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Perspective

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Mapping the Geology and Topography of the European Seas (European Marine Observation and Data Network, EMODnet)

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Abstract: Marine engineering geology requires good seabed maps and access to metadata. In 2009 the European Commission established the European Marine Observation and Data Network (EMODnet) programme, 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. This collection highlights the use of EMODnet Geology data for better understanding seafloor geology, coastal behaviour and geological events and probabilities. The papers illustrate methodological approaches to harmonizing and representing geological and geohazards information, resultant maps and datasets and their uses, alongside national datasets, for marine spatial planning.

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European Marine Observation and Data Network (EMODnet)

The European Marine Observation and Data Network (EMODnet) is a network of organizations, working together since 2009 in the framework of the EU's Integrated Maritime policy to address fragmented marine data collection, storage and access in Europe, as set out in the Green Paper – Marine Knowledge 2020. It provides a knowledge base, designed to stimulate innovation and improve understanding of the behaviour of the sea, in order to enable investments in marine observation from Member States and the EU to realize their potential for creating sustainable growth. The annual costs of acquiring marine data through ocean observations, including remote sensing via satellites and *in situ* data collection by public authorities and private bodies, are estimated at *c.* €4.5 billion. Access to these marine data is critical for marine industries, decision-making bodies and scientific research. EMODnet provides a single-entry point for accessing and retrieving marine data derived from observations, surveys or samples from the hundreds of databases maintained on behalf of agencies, public authorities, research institutions and universities throughout the EU. It delivers digital map layers of parameters derived from these primary data for entire sea basins around Europe. Harmonizing and making these data more widely available is estimated to save *c.* €1 billion each year in gathering and processing marine data for operational and planning purposes. These harmonized data also improve the efficiency of offshore operators and of marine planning and legislation as well as helping to improve scientific knowledge of, and ability to predict, the behaviour of the seas (European Commission 2012; Calewaert *et al.* 2016; Míguez *et al.* 2019). EMODnet, through its central portal (https://www.emodnet.eu/), provides access to European marine data across seven discipline-based themes: geology, bathymetry, seabed habitats, chemistry, biology, physics and human activities. The EMODnet checkpoint projects, for the Mediterranean, Atlantic, Arctic, Baltic, North and Black Seas, analyse the fitness for purpose of data provision by testing against specific end-user challenges (Populus *et al.* 2016; https://www.emodnet.eu/checkpoints).

EMODnet Geology

This thematic set of papers is associated with the work of the EMODnet Geology project (referred to in some of the papers herein as the Geology Lot). The Geology project, now in its fourth phase, which started in 2019, is detailed in Vallius *et al.* (2020). In brief, it is currently led by the Geological Survey of Finland (GTK) and provides access to information primarily held by national geological surveys, as well as other institutions, of 39 partner organizations in 30 European countries, most of whom are EuroGeoSurveys members. It delivers integrated geological map products that include seabed substrates, sedimentation rates, seafloor geology, Quaternary geology, geomorphology, coastal behaviour, submerged landscapes of the European continental shelf, geological events such as submarine landslides and earthquakes and marine mineral occurrences. The regional seas covered by the project are the Baltic Sea, Barents Sea, Bay of Biscay, Celtic Sea, Greater North Sea, Iberian Coast, Norwegian Sea, White Sea, the North Atlantic Ocean (continental shelves around Iceland, the Faroe Islands, and Macaronesia), Mediterranean Sea (within waters of EU countries), Black Sea and from the beginning of the fourth phase, the Caspian Sea (Fig. 1). Following the addition of the Caspian Sea in 2019, the next phase starting in 2021 will also include all jurisdictional waters of the Caribbean Sea, further expanding the geographical scope of the work programme and stimulating the adoption of EMODnet standards in other parts of the world.

EMODnet Geology outputs are delivered through the European Geological Data Infrastructure (EGDI) portal (www.emodnet-geology.eu/). All new map products have a resolution of

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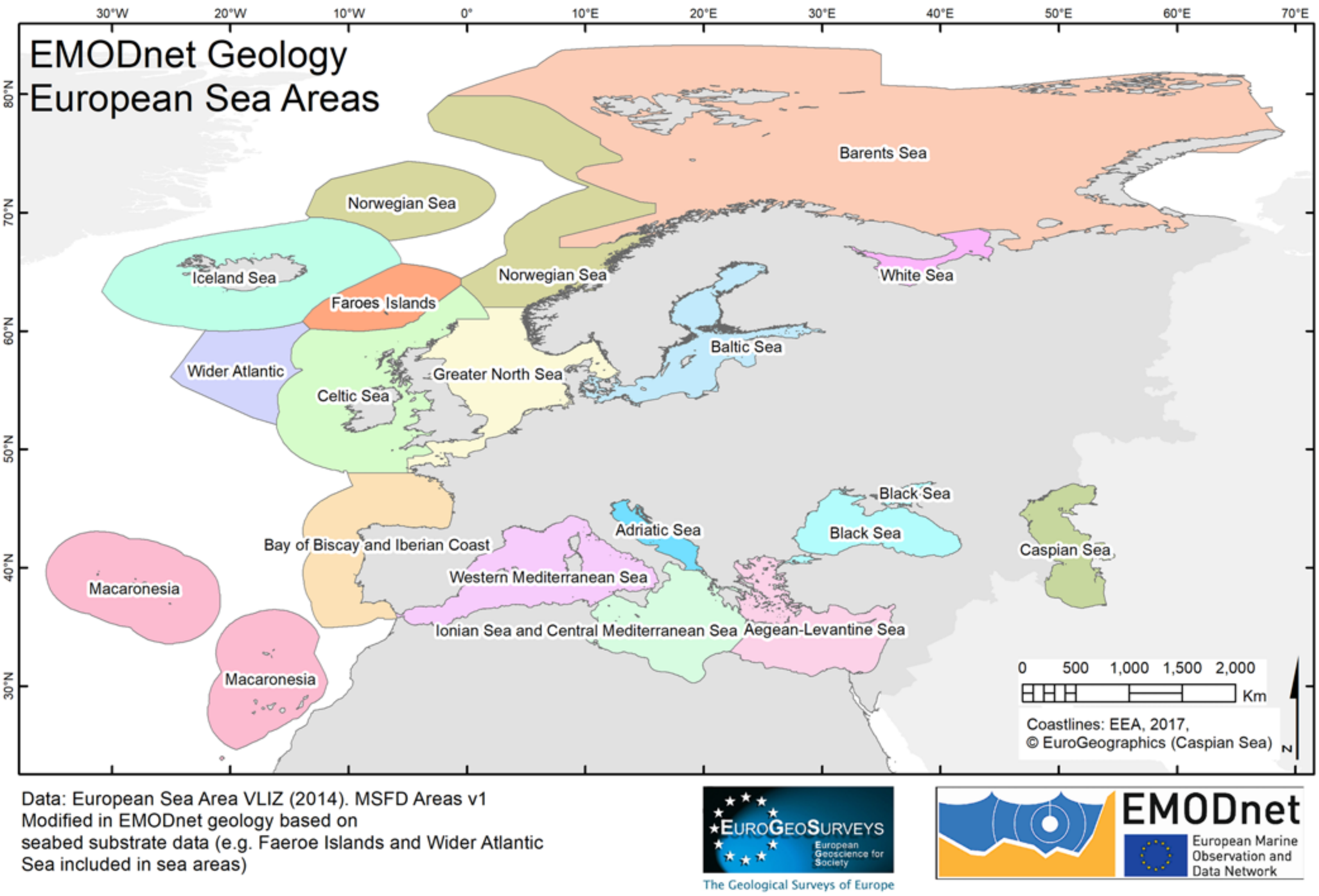

Fig. 1. The regional seas and sub-seas of Europe according to the Marine Strategy Framework Directive. Marine areas around Iceland, Faroe Islands and wider Atlantic Sea are included on the basis of the Exclusive Economic Zone (EEZ) areas and data delivery in the EMODnet Geology, phase 3. The Caspian Sea is also included in the areas of EMODnet Geology during phase 4 of the project (from Vallius *et al.* 2020). Map source: @EuroGeographics

1:100 000 although finer resolution is presented where the underlying data permit. Reaching this point of producing high-resolution maps has been a lengthy process, taking just over ten years. The first two phases of EMODnet Geology (2009–12 and 2013–16) identified relevant data held by the project partners and other national organizations, specifically interpreted geological information. During the first phase all data were harmonized and delivered at 1:1 million scale, improved to 1:250 000 scale during the second phase. The third phase (2017–19) has 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 and further developed during the current, fourth, phase (Vallius *et al.* 2020). All of the information (data and metadata) in the EMODnet Geology portal has bibliographic references associated, so that the original source of information can be accessed. Layers of information allow a free, versatile and quick way of cross-correlating geological objects and processes in vast marine areas and their comparison with onshore geology as is illustrated by Terrinha *et al.* (2020). During the next, fifth, phase of the project work will continue with a common classification process, adopted for all data, fine-tuned with specific focus on hierarchy of terms, linking maps to specific zoom ranges to improve clarity and increase flexibility for end users and stakeholders.

EMODnet Geology data for marine engineering geology

Mapping is central to engineering geology (Griffiths 2002) and the Engineering Group of the Geological Society of London recognizes that effective terrain analysis is of particular value for submarine engineering projects (Griffiths 2017). Seafloor data made available through EMODnet have already proved valuable for mapping the geomorphometry and geodiversity of seabed terrain (Lecours *et al.* 2016; Kaskela and Kotilainen 2017) in addition to providing harmonized geological maps and data (Vallius *et al.* 2020). In his reviews of engineering geology in the UK, Griffiths (2014, 2019) notes that one of the more remarkable remote sensing developments has been in submarine survey, helping to facilitate exploration, geohazard assessment and seabed investigation for offshore structures, drawing attention to the work of Hillier (2011) and Micalleff (2011). Improvements in multibeam swathe bathymetry systems has facilitated, together with geological data, sophisticated and comprehensive applications of terrain evaluation for the development of seabed oil and gas resources, for example in the Caspian Sea (Griffiths 2017). In recognition of a growing need for marine engineering geology, the International Association for Engineering Geology and the Environment has established, in 2012, a Marine Engineering Geology Commission. The Commission has held two international symposia to date, focusing on technological developments, training needs and strategies for developing marine engineering geology (Xiaolei *et al.* 2017, 2020).

The papers presented in this thematic issue contribute to this growing interest in marine engineering geology and arise from the higher resolution data made available during the third phase of EMODnet Geology. They include methodological approaches to harmonizing and representing geological and geohazards information, resultant maps and datasets and their uses, alongside national datasets, in marine spatial planning. The focus of this collection is on the use of EMODnet Geology data for (i) seafloor geology, (ii) coastal behaviour and (iii) geological events and probabilities. Complementary to this thematic issue is the Geological Society of

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London's Special Publication volume 505, *From Continental Shelf to Slope: Mapping the Oceanic Realm*, which presents the latest development of processes to map, harmonize and integrate marine data across Exclusive Economic Zone (EEZ) boundaries (Asch *et al.* 2021).

Seafloor geology

EMODnet geology includes maps and data products on seabed substrates, sedimentation rates, seafloor pre-Quaternary and Quaternary geology and, since the third phase, marine geomorphology. The harmonized datasets are derived from a variety of sources, as detailed in Vallius *et al.* (2020). Whilst a number of countries collect swath acoustic data for hydrographic charting purposes in a systematic way and possess a wealth of legacy datasets, including physical seabed sampling and seabed observations, Ireland is one of a limited number of countries to have initiated and executed large-scale seabed mapping programmes (Diesing *et al.* 2014). Integrated Mapping for the Sustainable Development of Ireland's Marine Resource (INFOMAR; https://www.infomar.ie/), a joint programme between the Geological Survey Ireland and the Marine Institute, provides bathymetry, backscatter, gravity, magnetics and LiDAR data for the Irish EEZ, delivered as accurate maps and data products to end users through a free and open source licensing agreement. These have been used to identify submerged landscapes in the country's coastal and nearshore environment, to characterize their morphological and sedimentary features and dynamics, and to produce a 1:250 000-scale map of Ireland's pre-Quaternary offshore geology (Judge 2015; O'Toole *et al.* 2020). The INFOMAR data are harmonized with other European seafloor datasets and available through EMODnet.

In this collection, Guinan *et al.* (2020) highlight the value of EMODnet Geology data in supporting offshore renewable energy (ORE) development and marine spatial planning in the Irish offshore. The authors describe how national seabed substrate data (INFOMAR data) have been produced and how they have been included into a pan-European seabed substrate dataset (EMODnet Geology). Two case study examples are presented to illustrate how transboundary data can benefit multiple users. Firstly, the importance of key baseline data is considered in the context of offshore wind energy development – not only in the identification of potential sites but also of potential geological constraints, such as sediment mobility and the presence of problematic geological deposits. Geomorphological mapping, combined with data on inferred sediment distribution and mobility, is used to illustrate the importance of a robust evaluation of geological constraints to the development of the Irish Sea ORE resource. The data provided through EMODnet Geology are valuable throughout the development process and include: potential site identification; evaluating geological constraints at sites; preparing Environmental Impact Assessments (EIA); siting cable routes associated with ORE projects and planning targeted surveys for advanced site investigation. Secondly, the authors highlight the importance of transboundary data in marine spatial planning, specifically in managing spatial uses and conflicts in marine areas through Cumulative Effects Assessment (CEA). Underpinning the Irish Sea CEA, EMODnet Geology substrate data are used to generate a habitat sensitivity map. With six different jurisdictions around the Irish Sea (Ireland, Northern Ireland, Scotland, England, Wales and Isle of Man), the EMODnet Geology portal has proved critical in harmonizing data with adjoining sea areas, providing reliable and accurate information about the marine environment and maritime activities. Guinan *et al.*'s (2020) case studies are more broadly applicable as industry interest in the use of marine resources continues to grow, and with it the need to utilize transboundary marine data.

Where such detailed seabed mapping data as those for the Irish Sea are not available, those available through EMODnet are being used to assess the relative merits of various approaches to spatially predicting seabed substrates (e.g. Diesing *et al.* 2014) and to develop harmonized maps of seabed substrate (Kaskela *et al.* 2019). In this collection, Kint *et al.* (2020) address issues around data uncertainties and the need for well-constrained values of geological and geotechnical properties. These have particular value, for example, in engineering projects (such as the design of wind turbine foundations, cable and pipeline infrastructure and radar masts), minimizing geological risk when identifying stable repository sites for dumping of dredged material or identifying viable sand and gravel reserves. Using the Belgian part of the North Sea as a case study, they develop uncertainty components to enable policy makers and other end users to better visualize overall confidence in seabed geological data and identify areas with insufficient coverage in meeting their needs.

Coastal behaviour

Initially EMODnet Geology, coastal behaviour, produced a geographical information system (GIS) layer based on the EUROSION database on coastal erosion, with sedimentation data supplemented and updated by the project partners. Since the third phase, a new approach has been adopted based on remote sensing and comparison of satellite photos over a 10-year period (2007–17) with a spacing of 500 m between the observations. This new approach provides, for the first time, full European coverage via a GIS layer and Web Mapping Service on coastal behaviour (Vallius *et al.* 2020; https://www.emodnet.eu/first-pan-european-shoreline-migration-map-2004). During the current phase, the coastal behaviour project is producing a GIS layer and Web Mapping Service on coastal geological 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 (van Heteren *et al.* 2017; Vallius *et al.* 2020). The next phase will broaden the scope of the coastal work, ensuring compatibility with terrestrial efforts at the sea–land interface. Through collaborations with other relevant EU initiatives and parties, analysing and disseminating data on coasts, EMODnet Geology coastal behaviour work aims to establish seamless data provision between coastal land and sea (the coastal ribbon). Aside from coastal behaviour, information on both the geology (age, lithology) and geomorphology of the coastal ribbon will be collated. This ribbon, extending a few kilometres landward and seaward of the present-day coastline, will be mapped by merging the expertise of land and sea geologists. As EGDI is an infrastructure that already includes marine and terrestrial data products, it will facilitate the creation and testing of such maps.

Although maps and data available through EMODnet Geology and coastal mapping portals are presented at a pan-European level, they enable access to data that may be used to elucidate coastal behaviour at local, regional and national levels. For example, Ryabchuk *et al.* (2020*a*) have used these data to improve understanding of postglacial development and Holocene sedimentation processes in the eastern Gulf of Finland. Combining acoustic-seismic stratigraphy and seabed morphology they produce detailed maps of Quaternary deposits and conduct geomorphological analyses to identify, for the first time, negative bottom relief features associated, at least in part, with near-shore bottom currents. In this collection, Ryabchuk *et al.* (2020*b*) focus their attention on coastal processes of the Russian Baltic in the eastern Gulf of Finland and Kaliningrad area. Combining offshore and onshore monitoring data, they identify a highly dynamic coastline, documenting how it is impacted by extreme hydrodynamic events and anthropogenic processes. The authors link the occurrence of different lithologies with different coastal behaviours, revealing natural and

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anthropogenic driving forces of coastline dynamics and proposing a strategy for coastal management and protection.

Geological events and probabilities

Particular attention has been paid, in recent years, to the occurrence and consequences of subaqueous mass movements. Tectonics, as well as fluid flow and the occurrence of gas hydrates in passive margins, influence the occurrence of subaqueous mass movements. With the development of new types of seafloor data, attention has focused on enhancing scientific understanding of their initiation, triggers and preconditioning, characterization and regional controls, mobility and kinematics as well as detailing their consequences and implications in order to provide advice for their mitigation and inform policy (see, for example, Lintern *et al.* 2019; Georgiopoulou *et al.* 2020). Contributing to this burgeoning area of research, EMODnet Geology 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.

In this collection, Battaglini *et al.* (2020*a*) explain how data have been sourced and harmonized to produce the digital maps of the occurrences of geological events detected in European seas. Elsewhere they also investigate, in more detail for the Italian seas, the correlation and interpretation of these data (Battaglini *et al.* 2020*b*). Terrinha *et al.* (2020) provide a case study example of how these data have been used to highlight mineral occurrences and natural hazards overlaid on geological and morphological maps for the Atlantic margin of Iberia. In this collection, Fiorentino *et al.* (2021) investigate the correlation and interpretation of EMODnet geological events data across different structural units. Gravitational mass movements are found to occur not only where the margin is characterized by a very narrow and steeply sloping continental shelf but also where the presence of fluid emissions, as hydrothermal vents related to volcanism or as gases produced by chemical physical alterations of organic material, enhances the potential for submarine deposits to slide. The susceptibility of the European seabed to landslides is addressed in this collection by Innocenti *et al.* (2020), using the maximum entropy model (MaxEnt). The EMODnet project, with its activities of marine data collection and harmonization, has made it possible for the first time to carry out a susceptibility study on a European scale. In their study the authors use the database of submarine landslides provided by EMODnet Geology together with data derived from bathymetry provided by EMODnet Bathymetry to produce a susceptibility map. The authors acknowledge that, while not replacing the accuracy of local studies based on detailed investigations of individual landslide phenomena, the map provides the first pan-European assessment of submarine landslide susceptibility.

Conclusions

EMODnet provides access to European marine data across seven discipline-based themes: geology, bathymetry, seabed habitats, chemistry, biology, physics and human activities. EMODnet Geology outputs, with maps at a resolution of 1:100 000, are delivered through the European Geological Data Infrastructure (EGDI) portal (www.emodnet-geology.eu/). The papers in this collection present case studies illustrating a range of uses of EMODnet Geology data on seafloor geology, coastal behaviour and geological events and probabilities. These include methodological approaches to harmonizing and representing geological and geohazards information, resultant maps and datasets and their uses, alongside national datasets, in marine spatial planning. With a growing international interest in marine engineering geology, EMODnet Geology makes an important contribution to understanding the engineering geology of the seafloor for a variety of purposes including marine spatial planning, management of marine resources, environmental assessments and forecasting.

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