MINDeSEA: exploring seabed mineral deposits in European seas, metallogeny and geological potential for strategic and critical raw materials

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Abstract: This study summarizes a compilation of studies and cartographical work on seabed mineral deposit types in pan-European seas developed under the GeoERA-MINDeSEA project. In total, 692 occurrences and 1194 individual mineral samples of volcanogenic massive sulfides and hydrothermal mineralization, ferromanganese crusts, phosphorites, marine placer deposits, polymetallic nodules, and their associated strategic and critical raw material (CRM) elements have been characterized. The GeoERA-MINDeSEA project has been built based on extensive studies carried out previously, which include geophysical surveys, sampling stations, underwater photography and remotely operated vehicle (ROV) surveys, and mineralogical, geochemical and isotopic studies. This study develops pan-European and national databases, and expands strategic and CRM knowledge through a compilation of mineral potential and metallogenic studies of CRM resources in European seas. For the first time, the GeoERA-MINDeSEA portal publishes harmonized marine mineral resource information, case studies and maps, and identifies potential areas for responsible resource exploration and extraction, strategic management, and marine spatial planning. This study also provides recommendations for future target areas, studies and standards to be used across Europe as part of this project.

Seas and oceans cover more than 70% of the planet and represent a potentially promising new frontier for the exploration of mineral resources. A large diversity of marine environments and mineral resources has been discovered during the last decades in the deep ocean. They include high- and low-temperature hydrothermal deposits (seafloor massive sulfides (SMS) and sedimentary exhalative (SEDEX) type deposits), phosphorite, cobalt-rich ferromanganese crusts, and manganese nodules.

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These deposit types are particularly attractive due to their polymetallic nature with high contents of rare and critical metals (Halbach *et al.* 1988; Hein *et al.* 2013, 2016, 2020; Cherkashov 2017; Kuhn *et al.* 2017; González *et al.* 2018). In addition, shallow-water resources, such as marine placer deposits, represent another source for many industrial materials, critical metals and gems (Kudrass 2000; Rona 2008; Sakellariadou *et al.* 2022). The marine technologies developed to explore the ocean (e.g. autonomous vehicles (AVs) and remotely operated vehicles (ROVs)) have facilitated recent discoveries of new deposit types such as rare earth element (REE)-rich muds from the Pacific Ocean (Kato *et al.* 2011) and alkaline hydrothermal vents from Lost City in the Atlantic Ocean (Kelley *et al.* 2001). In addition, technological advances onboard ships and in laboratories have increased our knowledge of resource estimates in the global ocean (e.g. Hein *et al.* 2015, 2020).

The international community is evaluating the raw materials sector as a priority for government agendas. Society's growth demands an ever-increasing number and quantity of elements and minerals (EC 2020; Sovacool *et al.* 2020; Bouckaert *et al.* 2021). The global ocean and its mineral resources are at the core of these issues. The industrial demand for strategic and critical metals, concurrent with the rapidly diminishing quality and quantity of known land-based deposits, has highlighted the seafloor as a promising new frontier for the exploration of mineral resources. Recent studies have shown the enormous potential for seabed mineral resources as the largest reservoir on Earth for metals such as cobalt, manganese, tellurium or rare earth elements, critical for the industrial sector (e.g. Hein *et al.* 2013, 2020; Sakellariadou *et al.* 2022). Nevertheless, the extraction of minerals from the deep ocean represents an enormous scientific and technological challenge for humankind.

The International Seabed Authority (ISA), made up of 167 Member States, and the European Union, is completing the deep-sea mining code that will permit States parties, State enterprises, or natural or juridical persons or consortium of entities to extract minerals in areas beyond national jurisdictions, the so-called 'Area'. Thirty-one contractors have entered into 15 year contracts with the ISA for the exploration of manganese nodules, polymetallic sulfides and cobalt-rich ferromanganese crusts in and on the seabed of the deep Atlantic, Pacific and Indian oceans (ISA 2022). Over the 15 years these exploration areas will be subject to relinquishment and will be smaller by the end of the contract (not more than 2500 km^2 in the case of polymetallic sulfides and not more than 1000 km^2 in the case of cobalt-rich ferromanganese crusts, and a maximum of 75 000 km^2 for nodules).

The global ocean can play a key role in improving the sustainable sourcing of mineral resources among the other uses of marine areas, with the priority being the preservation of aquatic environments and ecosystems (ISA 2022; UN 2022).

European initiatives on seabed minerals research

Several projects promoted by the European Union address the Raw Materials Initiative (EC 2008) to find and evaluate the sustainable production of strategic and critical minerals, for which Europe is strongly dependent upon imports (e.g. Minerals4EU, SCRREEN and ORAMA). A secure and sustainable supply of minerals has been identified by the European Commission as a challenge to address global climate change and high- and green-technologies required for a transition from a carbon-based to a green-energy-based world (e.g. EC 2019, 2020). These necessities are clearly reflected in the European Green Deal and the EU 2020 list of critical raw materials (CRMs). CRMs are a group of elements that are economically and strategically important for the technology industry and the economy of Europe. Their importance is growing faster due to their use in several environmental technologies (wind turbine and solar panels), high-tech industry (e.g. LCDs, touchscreens and smartphones) but also in health, defence and space exploration (several alloys with different uses) (CRM Alliance 2022). The EC's Blue Growth strategy and the EU Blue Economy Reports reflect this continuing growth of investments on seabed exploration and mining as an emerging sector (EC 2012, 2021). Recently, EU research programmes are funding projects to increase the knowledge concerning seabed minerals, marine minerals exploration and mapping, extraction technologies, and environmental monitoring (e.g. EMODnet-Geology, Blue Nodules and Marine E-tech). The European, national and international programmes related to the research, exploration and exploitation of marine minerals, and environmental impact studies of marine mining activities, will play pivotal roles in the emerging 'Blue Economy' and sustainable industrial growth.

The project GeoERA-MINDeSEA was funded under Horizon 2020 with the aim of mapping and establishing the metallogenic context for different seabed mineral deposits with economic potential in the pan-European setting. This project was part of the GeoERA Co-Fund action, a joint contribution of national and regional Geological Survey Organizations from European countries 'Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe (GeoERA)' (van Gessel *et al.* 2018). The four Raw Materials

GeoERA projects (FRAME, Eurolithos, MINTEL-L4EU and MINDeSEA) contribute to the best use and management of the subsurface (Wittemberg *et al.* 2022). Free access to GeoERA data by stakeholders has been launched by the European Commission (GeoERA: http://www.geoera.eu). The GeoERA portal gathers and provides free access to information on the raw materials, groundwater and geoenergy of Europe, including the pan-European seabed minerals, which were otherwise fragmented and difficult to access and cross-correlate. In addition to the dataset, the 45 participating organizations also carried out standardization and harmonization efforts to create an integrative information platform.

The pan-European seas cover about 15 000 000 km^2 in the Arctic and Atlantic oceans and the Mediterranean, Baltic and Black seas, from shallow waters up to 6000 m water depth. A large number of mineral occurrences of different deposit types have been reported across the European seabed. Nevertheless, integrated genetic and metallogenic studies and harmonized datasets and maps across borders have been lacking. GeoERA-MINDeSEA has addressed an integrative metallogenetic study of principal types of seabed mineral resources (seafloor sulfides and hydrothermal mineralization, ferromanganese crusts, phosphorites, marine placers, and polymetallic nodules) in the European seas. This study presents pan-European marine resource compilations and integrated data, and genetic models for all these deposit types based on extensive previous studies. The study shows the potential for the pan-European seas as a source for critical metals, and the enormous gaps in information covering vast marine sectors. Combining information of different seabed mineral deposits in a single portal allows direct visualization of georeferenced information beyond national jurisdictions.

Data and cartography

The geological and metallogenic products of GeoERA-MINDeSEA are organized around to the following five principal types of seabed mineral deposits in pan-European seas: SMS and hydrothermal mineralization; ferromanganese crusts; phosphorites; polymetallic nodules; and marine placers (Fig. 1). The geographical scope of the project includes the European Arctic Ocean, Atlantic Ocean, Mediterranean Sea, Baltic Sea and Black Sea (Exclusive Economic Zone (EEZ)), as well as zones of the seafloor of the legal continental shelf beyond 200 nautical miles (extended continental shelf (ECS)). They comprise the European marine regions and subregions according to the Marine Strategy Framework Directive (MSFD) (Table 1).

GeoERA-MINDeSEA products include occurrence maps and reports of seabed minerals, including genetic models and strategic and CRM elements associated with the different deposit types. In addition, metallogenic and mineral potential and prospective maps are also provided.

Each mineral deposit layer is accompanied by an attribute table organized into five categories: general, metallogenic, economic, environment and other data. The attribute table, in addition to the location, provides information and descriptions of interest such as deposit group and type geological setting, mining activity, metallic commodities, ore minerals, geochemistry, ages, and the primary sources of data with a comment on data quality.

The information in the GeoERA-MINDeSEA dataset is a compilation of existing data derived from a variety of sources: (1) Geological Survey Organization datasets; (2) collections of maps, genetic and metallogenic models, analytical and numerical data from published papers or published cartography, theses, and marine expedition reports; (3) data from open-access databases maintained by EMODnet-Geology, the ISA and InterRidge programmes; and (4) new data and interpretations from the authors of this paper on mineralogy, geochemistry, maps and multibeam bathymetry.

All of the collected information was organized and classified using attribute tables for each entry, forming transnational comprehensive, reliable, and harmonized maps and datasets of seabed mineral deposits throughout European seas. All attributes comply with the INSPIRE directive (https://inspire.ec.europa.eu/). Organizing information according to the INSPIRE directive and the use of a common vocabulary established in the project was the first level of harmonization, especially with regard to cartography across country borders, metallogeny and economic data. This harmonization agreement was achieved during work consortium meetings between the GeoERA partners, which also fixed bases for future mapping and metallogenic studies.

The maps, reports and additional data products are compiled and freely delivered at a scale of 1:250 000 through a data portal (http://www.geoera.eu and the European Geological Data Infrastructure (EGDI: https://www.europe-geology.eu/). The EGDI data portal provides access to Pan-European and national geological datasets and services from the Geological Survey Organizations of Europe. Digital terrain models are based on the European seas compilation of EMODnet-Bathymetry (https://www.emodnet-bathymetry.eu/). Users can browse all geospatial datasets in one single map viewer, combining data on different matters (e.g. mineral resources, marine geology and onshore geology) and from different portals (e.g. EMODnet and

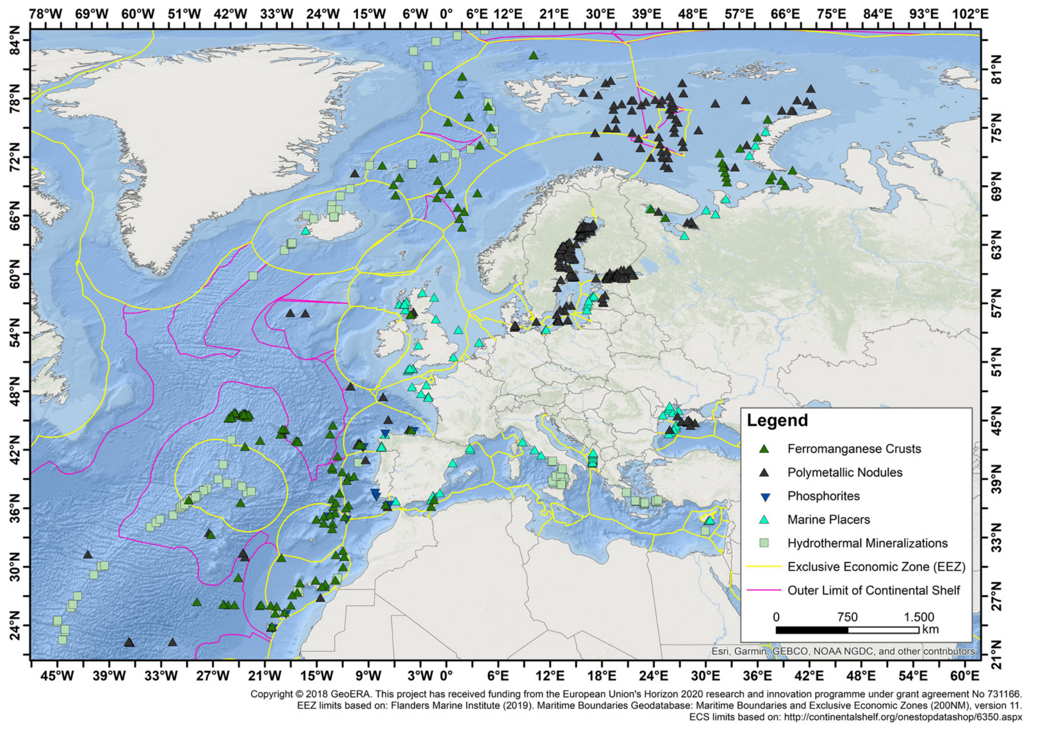

Fig. 1. Bathymetric map and seabed mineral occurrences of pan-European seas (https://www.gebco.net/data_and_products/gridded_bathymetry_data/). Onshore altimetry is also shown for offshore–onshore correlation of morphology (http://srtm.csi.cgiar.org). Mineral deposits include placers, phosphorites, ferromanganese crusts, seafloor massive sulfides and hydrothermal mineralization, and polymetallic nodules. The MINDeSEA database available at http://www.geoera.eu

Table 1. *MINDeSEA occurrence records in European marine regions and subregions for the different seabed mineral deposits*

Marine regions	Subregions	Sulfides	Fe–Mn crusts	Phosphorites	Polymetallic nodules	Placers
Arctic Ocean	Norwegian Sea	13	21			
	Iceland Sea	43	1		1	1
	Barents Sea	5	16		61	4
	White Sea		2		4	4
NE Atlantic Ocean	Greater North Sea					6
	Celtic Seas		1		7	16
	Bay of Biscay and the Iberian coast	1	13	8	10	8
	Macaronesia	49	85	4	16	
Mediterranean Sea	Western Mediterranean Sea	17	2			10
	Adriatic Sea					16
	Ionian Sea and Central Aegean–Levantine Sea	26				3
Black Sea					14	12
Baltic Sea					183	9

Source: MINDeSEA (2022).

GeoERA). This versatile access to maps and information for the general public, downstream users and decision-makers makes the GeoERA-MINDeSEA outputs a powerful tool for research and spatial planning, seabed mapping, regulation of offshore minerals exploration and exploitation, and environmental protection, in addition to other activities related to the marine environment.

Seabed mineral types and distribution in pan-European seas

The pan-European seas are represented by the North Atlantic and Arctic oceans together with the Mediterranean, Black, Baltic, White and Barents seas. They display several morphotectonic elements configured by different genetic processes. A long and complex history, from the opening of the proto-Atlantic Ocean in the Early and Middle Jurassic (Kotliński 1999; Seton *et al.* 2012), is the basis of the sedimentary, magmatic and tectonic processes that established the European seas. The Arctic Ocean was formed along the Atlantic evolution history, founding its first steps during the separation of Pangaea in the Triassic, and later in the Cretaceous with the formation of the Canadian and Amerasia basins and the separation of the North America and Eurasia plates (Gaina *et al.* 2014; Nikishin *et al.* 2017). The origin and formation of the Baltic Sea is still under discussion but it is considered that the basin was formed during the Cenozoic (Voipio 1981) or as a result of erosion from a complex system of rivers and lakes (Bijlsma 1981; Marks 2004). During Quaternary glaciations, the depression of the Baltic Sea was covered by ice sheets that brought sediments from adjacent areas, causing subsidence and isostatic rebound after retreat (Andrén *et al.* 2011). The Mediterranean Sea history is complex, part of it is the remnant of the Tethys Ocean that was located between Gondwana and Laurasia during the Mesozoic (Robinson *et al.* 1996). The offset of the western and eastern Black Sea basins, separated by the mid-Black Sea Ridge, originated in the Cretaceous, during the Cenomanian and Coniacian, along the former Albian volcanic arc (Nikishin 2003). The complexity and extent of their evolution exceeds the limits and objectives of this study.

Five marine geotectonic settings have been differentiated in the pan-European seas from coastal zones to deep-sea: (1) shallow waters or shelf; (2) banks and plateaus; (3) seamounts and hills; (4) ridges; and (5) abyssal plains. These marine environments play a critical role in the formation of different types of mineral deposits in Europe. The following subsections group the marine minerals according to these major geotectonic settings.

Marine placers

Marine placer deposits comprise detrital heavy metallic minerals and gemstones, eroded typically from igneous source rocks on land and transported to sea predominantly by rivers. Thereby, placer deposits are concentrated by water flow (waves, tides and currents) (McKelvey 1986; Harben and Bates 1990; Rona 2008). Sediment supply, sea-level fluctuations and marine energy control the formation and evolution of marine placers (Davis and Clifton 1987). Consolidated bottoms, erosive morphology, prograding landforms, bedforms, and gas-related and anthropogenic features are common in the continental shelf environment where placers develop (Durán and Guillén 2018). Glacio-eustatic and tectonic phenomenon can change sea level and placer deposit distribution.

Marine placers in pan-European seas are usually distributed at water depths of less than 100 m, from beaches, estuaries and deltas to the broad continental shelf, which is the natural prolongation of the continents and represents the transition between land and deep sea (MINDeSEA 2022) (Figs 1 & 2). Placers in European seas are composed of erosion-resistant minerals like gold, cassiterite (tin ore), rutile (titanium (Ti) ore), garnet, magnetite, ilmenite (titanium ore) and monazite (REE ore). The Celtic Seas (UK), Bay of Biscay (France), Iberian Atlantic coasts of Galicia (Spain) and the Gulf of Cadiz (Spain and Portugal) mark the location of several placer occurrences (Fig. 2a, b) of chemically resistant, physically durable minerals such as cassiterite, ilmenite, magnetite, zircon and monazite (IGME 1976; Pérez *et al.* 2008; Medialdea *et al.* 2021). In the Aegean Sea, iron (Fe), titanium (Ti) and chromium (Cr) placer deposits exist near the mouths of some of the rivers on the Cyprus continental shelf (Varnavas 1990; Dill 2007) and along the north coast in Greece: the Strymonikos and Samothraki plateaus (Perissoratis *et al.* 1988; Perissoratis and Mitropoulos 1989). The Black Sea hosts several placer deposits along the coasts of Romania and Ukraine (Fig. 2c). Diamond placers are documented from the White Sea in Russia (Ivanova *et al.* 1999).

The MINDeSEA database on marine placers contains 89 occurrences in 12 marine regions and subregions (Arctic Ocean, Baltic Sea, Great North Sea, Bay of Biscay and Iberian coast, Celtic Sea, English Channel, Inner Seas off the West Coast of Scotland, Irish Sea and St George's Channel, Macaronesia (Canary, Madeira and Açores islands), Adriatic Sea, Mediterranean Sea, and Black Sea), and 14 countries (Albania, Bulgaria, Cyprus, Iceland, Spain, France, the UK, Ireland, Italy, Latvia, Poland, Romania, Russia and Ukraine). Most of these deposits are located in the Adriatic Sea (16 occurrences, corresponding to 18% of the total), the Celtic Seas

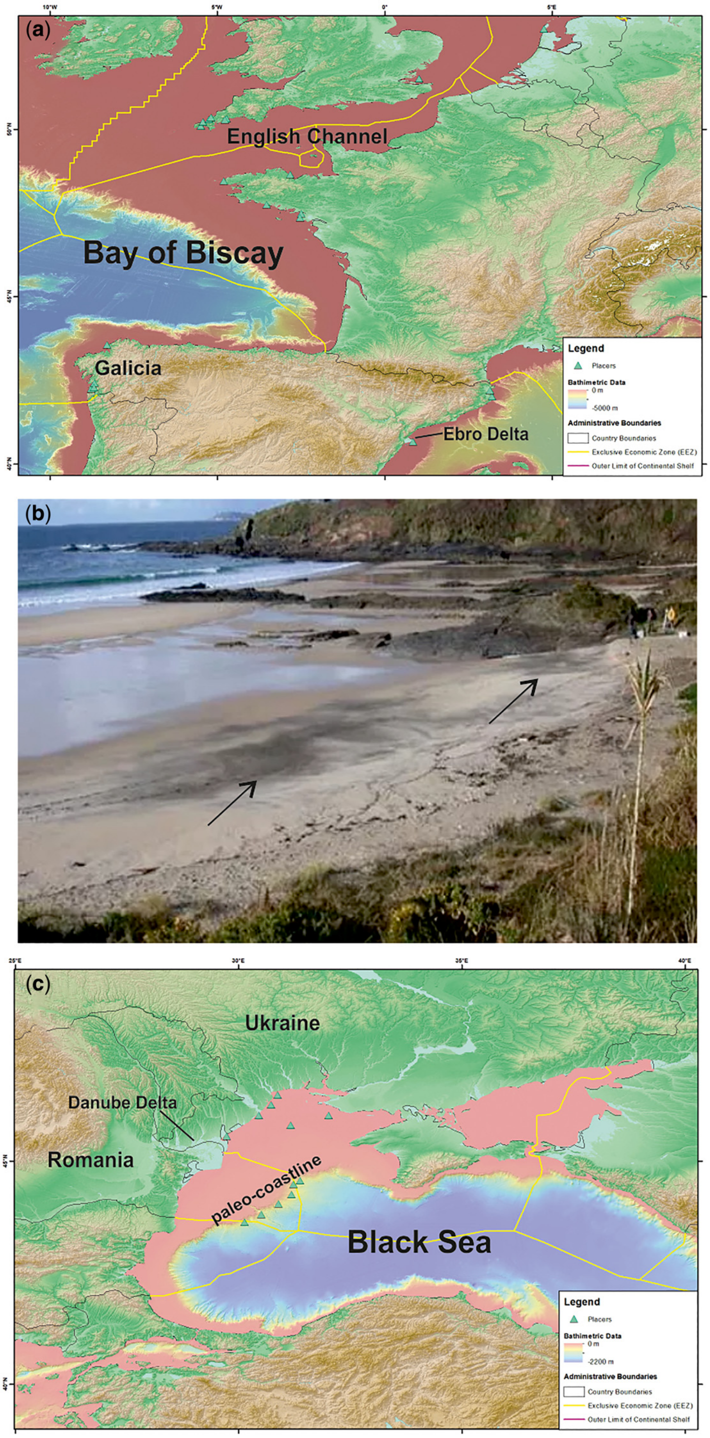

Fig. 2. Bathymetric maps (http://www.emodnet-bathymetry.eu), onshore altimetry and the location of marine placers. (**a**) North Iberia, France and the UK Atlantic margin. (**b**) Montalvo Beach magnetite-rich placer deposit (arrows), Galician coast (modified from Pérez *et al.* 2008). (**c**) Coastal areas and palaeocoastline from the Black Sea.

(15 occurrences, corresponding to 17% of the total), the Black Sea (12 occurrences, corresponding to 13% of the total) and the western Mediterranean (10 occurrences, corresponding to 11% of the total) (Fig. 1; Table 1).

Phosphorite

Submarine phosphorite is predominantly composed of carbonate fluorapatite (CFA) with variable admixtures of detrital minerals (Jarvis *et al.* 1994; Piper 1999; McMurtry 2019). Phosphorite can be found in three main environments: along continental margins (essentially in shelf, slopes, banks, etc.); on old seamounts; and in lagoons and on associated atolls (Baturin 1982; Hein *et al.* 1993, 2016; Glenn *et al.* 1994; González *et al.* 2016).

In European seas, marine phosphorites are usually accompanied by ferromanganese crust deposits on the seafloor of continental shelves and slopes, banks, plateaus, and volcanic seamounts in the Atlantic Ocean along the western continental margin (MINDeSEA 2022). Banks and plateaus form large elevated areas in the ocean as part of submerged continental crust or as thick oceanic crust (Roberts 1975). They can also form as relict continental crust separated by faults from the continents during the opening of the ocean and can be found near the continental margin (i.e. Galicia Bank and Rockall Plateau: Fig. 3a).

Phosphorite samples from European seas have been collected from different banks where it occurs as thick pavements (up to 15 cm thick), nodules and slabs (Fig. 3b); from the continental shelf (150 m water depth); and at medium depths on seamounts (1600 m water depth). Phosphorite is also found at the base or within the laminae of thick Fe–Mn crusts (Lamboy 1976; Lucas *et al.* 1978; Gaspar 1981, 1982, 1986, 2000; Gaspar and Halbach 1999; González *et al.* 2016, 2021*a*).

The MINDeSEA phosphorite database contains 12 occurrences and 45 analysed samples from two marine regions (Bay of Biscay and Iberian coast, and Macaronesia) and two EU countries (Spain and Portugal) (Fig. 1; Table 1). They are especially abundant on banks and plateaus in the Bay of Biscay and

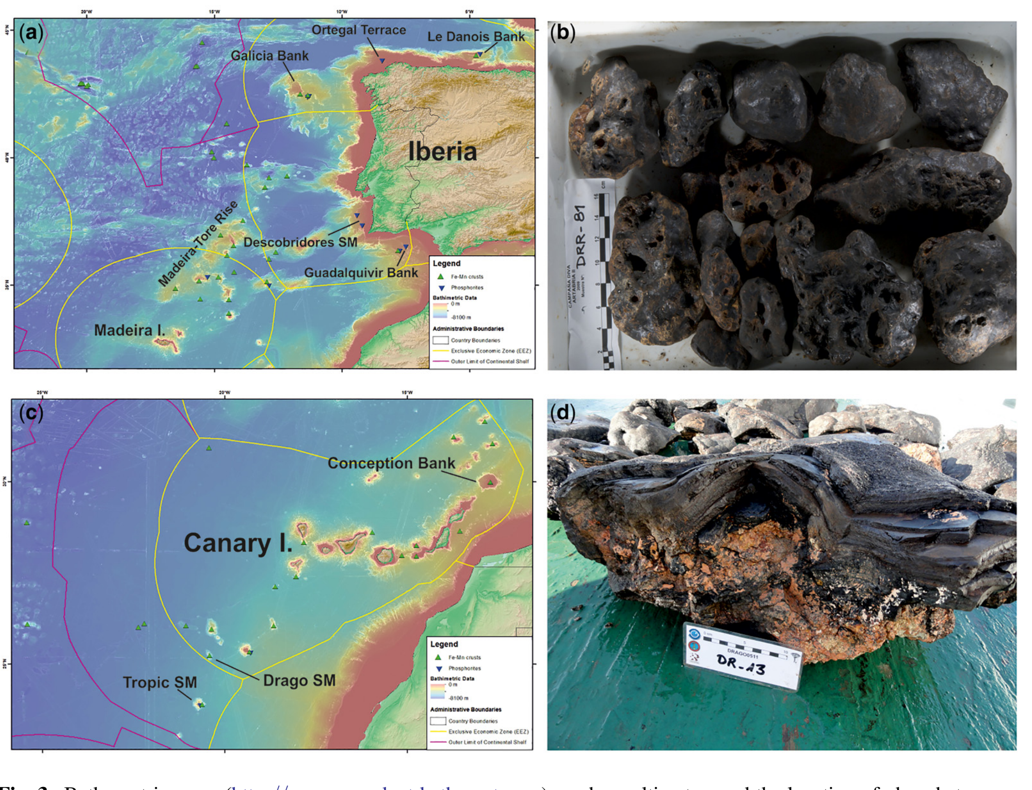

Fig. 3. Bathymetric maps (http://www.emodnet-bathymetry.eu), onshore altimetry, and the location of phosphate and ferromanganese crust deposits. (**a**) Iberian Atlantic margin. (**b**) Phosphate boulders covered by ferromanganese crusts from Galicia Bank. (**c**) The Canary Islands Seamount Province. (**d**) Thick ferromanganese crust from the Drago Seamount.

on the Iberian coast (Fig. 3a), and on the volcanic seamounts and ridges from the Macaronesia region (Fig. 3c). Four occurrences are within the Spanish EEZ and ECS, and two occurrences from Galicia Bank and a neighbouring seamount (Sancho Seamount), a vast plateau with an area of 30 000 km^2. One occurrence is located on Ortegal Terrace, 40 km north from the Galicia coast and the last occurrence is found on Le Danois Bank, 80 km from the Cantabrian coast (Lamboy 1976; Lucas *et al.* 1978; González *et al.* 2016). The other four occurrences are located within the Portuguese EEZ: two in the Gulf of Cadiz area (on the Guadalquivir Bank and Faro Plateau) and the other two in the Alentejo Basin (on the Descobridores and Prince de Avis seamounts: Fig. 3a) (Gaspar 1981, 1982, 1986, 2000). Finally, four occurrences of phosphorites (Fig. 3c) are located on seamounts from the Madeira (Lion and Ampere seamounts) and the Canary islands (Tropic and Echo seamounts) (Gaspar and Halbach 1999; González *et al.* 2021*a*, *b*; Medialdea *et al.* 2021).

Ferromanganese crusts

Ferromanganese crusts are formed by iron and manganese oxyhydroxides from direct precipitation of minerals from seawater onto the flanks and summits of seamounts, ridges and submarine hills. Ferromanganese crust deposits grow on hard substrates on which Fe and Mn oxyhydroxide colloids can accumulate over millions of years (Bogdanov *et al.* 1990, 1995; Koschinsky *et al.* 1996; Hein *et al.* 1997, 2000*a*, 2013; Bogdanova *et al.* 2008; Marino 2020; ISA 2022).

In the pan-European seas, morphotectonic structures (mainly seamounts) that rise from abyssal depths are suitable for the accretion of the ferromanganese crust pavements up to 25 cm thick (Fig. 3c, d) at depths ranging from 400 to 5000 m (MINDeSEA 2022). Seamounts are defined as any geographically isolated submarine feature higher than 100 m not located on a continental shelf (Staudigel and Clague 2010). Most of them formed by volcanism and other igneous activity in different areas (Buchs *et al.* 2016) such as close to the mid-ocean ridges (e.g. Great Meteor Seamount), on-axis along the mid-ocean ridge or off-axis if they are further away but on relatively young crust, islands arcs (e.g. Palinuro Seamount) and intraplate settings (e.g. Canary Islands Seamount Province). The Canary Island and Madeira seamount provinces represent clusters of ancient seamounts (Fig. 3c) in an oceanic intraplate context, linked to hotspot volcanism, with an abundance of ferromanganese crust deposits (Geldmacher *et al.* 2008; Muiños *et al.* 2013; Marino *et al.* 2017; González *et al.* 2021*a*) (Fig. 3c). Non-volcanic seamounts, formed by blocks of continental crusts during the opening of an ocean such as Galicia Bank and Le Danois Bank (Fig. 3a), host several occurrences of ferromanganese deposits (Lamboy 1976; González *et al.* 2016). Flat-top volcanic seamounts named ‘guyots’ can be found in the Macaronesia region (e.g. Tropic, Great Meteor and Echo seamounts) and represent promising targets for the exploration of ferromanganese deposits. The first documented description of ferromanganese crusts in the global ocean was collected from the Paps Seamount (Canary Islands) during the Challenger Expedition 1872–76 (Murray and Renard 1891).

The MINDeSEA database for ferromanganese crusts contains 141 occurrences and 260 analysed samples from seven marine regions (Arctic Ocean, Norwegian Sea, Bay of Biscay and Iberian coast, Celtic Sea, Central–NE Atlantic Ocean, Macaronesia, and Mediterranean Sea), seven countries (Denmark, Spain, Portugal, Iceland, Norway, Russia and the UK) and contiguous international waters (Fig. 1; Table 1). The marine region with the greatest number of recorded ferromanganese crust occurrences is Macaronesia and surrounding areas beyond European jurisdictions in which are found 78 of the 141 occurrences, corresponding to 55% of the total. The NE Atlantic Ocean hosts 20 occurrences, followed by the Barents Sea with 16 occurrences, the Norwegian Sea with 11, and the Bay of Biscay and the Iberian coast show 10 occurrences. The White Sea and western Mediterranean Sea have two reported occurrences each, and one reported occurrence in each of the Celtic and Iceland seas. The shallowest deposits appear in the Barents Sea on submarine banks at 250 m water depth as thin concretions enriched in Fe (Ingri 1985*a*, *b*; Strekopytov and Dubinin 2001). The occurrences of ferromanganese crusts in the Norwegian Sea are linked to ridges and seamounts associated with the triple junction formed among the Mid-Atlantic, Jan Mayen and Mohns ridges (NPD 2018). In Macaronesia, 21 locations are within the Spanish EEZ and ECS, and 45 within the Portuguese EEZ and ECS. The remaining occurrences are just SW of Macaronesia in the Central Atlantic Ocean. The typical marine setting for the formation of Fe–Mn crusts in this latter area is on ancient volcanic seamounts rising from the seafloor at water depths of 250–5000 m. Thick ferromanganese crusts (up to 25 cm thick) that form extensive pavements (Fig. 3d) have been documented on the Canary Islands Seamount Province (Muiños *et al.* 2013; Muiños 2015; Marino *et al.* 2017; Marino 2020; Kfouri *et al.* 2021). Phosphates appear as substrates or replacing Fe–Mn oxyhydroxides of ferromanganese crusts on the Tropic and Echo seamounts and Galicia Bank (González *et al.* 2016; Marino *et al.* 2017; Medialdea *et al.* 2021).

Seafloor massive sulfides and other hydrothermal mineralization

Seafloor hydrothermal deposits, most notably expressed as seafloor massive sulfides (SMS), are modern volcanogenic equivalents of onshore (fossil) deposits of volcanogenic massive sulfides (VMS) (Singer 1995; Pirajno 2009; Petersen *et al.* 2016, 2018; Cherkashov 2017). They form chimneys, stratabound deposits and sulfide mounds typically dominated by iron sulfides, mainly pyrite, with subordinate amounts of the copper sulfides chalcopyrite or isocubanite, and the zinc sulfide, sphalerite. Non-sulfide gangue minerals include sulfates such as barite and anhydrite, silicates, mainly amorphous silica (opal), and iron–manganese oxyhydroxides.

The setting of hydrothermal deposits in European waters are diverse and include mid-ocean ridge (MOR) spreading sites along the Mid-Atlantic Ridge, the Arctic MOR, intraplate hotspot sites in Macaronesia around the Canary Islands and sites related to arc/back-arc settings within the Mediterranean Sea (MINDeSEA 2022). Atlantic and Arctic MORs, defined as linear volcanic and tectonic regions marking the constructive boundary between two tectonic plates (Rubin 2016), form long mountain chains with abundant occurrences of hydrothermal vents (InterRidge 2022).

The MINDeSEA database on hydrothermal mineralization comprises 154 occurrences and 173 analysed samples in six marine regions (Arctic Ocean, Bay of Biscay and Iberian coast, Central–NE Atlantic Ocean, Macaronesia, Norwegian Sea, Aegean Sea, and Mediterranean Sea), eight EU/ESS countries (Cyprus, Greece, Greenland, Iceland, Italy, Norway, Portugal and Spain) and contiguous international waters (Table 1; Fig. 1). A number of active vent sites have been found along the Mid-Atlantic Ridge (Fig. 4) north and south of Iceland at shallow water depths (90–400 m). These are the Steinaholl hydrothermal field on the Reykjanes Ridge south of Iceland, and the Grimsey and Kolbeinsey hydrothermal fields on the Kolbeinsey Ridge north of Iceland. Squid Forest is an extinct field in Icelandic waters along the Kolbeinsey Ridge, located at 900 m water depth on the plateau of a flat-topped semi-circular volcano (Pedersen *et al.* 2010; Pedersen and Bjerkgård 2016). In the Norwegian Sea (Fig. 4a), several relatively shallow active vent fields, like the Seven Sisters and Soria Moria, occur on flat-topped volcanic edifices (Marques *et al.* 2020). Active and inactive vent fields occur along Mohns Ridge (Cooper Hill, Mohn's Treasure and Loki's Castle) in the Norwegian EEZ and ECS (Pedersen and Bjerkgård 2016; Juliani and Ellefmo 2018). A number of hydrothermal plumes have been observed on Gakkel Ridge (Fig. 4a) between 83 and 87°N but no sulfide samples have been retrieved (Pedersen and Bjerkgård 2016). Most plumes on the Gakkel Ridge are in international waters but the westernmost observations are located within the territorial waters of Greenland. Along the Mid-Atlantic Ridge around the Azores islands (Fig. 4b) are several hydrothermal fields, the Moytirra deposits in the north (Fig. 4b–d) and the Saldanha deposits in the south. All deposits here are under Portuguese jurisdiction (EEZ and ECS). Some of the most notable deposits are the Moytirra, Luso, Menez Gwen, Lucky Strike and Rainbow fields along the axis of a spreading ridge at variable water depths ranging from 1000 to 3000 m and typically covering relatively small venting areas (<10 000 m^2) (Fouquet *et al.* 1994, 1997; Langmuir *et al.* 1997; Charlou *et al.* 2000, 2002; Gràcia *et al.* 2000; Wheeler *et al.* 2013; Dias *et al.* 2019; Somoza *et al.* 2020, 2021*a*). Hydrothermal mineral deposits related to an intraplate hotspot are present in the Canary Islands Seamounts Province on the Henry Drago and Tropic seamounts, Tagoro Volcano, and seamounts east of Lanzarote Island (Klügel *et al.* 2011; Somoza *et al.* 2014, 2017; Marino *et al.* 2019; González *et al.* 2020; Marino 2020; Medialdea *et al.* 2021). Mediterranean arc/back-arc deposits occur in the Aeolian archipelago, in the South Tyrrhenian Sea in Italy and the Aegean Sea in Greece (Fig. 4e). They form hydrothermal deposits on volcanoes (Hein *et al.* 2000*b*; Glasby *et al.* 2001, 2005; Dekov and Savelli 2004; Hein and Mizell 2013).

Polymetallic nodules

Polymetallic nodules are marine sedimentary mineral deposits, composed mostly of iron and manganese oxyhydroxides, that precipitate very slowly from seawater or from bottom sediment porewaters but most nodules are a combination of both (Koschinsky and Hein 2017; Kuhn *et al.* 2017; Hein *et al.* 2020; ISA 2022). Polymetallic nodules grow on the surface of abyssal plain sediments in water depths of 4000–6500 m where they cover vast zones of the seafloor.

In the pan-European seas, polymetallic nodules are mostly located in shallow waters (<400 m water depth) in the Baltic, Barents, White and Black seas (Figs 1 & 5). There are also occurrences on seamounts (Fig. 5b), banks and undercurrent channels along the Iberian margin and Canary Islands in medium–deep water depths of 1000–4000 m (MINDeSEA 2022). The nodule fields exhibit a patchy distribution on silty–sandy post-glacial sediments. The nodules show diverse morphologies from spheroidal to tabular and irregular, and sizes that range from 1 to 20 cm (Fig. 5b, c). A high density of nodules covering the seabed is occasionally observed (up to 70%), as well as poorly

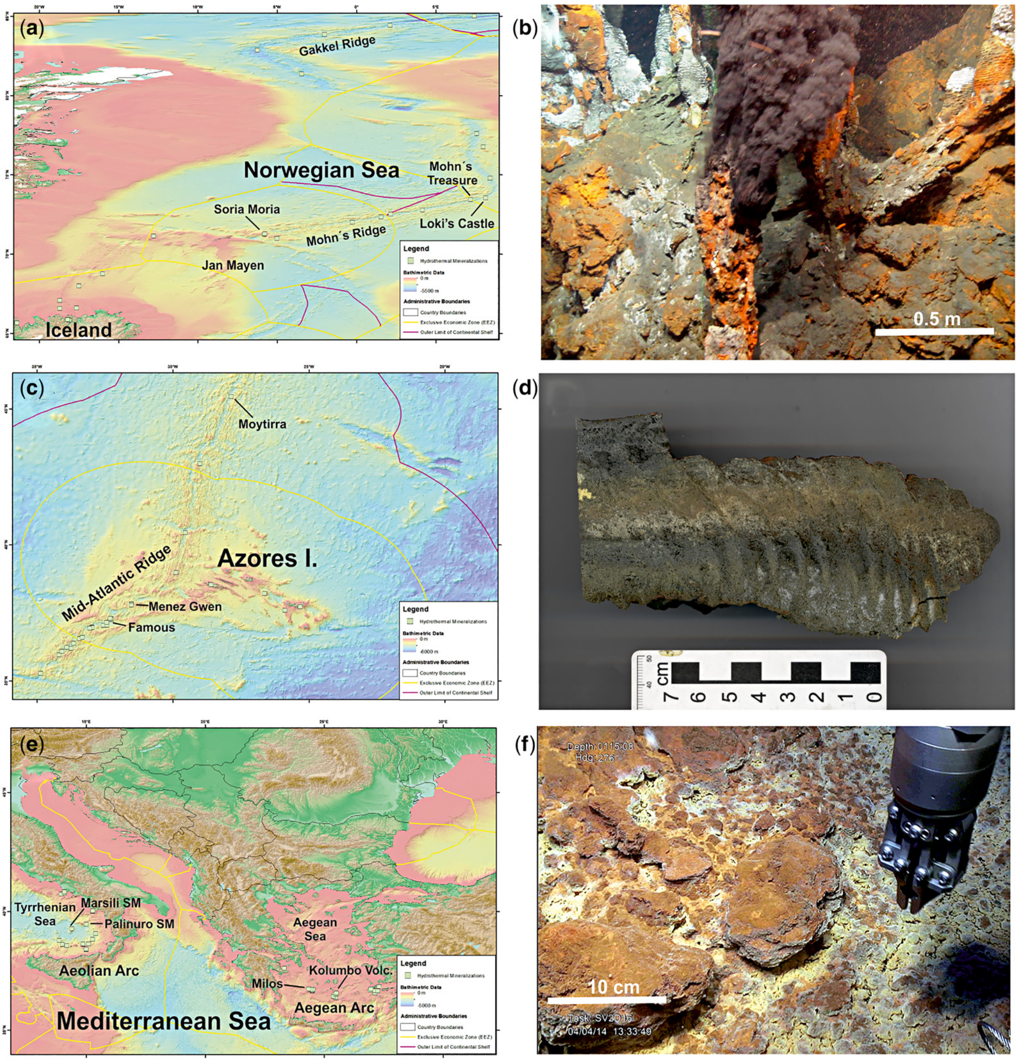

Fig. 4. Bathymetric maps (http://www.emodnet-bathymetry.eu), onshore altimetry, and the location of hydrothermal mineralization and seafloor massive sulfide deposits. (**a**) Norwegian Sea and Arctic Ocean fields. (**b**) A ROV *Luso* underwater image of active high-temperature black smoker and sulfide-anhydrite chimneys in the Moytirra field at a water depth of 2800 m. (**c**) Mid-Atlantic Ridge Azores Islands sector. (**d**) Cross-section of a hydrothermal chimney. (**e**) Low-temperature hydrothermal fields in the Tyrrhenian and Aegean seas. (**f**) Low-temperature oxyhydroxide deposits on Tagoro Volcano (Canary Islands).

covered areas (3–10%) (González *et al.* 2007, 2012, 2016; Zhamoida *et al.* 2017; Ferreira *et al.* 2021*a*).

The MINDeSEA database on polymetallic nodules reports 296 occurrences and 490 individual analysed samples in seven marine regions (Arctic Ocean, Baltic Sea, Bay of Biscay and Iberian coast, Celtic Sea, Central–NE Atlantic Ocean, Macaronesia, and Black Sea) and 16 countries (Denmark, Estonia, Germany, Finland, France, Ireland, Latvia, Norway, Poland, Portugal, Romania, Russia, Spain, Sweden, Ukraine and the UK) (see Fig. 6). Nodules are the dominant form on manganese deposits in the Baltic Sea (184 occurrences, corresponding to 62% of the total) followed by the NE Atlantic Ocean and the Arctic Ocean, with 68 recorded occurrences (23% of the total). The remaining occurrences (15%) are distributed through the other five marine regions/subregions (Table 1). About 4% of the occurrences (corresponding to 12 occurrences) are located in international waters,

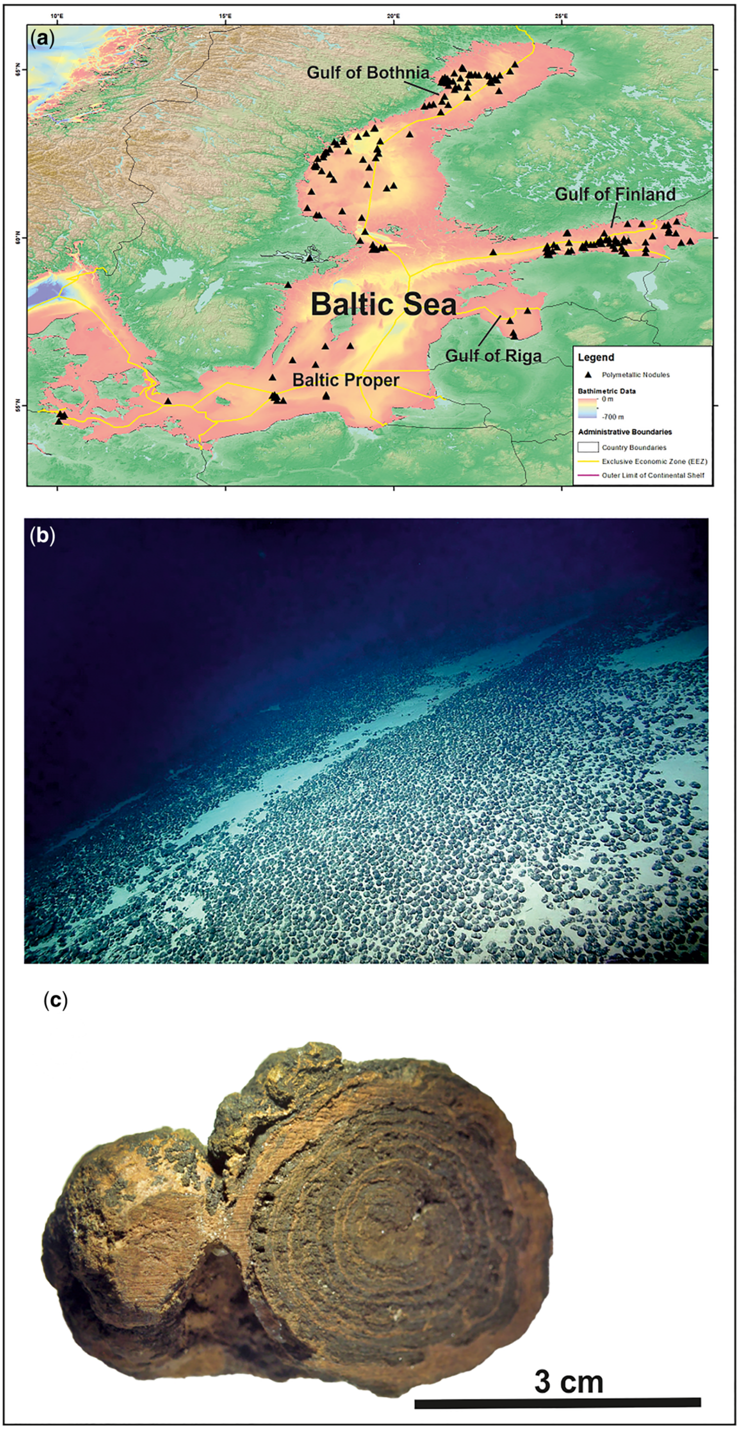

Fig. 5. Bathymetric maps (http://www.emodnet-bathymetry.eu), onshore altimetry and the location of polymetallic nodule deposits. (**a**) Baltic Sea. (**b**) ROV *Isis* underwater image of a polymetallic nodule field on the Tropic Seamount at a water depth of 2500 m. (**c**) Cross-section of a nodule from the Baltic Sea.

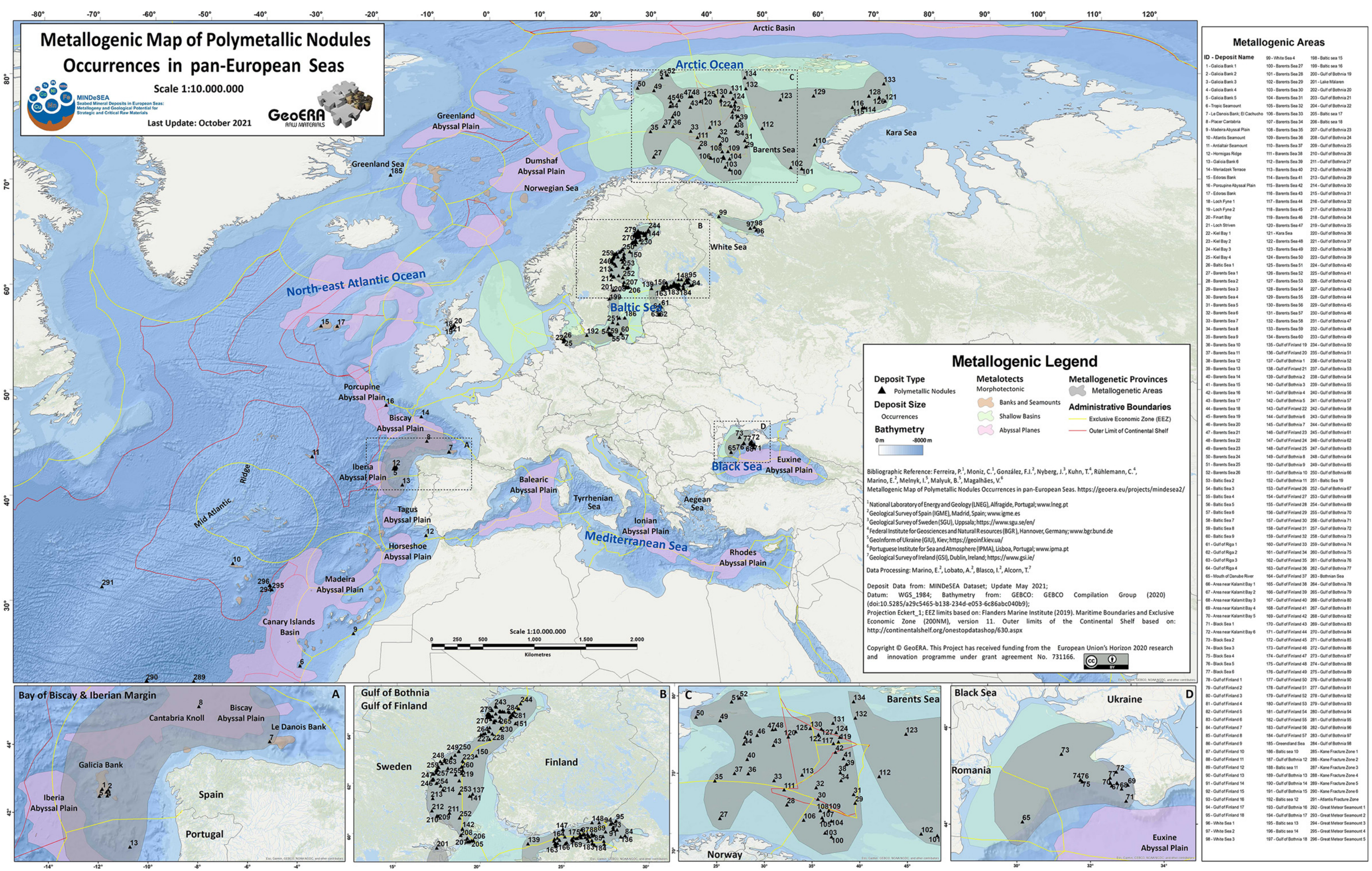

Fig. 6. Metallogenic map of polymetallic nodule occurrences in pan-European seas. Source: Ferreira *et al.* (2021*b*).

whereas 23 occurrences (*c.* 8%) are inside the ECS of various European countries. Polymetallic nodules within the Baltic Sea (Fig. 5a) have about half of the occurrences (99) distributed in the Gulf of Bothnia, 57 occurrences are from the Gulf of Finland and Gulf of Riga, and 27 occurrences are in the Baltic Sea proper, including Kiel Bay (Zhamoida *et al.* 2017; Ferreira *et al.* 2021*a*, *b*, *c*). Nodules from the Barents Sea are distributed at water depths ranging from 148 to 385 m (Strekopytov and Dubinin 2001). In the White Sea, nodules were collected at shallow depths of 42–226 m (Strekopytov and Dubinin 2001). Thirteen nodule occurrences are documented in the northwestern continental shelf of the Black Sea, between the Crimean Peninsula and the Danube Delta, mostly at depths shallower than 100 m (Ferreira *et al.* 2021*a*). Along the Galicia continental margin, the polymetallic nodules occur together with extensive phosphorite pavements on seamounts and banks, like those on Galicia Bank and the Sancho Seamount, at water depths of 800–1600 m (González *et al.* 2014, 2016; Terrinha *et al.* 2022). In the Gulf of Cadiz, nodule fields are associated with the Cadiz Contourite Channel and Hormigas Ridge at a water depth of 1000 m (González *et al.* 2007, 2009, 2012). The Rockall Plateau and Madeira Abyssal Plain show deeper, 2000–5500 m, polymetallic nodule deposits (Jehanno *et al.* 1984; Searle 1986; Ebbing *et al.* 1991). Extensive nodule fields have been reported on the top and flank sediments of the Tropic Seamount (Fig. 5b) at water depths ranging from 1000 to 2600 m (Murton 2017; Medialdea *et al.* 2021; González *et al.* 2021*a*).

Metallogeny and geological potential in pan-European seas

In this chapter, metallogenic models for the principal types of seabed mineral deposits in European seas are presented. The MINDeSEA project compiled the description of the principal styles of mineralization, including controls or metalotects, defined as any geological structure related to the presence of mineralization, influencing their genesis and distribution (Laffite *et al.* 1965). Metallogeny is the study of the genesis and regional to global distribution of mineral deposits, with emphasis on their relationship in space and time to regional petrological and tectonic features of the Earth's crust (De Launay 1913). The genetic models are discussed. It refers to geological, geochemical and geophysical characteristics favourable for resource accumulation (Taylor and Steven 1983). The MINDeSEA cartographies show predictive areas dealing with those matching predicted trends and behaviour patterns for a type of seabed mineral deposit formation or occurrence.

The relationships between deposit types and geotectonic environment are the basis for their grouping as diagenetic, hydrogenetic, hydrothermal and detrital mineralizations. Metallogenic events have been proposed when data are available. The MINDeSEA metallogenic dataset and reports are based on the analysis of several references and are subject to review as new data emerge.

The compilation maps show the principal metallogenic areas and metalotects for each deposit type in pan-European seas (see Figs 6, 7, 8 & 9).

Fe–Mn diagenetic-dominant mineralization

Early diagenesis is the most invoked mineralization process for polymetallic nodules in pan-European seas (Ingri 1985*b*; Ingri and Pontér 1986; Glasby *et al.* 1997; González 2008; González *et al.* 2009, 2012, 2016; Emelyanov 2011; Zhamoida *et al.* 2017; Zalba 2019). Diagenetic precipitation is dominant in polymetallic nodules in many settings such as areas affected by undercurrents (e.g. Gulf of Cadiz and the Edoras Bank), where there is alternation of diagenetic and hydrogenetic layers (González *et al.* 2012; Ferreira *et al.* 2021*d*). The hydrogenetic layers are formed by metal precipitation from oxic near-bottom seawater, whereas diagenetic layers are formed by metal mobilization in suboxic porewater and precipitation at the suboxic–oxic interface (Kuhn *et al.* 2017; Hein *et al.* 2020). The metals mobilized in the suboxic pore fluids diffuse upwards, and are incorporated into the Mn and Fe oxyhydroxides formed at the seabed at the seawater–sediment interface. Oxidation of organic matter in the seabed sediments results in the reduction and dissolution of Mn oxides, and the release of associated elements, Ni, Cu and Li among others, contributing to the redox cycle (Ingri 1985*a*, *b*; Hlawatsch *et al.* 2002; González *et al.* 2012; Koschinsky and Hein 2017; Kuhn *et al.* 2017).

The most common internal growth structure in nodules in the pan-European seas is fine concentric laminations around a nucleus (Fig. 5c). Diagenetic precipitation mainly leads to the development of dendritic to mottled layers and, less frequently, to dense, massive layers (Glasby *et al.* 1997; González 2008; González *et al.* 2009). The mineral composition consists of turbostratic phyllomanganates such as 10 Å vernadite, and to minor amounts of 7 Å vernadite, birnessite, jianshuiite, asbolane, romanechite and todorokite (González *et al.* 2010, 2012, 2016; Wegorzewski and Kuhn 2014). Some nodules with a diagenetic component show abundant Fe oxyhydroxides (goethite) (e.g. González *et al.* 2010). The diagenetic growth of nodules in European seas is very fast, reaching up to 250 mm Ma^{-1} (von Stackelberg 2000; Hlawatsch *et al.* 2002; González *et al.* 2012). Glacial and post-glacial host sediments for

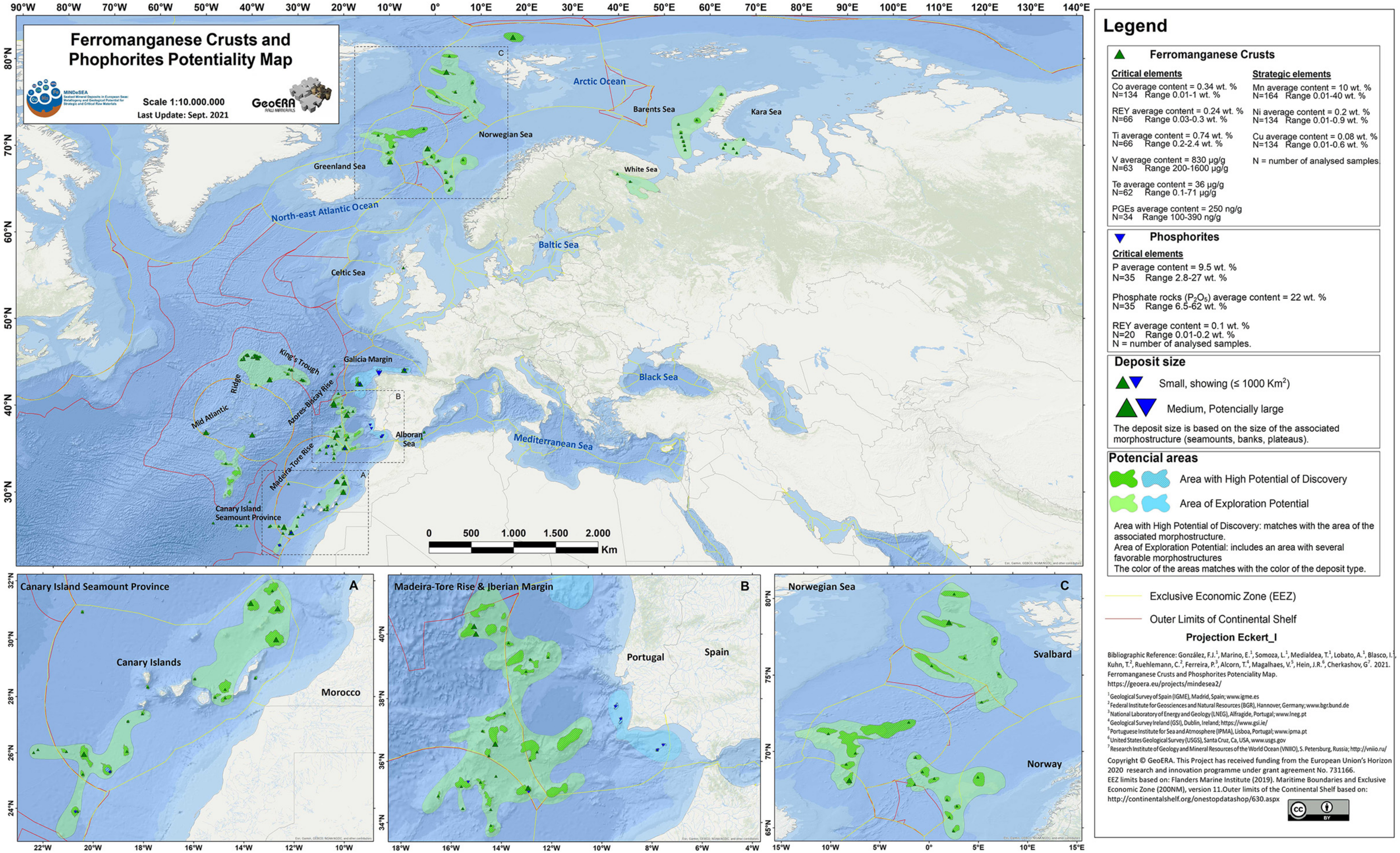

Fig. 7. Ferromanganese crusts and phosphorites potentiality map in pan-European seas. Source: González *et al.* (2021*d*).

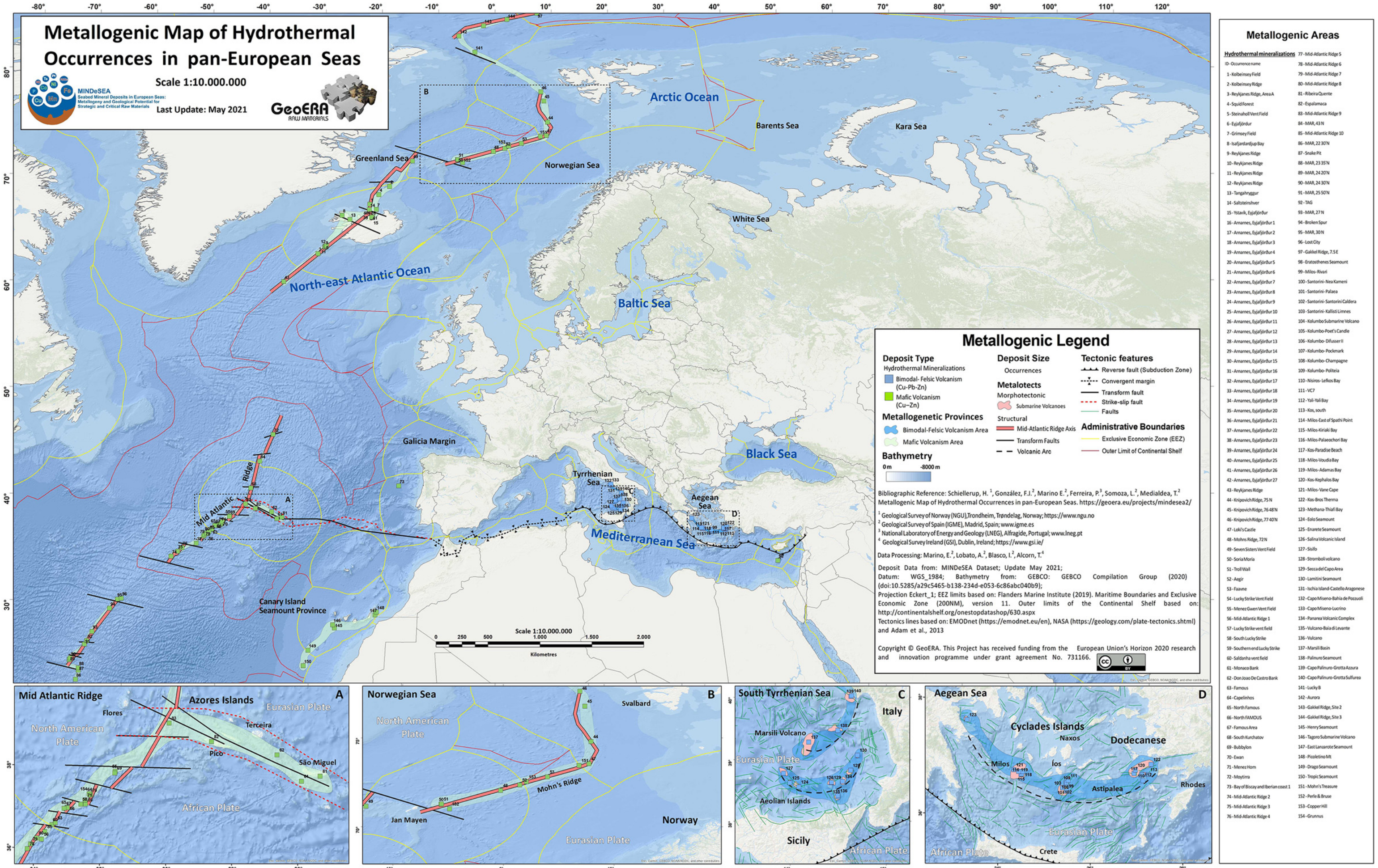

Fig. 8. Metallogenic map of hydrothermal occurrences in pan-European seas. Source: Schiellerup *et al.* (2021*b*).

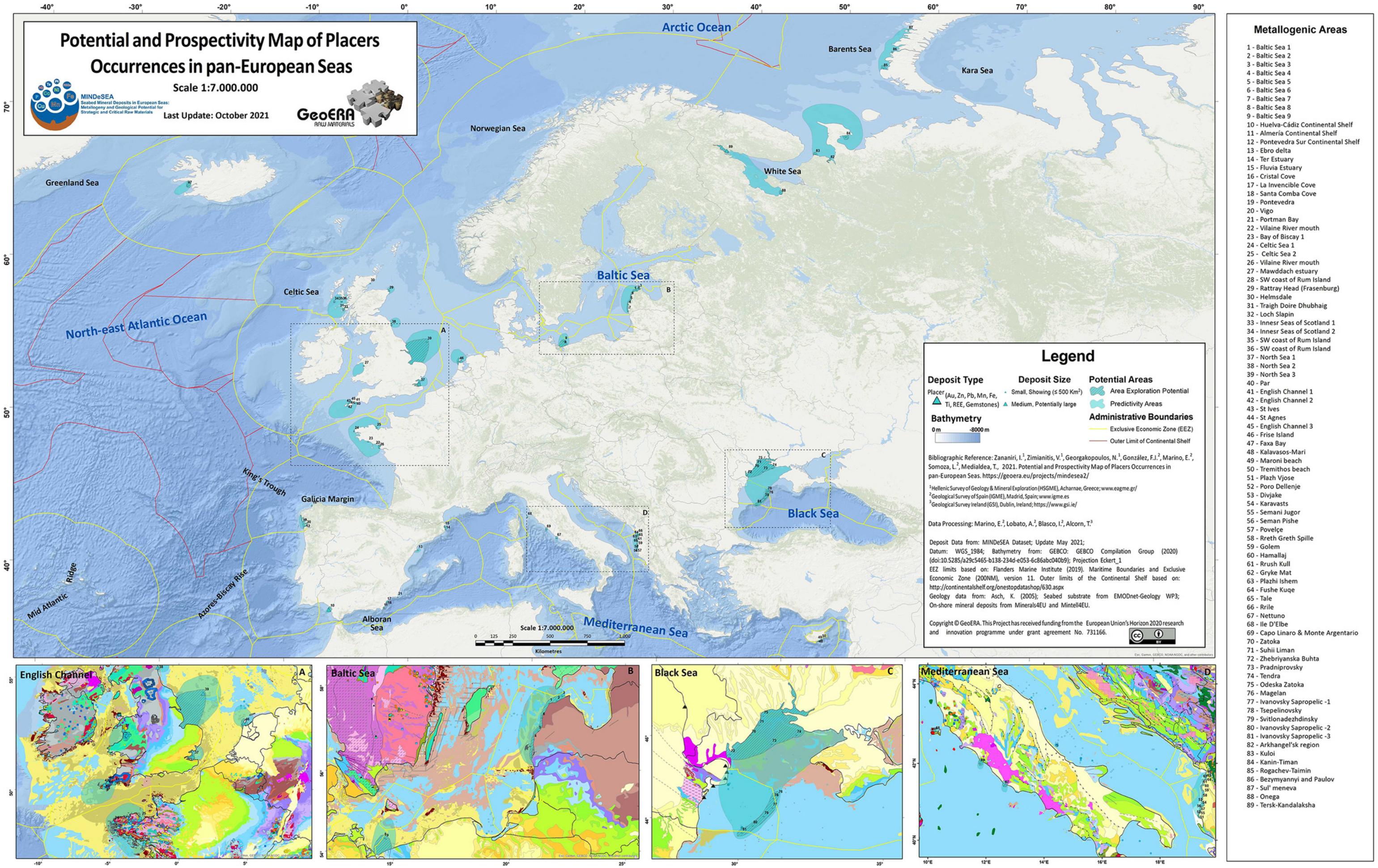

Fig. 9. Potential and prospectivity map of placer occurrences in pan-European seas. Source: Zananiri *et al.* (2021).

the Baltic Sea nodules indicate that they formed during the Quaternary (Pleistocene–Holocene) (Ingri 1985*a*, *b*; Hlawatsch *et al.* 2002).

Diagenetic nodules in European seas are characterized by two end members: Mn-rich and Fe-rich (Ingri 1985*b*; Baturin 2009; González *et al.* 2012; Ferreira *et al.* 2021*a*; MINDeSEA 2022). For instance, Mn-rich nodules from the Baltic Sea proper have contents of MnO >30 wt%, more Ni and Cu, and significantly more Ba, Zn, Mo and Li compared to hydrogenetic nodules. Lithium is especially high in diagenetic nodules from the Baltic Sea and areas of Macaronesia (up to 166 $\mu g\ g^{-1}$). They show low Co, Ce and total REE concentrations, high Y/Ho ratios, and low Th/U ratios compared to hydrogenetic nodules. Fe-rich nodules from the Baltic Sea and the Gulf of Cadiz, with Mn/Fe ratios of <1, also show low trace metal (between 0.01 and 0.09 wt%) and REE contents.

Based on the mineralogical and geochemical characteristics of nodules and their geotectonic settings, three principal environments have been proposed: shallow basins; banks and seamounts; and abyssal plains (Ferreira *et al.* 2021*d*). Most of the occurrences reported in the MINDeSEA dataset are located in shallow basins defining vast metallogenic areas of diagenetic dominant nodules (Fig. 6), growing very fast in the Baltic Sea, Barents Sea and Black Sea, and with a high potential for new discoveries in surrounding areas (Ferreira *et al.* 2021*d*).

The banks and seamounts from the Iberian Atlantic margin and Macaronesia host some settings for diagenetic and mixed diagenetic–hydrogenetic nodules. Recent discoveries of nodule fields in the area of Galicia Bank (horst block of continental crust) and the Tropic Seamount (Cretaceous intraplate hotspot volcano) indicate the potential (Fig. 10) for new resources in these settings (González *et al.* 2016; Murton 2017; Medialdea *et al.* 2021; Ferreira *et al.* 2021*d*).

The Madeira, Canary, Iberia, Biscay and Porcupine abyssal plains record deep (4000–5000 m) and sparse occurrences of nodules, which form on sands, muds, calcareous sediment and oceanic crust basalt. The Greenland, Dumshaf and Arctic abyssal plains represent areas that warrant further investigation and exploration, in addition to the Mediterranean Balearic, Ionian and Rhodes abyssal plains (Medialdea *et al.* 2021; Somoza *et al.* 2021*b*; Ferreira *et al.* 2021*d*).

Diagenetic phosphate mineralization

Early diagenesis has been proposed as the main genetic process for phosphate deposits on seamounts and along continental margins in pan-European seas (Lamboy 1976; Lucas *et al.* 1978; Gaspar 1981, 2000; Gaspar and Halbach 1999; González *et al.* 2016; Marino *et al.* 2017). In most of the European occurrences, marine phosphorites are accompanied by Fe–Mn mineralization (e.g. González *et al.* 2016), frequently incorporated as CFA into thick ferromanganese crusts (Marino *et al.* 2017). Phosphate deposits accumulate in the Atlantic Ocean along the western continental margin such as the Le Daoins Bank and Ortegal terrace, and also above banks and seamounts such as the Galicia Bank, and the Tropic and Lion seamounts, related to strong upwelling and high bioproductivity in surface waters (González *et al.* 2021*a*, *b*; Medialdea *et al.* 2021). Diagenetic phosphorite forms when the released phosphorus replaces carbonate biogenic material, forming irregularly distributed deposits. The morphologies of these deposits are usually slabs and cobbles (Fig. 3b); in the same environment, authigenic glauconite, dolomite and pyrite can also form (Lucas *et al.* 1978; González *et al.* 2016; Kudrass *et al.* 2017).

Phosphorite worldwide concentrates critical elements such as P, F, V, Sr and REY (Gaspar 1981; González *et al.* 2016; Hein *et al.* 2016; Marino *et al.* 2017; MINDeSEA 2022). Phosphorus and calcium are the main elements composing the apatite in phosphorites, with contents between 8 and 12 wt% (P_2O_5 contents ranging 15–37 wt%). REEs and yttrium (Y) (REY) are concentrated in phosphorites in the CFA, in which they substitute for Ca in the CFA lattice (Jarvis *et al.* 1994; Piper 1999). Light REEs (LREEs) enter and substitute for Ca in the Ca2 positions, while heavy REYs (HREYs) enter the phosphorite structure substituting Ca in its Ca1 position; elements like Eu and those with a similar radius do not have a preference for Ca1 or Ca2 sites (Hughes and Rakovan 2015; Hein *et al.* 2016). Moreover, heavy REEs (HREEs) plus Y (%HREYs) are highly enriched in phosphorites with respect to other REE-rich marine deposits such as crusts and nodules, as noted by their %HREY. Their phosphorites contents in continental margins, both worldwide and in European seas, reach an average value of 49%, while seamount phosphorites have an average of 60% and can reach 79% of the total REYs (González *et al.* 2016; Hein *et al.* 2016). The diagenetic fluid that contributes to the formation of the global phosphorites is less enriched in REYs compared to seawater unaltered by these diagenetic reactions (Hein *et al.* 2016). Similar behaviour has been observed in samples from the study areas. Geochemical analysis made on Iberian-margin phosphorites show V contents of 150 $\mu g\ g^{-1}$ (González *et al.* 2016).

The phosphatization was discontinuous in space and time during the Miocene–Quaternary in all the European recorded settings, and was driven in all locations by the diagenetic replacement of carbonate sediments and rock by CFA (Lamboy and Lucas 1979; González *et al.* 2016).

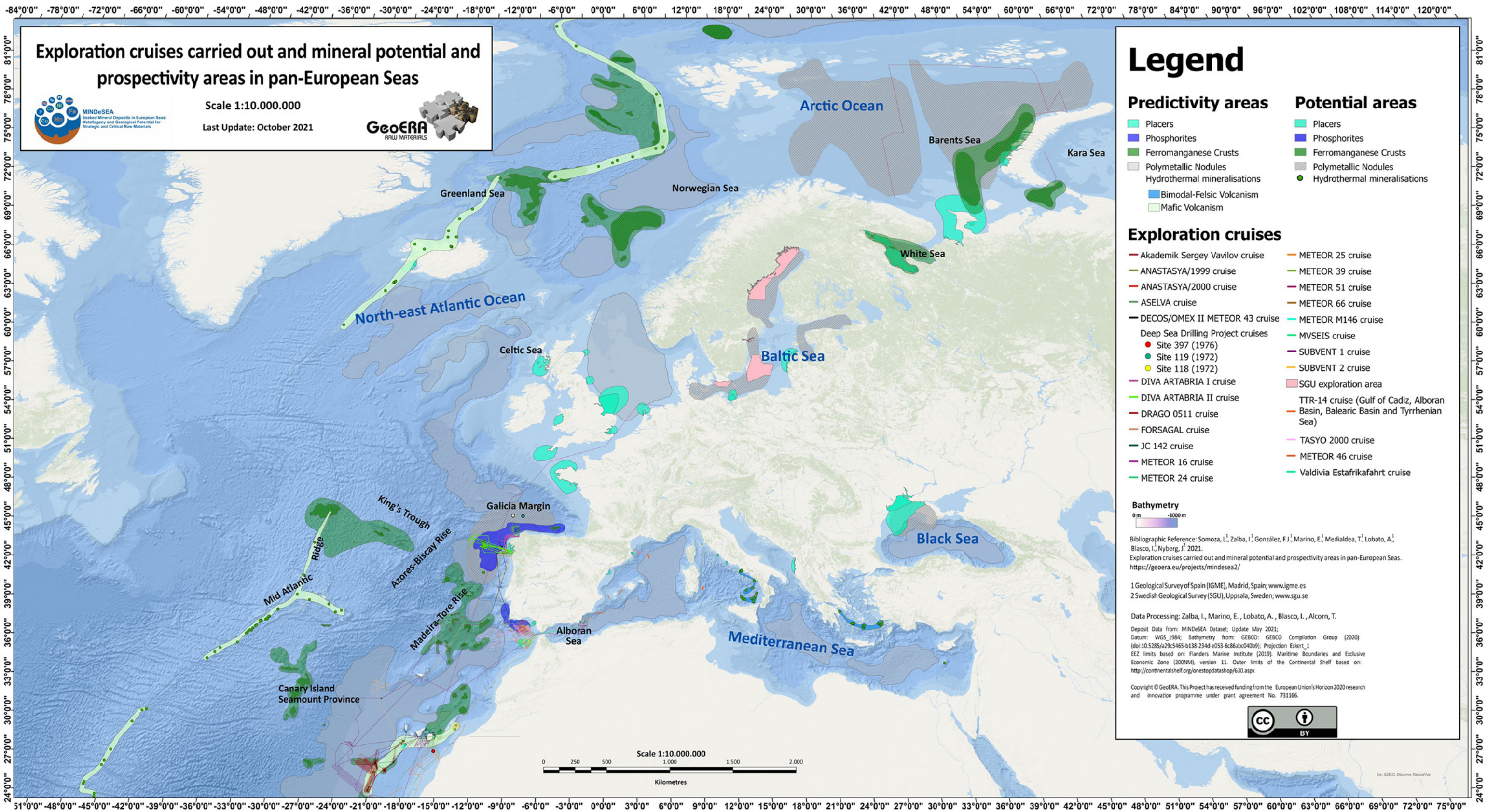

Fig. 10. Exploration cruises carried out, and the mineral potential and prospectivity areas in pan-European seas. Source: Somoza *et al.* (2021*b*).

Phosphorites from seamount environments, the Galicia bank, Madeira-Tore Rise and Canary Islands Seamount Province, show phosphate occurrences forming laminae, slabs and veins, or replacements in Fe–Mn crusts with an average of 11.4 wt% P (26 wt% P_2O_5). F reaches on average 1.7 wt% with a maximum of 2.5 wt% and average REY contents of 0.1 wt% with a maximum of 0.2 wt% (Murton 2017; Marino *et al.* 2017; González *et al.* 2021*c*; MINDeSEA 2022). The Sr content in phosphorites from Galicia Bank region ranges from 0.8 to 1.8 wt % (González *et al.* 2016). Continental-margin samples from the Iberian margin, however (Figs 7 & 10), reach up to 21 wt% P_2O_5 (9.2 wt% P). Data on REY and F contents are not present in the database but due to their similarity with seamounts samples, we expect similar contents (Baturin and Bezrukov 1971; Lamboy 1976; Lucas *et al.* 1978; Lamboy and Lucas 1979; Gaspar 1981, 1982, 1986, 2000; Baturin 1982; Rona 2008; González *et al.* 2016).

Fe–Mn hydrogenetic mineralization

Ferromanganese crusts in pan-European seas, as in the global ocean form, by hydrogenesis derived from cold seawater (Hein *et al.* 2000*a*; González 2008; Muiños *et al.* 2013; González *et al.* 2014, 2016; Muiños 2015; Marino *et al.* 2017, 2019; Marino 2020; González *et al.* 2021*a*). They grow on rock outcrops on seamounts, ridges and plateaus by the slow accretion of Fe and Mn oxyhydroxide floccules, with growth rates typically of 1–5 mm Ma^{-1} (Hein *et al.* 1997, 2000*a*, 2013; González *et al.* 2016; Marino 2020). Extensive pavements of brown to black Fe–Mn crusts with sub-parallel laminations and with thickness ranging from a patina up to 25 cm have been documented (i.e. Marino *et al.* 2017, 2018, 2019; MINDeSEA 2022). Mn oxides and Fe oxyhydroxides form the framework of Fe–Mn crusts, with contents between 18 and 22% by direct precipitation from cold seawater (Koschinsky and Halbach 1995; Hein *et al.* 1997, 2000*a*). Similar values have also been observed in samples from the pan-European seas (average of Fe = 17 wt% and Mn = 10 wt%). Dissolved and colloidal manganese and associated elements are especially enriched in the oxygen minimum zone (OMZ), and occur in lesser concentrations throughout the water column. The OMZ thickness and position depends on the biological productivity and on the currents that flow at different depths: for example in the Canary Islands Seamount Province area the OMZ reaches 1000 m depth, excluding most of the seamounts in the area (Hein *et al.* 2000*a*; Brandt *et al.* 2010, 2012). The principal Mn mineral in purely hydrogenetic Fe–Mn crust deposits in European seas is Fe-vernadite, a phyllomanganate with 1.4 and 2.4 Å reflections, which are also the principal minerals in pan-European samples. Other phyllomanganates are also found in some Fe–Mn crusts affected by diagenesis, and include birnessite (also 7 Å), and asbolane and buserite (with a 10 Å basal reflection). Fe minerals are X-ray amorphous FeO(OH) (feroxyhyte, ferrihydrite), which crystallize to goethite in some samples (González *et al.* 2012, 2016; Marino *et al.* 2017, 2019; Marino 2020).

These Fe–Mn oxyhydroxides incorporate several critical and strategic elements (e.g. Co, Ni, Cu, Mo, V, Ba, Tl, Ti and REYs) through sorption, co-precipitation and substitution in the structure (i.e. Co up to 1 wt% and REYs up to 0.4 wt%) (Hein *et al.* 2000*a*; Muiños 2015; González *et al.* 2016, 2018; Marino 2020). The enrichment of Co, up to 1%, is due to the slow sorption from seawater (Co^{2+}) that is directly oxidized to insoluble Co^{3+} on the surface of the Mn oxides (Hein *et al.* 2000*a*; Marino *et al.* 2019; Marino 2020). REYs can be found dissolved in seawater as monocarbonate and dicarbonate complexes, and are concentrated on the surface of Mn oxides and Fe oxyhydroxides of Fe–Mn crusts depending on their charge. Generally, dissolved light REEs (LREEs) form monocarbonate complexes in seawater that have a positive charge and are attracted to the negatively charged hydrogenetic Mn minerals such as vernadite. Generally, dissolved HREEs and Y, on the other hand, form dicarbonate complexes with a negative charge that are essentially linked to the positive surface charge of Fe oxyhydroxides (Koschinsky and Halbach 1995; Hein *et al.* 1997, 2000*a*; Marino *et al.* 2017). Other strategic and critical metals (V, Ti, Nb, Te and Pt) are especially enriched in thick hydrogenetic Fe–Mn crust deposits from European seas (Muiños *et al.* 2013; Marino 2020; González *et al.* 2021*a*; MINDeSEA 2022). Geochemical analyses plotted on several diagrams to identify their genesis (Bonatti *et al.* 1972; Dymond *et al.* 1984; Bau *et al.* 2014) verify that the Fe–Mn crusts are hydrogenetic.

Initiation of Fe–Mn crust growth, determined using a cobalt chronometer proposed by Manheim and Lane-Bostwick (1988) and Os isotopes, ranges from 90 to 20 Ma (Tropic Seamount samples), indicating very slow growth rates (1–5 mm Ma^{-1}) that are typical of hydrogenetic Fe–Mn crusts elsewhere in the European seas (Hein *et al.* 2000*a*; Marino *et al.* 2017; Marino 2020).

The principal environments controlling and hosting the distribution of thick (*c.* 20 cm) hydrogenetic Fe–Mn crust deposits in European seas are seamounts, banks and ridges, defining two main metallogenetic areas: (i) Macaronesia and (ii) the Norwegian Sea (González *et al.* 2021*b*; Medialdea *et al.* 2021). In the Macaronesia area (Fig. 7), the highest concentration of this deposit type is associated with a great number of Cretaceous–Cenozoic volcanic seamounts and ridges (Canary, Madeira and Açores islands). In this area, several Fe–Mn crusts with average contents of Co of 0.35% (and up to 0.79%) and highly enriched in several strategic elements (of which the most important for their economic value are Co, Ni, Cu, Mo, REYs, Te and Pt) have been collected (Muiños 2015; Merle *et al.* 2018; Marino 2020). In the Norwegian Sea (Fig. 7), Fe–Mn crusts are located along volcanic ridges such as the Jan Mayen Ridge. They show highest contents of aluminum-silicate-hosted elements (mean 16%) and lower contents of Fe and Mn (means of 22 and 12%, respectively) in comparison with Macaronesia crusts. Trace elements are also depleted, such as Co, Ni, Cu, Mo and REYs (2300, 2000, 400, 350 and 3000 µg g^{-1}, respectively) (MINDeSEA 2022). Other minor metallogenic areas are located along the Iberian-margin banks and plateaus, and some shallow seamounts formed by continental crust blocks. Encrustations found on the top of the sediments in shallow water in the Barents and Kara seas (Figs 7 & 10) represent a secondary occurrence target due to their low contents in trace metals (González *et al.* 2021*c*; MINDeSEA 2022).

Polymetallic hydrothermal mineralization

High- to low-temperature hydrothermal processes form the seafloor massive sulfides (SMS) and associated minerals in European seas (Schiellerup *et al.* 2021*a*; MINDeSEA 2022 and citations contained). High-temperature black smoker systems are primarily dependent on the tectonic setting (Fig. 8) in which they occur (Hannington *et al.* 2005) and the geodynamic setting controls the lithostratigraphic environment of the massive sulfide deposits (Franklin *et al.* 2005). The MINDeSEA dataset classifies the European deposits according to their setting into two categories: (1) mafic; and (2) bimodal-felsic, which can form deposits comprising chimneys, mounds and near-vent metalliferous sediments. A general model suggests that massive sulfide deposits contain pyrite and chalcopyrite at the centre of the vent system and feeder zone, and a halo of chalcopyrite–sphalerite–pyrite grading into a distal sphalerite–galena, galena and manganese–barite, and finally into a silica–manganese–hematite facies. Lower-temperature venting, such as that observed at white smoker vent sites, will generally be dominated by sulfate, carbonate or hydroxide minerals. The Lost City vent field shows variably serpentinized peridotite and gabbro rocks exposed on the seafloor (Kelley *et al.* 2001). The field, dominated by steep-sided pinnacles, is composed entirely of carbonates and magnesium hydroxides, which are driven by the heat from exothermic serpentinization reactions between seawater and the mantle rocks. Low-temperature hydrothermal Fe–Mn oxides have been observed covering the flanks and summits of several seamounts in the Aeolian archipelago (Lametini, Eolo, Enarete and Palinuro seamounts) and the Canary Islands (Tagoro), and as a minor component forming microlayers in hydrogenetic ferromanganese crusts (Dekov and Savelli 2004; Marino *et al.* 2019; González *et al.* 2020). Geothermal systems containing metals and water circulation along deep-seated fractures and faults have been invoked to explain the formation of epithermal or mixed hydrothermal–diagenetic deposits of Fe, Mn, Si and Ba on the island of Milos, the South Tyrrhenian Mn nodules, and Co-rich Mn nodules in Galicia Bank (Hein *et al.* 2000*b*; Dekov and Savelli 2004; González *et al.* 2016).

ROV observations of active vent fields (younger than 1.5 Ma) and isotopic ages obtained for hydrothermal deposits indicate Quaternary ages for the formation of most of the deposits (Gràcia *et al.* 2000; Kelley *et al.* 2001; Klügel *et al.* 2011).

Most of the MINDeSEA recorded deposits (MINDeSEA 2022) (Fig. 8) are located along the Mid-Atlantic Ridge (e.g. Trans-Atlantic Geotraverse (TAG), Famous and Moytirra), including the Azores Triple Junction (e.g. Capelhinos, Luso), the ridge segments affected by the Icelandic hotspot (e.g. Reykjanes Ridge) and the Mohńs Ridge (e.g. Soria Moria and Loki's Castle). Based on the number of deposits, the MOR setting (Fig. 10) must be considered the most important metallogenic setting of the European seafloor hydrothermal deposits (Schiellerup *et al.* 2021*c*; Somoza *et al.* 2021*b*). Fracture zones along the ridge axis are the main environment for mineralization. The sulfide deposits within this setting are mafic (or ultramafic) hosted, and are potential sources for copper, zinc, lead, silver and gold. However, the setting also includes shallow or colder vent systems precipitating mainly the sulfates anhydrite and barite. Deposits related to intraplate hotspots are represented by occurrences in the Canary Island archipelago (Medialdea *et al.* 2021). The principal environment for deposit formation is found in the fractures of submarine volcanoes frequently located at active volcanic centres (e.g. Tagoro Volcano: Fig. 4f). These deposits are epithermal, volcanogenic massive sulfide deposits (VMS) and exsolved oxyhydroxides, and their main products are copper–zinc sulfides, barite and iron oxyhydroxides. In the Mediterranean Sea, hydrothermal deposits are related to back-arc spreading, either in the Central and South Tyrrhenian Sea or in the Aegean Sea (Fig. 10). These deposits are considered bimodal to felsic exhalative types, or of epigenetic origin. In both the Aegean and the Tyrrhenian Sea, deposits generally consist of iron (average of 15 wt% and up to 40 wt%) and/or manganese (average of 9 wt% and up to 60 wt%), with a few occurrences of lead and zinc precipitates (average of 0.5 and 0.6 wt%, respectively). These deposits tend to be richer in lead, silver and antimony compared to the mafic sulfides. In contrast, Mid-Atlantic Ridge deposits are richer in base metals, including copper, zinc and barium.

Detrital mineralization

Marine placers in Europe reported in the MINDeSEA database are erosional products mainly located in depositional environments along coastlines (McKelvey 1986; Harben and Bates 1990; Rona 2008; Zananiri 2021; MINDeSEA 2022). Waves, tides and currents concentrate the economically valuable minerals by gravity separation during sedimentary processes; the minerals are both mechanically and chemically resistant. According to the multifactor classification proposed by Emory-Moore and Solomon (1989), most of the European marine placers listed in the MINDeSEA library can be classified as primarily formed by post-glacial weathering of bedrocks and transport to shallow beach/nearshore environments at variable distances from their source (Fig. 10). The most abundant deposits are the light to heavy mineral placers (e.g. monazite, zircón, xenotime, garnet, ilmenite and rutile), with a minor presence of heavy minerals (e.g. gold and cassiterite).

Beaches and near-shore are the principal environments for marine placers in European seas (Fig. 10). Different metallogenic areas have been differentiated in the MINDeSEA dataset and the metallogenic and potential maps: Black Sea, Aegean–Levantine Sea, Adriatic Sea, western Mediterranean Sea, Bay of Biscay and Iberian coast, Greater North Sea, Baltic Sea, and Barents and White seas (Zananiri *et al.* 2021). The Black Sea and North Sea have relict, submerged placer deposits that changed from a subaerial to a marine environment due to climate change, tectonic movements and other processes. These offshore occurrences are found in the area between the breaker zone and the outer margin of the continental shelf, probably indicating palaeocoastlines (Zananiri *et al.* 2021). Numerous placers recorded along the Iberian Atlantic coast, Bay of Biscay and Celtic Seas (Fig. 10) are at the southern limit of glaciation of the European continental margin (Praeg *et al.* 2015). These settings are linked to the weathering of onshore rocks and ore deposits from the Variscan Belt containing ilmenite, rutile and REE-bearing minerals among others (IGME 1976; Geoghegan *et al.* 1989; Medialdea *et al.* 2021). Placer occurrences in the Baltic Sea (Fig. 10) occur off the western coast of Latvia, with titanium and zirconium as the main metals of economic interest, and in the marine sands from the Odra and Słupsk Banks (Mikulski *et al.* 2016). Marine placer occurrences, mainly titanium, iron and REEs, have been documented off the western shorelines of the Severny and Yuzhny islands, within the gulfs of the White Sea and offshore the Kanin Peninsula (Ivanova *et al.* 1999). The crucial role for placer formation in the broader area of the Arctic shelf was most likely played by the duration of deposit emplacement of the occurrences under relatively stable subplatform environments and permanent downwarping. These long-lived occurrences may have productive horizons of great thickness and a wide age range. Marine placers in the Aegean–Levantine Sea are similar deposits occurring onshore (Perissoratis and Mitropoulos 1989). Fe, Ti and Cr placer deposits near the mouths of some of the rivers on the Cyprus continental shelf are sourced from the mafic and ultramafic rocks of the Troodos ophiolite complex (Varnavas 1990). Adriatic Sea placers (Fig. 10) occur in the Vjosa and Mati river-delta deposits (Xhaferri *et al.* 2020). Marine placers in the western Mediterranean are linked to estuaries and the Ebro delta deposits at the eastern margins of the Iberian Peninsula. Placers are absent along the north European oceanic coasts due to glacial erosion.

Final remarks

The GeoERA-MINDeSEA project has compiled data and genetic models for all the principal seabed deposit types in the European seas based on extensive studies carried out previously, which have included geophysical surveys, dredging stations, underwater photography and ROV surveys, and mineralogical, geochemical and isotopic studies. The project is built on previously and currently developed pan-European and national databases, and expands the knowledge of strategic and CRMs through a compilation of mineral potential and metallogenic studies of CRM resources in pan-European seas. The project provides recommendations for future target areas, studies and standards to be used across Europe as part of this project (MINDeSEA 2022).

The harmonized and standardized datasets and cartography provided by GeoERA-MINDeSEA allow a review of seabed mineral occurrences in combination with other parameters that allow better integration with marine spatial planning. The versatile maps have overlapping layers – mineral occurrences, metallogeny, potential exploration areas, and predictivity – on top of an EMODnet-Bathymetry layer. In addition to visual information, lists of attributes and metadata add direct information to the geological and metallogenic features, and redirects readers to specific key references and other pertinent information allocated on external websites. The analysis of original data sources of all the georeferenced material has provided the first compilation reports and maps on metallogeny for seabed minerals in pan-European seas. All of this information, freely available on the GeoERA portal, can be interpreted, cross-correlated and downloaded for further studies on seabed mineral deposits. These informative products will better educate the EC and society regarding the CRM potential in European seas, being a multinational work that harmonizes data across borders.

The GeoERA-MINDeSEA results enable the visualization and inspection of vast regions of the European seas. The selection of layers of information on each deposit type can be analysed interactively with other sources such as the EMODnet portals (geology, bathymetry, chemistry, physics, seabed habitats, biology and human activities of the European seas), providing input for an analysis of environmental issues, obtaining social licences or establishing regulations for mining activities.

Particular innovations of MINDeSEA include: (1) a definition of metallogenic provinces for offshore mineral deposits in the pan-European setting; (2) the characterization of critical minerals and elements for submarine deposits; (3) a map of the offshore CRMs in Europe; (4) a differentiation of data gaps in underexplored areas with a high geological potential to host CRM deposits within European waters; and (5) proposals for pilot zones with a high mineral potential for future research/exploration.

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Author contributions **FJG**: conceptualization (lead), funding acquisition (lead), investigation (lead), methodology (lead), project administration (equal), supervision (equal), validation (equal), writing – original draft (lead), writing – review & editing (lead); **TM**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **HS**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **IZ**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **PF**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **LS**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **XM**: conceptualization (equal), data curation (equal), validation (equal), visualization (equal), writing – review & editing (supporting); **TA**: conceptualization (equal), data curation (equal), validation (equal), visualization (equal), writing – review & editing (supporting); **EM**: data curation (equal), investigation (equal), writing – original draft (supporting); **ABL**: data curation (equal), writing – original draft (supporting); **ÍZ-B**: data curation (equal), writing – original draft (supporting); **TK**: investigation (equal), writing – original draft (supporting); **JN**: investigation (equal), writing – original draft (supporting); **BM**: investigation (equal), writing – original draft (supporting); **VM**: investigation (equal), writing – original draft (supporting); **JRH**: investigation (equal), writing – original draft (supporting); **GC**: investigation (equal), writing – original draft (supporting).

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