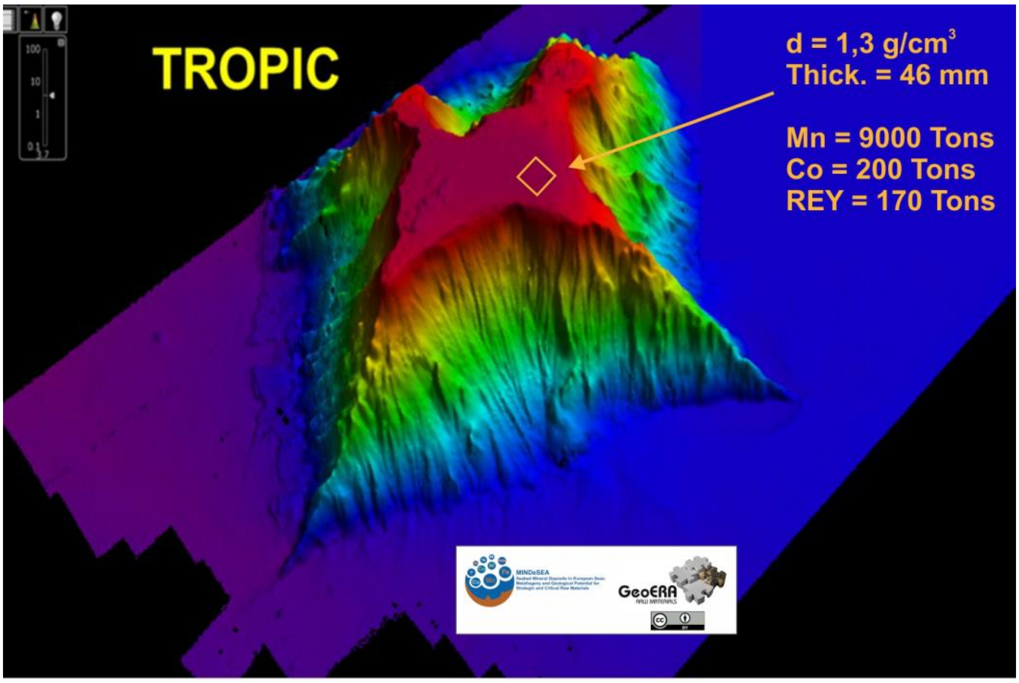

Figure 9: 3D view of the Tropic Sm. with a potential mining site and evaluation of strategic and critical metals for 1 Km^2 of seamount surface with Fe-Mn crust pavements.

The calculation of metal recovery in tons can be performed with the recovery rate data obtained in the hydrometallurgical experiments for sample DR16-14, and the average thickness of the crusts at the top of Tropic seamount. For this calculation the average thickness, 46 mm (Yeo et al., 2019) and dry density, 1.3 g/cm^3 of the crusts (Hein et al., 2009; Hein and Koschinsky, 2014) in addition to the average content of Mn, Fe, Co, Ni, Cu, V, Mo and REYs obtained in the different seamount samples (respectively 19.4, 27, 0.6, 0.2, 0.04, 0.1, 0.05 and 0.3 wt. %) have to be taken into account. With these data, the Tons per km^2 of the different valuable metals Co, Ni, Cu, V, Mo and REY, shown in **Table 3**, have been calculated (**Fig. 9**).

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