Discovering Europe's seabed geology: the EMODnet concept of uniform collection and harmonization of marine data

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Abstract: Maritime spatial planning, management of marine resources, environmental assessments and forecasting all require good seabed maps. Similarly there is a need to support the objectives to achieve Good Environmental Status in Europe's seas by 2020, set up by the European Commission's Marine Strategy Framework Directive. Hence the European Commission established the European Marine Observation and Data Network (EMODnet) programme in 2009, which is now in its fourth phase (2019–21). The programme is designed to assemble existing, but fragmented and partly inaccessible, marine data and to create contiguous and publicly available information layers which are interoperable and free of restrictions on use, and which encompass whole marine basins.

The EMODnet Geology project is delivering integrated geological map products that include seabed substrates, sedimentation rates, seafloor geology, Quaternary geology, geomorphology, coastal behaviour, geological events such as submarine landslides and earthquakes, and marine mineral occurrences. Additionally, as a new product during the ongoing and preceding phase of the project, map products on submerged landscapes of the European continental shelf have been compiled at various time frames. All new map products have a resolution of 1:100 000, although finer resolution is presented where the underlying data permit. A multi-scale approach is adopted whenever possible.

Numerous national seabed mapping programmes worldwide have demonstrated the necessity for proper knowledge of the seafloor. Acting on this, the European Commission established the European Marine Observation and Data Network (EMODnet) programme in 2009. The national geological survey organizations of Europe have a strong network of marine geological teams through the Marine Geology Expert Group of the association of European geological surveys (Eurogeosurveys). This network was the foundation of the EMODnet Geology consortium which today consists of the national geological surveys of Finland, the UK, Sweden, Norway, Denmark, Estonia, Latvia, Lithuania, Poland, The Netherlands, Belgium, France, Ireland, Spain, Italy, Slovenia, Croatia, Albania, Greece, Cyprus, Malta, Russia, Germany, Montenegro and Iceland, as well as marine teams of research organizations in Portugal (IPMA), Bulgaria (IO-BAS), Romania (GeoEcoMar), the UK (CEFAS), Greece (HCMR) and Ukraine (PSRGE, replaced in the fourth phase by Institute of Geological Sciences, NAS of Ukraine). The consortium is further strengthened with experts from six universities: Edge Hill University (UK), Sapienza University of Rome (Italy), University of Tartu (Estonia), University of Crete through FORTH-ICS, Institute of Marine Science and Technology of Dokuz Eylul University (Turkey), and EMCOL Research Centre of Istanbul Technical University – altogether, 30 partners and nine subcontractors. The EMODnet Geology programme is now in its fourth phase, which started in September 2019. In addition to geological information, the wider EMODnet programme aims to also bring together information from

European seas on seabed habitats, physical properties, chemistry, biology, human activities and hydrography. This paper describes the EMODnet Geology project and the different end products which were delivered in the end of the third phase and will be further developed during the recent fourth phase of the project.

Project objectives

EMODnet Geology compiles marine geological information held primarily by the project partners with some additional datasets that are publicly available. The project outputs are delivered through the European Geological Data Infrastructure (EGDI) portal (http://www.emodnet-geology.eu/). The consortium delivers 'Operation, development and maintenance of a European Marine Observation and Data Network', collecting and harmonizing datasets on seabed substrates, sedimentation rates, seafloor (bedrock) lithology, seafloor (bedrock) stratigraphy, coastal behaviour (migration direction, rate and volume, resilience), mineral occurrences (e.g. oil and gas, aggregates, metallic minerals), geological events and probabilities (e.g. earthquakes, submarine landslides, volcanic centres). As a new output, included for the third phase of the project, information on the submerged landscapes of the European continental shelves have been compiled at various time frames (e.g. Last Glacial Maximum (LGM) and younger low sea-level stages). The submerged landscapes product includes: (1) shorelines and coastal environments and deposits (such as lagoons, dunes, estuaries and beachrocks); (2) valleys and riverbeds, terraces and associated deposits; (3) river deltas and delta clinoforms; (4) submerged water points (such as submerged springs and freshwater lakes); (5) thickness of Holocene deposits; and (6) flora and fauna on the submerged landscapes. A common classification process will be adopted for all EMODnet Geology data compilations, with the resolution of the map products at a scale of 1:100 000 but finer-resolution layers where the underlying data permit. The regional seas covered by the project are the Baltic Sea, the Barents Sea, the Bay of Biscay, the Celtic Sea, the Greater North Sea, the Iberian Coast, the Norwegian Sea, the White Sea, the North Atlantic Ocean (continental shelves around Iceland, the Faroe Islands and Macaronesia), the Mediterranean Sea (within waters of EU countries), the Black Sea and, from the beginning of the fourth phase, the Caspian Sea (Fig. 1)

Geological data and metadata

During the first two phases of EMODnet Geology (2009–12 and 2013–16), the project identified relevant data held by the project partners and other national organizations, specifically interpreted

geological information. This involved a comprehensive audit and evaluation of national geological spatial datasets that could be compiled at the specified scales in all partner countries. During the first phase, all data were harmonized and delivered at 1:1 million scale, this was improved to 1:250 000 scale during the second phase. Subsequently, during the early stages of the third phase, all data that were available at a scale finer than 1:250 000 were compiled for addition to the harmonized EMODnet Geology datasets. The third phase (2017–19) delivered products at a scale of 1:100 000 or finer where the underlying data permitted, using the standards developed during the previous phases of the project.

The geographical scope of the project area has evolved from the first phase, which only included the northern European seas, with the inclusion of the other European seas from the start of the second phase. The Caspian Sea was included into EMODnet Geology from the beginning of the fourth phase.

The specification of the third phase also included the supply of metadata on multibeam echo-sounder and seismic surveys, and seabed cores to be made available. The EMODnet Geology project has collected such available metadata and delivered this through the European Geological Data Infrastructure (EGDI) portal as indexes with links to the owner of the original data. It is planned for this portal to continue to be maintained after the duration of the project.

Emodnet Geology deliverables and products

The deliverables for the EMODnet Geology project mainly comprise spatial data: that is, maps and data points open and freely accessible via a map viewer on the EMODnet Geology portal. These products are downloadable (e.g. as shapefiles), and are described here in detail.

Seabed substrate information and harmonization of European-wide data

The first map layer to be compiled comprised information on the seabed substrate. The information was harmonized by evaluating the different classification schemes used in each country, translating the submissions to a uniform sediment scheme (Kaskela *et al.* 2019), and generalizing those interpretations to 1:100 000 scale before combining them into a single seabed substrate dataset. The derived dataset was
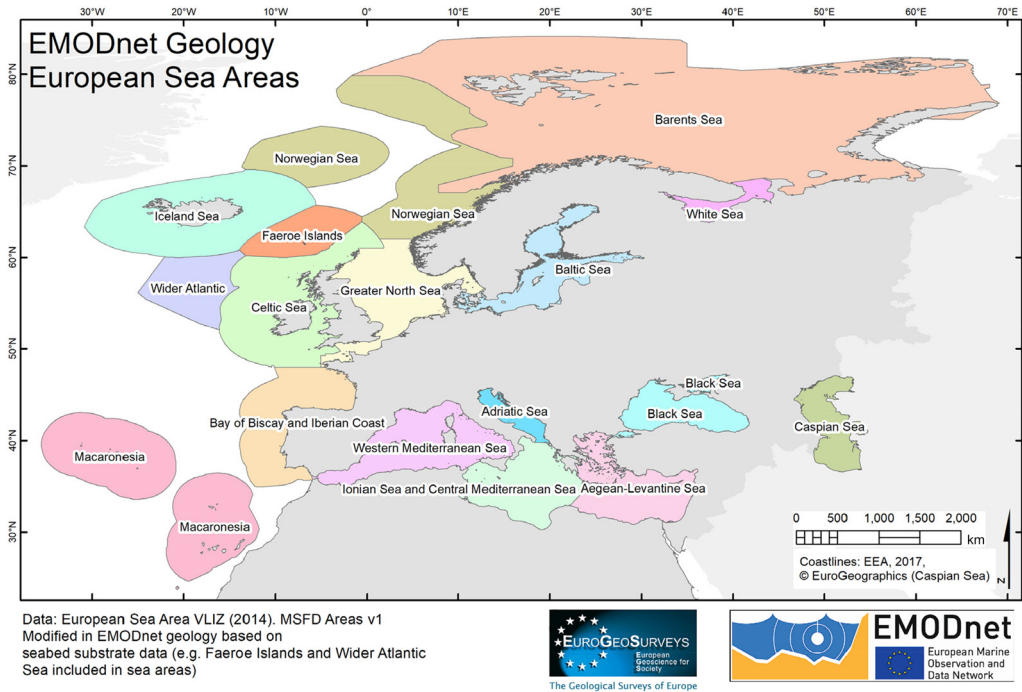
Fig. 1. The regional seas and sub-seas of Europe according to the Marine Strategy Framework Directive. Marine areas around Iceland, the Faeroe Islands and the wider Atlantic Sea are included on the basis of the exclusive economic zone (EEZ) areas and data delivery in the EMODnet Geology phase III. The Caspian Sea is also included in the areas of EMODnet Geology during phase IV of the project.

delivered as geographic information system (GIS) shapefiles showing seabed substrate polygon features, with all maps provided in the WGS84 geographical coordinate system.

Owing to the vast heterogeneity in the different national classification schemes, a simplified reclassification scheme was adopted (Kaskela *et al.* 2019) that provides an estimate of the substrate representing sediments within 30 cm of the seafloor, whilst remaining ecologically relevant units.

It was agreed to follow the Folk sediment classification (Folk 1954) to include all 15 substrate classes, and also data on rock and boulders where possible. A nested hierarchy of Folk classifications was created with 16, seven and five classes (Kaskela *et al.* 2019). Thus, all classes could be translated into the simpler five class scheme to be used on the final map. The cutoff between 'Mud to muddy sand' and 'Sand' was changed from 4:1 to 9:1 during the first phase of the EMODnet Geology project.

Any submissions not originally provided using the Folk classification system were reclassified, with harmonization undertaken by the respective contributing partner to ensure the integrity of the interpretations were retained. The reclassification process required analysis of the surface material based on vast archives of seafloor samples, and an expert-based prediction. In each case, an attribute table that contains information related to the reclassification was created, with the reclassification validated by ground-truthing where possible. The final step was to combine the validated reclassified substrate maps, undertake quality control checks and to publish, for the first time, a Europe-wide coverage seabed substrate map (Fig. 2).

Sedimentation rates

The EMODnet Geology project has, since its first phase, collected all available data on sedimentation rates within European seas. Much of the data were compiled during the first phase of EMODnet Geology, although the dataset has been updated during the later phases, partly through further data mining and partly through input of new measurements, as well as through the inclusion of the European sea areas which were absent in the first phase of EMODnet Geology. The dataset now contains sedimentation rate (cm a^{-1}) data from over 1350 sites, with a clear difference in geographical coverage. The Baltic
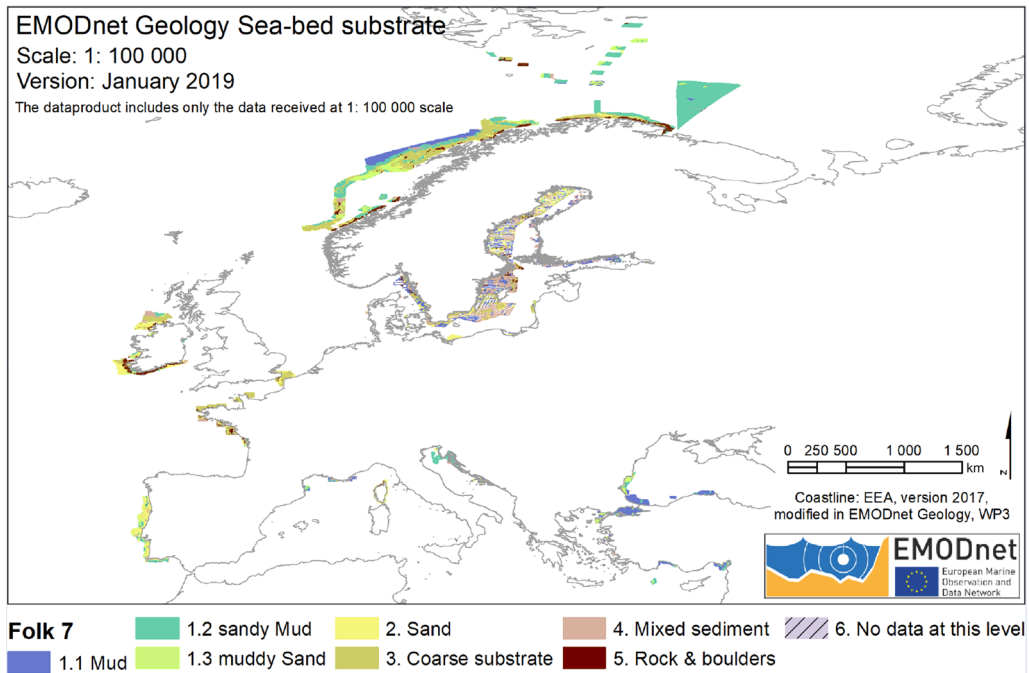
Fig. 2. EMODnet Geology seabed substrate data at a scale of 1:100 000 for the European seas hierarchy of seven Folk classes. The map shows one data layer (seabed substrate) as visualized in the EMODnet Geology map viewer on 1 April 2019. This open and freely-accessible product was made available by the EMODnet Geology project (http://www.emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by Anu Kaskela and Susanna Kihlman (GTK) from the EMODnet-3 Geology partners.

Sea, the Mediterranean Sea and, partly, also the Black Sea are well covered by sedimentation rate data, while there is a paucity of data from the nations bordering the North Atlantic Ocean, with the exception of areas offshore Norway and Iceland, as well as the Kattegat and Skagerrak straits. This is likely to be a result of local geological conditions as the coastal areas of the Atlantic Ocean are generally so highly dynamic that the accumulation of soft fine-grained sediments, which are best for accumulation measurements, do not occur in a comparable way to the enclosed seas such as the Baltic, the Mediterranean and the Black seas.

Pre-Quaternary geology and harmonization

During the first phase of EMODnet Geology, the offshore component of the harmonized 1:5 million-scale *International Geological Map of Europe and Adjacent Areas* (Asch 2005) was used as base to compile a pre-Quaternary geological map for the northern European sea areas. It was implemented as a Web Map Service (WMS) delivering information on both the lithology and chronostratigraphy

(labelled 'age' in the figure captions) of the seafloor. These datasets have since been updated during the subsequent phases of EMODnet Geology to cover all European sea areas, with improvements in both the detail of the rock descriptions and in the product resolution, so that today the best resolution available is 1:50 000 (Fig. 3). Currently, these data encompass not only information on the age and lithology of the seafloor in more detail but also on the genesis (event environment, event process) and structures (fault types) based on the INSPIRE Geology data specifications (https://inspire.ec.europa.eu/Themes/128/2892).

Quaternary geology

The Quaternary geology layer was added during the third phase of the EMODnet Geology project (Fig. 4). The aim was to compile all available Quaternary geology maps from each participating country, and resolve any major boundary issues to deliver information on the lithology, chronostratigraphy (labelled 'age' in the figure captions) and genesis at the best available resolution. Similarly to the
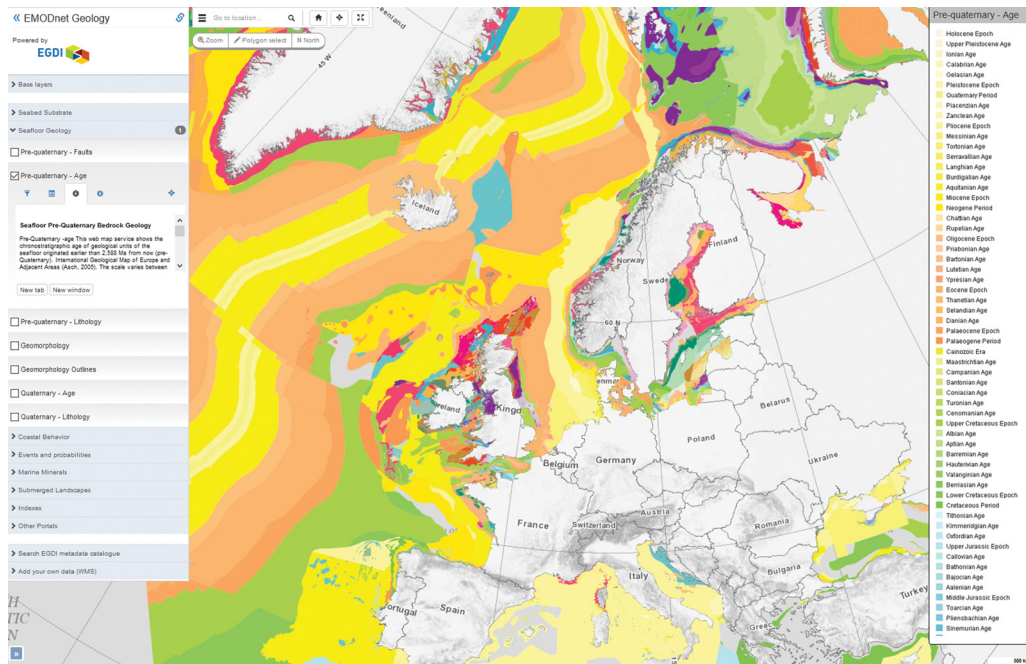
Fig. 3. Offshore pre-Quaternary geology as displayed on the EMODnet Geology portal. The map shows one data layer (seafloor age of the pre-Quaternary), as visualized in the EMODnet Geology map viewer on 1 April 2019. This open and freely-accessible product was made available by the EMODnet Geology project (http://www. emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by Kristine Asch (BGR) from the EMODnet-3 Geology partners.

pre-Quaternary dataset, the descriptions are based on the INSPIRE Geology specifications which may be further developed in phase IV as necessary.

Geomorphology

The geomorphology of the European seas was a new theme included in EMODnet Geology during phase III. A harmonized synthesis of geomorphological structures of the European seas did not exist prior to this project. Marine geomorphology in the framework of EMODnet Geology comprises delineated seafloor features, describing the submarine 'landscape', including information on their genesis.

Similarly to other themes within phase III of the project, this theme aimed to deliver information on the seafloor geomorphology at the best available resolution. This product utilized vocabulary and definitions developed in conjunction with the Commission for the Geological Map of the World/International Union for Quaternary Science CGMW/INQUA project of the *International Quaternary Map of Europe and Adjacent Areas*, produced at a scale of 1:2500 000 (IQUAME2500) (Asch 2019); work

which took place concurrent with phases II and III of the EMODnet Geology project.

The published data layer includes the major geological and geomorphological boundaries displayed at scales as detailed as possible as supplied by partner organizations (Fig. 5). Where information was not available at the stipulated 1:100 000 resolution, these data gaps were infilled using coarser-resolution products compiled during EMODnet Geology phases I and II.

Coastal behaviour

During the first phase of EMODnet Geology a GIS layer based on the EUROSION database on coastal erosion and sedimentation was supplemented and updated by the project partners. However, the dataset did not offer complete coverage of the European coasts and, moreover, the data were compiled from observations from different time periods, reducing the usefulness of the data. During the third phase of the project, a completely new approach was developed and applied. The new approach is based on remote sensing and comparison of satellite photographs over a time span of 10 years (2007–17)
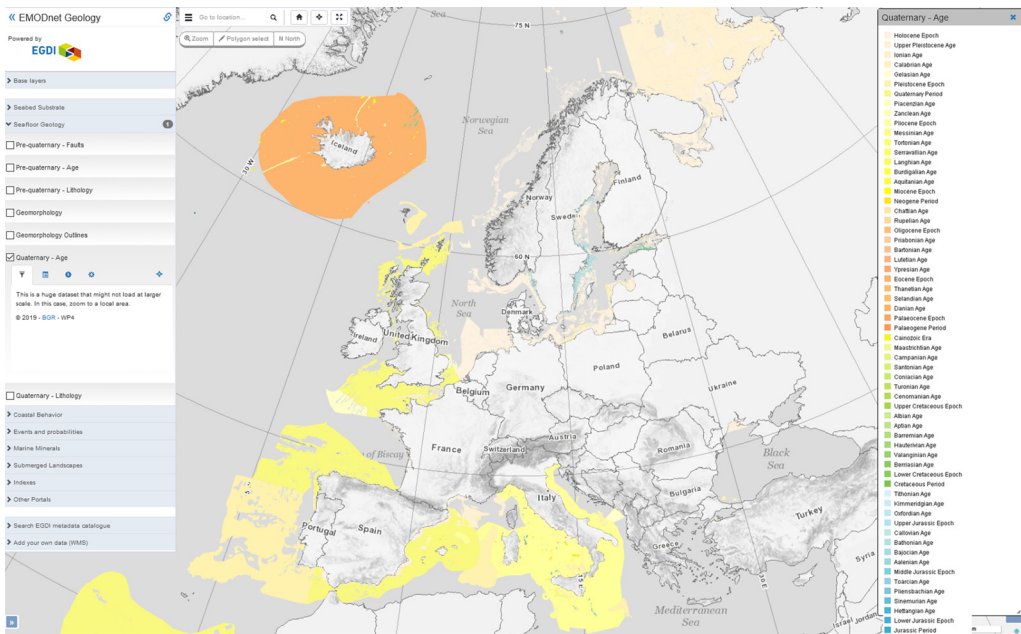
Fig. 4. Offshore Quaternary geology as displayed on the EMODnet Geology portal. The map shows one data layer (chronostratigraphical 'age' of the Quaternary), as visualized in the EMODnet Geology map viewer on 10 February 2020. This open and freely-accessible product was made available by the EMODnet Geology project (http://www.emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by Kristine Asch (BGR) from the EMODnet-3 Geology partners.

with a spacing of 500 m between the observations. Importantly, for the first time, these observations were made with full European coverage. This approach gives very good resolution on both local and regional scales. The obtained results have been validated with field tests at a number of locations by project partners. The final outcome is a fully populated GIS layer and WMS of coastal behaviour information (Fig. 6). This will be followed up in the current phase by a GIS layer and WMS on coastal resilience, to be used as a pan-European tool for assessing the capacity to cope with the adverse effects of sea-level rise and coastal erosion. The resilience map then visualizes the socio-economic relevance of coastal–geological change as captured in the previous EMODnet Geology phases.

Geological events and probabilities

Data on geological events and probabilities have been collated from various sources but the major sources of information for this product were the national mapping programmes of the project partners. The web-page map-viewer provides fully populated GIS layers consisting of locations and, where available, additional attributes of features, such as

landslides, tectonics, fluid emissions, volcanoes and tsunamis, as polygons, lines and points (Fig. 7). Considering the diverse settings of European seas, it was necessary to compile an extensive and detailed list of attributes for the different features to represent the diverse characteristics of each occurrence (Battaglini *et al.* 2020). The EMODnet Geology portal links directly to the European–Mediterranean Seismological Centre (EMSC), which provides up-to-date information on earthquakes.

Minerals

As there has been a lack of compiled data on marine minerals within European waters, the aim of the minerals theme has been to identify areas of mineral occurrences (including aggregates, hydrocarbons and metalliferous minerals) both on and beneath the seabed. Each project partner collated and standardized known marine mineral occurrences from sources including publicly-available information (e.g. published scientific papers) for all EMODnet participating countries encompassing European marine regions and subregions.

During the third phase of the project the aim of delivering the first catalogue of marine minerals,
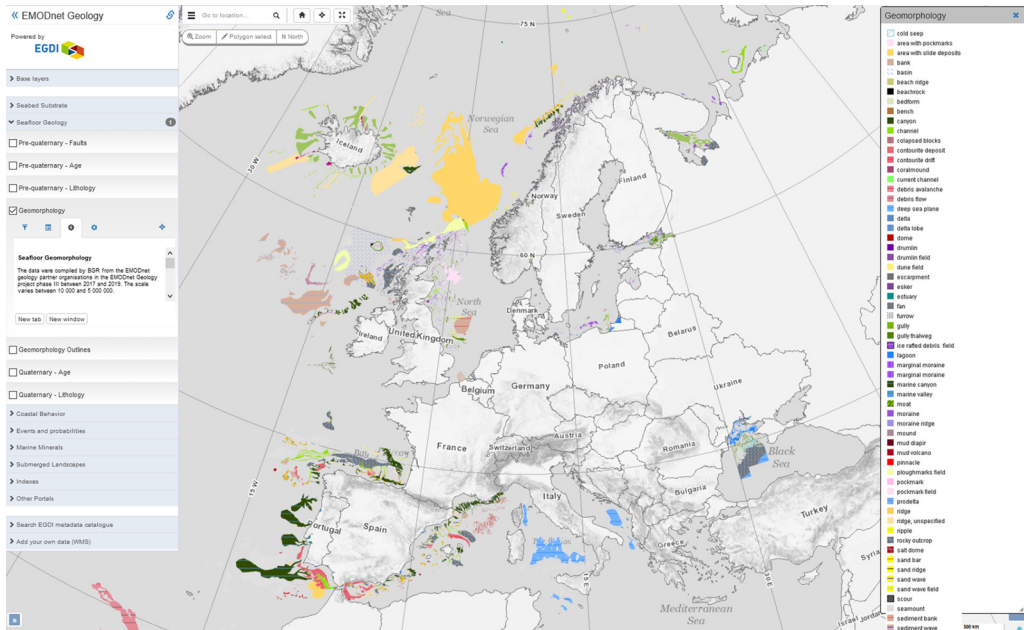
Fig. 5. Seafloor geomorphology of the European seas as displayed on the EMODnet Geology portal. The map shows one data layer (basic geomorphology), as visualized in the EMODnet Geology map viewer on 10 February 2020. This open and freely-accessible product was made available by the EMODnet Geology project (http://www. emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by Kristine Asch (BGR) from the EMODnet-3 Geology partners.

raw materials, hydrocarbons and metalliferous minerals offshore Europe was achieved. Now, standardized information on the spatial distribution of 12 mineral types across all European seas is available to download. The dataset and maps present information on: aggregates; cobalt-rich ferromanganese crusts; evaporites; gas hydrates; hydrocarbons; marine placers; metal-rich sediments; outcrops of rock, pegmatite and vein-hosted mineralization; polymetallic nodules; polymetallic sulfides; phosphorites; and sapropel (Fig. 8). It is important to understand that the marine mineral accumulations mapped are not just indicators of potential economic deposits but also indicators of palaeoenvironments like palaeobeaches. Take the Southern North Sea, for instance, where aggregate deposits indicate a glacial palaeoenvironment in the Quaternary, and evidence of evaporites in this area indicate salt deposits laid down during evaporation of a marine incursion during the Permian era. Extensive evaporites also have implications in terms of hydrocarbon trapping. While the profusion of cobalt-rich ferromanganese crust in the Canary Island Seamount Province indicates an environment dominated by longstanding volcanic precipitation of metals dissolved in seawater (Marino *et al.* 2017). Evaporites

are useful for carbon/methane sequestration, while sulfides, hydrates and nodules are endemic habitat indicators. Aggregates are valuable for offshore wind farm development and beach nourishment projects. Marine mineral information, together with other geological products, is a valuable resource for marine spatial planning.

Submerged landscapes

One of the new challenges for EMODnet Geology during the third phase was the request for data on reconstructions of the submerged landscapes of the European continental shelves at various time frames (e.g. LGM and younger low sea-level stages). Sea level is known to have fluctuated by more than 100 m over repeated glacial cycles, resulting in recurring exposure, inundation and migration of coastlines not only across Europe but worldwide. Landscape response to these changes in sea level, and the preservation of these features on continental shelves around Europe, are an invaluable resource for improving our understanding of human history and environmental change over geological time, while also providing data for potential use in examining future sea-level rise scenarios.
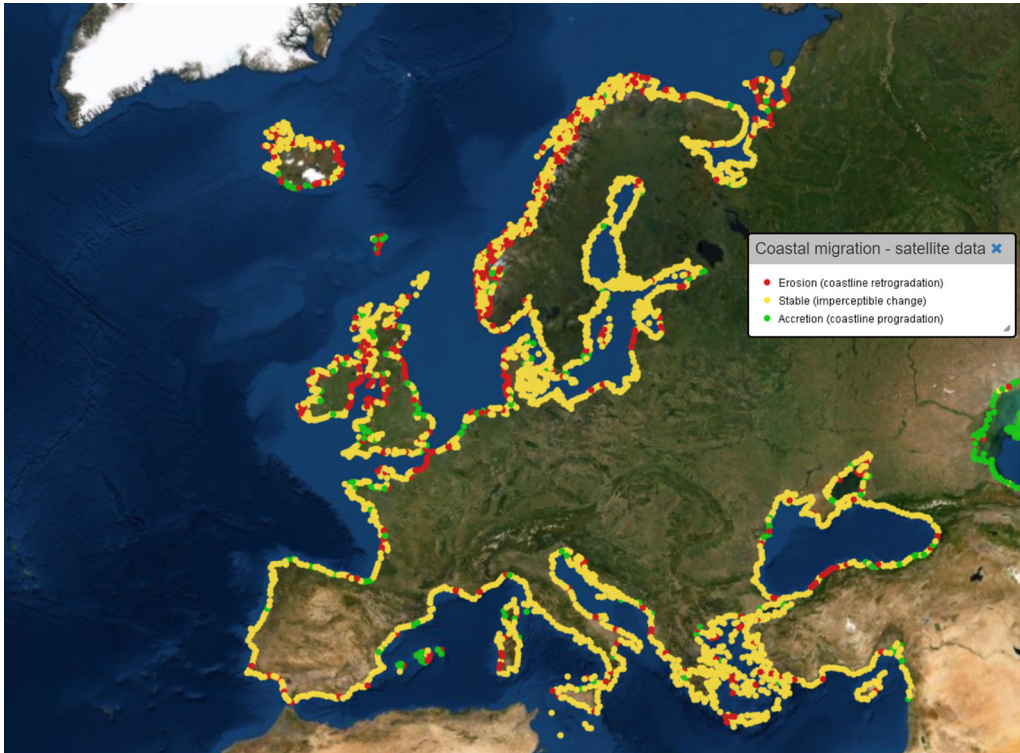
Fig. 6. Pan-European coastal behaviour based on satellite imagery from the years 2007–17 as displayed on the EMODnet Geology portal. The different colours mark erosion, stable coast or accretion. This open and freely-accessible product was made available by the EMODnet Geology project (http://www.emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by Deltares and Sytze Van Heteren (TNO). Base map ESRI World imagery.

The work package aimed to compile and harmonize available information on submerged landscape features by integrating existing records of palaeoenvironmental indicators with interpretations of geomorphology, stratigraphy and type of sediment (Fig. 9). The fully attributed GIS layer will be used to underpin palaeogeographical reconstructions across various time frames during the fourth phase of the project.

More than 10 000 features representing 26 classes of submerged landscape and palaeoenvironmental indicators ranging from mapped and modelled palaeocoastlines, evidence for submerged forests and peats, thickness of post-LGM sediments and submerged freshwater springs across all European seas have been collated and delivered on the EGDI portal for the first time. Building on the work of other projects, such as the COST Action SPLASHCOS project (http://www.splashcos.org/), the EU FP-7 project SASMAP (http://sasmap.eu/); and the MED-FLOOD project, this theme aimed at meeting the recommendations of the European Marine Board SUBLAND group (http://www.marineboard.eu/continental-shelf-prehistoric-research-wg-subland). Recent advances in both data acquisition and availability over the last two decades has enabled researchers to more accurately reconstruct the extent and dynamics of fluctuating palaeocoastlines. High-resolution multibeam bathymetry and sub-bottom seismic data, in particular, have resulted in a step change in our understanding of palaeoshorelines and other traces of the original landscape topography and sediments. With preservation of these now submerged features under threat from commercial activities and natural erosion, bringing together existing knowledge through delivery of this work package is timely.

As this theme was new in the third phase of the project, data compilation and harmonization is ongoing with not all jurisdictional waters represented as yet. Furthermore, visualization of these data and interpretations at the European scale was challenging
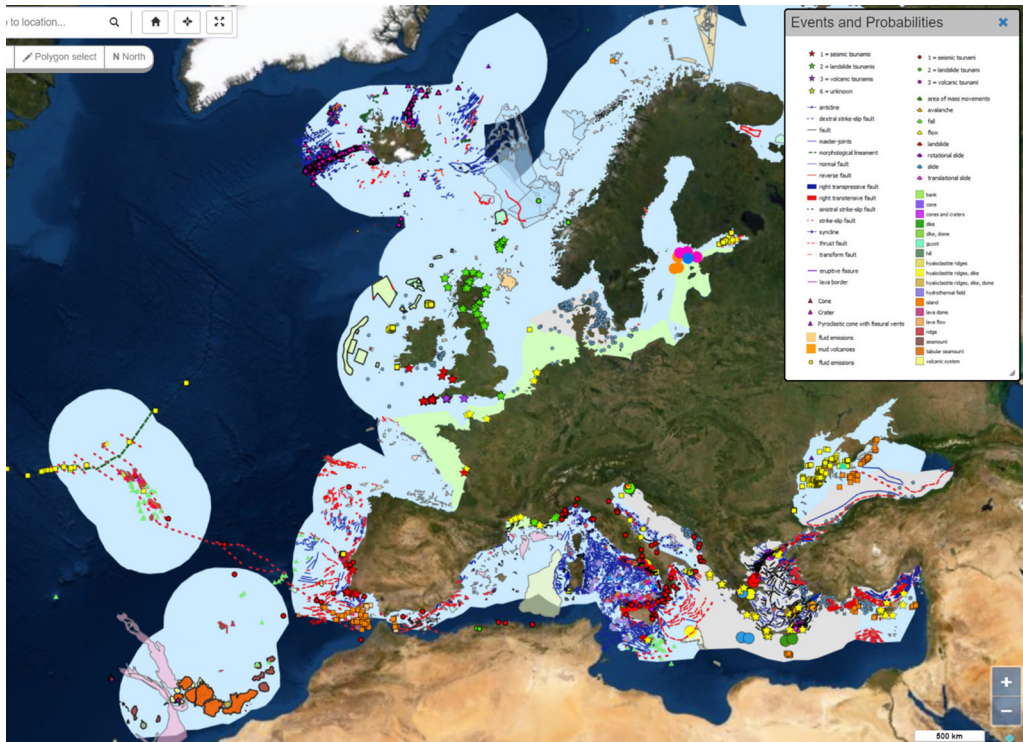
Fig. 7. Geological events and probabilities of the European seas as displayed on the EMODnet Geology portal, as visualized in the EMODnet Geology map viewer on 1 April 2019. This open and freely-accessible product was made available by the EMODnet Geology project (http://www.emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by ISPRA from submissions from the EMODnet-3 Geology partners.

as much of the obtained data are restricted in both geological time and spatial coverage, and therefore not easy to correlate across a whole continent. Future work will look to add and develop these data layers, incorporating feedback from the wider community and work on reconstructions at key snapshots in time.

Challenges of map production

There are a number of major challenges involved in the production of pan-European maps. A main issue is the scattering of data, which in fact was one of the main reasons for starting the EMODnet programme. It has been known for a long time that there are a lot of data collected from the European seas but by many different organizations, in many different countries and stored in many different ways, often inaccessible for the public. That being said, a strength of the EMODnet Geology consortium was access to key data repositories, as the project partners are the geological survey organizations of all European maritime nations, themselves the

major geological data owners in Europe. After the initial phase of collecting available data, the first drawbacks – the data gaps – were observed. It was known from the outset that a large number of data gaps existed, which was confirmed during the execution of the EMODnet Geology project. One of the main issues of importance for the European Union and member states should be the recognition of these knowledge gaps which should be prioritized so they can be strategically addressed in the future, based on environmental values and level of (conflicting) interests in the respective European sea areas.

After, collection of all available data it was clear that there were a number of different classification schemes describing the data made available from various partners. This highlighted the necessary steps in harmonizing the data, often a rather time-consuming process which can, unfortunately, also impact the quality of the result. For example, the compilation of seabed substrate data and their harmonization has been discussed here as an example of this complex process.
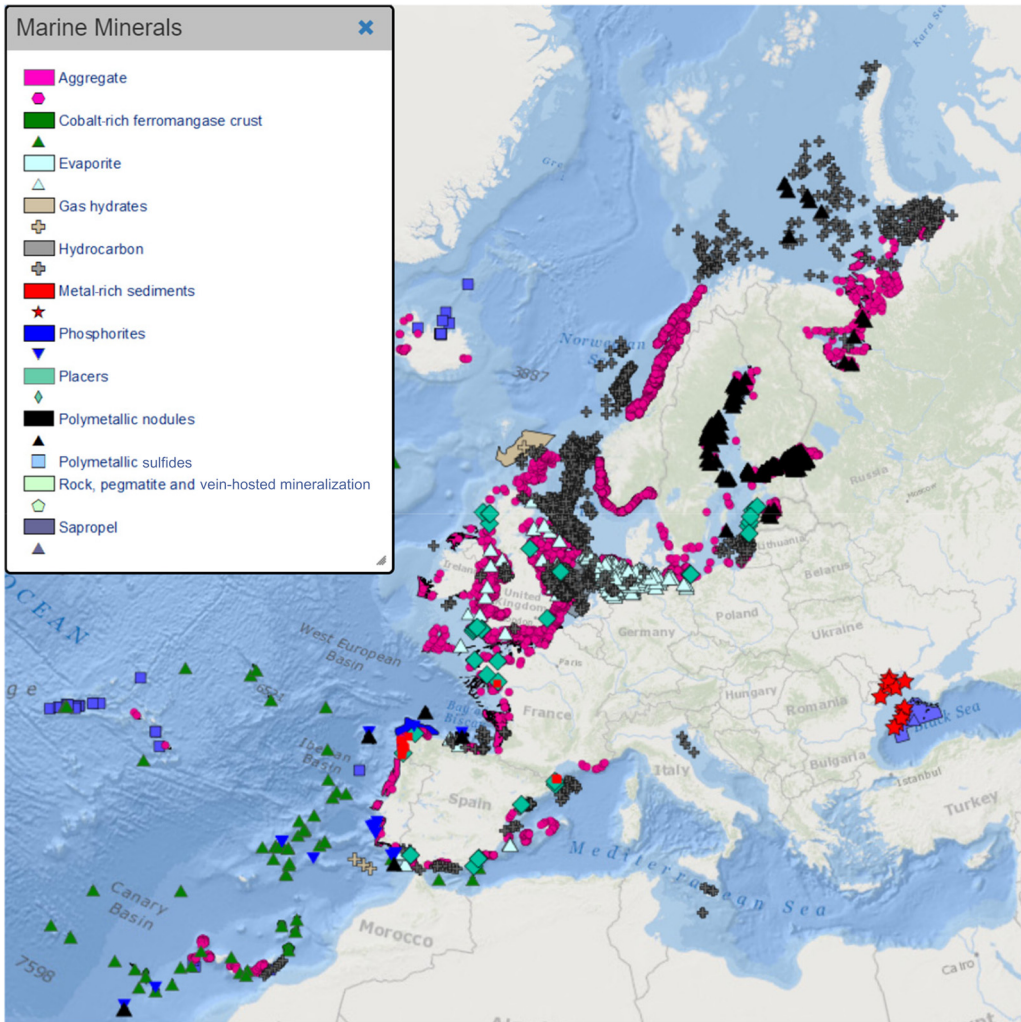
Fig. 8. Screenshot from the EMODnet Geology map viewer (on 1 February 2020) of the marine minerals map including 12 different mineral types, displayed here in point format. These points represent the single-point location for occurrences such as polymetallic sulfides. Where occurrences, such as aggregates, span a larger geographical footprint the central point of this geographical area is illustrated as the unique point representing that unique dataset. Polygons that illustrate the geographical distribution for each of these datasets are also available. This open and freely-accessible product was made available by the EMODnet Geology project (http://www.emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by Maria Judge (GSI).

Another issue affecting the value of the resulting maps is the quality of the original data. The quality does not concern only the measurements but also the data acquisition and, in the earlier days, accurate positional data. For instance, the low-resolution data on which many of the national geological interpretations are based have highlighted the data gaps and deficiencies. Sometimes, a cross-border connection of the maps has been difficult to reconcile due to such issues. The high-resolution datasets of today, using the latest acquisition and imaging techniques, are of a completely different standard to the archived datasets, which can make harmonization difficult.

Web portal and presentation of data products

The Geological Survey of Denmark and Greenland (GEUS) has, since the beginning of phase III of the project, been responsible for hosting and upgrading the portal, managing data products and allowing
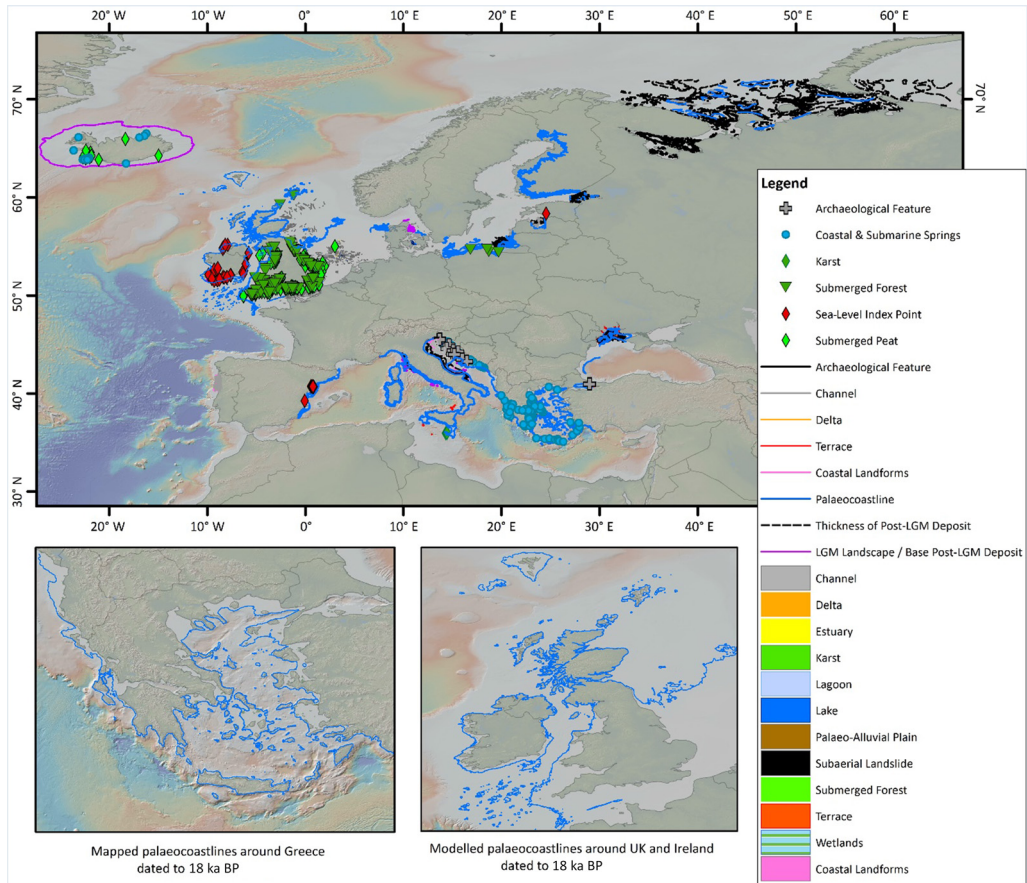
Fig. 9. Submerged landscapes of European seas as displayed on the EMODnet Geology portal (main panel). Mapped palaeocoastlines around Greece (lower left panel) and modelled palaeocoastlines around the UK and the Republic of Ireland (lower right) dated to 18 ka BP are displayed. These data were visualized in the EMODnet Geology map viewer on 1 April 2019. This open and freely-accessible product was made available by the EMODnet Geology project (http://www.emodnet-geology.eu/), implemented by EMODnet Geology phase III partners, and funded by the European Commission Directorate General for Maritime Affairs and Fisheries. These data were compiled by Heather Stewart (BGS) from the EMODnet-3 Geology partners.

users easy access to data products. Access includes downloading, machine-to-machine services and interactive maps. Synergies were found with other EU projects by adopting the technical infrastructure of Eurogeosurveys, called EGDI (see http://www.europe-geology.eu). Using this approach, a suite of functionality came 'out-of-the-box' and reduced initial costs. The service includes access to all EMODnet Geology products and, in case of technical queries regarding data access or contributions, a help desk is available during office hours.

Data availability statement The datasets generated during and/or analysed during the current study are available in the EMODnet repository, https://www.emodnet.eu/.

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