Appendix 1b: Geology, Substrates & Coastal Processes

A1b.1 Introduction

The present geology and substrates of the UKCS reflect a combination of processes having taken place over millions of years, most recently influenced by glacial reworking and sedimentation during the Pleistocene which is now interacting with Holocene wave and tidal processes. This reworking is very slow for much of the UKCS, but more rapid at shallower depths and in proximity to the shore where wave base interaction and strong tidal currents may enhance the rate of change. The speed and nature of such change is also linked to underlying geology, with softer coasts generally eroding and changing much faster, particularly those comprising poorly consolidated rock or sediments. The deep geological history of the UKCS has led to the maturation of hydrocarbons where conditions are favourable (suitable reservoirs at depth and structural traps), and other sedimentary formations such as saline aquifers provide potential opportunities for gas storage including of carbon dioxide. The following section provides an overview of the UK context including a number of programmes which have enabled a characterisation of geology and substrates at a range of scales, and thereafter provides a discussion of the topic for each Regional Sea.

A1b.2 UK context

The principal sources of information used in this geology and substrates compilation include the BGS offshore regional reports (e.g. Cameron *et al.* 1992, Tappin *et al.* 1994, Gatliff *et al.* 1994, Ritchie *et al.* 2011, Hitchen *et al.* 2013) the JNCC, *Coasts and seas of the United Kingdom*, series, technical reports commissioned to support the previous offshore SEAs, peer-reviewed publications and other relevant "grey" sources of literature.

A1b.2.1 Seabed topography and substrates

The current understanding of the seabed sediments of the UKCS is the culmination of sampling efforts primarily spanning the last 50-60 years. The British Geological Survey (BGS) systematically collected and analysed sediments samples in the 1960s and 1970s across much of the UKCS, and since then a range of industry, academic and conservation agency-led surveys have augmented this dataset. However, to a large extent these datasets have not been integrated with earlier BGS data, and harmonised maps of seabed sediments do not include the full suite of data which has been collected. The BGS data tends to underpin many descriptions of broadscale sediment type[1], including by informing habitat classification maps which, for example, contributed to the selection and designation of several Marine Protected Areas but which are now being updated through further survey effort[2]. Whilst the sediments of

[1] Note that recent updates to broadscale sediment mapping for Europe, which includes the UKCS, includes a range of updates including those collected through the MAREMAP initiative. See: https://www.emodnet-geology.eu/map-viewer/?p=seabed_substrate
[2] e.g. Eggleton *et al.* (2015)

the UKCS are relatively well understood, most data is broadscale in nature and presented at map scales of 1:250,000 with relatively few areas mapped at a smaller scale of 1:50,000 to date (for example in the Forth Approaches). A number of attempts have been made to generate harmonised maps of seabed substrates across European waters (e.g. Mitchell *et al.* 2019), the most notable attempt being that through the European Marine Observation and Data Network (EMODnet, see Kaskela *et al.* 2019). The creation of such a harmonised map of seabed sediments is challenging due to differences in sediment sampling and measurement methods (both spatially and temporally), and a lack of metadata for legacy data detailing the methods used in sample collection and measurement (see Bockelmann *et al*. 2018). Without recourse to raw sample data, properly integrated with other sources of data such as seabed imaging, integrated datasets may rely on reworking already classified data, which could result in the simplification of datasets, and there is a need for such maps to be accompanied by robust confidence assessments to ensure users are aware of their limitations.

The UKSeaMap (Connor *et al.* 2006), UKSeaMap 2010 (McBreen *et al.* 2011), UKSeaMap 2018, and most recently EUSeaMap, are instructive, presenting oceanographic, bedform, substrate and ecological features of UK waters as a series of map layers. UKSeaMap shows the geographical distribution of topographic and bed-form features including subtidal sediment banks, shelf mounds and pinnacles, shelf troughs, submarine canyons, deep water and carbonate mounds; in additional to broadscale features such as continental slope, deep ocean rise, pockmark fields, and iceberg ploughmark zones. These were identified on the basis of bathymetry and derived slope data, and data compiled by BGS (shelf troughs, ploughmarks, and pockmarks), and reviews such as Brooks *et al* (2013) in relation to marine geological conservation sites, have contributed to categorising marine geological features. The compilation of glacial features in Clark *et al.* (2017), has provided a comprehensive map of terrestrial and marine features (BRITICE[3]), many of which are notable seabed features.

Recent improvements in the understanding of the Quaternary of the North Sea have been noted in a special issue of Journal of Quaternary Science, *The Quaternary Geology of the North Sea Basin*, with contributions including those from Lamb *et al*. (2017), Buckley (2017), Westaway (2017), Pedersen & Boldreel (2017), Vaughan-Hirsch and Phillips (2017), Gehrmann *et al.* (2017) White *et al.* (2017), Merritt *et al.* (2017) and Evans *et al.* (2017), and also in Ottesen *et al.* (2018).

The seabed habitat data presented in EUSeaMap (and the latest UKSeaMap which is a derivative map) is relevant in that the habitat definitions relate to seabed substrate and energy, which are controlling factors in the contemporary nature of seabed and coastal form (also see Appendix 1a.2 Benthos for details). While usually considering a range of factors in defining habitats, those points noted above in relation to substrate harmonisation are also relevant here, and decision making based on such broadscale maps should ideally be complemented by contemporary data collection and ground truthing.

A number of bathymetric studies of the UKCS have been carried out since 2003 by the MCA as part of the ongoing Civil Hydrography Programme. Reports are available from the Civil Hydrography Programme Results webpage and bathymetry data is viewable and available for download via the UKHO INSPIRE portal and bathymetry Data Archive Centre (DAC). Survey areas include the Sound of Harris, South West Approaches, Western Solent, the Dover Strait, and the Thames Estuary, and repeat surveys are undertaken in areas of mobile seabed with changes in bathymetry reflected on new charts. The Maritime Environment Mapping

[3] https://shefuni.maps.arcgis.com/apps/webappviewer/index.html?id=fd78b03a74bb477c906c5d4e0ba9abaf

Programme (MAREMAP) was launched in 2010 and is jointly led by the BGS, the National Oceanography Centre (NOC) and the Scottish Association for Marine Science (SAMS) with partners from the University of Southampton, Channel Coastal Observatory, the University of Plymouth, the MCA, the Centre for Environment, Fisheries & Aquaculture Science (CEFAS) and Marine Scotland. MAREMAP uses recent advances in mapping technology to conduct research on themes ranging from coastal, shelf and deep water geology and habitat models, submarine hazards, 4D monitoring and modelling, technology and heritage. Outputs from the programme are available via the MAREMAP website and have contributed to peer-reviewed publications, and are now being integrated into wider work such as that of EMODnet (above). The MESH INTERREG programme conducted more than 40 surveys in UK waters with the principal aim of mapping seabed habitats. Associated bathymetric and geological reports are available in document and online GIS format via the MESH website. In Northern Irish waters, the Joint Irish Bathymetric Survey (JIBS) has resulted in a high resolution bathymetric map for inshore waters. The work resulted from a partnership between the MCA and the Marine Institute (MI), funded through the INTERREG IIIA Programme. Additional, more localised work has been undertaken through the Ireland, Northern Ireland and Scotland Hydrographic Survey (INIS Hydro) to generate high-resolution bathymetric charts of 1,400km^2 of key seabed areas.

Surveys undertaken in relation to the aggregates industry under the Marine Aggregate Levy Sustainability Fund (ALSF), include a series of Regional Environment Characterisations (RECs) covering parts of the East Coast (Limpenny *et al.* 2011), Humber (Tappin *et al.* 2011), Outer Thames (Emu Ltd & University of Southampton 2009), Eastern English Channel (James *et al.* 2007), South Coast (James *et al*. 2010) and Outer Bristol Channel. The RECs employed a series of geophysical and environmental survey methods, placing new information within a wider context and understanding of the areas being studied.

Despite a significant history of seabed mapping (including those initiatives above and other sources such as OLEX data) and deep geological seismic survey of the UKCS, gaps still exist in the UKCS coverage, particularly of multibeam data for which only 30-40% of the UKCS has coverage. Additionally, a comprehensive high resolution integrated bathymetric dataset of all available data is not yet available and there remains a lack of coordination (for example in the re-use of data from commercial programmes) which means that studies are not necessarily contributing to a single national dataset, despite initiatives to make data at least discoverable (e.g. via the MEDIN initiative). A European scale bathymetric dataset is available through EMODnet[4], now in a fourth development phase with the aim of developing a ¼ arc minute resolution DTM, with data gaps to be filled by satellite derived bathymetry and extended coverage for coastal zones. The current EMODnet data has a 1/16 arc minute resolution.

Commercial programmes also collect data which may be of wider use, but the lack of coordination in efforts in this area means that separate studies are not always contributing to a single national dataset. Initiatives such as MEDIN and The Crown Estate's Marine Data Exchange make available data for individual developments or survey programmes, or provide metadata such that the type and availability of data is made more widely available, and where available, these are also ingested by EMODnet.

Hard substrates which are resistant to reworking are of both conservation and operational interest as they form areas of stable seabed for biota and may present challenges for seabed

[4] See the EMODnet harmonised Digital Terrain Model (DTM) for European Seas (http://www.emodnet-bathymetry.eu/), and the larger Nippon Foundation-GEBCO Seabed 2030 project to map the world's oceans at high resolution (https://seabed2030.gebco.net/).

developments. The three main types of hard substrate occurring at or near seabed comprise unconsolidated gravel spreads and hard cohesive sediments which were formed during the glaciations (“non-rock” hard substrates), and rock outcrops. All three commonly occur together in the nearshore western margins of the North Sea. The distribution patterns of rock, gravel spreads and the hard cohesive gravelly Quaternary sediments are quite well known and have been mapped by regional surveys and also reviewed in Gafeira *et al.* (2011). Seabed substrates, amongst other data, have been used to characterise and predict potential habitat (see McBreen *et al.* 2011, and also Appendix 1a.2), or for specific habitats of interest such as reef (Gafeira *et al.* 2010, Diesing *et al.* 2015, Downie *et al.* 2016, Brown *et al.* 2017, JNCC 2019; see Figure A1b.3) and sandbanks[5] (JNCC 2014, JNCC 2020) that have been used to inform conservation site selection. In addition to bedrock, the presence of boulders/cobbles has been interpreted and mapped, which together are available as the BGS Hard Substate map which includes an indication of confidence in the underlying data.

JNCC have mapped wider sandbank areas on the UKCS potentially qualifying as Annex I habitat[6] based on the depth and slope of sandy sediments, and continue to update this map as new information becomes available from offshore seabed survey work. Confidence data accompanies these mapped data to assist in its interpretation, as in some areas data resolution and/or ground truthing are poor.

A1b.2.2 Coastal geomorphology and processes

The UK coastline has been described comprehensively in a series of JNCC reports (e.g. Barne *et al.* 1995a-d, 1996a-d, 1997a-f, 1998a-b), with notable geological and geomorphological features being further described in SSSI citations or as part of the Geological Conservation Review (GCR). McBreen *et al.* (2011) identified a number of coastal physiographic features, modified from the original UKSeaMap project (Connor *et al.* 2006) to account for a larger number of features (e.g. sub-types of sea loch) and to add relevant features to Northern Ireland – the dataset was largely derived from manual digitisation. The features described include bays, sounds or straits, barrier beaches, embayments, sea lochs, rias, estuaries and lagoons. A number of these features have the potential to qualify for designation as indicated above (e.g. as SACs). The coast is monitored through a series of regional monitoring programmes, developed from recommendations from the first set of Shoreline Management Plans (SMPs). In Scotland, Local Coastal Partnerships and Marine Scotland have management and monitoring roles for the coast and Northern Ireland has an equivalent Coastal Monitoring Programme. Wales established the Wales Coastal Monitoring Centre in 2011 to deliver regional and national coastal monitoring and to help inform the Flood and Coastal Erosion Risk Management programme.

Sediment transport and suspended sediment concentrations for the UKCS or regions of the UKCS have been described both in the above JNCC Coasts & Seas of the UK series, in addition to being covered by former offshore energy SEA technical reports (e.g. Holmes *et al.* 2004, Kenyon & Cooper 2005, Holmes *et al.* 2006), Regional Environmental Characterisations, and dedicated studies such as the Southern North Sea Sediment Transport Study (HR Wallingford 2002) and Dolphin *et al.* (2011) – see Figure A1b.1 and Figure A1b.2.

[5] Note that predicted seabed habitat types or substrates typically have accompanying maps showing data confidence, which is an important factor to consider when interpreting these data, some of which are based on limited direct measurements.
[6] Note this is intended as a guide only and actual extent of sandbanks is likely to lie between the “area” (sands <20m) and “range” (between 20m and 60m depth and adjoining an area of shallower (<20m) sands) estimates.

A1b.2.3 Economic geology

The geological and geomorphological history of the UKCS has led to commercial resources being present at the seabed and in shallow geology (e.g. associated with aggregate extraction) or at depth (e.g. hydrocarbon prospectivity and potential storage structures for natural gas and carbon dioxide), in addition to presenting various topographic and sedimentary constraints, for instance in relation to wind farm installation. The location and importance of these industries is discussed in Appendix 1h; the influence of geology and geomorphology on their location is discussed in this section.

Below surficial sediments and at depth, the underlying hard geology of the North Sea, eastern Irish Sea, Faroe-Shetland Basin and to some extent the English Channel, has given rise to hydrocarbon prospectivity ranging from reserves of primarily oil and condensate in the central and northern North Sea and Faroe-Shetland Basin to gas in the southern North Sea and eastern Irish Sea. Many of the North Sea and Irish Sea fields are at a mature stage of development, and so the location and prospectivity of hydrocarbon reserves in these locations are relatively well-known, though some areas are comparatively underexplored, such as the mid-North Sea High and to the west of the Hebrides. To the north and west of Shetland, exploration effort has been small relative to the North Sea, though discoveries have culminated in the development of the Clair, Schiehallion/Loyal, Foinaven, Solan, Edradour, Glenlivet and Laggan/Tormore fields. The area of the Faroe-Shetland Channel has been relatively underexplored and exploration in other areas, such as the Celtic Sea, Bristol Channel and Western Approaches, has failed to find working hydrocarbon systems containing any commercial accumulations.

In addition to hydrocarbon prospectivity, the potential storage formations for carbon dioxide have also been studied on the UKCS (e.g. Holloway *et al.* 2006, Smith *et al.* 2010, Noy *et al.* 2012) and a database, CO_2 Stored, has been produced of over 500 potential UK storage sites (Bentham *et al.* 2014), comprising a combination of depleted or producing hydrocarbon fields and saline aquifers. Similarly, and more recently, there has been interest this capacity in relation to hydrogen storage (Scafidi *et al.* 2021).

A1b.2.4 Geological conservation

In the marine environment, many geological features are gaining protection through designations for which they are a qualifying habitat feature (e.g. SACs designated under the *Conservation of Habitats and Species Regulations 2017*). The *Marine and Coastal Access Act 2009*, *Marine (Scotland) Act 2010* and *Marine Act (Northern Ireland) 2013* provide a means for the conservation of specific “features of geological and geomorphological interest” through the designation of MCZs or MPAs. Brooks *et al.* (2013) identified 35 key geodiversity areas in Scottish waters using methods similar to those used for the Geological Conservation Review (GCR), and a number of sites in Scottish and English waters have now been designated in part or whole for this reason. Further information on the basis for these designations and tabulations and maps of relevant sites are provided in Appendix 2 and Appendix 1j respectively.

A1b.2.5 Blue carbon

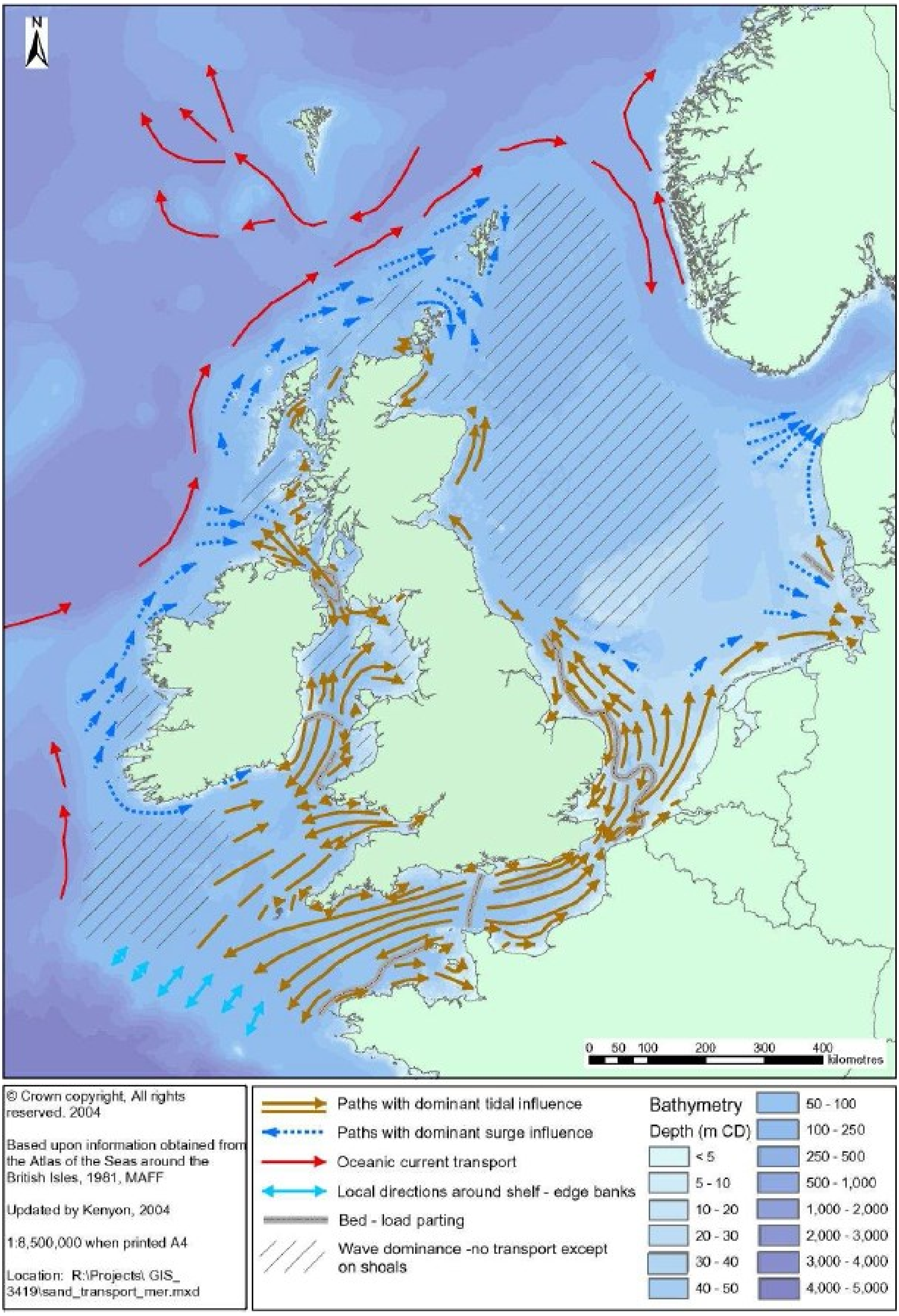
The coastal and shelf seas of the UK contain quantities of organic and inorganic carbon which, analogous to terrestrial environments including peatland, represent a carbon store, some of which was deposited throughout the Holocene period, and continue to sequester and be sinks for carbon. Studies of the role that marine intertidal environments such as seagrass meadows and saltmarsh (see Duarte *et al.* 2013, Macreadie *et al.* 2014) play in the sequestration and storage of “blue carbon”, have expanded to include the role of shelf sediments (i.e. to ~200m depth, see below) and less-well studied areas such as fjords (see Smeaton *et al.* 2017, Smeaton & Austin 2019, Luisetti *et al*. 2019, Smeaton *et al*. 2020). Blue carbon is a topic of active research as the major gaps in understanding of sources, processing, turnover, sequestration and influence of human activities have become evident (see e.g. Smeaton *et al*. 2021, Diesing *et al*. 2021, Luisetti *et al*. 2020), along with its potential role in climate change mitigation.

While there is no global estimate of blue carbon stocks in shelf sediments, the estimated stock within northwest European shelf seas has a relatively high range of between 8 and 22 billion tonnes, with between 12 and 30% being in the water column, and much of the remainder contained in inorganic material in surficial sediments (Kröger *et al.* 2018). For example, Diesing *et al.* (2017) estimated that only 250Mt of organic carbon is stored in north west European shelf sea sediments. Smeaton *et al.* (2020) estimated the quantity of blue carbon contained in Scottish waters to be 1,515 +/- 252Mt, with the majority (1,294 +/- 161Mt) being inorganic in the form of $CaCO_3$. Similarly, in an estimate of blue carbon stocks in Orkney waters, Porter *et al.* (2020) found a similar ratio of organic (8.17Mt in organic stocks and carbon) to inorganic (59.1Mt) carbon. The data used to make these estimates included the UKCS sediment classifications of BGS and EMODnet (see A1b.2.1 above), and only considered the top 10cm in the calculations. While this may provide a relative indication of the potential carbon stock of such sediments, the authors acknowledge that Quaternary (including Holocene) sediment thickness varies greatly, and the actual carbon stock is therefore likely to be significantly larger.

In addition to seagrass meadows and saltmarsh acting as blue carbon stores, there is also the potential for significant contributions to carbon sequestration by macroalgae and plankton (Kraus-Jensen *et al.* 2016, Raven 2018), however, these are challenging to locally attribute to any particular “store”, resulting in a limited potential for management or to account for carbon sequestration (Lovelock & Duarte 2019). There is a question over whether macroalgae should be defined as blue carbon, but this largely relates to the ability to spatially account for their contribution to sequestration and storage rather than a question over whether they perform such functions (e.g. see Krause-Jensen *et al.* 2018, Macreadie *et al.* 2019); for context to the contribution of macroalgae to blue carbon (see Queirós *et al.* 2019). Considerable uncertainty remains in understanding the carbon fluxes from the majority of these environments, and in the context of climate change, this includes the role such environments also play in the flux of other greenhouse gas species including CH_4 and N_2O, which may have a significant role in the contribution to net radiative forcing (e.g. Kröger *et al.* 2017), though these systems still tend to have a net GHG benefit. Significant gaps in understanding need to be filled to properly account for the scale of carbon stocks and the potential sequestration rates across different coastal and marine habitats (Krause-Jensen *et al.* 2018, Lovelock & Duarte 2019, also see the review in Gregg *et al*. 2021).

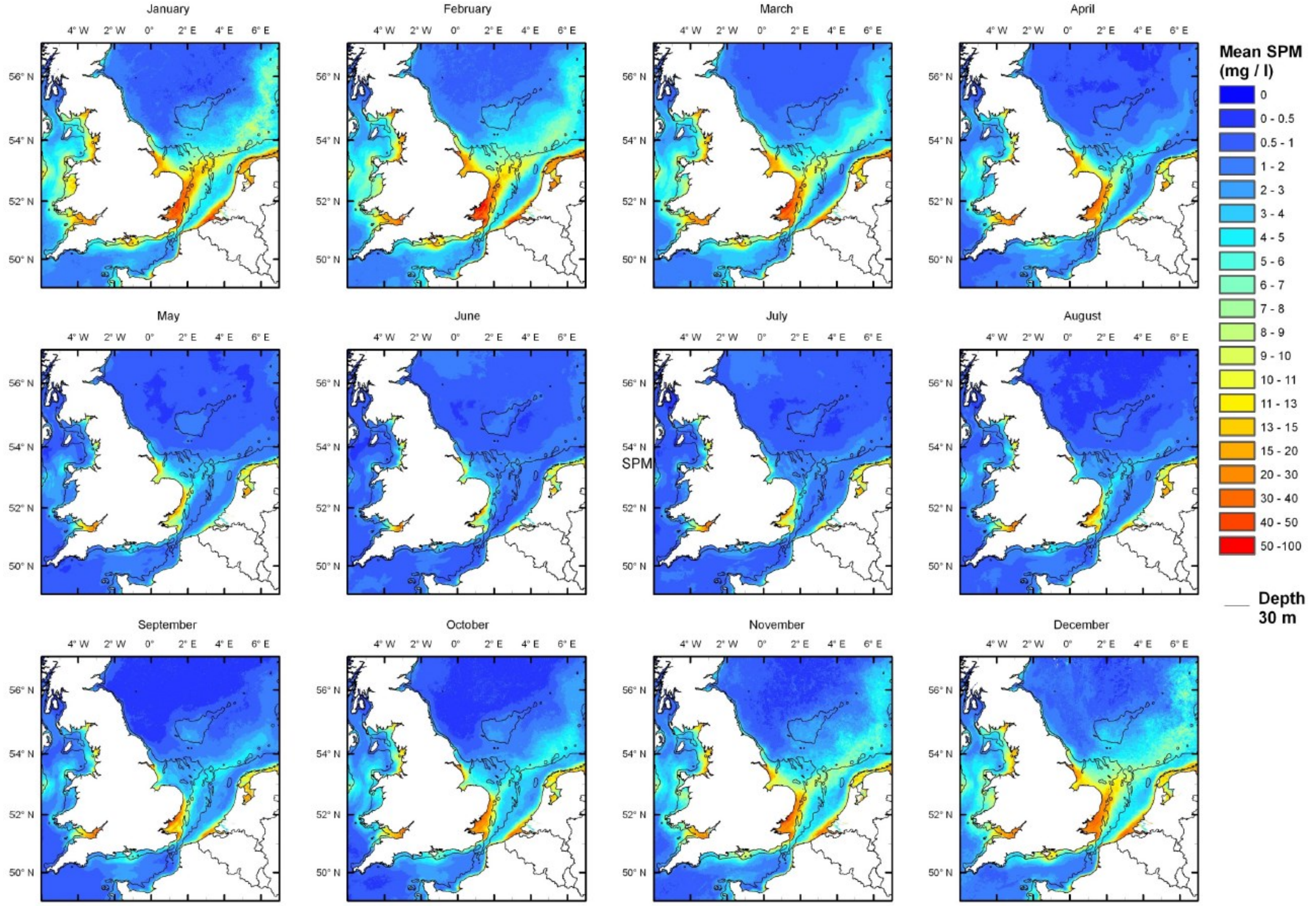
There is significant interest in understanding the capacity of coastal, intertidal and marine carbon stores and the mechanisms for long-term carbon sequestration in these environments, in view of the contribution that they make, and could continue to make, in limiting the effects of anthropogenically induced climate change. In order to fully understand this, impacts of well understood perturbations from climate change (e.g. sea surface temperature and acidity, see Raven 2018, Macreadie *et al.* 2019) will have on this aspect of the global carbon cycle (see Appendix A1.f and sections A1.b.15 and Ab1.16 of this Appendix) are also required. Also of interest is the role that human activities play in the disturbance and resuspension of shelf sediments which can result in carbon remineralisation, some of which will result in net carbon losses to the atmosphere (e.g. see van de Velde *et al.* 2018). In this context, such areas would need appropriate management to maintain their integrity and that of the carbon they store (e.g. see Oreska *et al.* 2020, Luisetti *et al*. 2020), and their continued contribution to carbon sequestration (e.g. considering the loss of saltmarsh through coastal squeeze, and noting that managed realignment or compensatory schemes may not be as effective stores, e.g. Burden *et al.* 2019, 2013, Lawrence *et al.* 2018, Moreno-Mateos *et al.* 2012). There is also interest in accounting for these carbon stores, and the carbon flux associated with them, so that this can be properly accounted for in carbon inventories (e.g. IPCC 2013 and see Oreska *et al.* 2020). However, information gaps remain which will hinder the comprehensive accounting of the flux of carbon from marine sediments, including from losses resulting from anthropogenic activities. Similarly, the effects that the activities covered by the draft plan assessed in OESEA4 may have on sedimentary blue carbon storage, and their significance relative to natural physical and biological processes remain important evidence gaps.

Figure A1b.1: Major sand transport paths around the British Isles



Source: Kenyon & Cooper (2005)

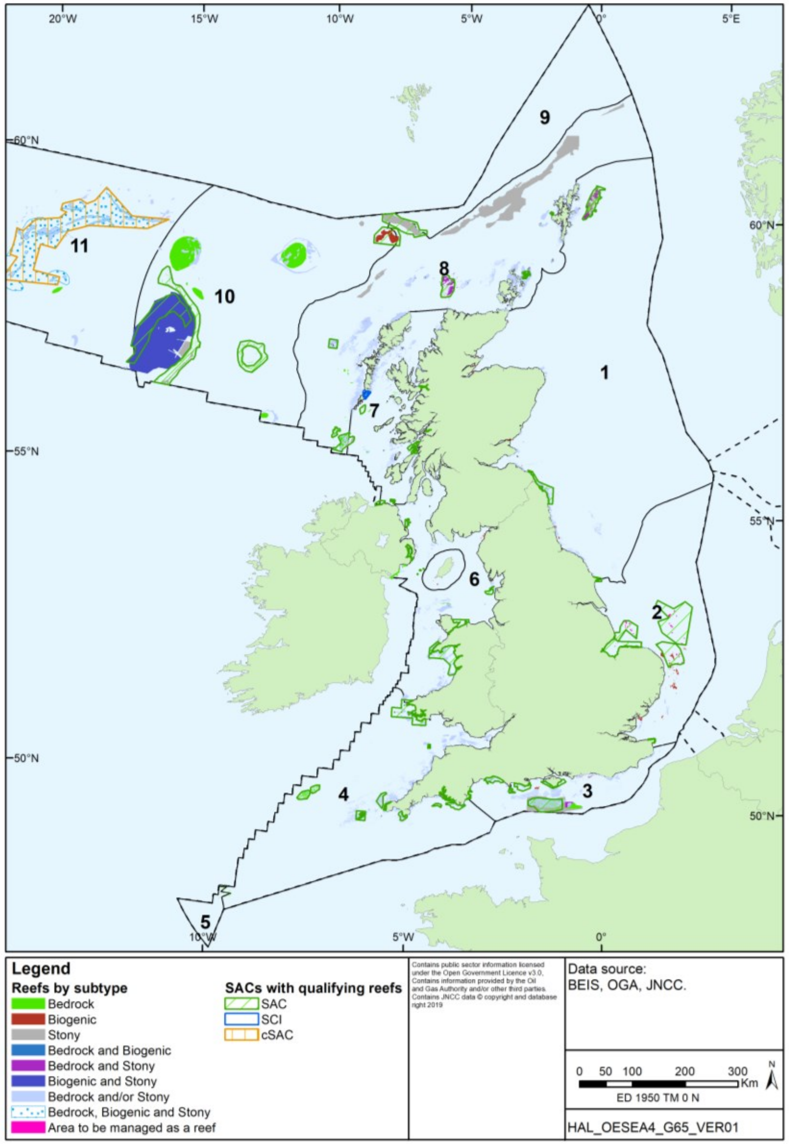
Figure A1b.2: Climatological mean of Suspended Particulate Matter derived from MODIS satellite images, 07/02 - 05/10



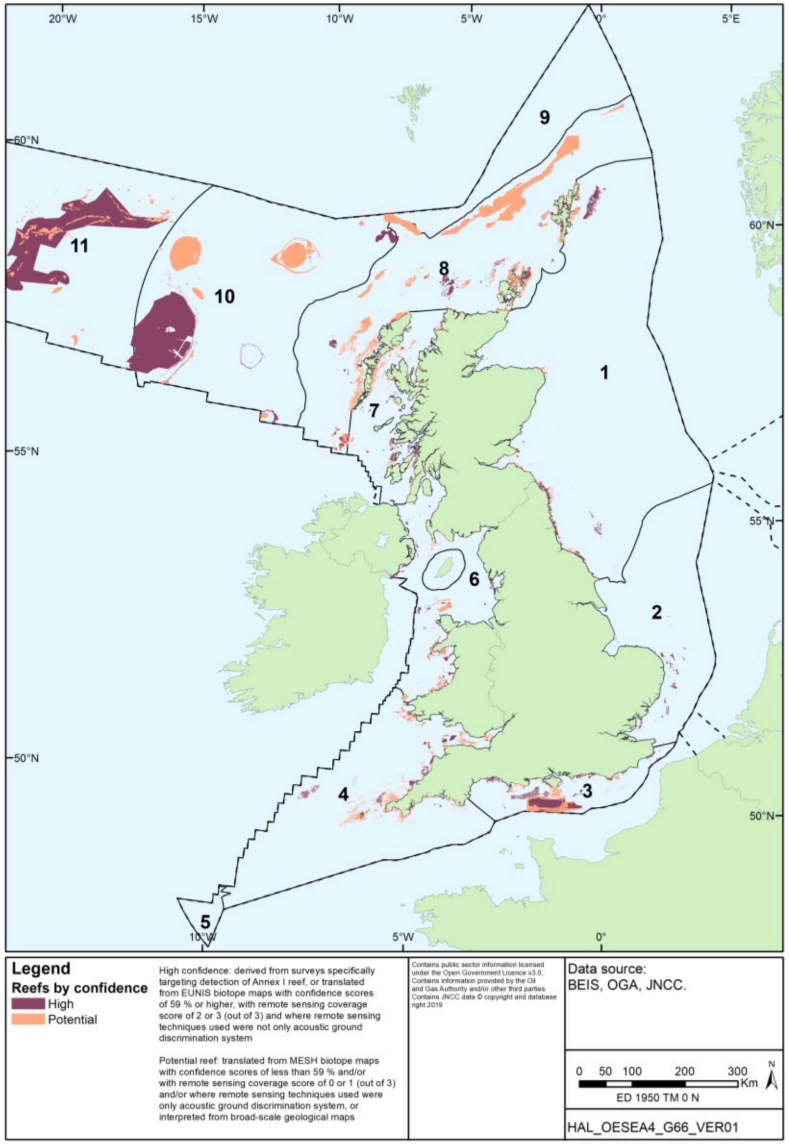
Source: Dolphin *et al.* (2011)

Figure A1b.3: Interpreted hard ground and reef on the UKCS

a: Interpreted reef type (Annex I) and related SAC sites



b: confidence in assessment of reef



A1b.3 Features of Regional Sea 1

The bulk of modern seabed sediments are more than 10,000 years old and have been reworked from strata by currents generated by tides and waves throughout the Holocene. The reworked sediments typically form large areas of seabed sand and gravel, and also form large-scale sandbanks and ridges and smaller sand waves.

A1b.3.1 Seabed substrates

Three main types of natural hard substrate occurring at or near the seabed in Regional Sea 1 comprise unconsolidated gravel spreads, hard cohesive sediments which were formed during glaciations, and rock outcrops. All three commonly occur together in the nearshore western margins of the North Sea. The distribution patterns of rock, gravel spreads and the hard cohesive gravelly Quaternary sediments are relatively well known, have been recorded by regional surveys and mapped more widely for the UKCS (e.g. Gafeira *et al.* 2010, see Figure A1b.4).

Large cobbles and boulders are numerous on the UKCS and widely recorded on sidescan sonar either as boulder fields or more isolated contacts, and in many cases may be glacial dropstones. Outcrops of bedrock are largely restricted to the near coast, revealed mainly along the Scottish coast in the Pentland Firth, Fraserburgh area, around Brora and Helmsdale in the Moray Firth, and in the outer Firth of Forth. Gravel spreads mostly occur in the nearshore area from Shetland in the north to Flamborough Head in the south, interrupted by a dominance of sand to sandy mud in the Moray Firth and along much of the coast from north of Aberdeen to just south of Hartlepool.

Granular to pebble size classes of gravel are probably mobile during peak tidal currents and storm waves but are virtually static in areas below wave-base (Pantin 1991). In the Moray Firth, there is a large area (greater than $100km^2$) of gravel off the mouth of the River Spey at Lossiemouth which fines eastwards; smaller patches are also present along the northwest coast of the Firth (Andrews *et al.* 1990).

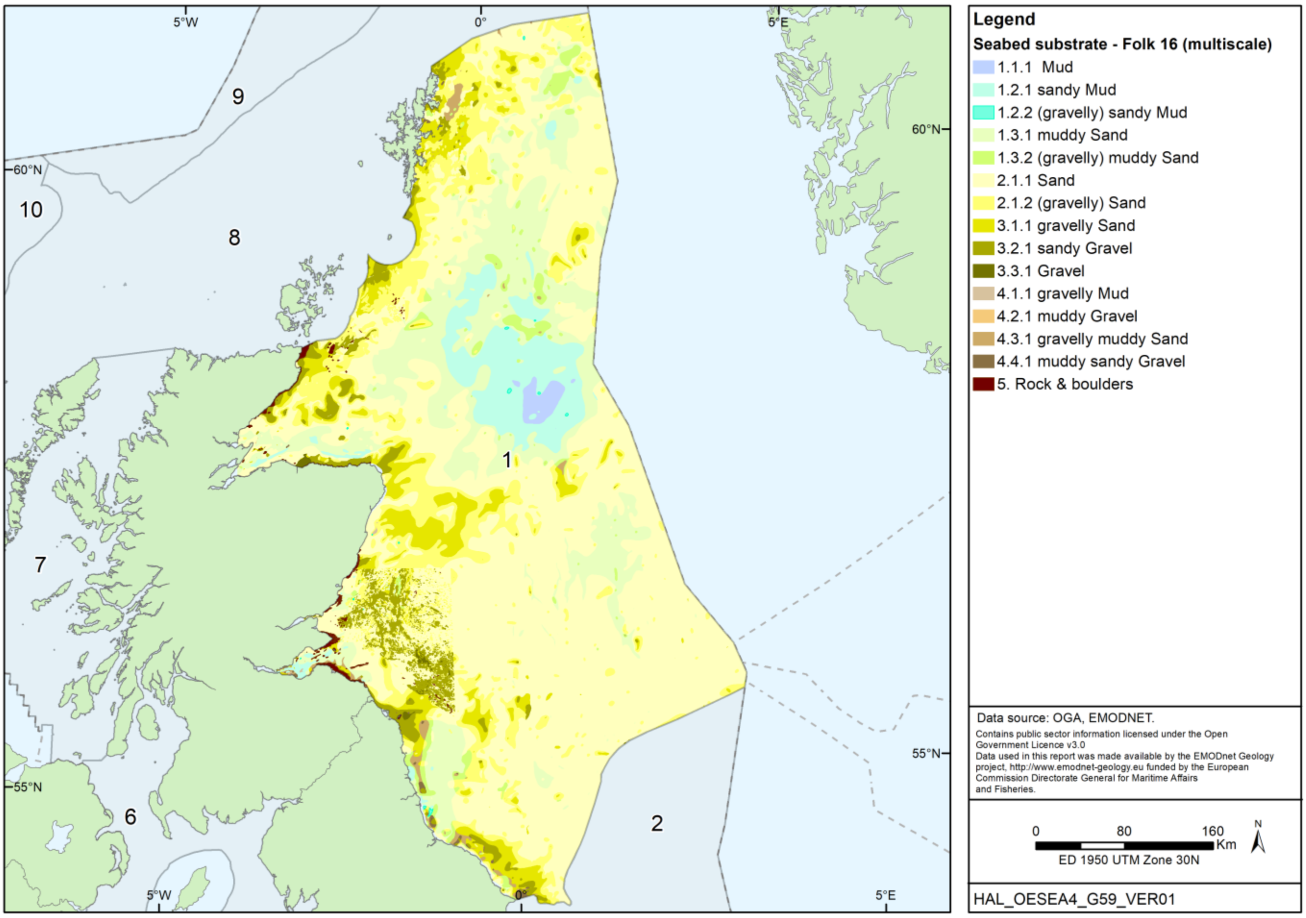
Gravelly sand and sandy gravel occur extensively to the north of Shetland, on the Orkney-Shetland Platform, and on upstanding areas to the east of Shetland; isolated patches are found on Bressay Bank and Halibut Bank. A 2003 DTI survey found sediments around Fair Isle comprised typically coarse to very coarse calcareous sand and gravel with a mean gravel content of approximately 40%. The gravel content of sediments collected from the Sandy Riddle (Figure A1b.6, Figure A1b.5) commonly exceed 50%, and comprise broken as well as whole shells (Black 2004). Sandy gravel also occurs on Smith Bank where the gravel is predominantly biogenic. A tongue of well sorted sandy gravel extends northeast from Rattray Head and further south, gravelly sediments are restricted mainly to offshore banks, notably the Marr and Aberdeen Banks (Gatliff *et al*. 1994).

Sand and slightly gravelly sand covers much of the bed of the central to northern North Sea and occurs within a wide range of water depths from the shallow coastal zone to 110m in the north and to below 120m in isolated deeps in the south and west (Andrews *et al.* 1990). Sand deposits in the northern North Sea exhibit significant regional variations in grain size, sorting and carbonate content. These reflect the spectrum of environments, from relatively high energy around Orkney and Shetland where there are sources of carbonate material to low energy further offshore where there is relatively little sediment input. To the east of Shetland, a sand zone 40-60km wide occurs in water depths ranging from 100m to over 120m. The sand is mainly fine grained and well sorted, becoming moderately sorted northwards (Johnson *et al.* 1993). A broad, irregular swath of sand extends from 50km east of Fair Isle to 50km east of Peterhead. Further south in the Moray Firth, the sand has a much lower carbonate content (<20%) and is moderately well sorted.

Fine-grained sediments are found in the outer Moray Firth and estuarine areas including the Forth, but the primary distribution of muds in Regional Sea 1 is within the Fladen and Witch Grounds. These sediments are typical of water depths greater than 120m and may therefore occur in other isolated deeps (e.g. the Southern Trench) closer to shore (Andrews *et al.* 1990). The Fladen Ground was surveyed as part of SEA 2 (2002), and was resurveyed as part of the OESEA3 programme (2015).

In addition to seabed sediments, sediments in suspension in UK waters have been measured using remote sensing or modelled for parts of Regional Sea 1 (Dolphin *et al.* 2011, Eggleton *et al.* 2011) and display generally low concentrations (<5mg/l) throughout the year with the exception of coastal areas where wave interaction with sediments occurs as waters shallow, though the absence of substantial sediment plumes from coastal erosion or estuarine areas (see Regional Sea 2) means that even coastal waters have a generally low suspended sediment concentration (Figure A1b.2).

Figure A1b.4: Seabed substrates in Regional Sea 1



A1b.3.2 Glacigenic bedforms

A number of features (Figure A1b.5) including moraines are present to the north and east of the UK which evidence past glacial activity, and have been used to construct scenarios of the pattern and timing of the retreat of the last British-Irish Ice Sheet (e.g. Clark *et al.* 2012, also see Hughes *et al.* 2016) which, along with recent core and dating evidence (Bradwell *et al.* 2019) has extended or improved the understanding of the nature, extent and timing of the ice sheet during the last glacial maximum, its variation and demise. Regional Sea 1 includes a number of tunnel valleys which were formed subglacially by the flow of pressurised water, for example as represented in the Fladen Deeps, the Devil's Hole to the south, with the Southern Trench off the north east coast potentially, in part, influenced by such a process, along with catastrophic meltwater flooding (Brookes *et al.* 2013). These large scale features are up to 150m deep, 4km wide and 40km long, are ubiquitous off Scotland's east coast (Lonergan *et al.* 2006, Stewart *et al.* 2013, Gordon *et al.* 2013, Huuse & Kistensen 2016, Ottesen *et al.* 2020) and hold potentially valuable information in reconstructing the past extent and geometry of the British-Irish Ice Sheet (Brooks *et al.* 2013).

Regional Sea 1 includes a large number of offshore moraine complexes (e.g. see Bradwell *et al.* 2008), with Bosies Bank and Wee Bankie, being notable large moraine features, which have contributed to the debate on the extent of Late Devensian ice in the North Sea (Brooks *et al.* 2013). The banks are located approximately in the Outer Moray Firth and off the east coast of Scotland between Aberdeen in the north and Outer Firth of Forth in the south respectively, in water depths of 100m and 50m, and comprise a series of submarine ridges. The banks were originally interpreted to represent the limits of the British-Irish Ice Sheet, however, more recent evidence in the form of till and tunnel valleys to the east of these features suggests they were formed during a stillstand, during ice retreat or re-advance during the late Dimlington stadial (Graham *et al.* 2009, Brooks *et al.* 2013).

Mega-scale glacial lineations indicative of glacial ice-streaming and drumlins suggesting fast-flowing and persistent ice-sheet configurations are preserved on the sea floor offshore eastern Scotland and north-eastern England (Stewart & Cooper 2015, Stewart *et al.* 2015). Partially infilled iceberg ploughmarks occur in the northernmost area of Regional Sea 1 (but are more characteristic of Regional Sea 8) and were generated by grounding of floating ice on the edge of the continental shelf during the late Pleistocene (Belderson *et al*. 1973, Johnson *et al.* 1993). Their morphology ranges from straight to sinuous and overlapping, spreading for hundreds of metres with a width of c. 20m and depth of c. 2m, flanked by ridges of gravelly material – see Section A1b.9 for more information.

A1b.3.3 Pockmarks

In the central and northern North Sea spreads of soft muds are locally characterised by small depressions or 'pockmarks', most of which appear to have been formed at times of fluid/gas escape resulting in fine sediment being vented into suspension which is then redeposited away from the site of emission. The largest areas and densities of pockmarks occur in the Witch Ground Basin, an area of thick fine grained sediments deposited in the Weichselian late-glacial period (Gafeira & Long 2015a, b). In some cases, where these are associated with modern fluid/gas escape, they may contain distinctive biota of conservation interest. Pockmarks often support a diverse fauna which includes anemones and squat lobsters, fish using the feature for shelter and chemosynthetic species, which feed on methane and hydrogen sulphide. A survey programme carried out for SEA 2 in 2001 collected extensive data on pockmarks in the central and northern North Sea including multibeam bathymetry, photography and seabed sampling (Judd 2001).

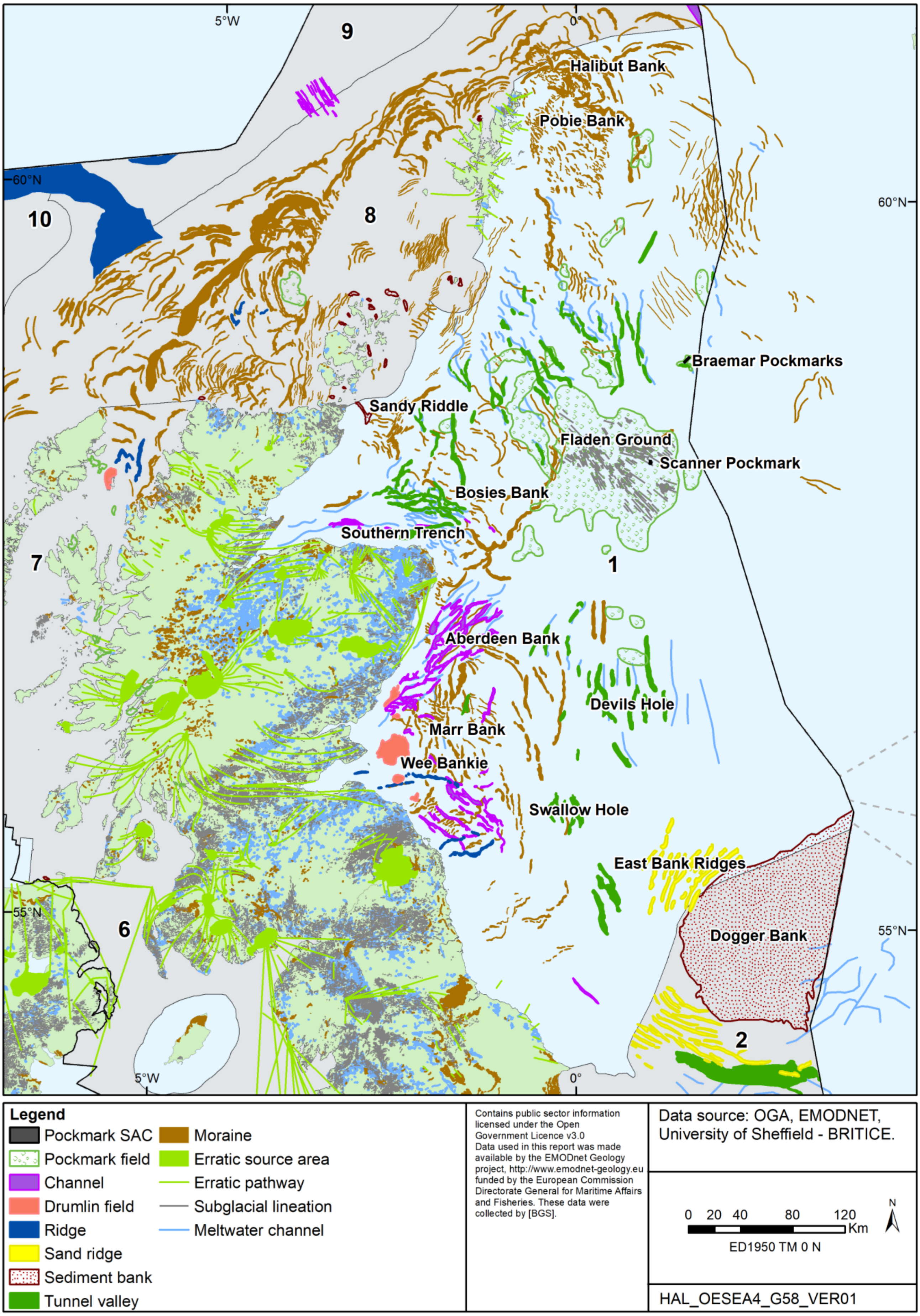
Within individual areas the pockmark size, density and distribution pattern are not uniform. In the Witch Ground Formation, such variation is caused by the coarseness of the sediments, which fine towards the deeper, central part of the basin. Long (1986) reported that the highest densities (>30/km^2) occur where the seabed sediments are sandy muds, whilst in the pure muds in the centre of the Basin densities are 10-15/km^2. Towards the edges of the Basin, where the Witch Ground Formation sediments are coarser and thinner, pockmarks decrease in size until they are too small to identify acoustically (Judd 2001).

Pockmarks have the potential to qualify as Special Areas of Conservation (SAC) where they contain the habitat, *submarine structures made by leaking gases.* In the northern North Sea, two examples of this habitat; the Scanner pockmark in Block 15/25 (comprising the Scanner and Scotia pockmark complexes) and a series of pockmarks near the Braemar oil field (Block 16/03) have been designated as SACs (see Appendix 1j). A survey of the Scanner Pockmark SAC in 2012 identified 67 pockmarks, 61 of which were located within the site boundaries, with an area of seabed 468,000m^2 disrupted by gas escape features, equal to 14% of the area of the SAC (Gafeira & Long 2015a). Most of these were small with a depth generally ranging between 1-2m, consistent with other parts of the Witch Ground, though 17 were of medium size and greater than 2m in depth. Four very large pockmarks (depth >12m) make up the two designated pockmark complexes within the SAC, Scanner and Scotia. These have a U- or W-shaped cross section, associated with the presence of the Coal Pit formation below the Witch Ground formation, unlike the V-shaped profile of smaller pockmarks. A comparison of repeat surveys between SEA2 (2001) and 2012 indicates only one pockmark showing deepening which may be related to gas escape, with a higher number showing infill possibly related to sidewall collapse, which may have covered MDAC or bacterial mats (Gafeira & Long 2015a). Further survey of the site (Rance *et al.* 2017) indicates some of the pockmarks have been infilled due to slope failure, interrupting gas migration and obscuring characteristic features including MDAC or bacterial mats. The cause of this slope failure is not known but may be a combination of natural and anthropogenic factors (JNCC 2018a).

A similar study of the Braemar pockmarks SAC was undertaken by Gafeira & Long (2015b), who reported 49 pockmarks, 27 of which were within the existing site boundaries, with the remainder, apart from 1, within 1km of the boundaries. Comparable to the study of the Scanner pockmark complex and wider Witch Ground pockmarks, most were small and relatively shallow (1-3m), with a single pockmark being significantly larger than the others, there were however differences in plan and cross-sectional geometry, the pockmarks being less regular and often having W-shaped profiles. The profiles may be explained by more than one gas escape location and sidewall failure (Gafeira & Long 2015b). Six pockmarks contain verified records of the Annex I habitat, with a further 14 showing strong acoustic reflectance which is indicative of hard carbonate structures typical of the habitat type (Gafeira & Long 2015b, JNCC 2018b).

Johnston *et al.* (2002) identified potential areas to the east of Shetland which, based on BGS seabed sediment maps, may contain the Annex I habitat, *submarine structures made by leaking gases*. JNCC have produced maps of potential offshore Annex I habitat including “fluid seep areas”, which correspond the Witch and Fladen Ground areas, and some areas to the east of Shetland. This does not confer any designation but does provide areas which further survey could lead to confirmation that the habitat is present.

Figure A1b.5: Seabed features in Regional Sea 1 referred to in the text



A1b.3.4 Sandbanks and sandwaves

Sandbanks are located throughout the inshore and shallow areas of Regional Sea 1. Sandwaves are smaller features, more widely distributed throughout the central North Sea, and unlike sandbanks these are flow-transverse bedforms (Cameron *et al.* 1992). The following describes notable bedform features located in Regional Sea 1.

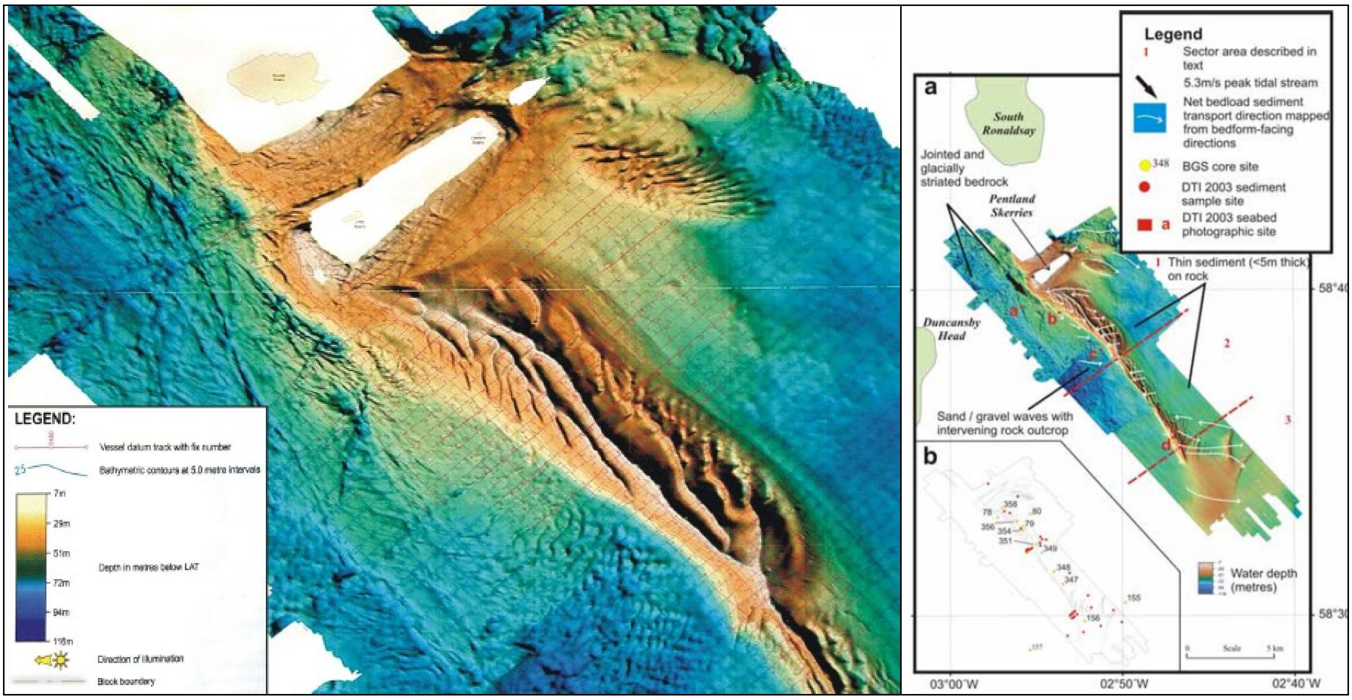
The Sandy Riddle is a large carbonate gravel and sandbank set at the east end of the Pentland Firth (Figure A1b.6). The area is characterised by high current velocities generated from tidal streams which have profoundly affected the regional distribution and composition of seabed sediments. Sediment transport and the resulting geomorphology of the Sandy Riddle are determined by the complex pattern of eddies generated over the area under the influence of tidal and wave-induced currents. Maximum east-travelling surface tidal streams of 5.3m/s are recorded on the west margin of the Pentland Skerries, at which time a strong tidal eddy extends some 3.2km to the south east. Near-bed spring tide currents are more than 2.75m/s near the head of the Sandy Riddle and decrease rapidly to around 0.875m/s further to the south-east (Holmes *et al*. 2004).

To the north and west of the Sandy Riddle, areas with the strongest tides are swept clean of sediments, exposing bedrock. Cobbles and boulders are also largely swept clean of sandy sediments except in the spaces between the rocks. In this sediment-starved environment the surfaces of the pebbles and cobbles are characterised by abundant attached biota. In areas of weaker currents the seabed is still characterised by cobbles and pebbles but also by mobile bedforms with coarse-grained sands. The mobile sands are thick enough to migrate as sediment waves over the seabed and periodically bury the underlying pavement of cobbles and pebbles. This process appears to prevent the establishment of abundant permanently attached biota found on the pebbles and cobbles in areas of weaker current. Sand and gravel carbonates accumulate in areas of weak or convergent currents.

Other sandbanks in Regional Sea 1 include those located within the Moray Firth SAC as the qualifying habitat, *Sandbanks which are slightly covered by sea water all the time* (see Appendix 1j). The 2003 DTI survey indicated that low sediment waves were present on the northern flanks of the Smith Bank (Moray Firth), with crests of 0.5-1.5m and wavelengths of 50m, showing migration to the south-west, consistent with the dominant mean peak-spring near-bed tidal regime (Holmes *et al.* 2004). The same DTI survey revealed details of sediment waves surrounding Fair Isle, with a large-scale wave or bank to the east, and a smaller one to the west, with waves migrating in the north over the latter, western bank. Sandwaves appear more abundantly offshore along the Scottish east coast from Fraserburgh to the Firth of Forth. The largest areas are to the south and east of the Aberdeen Bank in water depths of *c.* 80m, where waves 8m in height and with wavelengths of 160-270m are present (Gatliff *et al.* 1994). Their size is somewhat large for the prevailing oceanic conditions, and these waves may only be active during storms (Owens 1981). Further offshore, hydraulic conditions are not favourable for the generation of such features (Gatliff *et al.* 1994).

The East Bank Ridges are a group of sub-parallel ridges in relatively deep water to the north west of the Dogger Bank. The Banks trend north-northeast to south-southwest and are between 17km and 60km in length, 3-4km wide and have amplitudes of 15-30m. These banks are considered to be inactive (moribund), formed in the Holocene transgression approximately 9,000 years ago but which are now in water depths too great and with tidal currents too weak for their active maintenance (Stride 1982, Gatliff *et al.* 1994, Diesing *et al.* 2009). They are composed of very fine to fine sand (Davis & Balson 1992) which contrasts with the fine to coarse sand composition of other sandbanks in shallower water further to the south. Their surfaces are smooth and lack the cover of mobile sandwaves seen on other sandbanks in the area.

Figure A1b.6: Sandy riddle – shaded relief and net sediment transport direction



A1b.3.5 Reefs

Potential reef areas described as rocky marine habitats (bedrock or stony reef) or biological concretions that arise from the seabed occur at a number of locations in Regional Sea 1, particularly to the north and west of the Scottish mainland and around Orkney and Shetland, though areas of hard ground are also noted to the south between the Firth of Forth and Flamborough Head (Figure A1b.3). The distribution of reefs is partly controlled by underlying geology in addition to depth and oceanographic characteristics, and their potential qualification as Annex I habitat has generated interest in furthering knowledge in their location.

Pobie Bank is located 25-30km east of Shetland, is approximately 70km long and up to 30km wide elongated in a northeast to southwest trend. The bank rises from c. 110m below sea level to less than 80m water depth along its crest. Bedrock underlies Pobie Bank, with rocky outcrops predominating in depths shallower than 100m (e.g. as observed in surveys undertaken for SEA5), with the rock elsewhere having a covering of sediment (as summarised in Foster-smith *et al.* 2009). Seabed sediments comprised sand and gravelly sand with patches of sandy gravel located on the northern and eastern margins of the bank and slightly gravelly muddy sand on the southern and western margins and southern bank crest. Overall, the patterns of sediment distribution indicate the impact of winnowing by higher energy near-bed currents on the north and east flanks. These patterns are consistent with the predictions for the mean peak spring-tide near-bed currents in stormy conditions and peak near-bed orbital currents having the greatest impact on the northern flanks in stormy conditions (Holmes *et al.* 2004). The reef has an underlying geology of metamorphic and sedimentary rock, with bedrock outcrops being topographically complex in the bank centre and surrounded with large boulders and cobbles in a sandy matrix, with areas to the north and south having smoother bedrock areas integrated with extensive areas of stony reef (JNCC 2012). The reef has been designated as an SAC due to the occurrence of Annex I reef habitat (see Appendix 1j).

A1b.3.6 Coastal geomorphology

The complex coastline of Shetland is formed from a variety of metamorphic, igneous and sedimentary rock types. Extensive stretches of exposed cliffs and rocky shorelines characterise the outer coast with long, narrow inlets known locally as voes extending for several kilometres inland (Stoker *et al.* 1993). Soft shorelines (sand spits, tombolos and bars) are rare and largely restricted to sheltered areas. In some of these, small lagoons have been impounded behind shingle or gravel sand bars providing habitats including salt marsh.

Old Red Sandstone cliffs of Devonian age predominate along the Caithness and outer Moray Firth coast. These cliffs are exposed to the full force of winter storms, allowing few opportunities for accretionary habitats such as sand dunes to develop, except in sheltered bays. Inner regions of the Moray Firth are less exposed, although tidal and storm effects have created extensive sand and shingle formations on either side of the Firth. The sheltered inlets of the firths (Dornoch, Cromarty and the Inner Moray Firth and Beauly Firth) represent much lower energy environments in which intertidal mudflats and saltmarshes have developed (Doody 1996).

At Peterhead, sandy beach is replaced by a rocky platform and red granite cliffs. The cliffs continue to the Sands of Forvie, a large (810ha) area of sand dunes to the north of the mouth of the Ythan Estuary, characterised by unique dune forms and others which are characteristic of the wider dune systems of north-east Scotland (Hansom 2003). Dune-backed sandy beaches characterise the coast to Aberdeen and thereafter, rugged cliffs give way to the sandy shores and dunes of the outer Firth of Tay and the low lying rock platforms of Fife (Scott Wilson 1997), a notable exception being at St Cyrus and Montrose.

The Firths of Tay and Forth are major features, formed during the inundation of the land by the sea at the end of the last glaciation. Much of the shoreline is composed of exposed rock platforms with deposits of glacial drift. There are large areas of sand dunes on the outer coast, including the Fife promontory with sheltered inlets holding extensive mud and sand flats, and related Special Area of Conservation (SAC) and Special Protection Area (SPA) designations. South of the Firth of Forth, cliffs reappear, rising to 152m at St. Abb's Head (Scott Wilson Resource Consultants 1997).

The English section of the coastline is generally composed of (with some local variations) Carboniferous material from its northern point to Newcastle, with Permian rocks dominating the coast to the south until just north of Hartlepool, before moving into Jurassic limestones and clays until around Filey where Cretaceous chalks, clays and sand take over to the south of Flamborough Head (May & Hansom 2003). These younger rocks are relatively weak compared with the Scottish coast and are therefore more susceptible to erosion and coastal retreat (Clayton & Shamoon 1998).

Sandstone cliffs and rocky offshore platforms characterise the far north of the English coast. Hard rock cliffs continue south to Beadwell where sandy cliffs backed by low cliffs or dunes dominate. Limestone caves are a feature to the south of Howick and Craston. Sandy bays backed by glacial till make up much of the coast to the south of the Tyne, interspersed by rocky cliffs and platforms. Druridge Bay to the north of the Tyne supports extensive sandy beaches and dunes. Between Tynemouth and Lynemouth cliffs there is the most complete set of Westphalian rocks in the region, which includes coal seams of historical economic importance. Quaternary deposits which include peat are visible at Hauxley and further north, between Boulmer and Howick, Carboniferous limestones form low cliffs and platforms.

Sandstone cliffs are a feature of the coast north of Berwick upon Tweed. Between the Tyne and the Tees several geological features are of note, particularly sequences from the Upper Carboniferous, Marine Permian, Lower Jurassic and Quaternary, many of which are associated with SSSI sites such as at Wear River Bank, Trow Point to Whitburn Steel and Seaham Harbour. Associated with these sequences are geomorphological landforms including wave-cut platforms, caves, arches and stacks, some sandy bays and sand dunes. The underlying geology promotes calcareous and limestone grassland cliff-top vegetation and though severely depleted by reclamation for industry, saltmarsh areas support substantial bird life which is recognised in SAC and SPA designations for some locations (e.g. Lindisfarne, the Northumbria Coast).

Further south, Lower Jurassic rock rich in ammonites and historically important for iron extraction is found from Saltburn-on-Sea. From Whitby to Scarborough Middle Jurassic sandstones and shales dominate, moving into Upper Jurassic ironstone, limestone and clay towards Filey. Lower Cretaceous clays and Upper Cretaceous chalk from Speeton to Flamborough Head are overlain by Pleistocene deposits which include glacial tills. The chalk forms eroded wave-cut platforms forming sub-littoral reefs extending up to 6km offshore.

A1b.4 Features of Regional Sea 2

Surficial sediments consist largely of material greater than 10,000 years old, reworked by tides and waves into various bedforms. Coastline erosion has provided substantial inputs of sediment to the southern North Sea throughout the Holocene (e.g. from the Holderness coast) in addition to large inputs of material from the Humber, Thames, Rhine and Scheldt estuaries (Cameron *et al.* 1992). Sediments reworked during the Holocene typically form large areas of seabed sand and gravel. Such sediments also form large-scale sandbanks and ridges and smaller sandwaves.

A1b.4.1 Seabed substrates

Bedrock is rarely exposed on the sea floor in Regional Sea 2, it being covered in Pleistocene and Holocene sediments (Figure A1b.3, Figure A1b.7), but where exposures exist or where rock shallowly subcrops surficial sediments, this is usually of chalk (Cameron *et al.* 1992, Jones *et al.* 2004a). Chalk bedrock is the dominant characteristic of the coast around Flamborough Head, representing nearly 9% of Europe’s coastal chalk and is the most northerly outcrop of coastal chalk in the British Isles. The area is also exceptional in the distance that the chalk is found offshore at the seabed, at up to 6km or 30m water depth from the headland. Shallow sub-cropping chalk is found at greater distance offshore than this, with shallow (<5m) Quaternary sediments overlying bedrock extending some 60km offshore, to the north and east of Flamborough Head. Such shallow subcropping/outcropping has been evidenced, for example, in the troughs of large sandwaves where sediment can be thin or absent.

South of the Humber, isolated outcrops of hard substrate are formed mainly of glacial tills. However, stretches of chalk bedrock also extend into the sublittoral at various locations in North Norfolk, mainly between Sheringham and West Runton but also at East Runton and Cromer, representing the only appreciable area of natural hard substrate on the coast of East Anglia. Rocks of Carboniferous age which include coal measures are found north of the North Norfolk coast and form the main source of natural gas in the area (Jones *et al.* 2004a). Outcropping chalk is also characteristic of the coast and nearshore area of Thanet in Kent.

The pattern of sediments reworked during the Pleistocene and later is a key control on the distribution of benthic habitats, reducing or removing the influence of the underlying geology on these habitats (Jones *et al.* 2004a). Unconsolidated sediment distribution in the southern North Sea is complex, and reflects both sediment sources and ongoing redistribution by hydrographic processes. Surficial sediments in the coastal area are largely gravelly sands and sandy gravel, extending from Flamborough Head to the outer Thames Estuary and further south, with a large area of sandy gravel off the coast of the Humber and the Wash. In the areas of the Dogger Bank, Norfolk Banks and Southern Bight, sand is the dominant surface sediments, with muddy sands restricted to the Outer Silver Pit and estuarine areas.

Between Flamborough Head and Norfolk, seabed sediment distribution is complex with Holocene sediments generally forming a veneer less than 1m thick. The sand-rich sediments comprising the Norfolk Banks attain a maximum thickness of about 40m, but the intervening gravelly sand substrate remains thin. Extensive sheets of gravel and sandy gravel occur off the coasts of Lincolnshire. The gravels off the Humber estuary have a varied composition: Carboniferous sandstone and limestones are particularly common, but chalk, Jurassic mudstone, flint and igneous and metamorphic rock types are also found. The gravels are believed to be derived by marine winnowing of glacial moraines and outwash fans deposited during the Devensian glaciation.

Seabed sediments in the southern North Sea are mostly relict, with the distribution of gravelly sediments reflecting glacial, fluvial and coastal processes which have now ceased (Cameron *et al.* 1992). Carbonate gravels, which occur in the east part of the region, were probably reworked from Pliocene Crag deposits similar to those that outcrop onshore in north-east Essex and Suffolk. The carbonate content of seabed sediments is generally low in the area (<10%), probably due to a high glacigenic source for sediments (Pantin 1991, referenced in Cameron *et al.* 1992); carbonate contributions being modern, reworked early Holocene sediments and older carbonate rich formations (Cameron *et al.* 1992). In the Thames Estuary the seabed sediments were derived by the erosion of beach gravels and fluvial terrace deposits (which mark the ancient courses of the Rivers Thames and Medway) or else from the erosion of underlying Tertiary deposits. There is great lithological variation in these gravels, but flint dominates, and quartz and quartzite are locally common in the north (Cameron *et al.* 1992).

The strong currents and large coastal sediment supplies contribute to the East Anglian sediment plume (Dyer & Moffat 1998) which extends eastwards across the Southern Bight and the North Norfolk sandbanks (HR Wallingford 2002), with highest average sediment concentrations in winter months at more than 30mg/l (Cefas 2016). Summer concentrations tend to be less than 10mg/l. The banks represent a significant sink for sand sized sediment, with major sediment sources including Holderness and the east Norfolk coast.

A1b.4.2 Sandbanks and sandwaves

Both active sandbanks maintained by modern tidal current regimes, and inactive sandbanks formed at periods of lower sea level, are found in the southern North Sea (Belderson 1986, Cameron *et al.* 1992, Collins *et al.* 1995).

Linear sandbanks in the southern North Sea have been studied since the early days of hydrographic surveying, with significant early echosounder observations made by Van Veen (1935, 1936). Detailed investigations commenced in connection with offshore oil and gas exploration and production activities in the late 1960s and early 1970s (Caston 1970, 1972) and has continued in relation to offshore renewables (e.g. Games & Gordon 2015). To support the offshore energy SEA process, sandbanks within the southern North Sea were investigated by a survey programme, commissioned by the DTI in June-July 2001. This included high-resolution multibeam bathymetry, photography of sediment features, and epifauna and seabed sampling. Additional mapping and survey work has been undertaken as part of the MALSF Regional Environmental Characterisation Programme, with three study areas contained in Regional Sea 2 (Humber, East of England and the Outer Thames), and in relation to a number of conservation sites in Regional Sea 2 such as Dogger Bank SAC.

Five major groups of sandbanks are represented in Regional Sea 2:

- The Sand Hills (or The Hills) are a group of large (12-21m in height) symmetrical, parallel ridges orientated north-west to south-east to the south west of the Dogger Bank. These ridges were formed during periods of lower sea-level and stronger currents during the marine transgression following the last ice age, beginning ca. 9,000 years BP (Cameron *et al.* 1992), analogous to the East Bank Ridges (Section A1b.3). The western extent of the Sand Hills is superimposed by active sandwaves and megaripples indicating ongoing activity, whereas the eastern extent is now regarded to be moribund (i.e. no longer active).
- The Wash contains extensive intertidal flats around its margins and a number of large sandbanks within it. These banks are aligned parallel to the sides of the embayment and to the dominant tidal current directions in and out of the embayment. Most of these banks are partially exposed at low tide. A range of sandbank types are located in the mouth of The Wash, including banks bordering channels, linear relict banks and sinusoidal banks with distinctive subsidiary banks, and are associated with Inner Dowsing, Race Bank and North Ridge SAC. Other banks in the area offshore of the Humber and Wash include Burnham Flats, Docking Shoal, Dudgeon Shoals and Triton Knoll, which have an asymmetry suggesting movement to the southwest (Tappin *et al.* 2011). 10km to the north east of Triton Knoll, Outer Dowsing Shoal and Cromer Knoll form a single asymmetric feature 50km in length with an elevation of 5m above seabed, showing possible movement to the southwest and northeast (Tappin *et al.* 2011).
- The Norfolk Banks are the best known group of linear ridge sandbanks in UK waters (Tappin *et al.* 2011) and lie off the coast of north east Norfolk. These can be subdivided into a nearshore parabolic group with sandwaves on their flanks (Leman, Ower, Inner, Well, Broken and Swarte Banks), and a linear, comparatively stable offshore group of probably older derivation (Cameron *et al.* 1992). The banks are orientated in a north-west to south-east direction and are mostly parallel; the largest bank is Well Bank which is over 50km long, 1.7km wide and rises 38m above the sea floor (Tappin *et al.* 2011), with the bank crests being generally at less than 20m water depth. The nearshore banks are subject to stronger currents and are more active, progressively elongating in a north-easterly direction and are generally asymmetric with a steeper face to the northeast (Cooper *et al.* 2008, also see Caston 1972, HR Wallingford 2002) – the stronger currents and greater disturbance on the inner banks are reflected in the faunal communities present (JNCC 2010). There are uncertainties about the rate of migration of these banks, but observations suggest that it could be between 0.4m/yr to 1m/year (Cooper *et al.* 2008, also see Jenkins *et al.* 2015).

- The sandbanks or sandwaves in the outer Thames Estuary area form a complex array aligned approximately parallel to the coast, most of the intervening sea-floor being covered by winnowed 'lag' deposits. In the mouth of the estuary, large sandbanks are exposed at low tide, separated by narrow scoured channels. Narrower, linear banks oriented approximately north-south occur in deeper water north of the Dover Straits.

Models for sandbank development include spiral water circulation with convergence over the crestline (Houbolt 1968, Caston 1972); lateral migration; and stratigraphic evolution associated with submergence of coastal sand bodies. Detailed hydrography and sediment transport have been studied on Leman and Well Banks (Caston & Stride 1970, Caston 1972) and Broken Bank (Collins *et al.* 1995). From analysis of historic bathymetric charts, Caston (1972) found that some of the more offshore Norfolk Banks had elongated towards the northwest, the direction of net regional sand transport. The evidence for bank migration perpendicular to their long axis is, however, more equivocal. These offshore banks are markedly asymmetrical in cross-section with their steeper flanks oriented towards the north east suggestive of migration in that direction, The internal structure within some of the offshore banks is evidence of north eastward migration although it is uncertain whether migration still occurs at the present time (Cooper *et al.* 2008).

Understanding of past and potential future movement of sandbanks has been important to several of the wind farm developers in this region. For example several coastal process and geological studies were commissioned for Greater Gabbard (ABPmer 2005, & 2006, Poulton *et al*. 2005, Kenyon 2005), of the Inner Gabbard and Galloper sandbanks in the outer Thames Estuary which were brought together in the project Environment Statement (GGOWL 2005). These banks are approximately 10km long, 1-2km in width and have their ridges at 10-20m water depth. The Greater Gabbard wind farm work showed that these banks were in very dynamic areas of sand transport. Kenyon (2005) noted that the area around these banks has the highest suspended sediment load in the southern North Sea (see Dolphin *et al.* 2011, Eggleton *et al.* 2011) and could be expected to extend to the south by up to 10s of metres per year with a smaller extension to the north at the same time, and a general westerly progression laterally of the order of up to a few metres per year, however Emu Ltd & University of Southampton (2009) note that bathymetric comparisons by Burningham & French (2008) suggest that the ridges have shown no significant erosional or depositional change over the last 200-300 years since they were first charted.

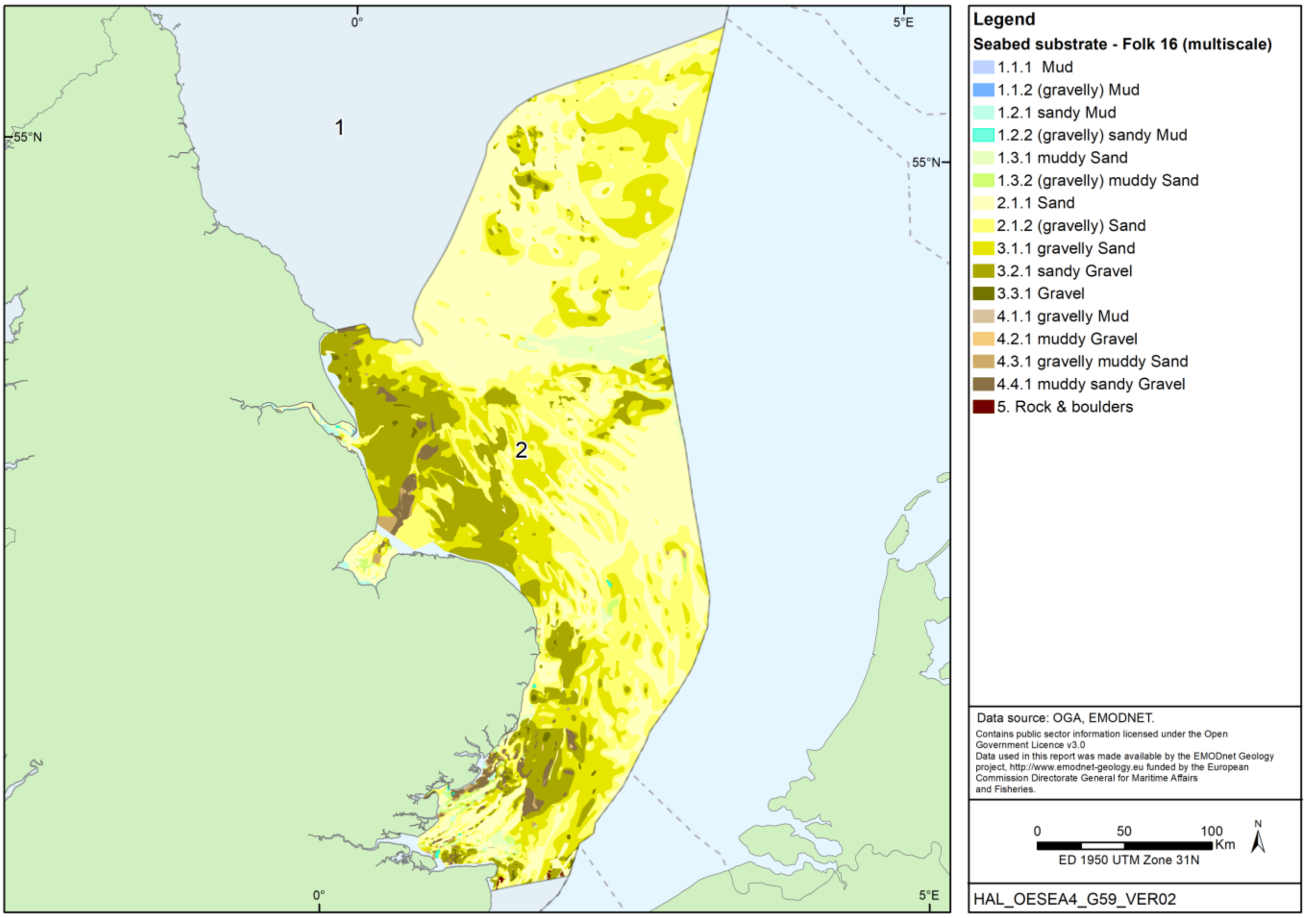
Sandwaves are smaller features, more widely distributed throughout the southern North Sea (Figure A1b.8) and unlike sandbanks, these are flow-transverse bedforms (Cameron *et al.* 1992). This morphological feature occurs extensively offshore and intertidally throughout the southern North Sea area from north of the Dover Straits to south west of the Dogger Bank in water depths of between 18 and 60m, limited at shallower depths due to storm-wave action, and are also often superimposed on larger sandbank features. The dynamic nature of the area in its interactions with infrastructure were further investigated by Games & Gordon (2015), who noted large-scale movements in sand waves in southern North Sea wind farms (including Greater Gabbard), with large scale features moving between 50m and 155m over a 5 year period.

The Dogger Bank is a relict landform with its early stages being terrestrial as an extensive tundra plain intersected by braided channels, which was subsequently incised further by meltwater, and overridden and reworked by advancing ice, generating an extensive clay-rich diamict (Cotterill *et al.* 2017). Further ice retreat and re-advance exposed the area to periglacial activity, further incision by meltwater, the formation of small proglacial lakes, the thrusting and folding of sediments and construction of large arcuate moraine systems. Repeated re-advances led to the deposition of a complex sequence of outwash sediments and recessional moraines, which eventually resulted in the formation of a significant topographic barrier restricting further re-advances (Cotterill *et al.* 2017, Phillips *et al.* 2018, Roberts *et al.* 2018). The moraine complexes that are now reflected in the internal structure of the Dogger Bank, can be related to former positions of the Weichselian ice sheet margin during its retreat following the LGM (Phillips *et al.* 2018).

The Dogger Bank would have formed an island in the southern North Sea as sea levels rose, being inundated by water *c*. 8,000 years BP (Lambeck 1995, Weninger *et al.* 2008, Sturt *et al.* 2013, also see Appendix 1i) and evidence of former coastal environments around the bank come in the form of saltmarsh peat beds and clays containing intertidal molluscs (Balson *et al*. 2002) and geomorphological evidence (Emery *et al.* 2019). Holocene sands and modern sandwaves overly earlier glacigenic deposits (Cameron *et al*. 1992) and the extensive fluvial network which followed glacial retreat (Fitch *et al*. 2005, Cotterill *et al.* 2017). These sands may locally reach a thickness of >25m when they infill depressions, but there are large areas where they are <1m thick or absent, with the composition of the sands suggesting they were derived from underlying glacial deposits reworked during the marine transgression (Cotterill *et al.* 2017). The covering of sandy sediments in areas to the south west and its associated benthic fauna (e.g. *Echinocardium cordatum, Fabulina fabula, Lanice conchilega, Owenia fusiformis*) has been interpreted as falling within the Annex I classification, Sandbanks which are slightly covered by seawater all of the time (Johnston *et al*. 2002). Areas of the Dogger Bank have been designated as an offshore SAC (Diesing *et al.* 2009, JNCC 2011).

Water depths in the region of the bank vary from 15 to 40m (Diesing *et al*. 2009), and the convergence of Atlantic water and residual flows from the English Channel is influenced by its form (Jones *et al*. 2004a). Depth increases away from the bank at up to 80m with narrow deeps (Sole Pit, Markhams Hole and Silver Pit) located in close proximity (Diesing *et al.* 2009).

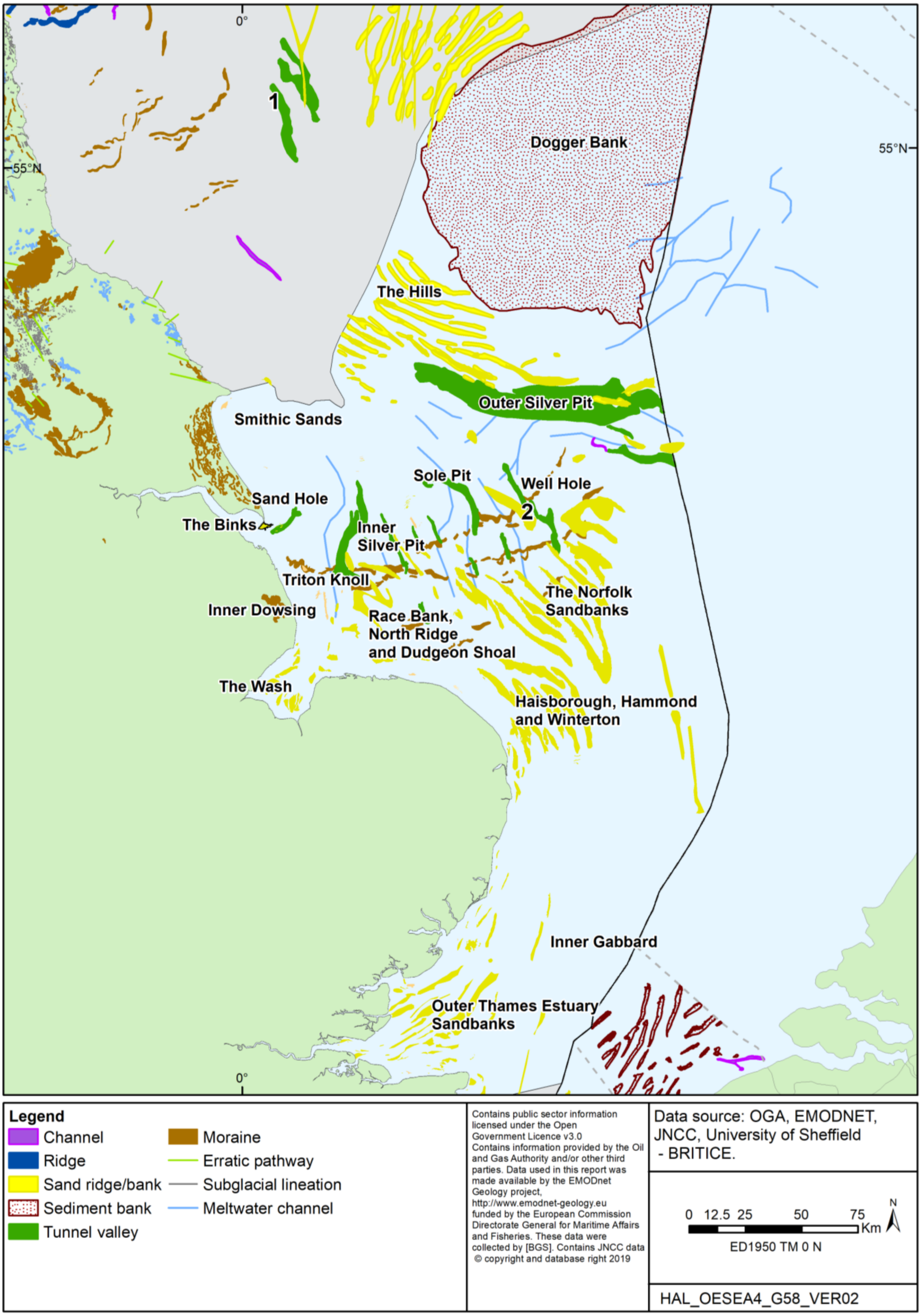
Figure A1b.7: Seabed substrates in Regional Sea 2



A1b.4.3 Reefs

The potential for reef in Regional Sea 2 is less than other regional seas due to the dominance of sandy sediment, however a number of nearshore areas around the Wash and North Norfolk contain areas of hard ground, in addition to biogenic reef formed by *Sabellaria spinulosa* confirmed through survey which has also contributed to the designation of several conservation sites including The Wash and North Norfolk Coast SAC, Haisborough, Hammond and Winterton SAC, Inner Dowsing, Race Bank and North Ridge, and North Norfolk Sandbanks and Saturn Reef SAC.

Figure A1b.8: Seabed features in Regional Sea 2 referred to in the text



A1b.4.4 Coastal geomorphology

The geomorphology of the English southern North Sea coastline varies from exposed, heavily faulted ‘soft’ chalk cliffs and glacial till/diamict cliffs undergoing retreat, to saltmarsh, small areas of dune systems and sand and shingle beaches and spits. The relatively young rocks of the south east coast are weak compared with those in the north and Scottish coast and are therefore generally more susceptible to erosion and coastal retreat (Clayton & Shamoon 1998). This erosion resulting from, and in combination with, wave and tidal processes, also contributes to the creation and maintenance of other coastal forms. The sediment transport sources and pathways in Regional Sea 2 were extensively studied as part of the Southern North Sea Sediment Transport Study (HR Wallingford 2002), which was supported by 15 technical Appendices. The study provided reviews of available information sources on sediment sources and sinks, longshore and offshore transport directions, the influence of storm surge and also computational modelling of sediment transport by tides, waves and surge for a variety of sediment sizes. Additionally, a series of maps were produced to show suspended sediment concentrations across mean winter and summer conditions, now later updated using both MODIS satellite imagery and more recent modelling techniques (see Dolphin *et al.* 2011 and Eggleton *et al.* 2011; Figure A1b.2) – the southern North Sea has the highest suspended sediment concentrations of anywhere on the UKCS outside of the Severn.

At the most northerly point of the SEA area, the chalk cliffs of Flamborough Head are capped with glacial till material and have the most diverse array of active erosional landforms of any chalk coastline in England (May 2003a), though wave diffraction in the intertidal zone in the area prevents extensive erosion like that seen in the Holderness coast to the south. The cliffs of the Holderness coast vary in height from between just a few metres to over 20m, and back sandy beaches between Bridlington in the north and Spurn Head in the south (approximately 60km). The cliffs are comprised of unconsolidated material including mainly glacial tills (Skipsea, etc. tills) overlain by sands (Balson *et al.* 1998, Blewett & Huntley 1998). This material is readily eroded by wave action which is augmented by aerial weathering processes and local hydrological conditions (Quinn *et al.* 2009). The cliffs retreat on average (1989-2014) by up to 3.4m per year[7], though this is spatially and temporally variable due to the sheltering effect of Flamborough Head on northern areas from the dominant north easterly wave approach (Pethick 1994) and the episodic nature of cliff falls (Quinn *et al.* 2009, also see Hobbs *et al.* 2019). Approximately 3 million m^3 of sediment is eroded from Holderness annually, approximately two thirds of which are fines (<63μm), with a smaller proportion being larger material transported as bedload and alongshore, contributing to the maintenance of coastal features including the characteristic “Ords” of Holderness and the thin veneer of sandy beach sediments, and terminating at Spurn Head (see Ciavola 1997), a dynamic shingle spit at the entrance to the Humber Estuary. Spurn was probably initiated as sea-levels began to reach modern levels in the region approximately 6,000 years BP, and as sediment from Holderness began to be available from erosion. The feature has extended laterally and in a westerly direction over time and having been breached several times in the 19th century, is now partly maintained by artificial defences – Spurn Head is unique in forming across a macrotidal estuary (May 2003).

Much of the material eroded from Holderness is transported to sinks such as The Binks, New Sand Hole, Humber Estuary and Donna Nook (see D’Olier 2002, Cox 2002). Additionally, sediment eroded from Holderness (c. 29%) contributes to accretion along the Lincolnshire coast, most likely being temporarily stored in the nearshore area and in offshore sandbanks before being redistributed (Montreuil & Bullard 2012). Extensive erosion is also a feature of

[7] http://www.eastriding.gov.uk/coastalexplorer/documents.html (accessed: 18/09/2020)

the Norfolk and Suffolk coasts, for example Brooks & Spencer (2010) used georeferenced maps and aerial photographs to reconstruct former Suffolk shorelines, illustrating retreat rates in the order of 2.3-3.5 m/yr^{-1} (Benacre-Southwold) and 0.9 m/yr^{-1} (Dunwich-Minsmere). Along the Norfolk coast, for example between Sheringham and Mundesley, the cliffs are unstable and subject to mass movement (Barne *et al,* 1995c). Further south, the chalk cliffs of Kent are less prone to erosion but have formed a number of coastal features including sea stacks and arches such as at Botany Bay (Barne *et al.* 1998a).

Active saltmarsh is a feature which covers extensive areas of the coastline in Regional Sea 2. This includes the northern Humber Estuary, much of the Lincolnshire coast (e.g. between Tetney Haven and Donna Nook, and at Gibraltar Point), the area of the Wash, sections of the North Norfolk coast (see May 2003) and the Greater Thames Estuary. As indicated above, much of the soft sediments of the Humber are a result of the fine sediment eroded from Holderness being drawn into the estuary by tidal currents, which maintains mudflats and saltmarsh areas, with the north and south of the Humber affected by varying historical land use – the south being more industrialised and therefore protected by hard defences, and the north having been subject to historic reclamation (Scott Wilson 2009).

The Wash is characterised by saltmarsh and mudflat which has developed over the last 8,000-2,000 years as sea levels rose and now provides a range of habitats for flora and fauna and also has a flood defence role. Like many saltmarsh areas in the UK, the Wash has been subject to historical land claim which started in the 13th century but the major phases took place in the 16th and 17th centuries. Characteristic changes include a change in shoreline position, and loss on intertidal mud and sand flat and a compression in the succession from mudflat to saltmarsh – land claim has not ceased and managed realignment has now also taken place (Environment Agency 2010 – also see Section A1b.12).

Sand and shingle spits are a common feature of the coast in Regional Sea 2, occurring at Spurn Head (discussed above), Gibraltar Point, Scolt Head Island and Blakeney Point on the North Norfolk coast and Benacre Ness, Winterton Ness, Orfordness, St. Osyth and Dengie on the Suffolk coastline. Dunes are relatively sparse and small in Regional Sea 2, largely concentrated between the south of the Holderness coastline and Blakeney, with few examples further south (e.g. Winterton and Horsey, Caister to Yarmouth and Sandwich Bay dunes).

A1b.5 Features of Regional Sea 3

The bathymetry of the area is extensively controlled by a planation surface of Neogene age (~5 million years ago) which slopes away from the coast at an orientation of south-south-east at 1°, where it is interrupted at a maximum distance of 20km from the coast by the more recent palaeo-valley system (Hamblin *et al.* 1992). The planation surface is interrupted by isolated deeps, rarely exceeding 60m (such as St Catherine's Deep off the south Isle of Wight coast)). The area has many palaeo-channels of extinct rivers which dominated the English Channel region during glacial low-stands of the Pleistocene period. Some of these channels are remnants of the former extension of the Seine, Somme, Solent and Arun rivers, and by the mid-Pleistocene with the opening of the Straits of Dover (Hamblin *et al.* 1992, Toucanne *et al.* 2009), the Rhine, Meuse and Thames (Evans 1990, Gibbard & Lautridou 2003, Lericolais *et al.* 2003, Reynaud *et al.* 2003, also see Mellett *et al.* 2013). Many of these palaeochannels are infilled with sediment (e.g. palaeo-Solent), generally of fluvial and later marine origin, and therefore indistinguishable from the surrounding seabed, though others remain open, including the Northern Palaeovalley (James *et al.* 2007). Quaternary deposits dominate the seafloor, and in some areas are shaped by modern oceanic processes into bedforms including sandbanks and sandwaves.

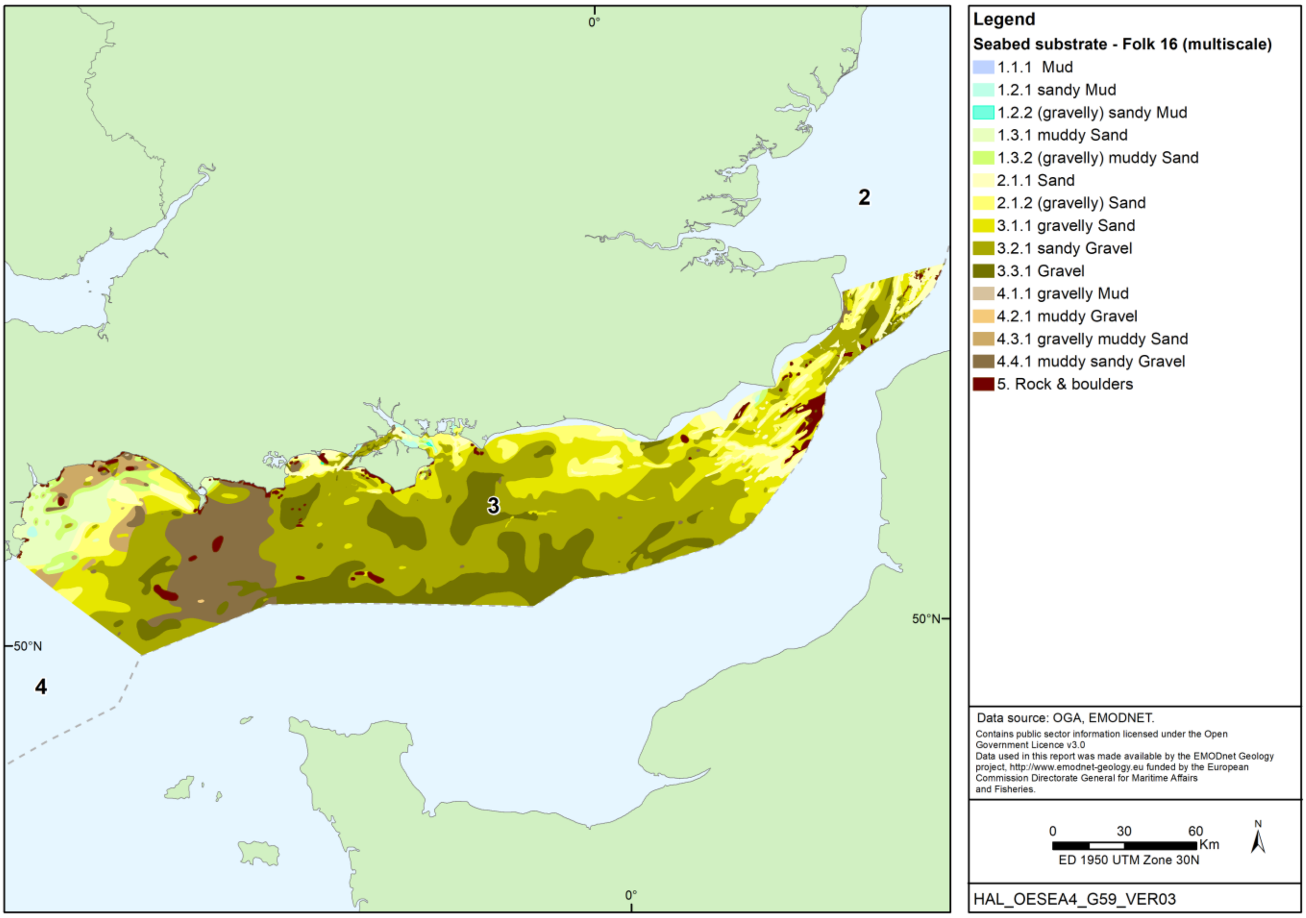
A1b.5.1 Substrates

The substrates of the central English Channel consist principally of a thin (generally 0-5m, though often only up to 0.5m), coarse Quaternary lag deposit which is relatively immobile (indicated by encrusted barnacles, serpulids and bryozoa) in modern oceanic conditions, though locally up to 30m where it forms palaeochannel infill (Hamblin *et al.* 1992, BGS 1996). Modern sediment input is limited to riverine and coastal sources, with minimal offshore input from erosion of exposed seabed (James *et al.* 2007). The lag deposit has its origins in the underlying solid geology which closely subcrops or outcrops in the Channel and is largely comprised of upper and middle Jurassic, upper and middle Cretaceous, and later Eocene and Palaeocene sediments (Hamblin *et al.* 1992), and the coarse sediments tend to be poorly sorted. The dominance of coarse sediments is in part due to the glacial history of the area, as ice did not reach this far south in past glacial periods and the east-west structure of onshore catchments means that long rivers which could have carried substantial finer sediments to the Channel have not formed (James *et al.* 2010).

The dominance of coarse sediment has led to the central Channel being prospective for marine aggregate extraction (see Appendix 1h), and coastal and offshore areas of bedrock and coarse sediments also have associated reef habitats (see below). Less coarse sediments occur to the west and east of the central Channel lag deposit where it is overlain by deeper (5-10m) sands and gravelly sands which have developed into large, mobile sandbanks, however in general such bedforms are limited in extent. The change in seabed character is partly associated with a bedload parting zone in the central Channel, also known as “The Narrows”, with divergent tidal flow resulting in set sediment transport away from this area to the west and east where it is deposited, leaving the parting zone largely bare of deposits, and with depths shoaling to the east creating a change in oceanographic conditions in the Channel (e.g. wave base interaction, stratification) (Coggan *et al.* 2009, 2012, James *et al.* 2010). At the eastern extent of Regional Sea 3, there is a bedload convergence zone resulting from the net ebb-flood tidal currents of the Dover Strait (Anthony 2004, cited in James *et al.* 2007).

Fine and sandy sediments in the Channel tend to be swept to the north and east by tidal and possibly also wave action where coastal margins and sandwaves fields and banks act as a sink (James *et al.* 2007). Mobile substrates of Holocene age show a tendency to fine towards the coast, with very fine material (phi value of up to 4) present to the east and west of the Isle of Wight, off Selsey Bill, Beachy Head and the Dungeness foreland (James *et al.* 2010). Holocene and modern sediment supply is largely derived from coastal erosion, with riverine inputs having declined from terrestrial sources since the early Holocene due to reduced subaerial weathering and the development of depositional estuaries (Hamblin *et al.* 1992). Mud is present only in isolated areas behind headlands and other sheltered areas such as Lyme Bay (Hamblin *et al.* 1992), though areas underlain by London Clay, Bracklesham Group, Barton Group and Wealden Group clays and silts may contain isolated fine components (James *et al.* 2010).

Figure A1b.9: Seabed substrates in Regional Sea 3



A1b.5.2 Sandbanks and sandwaves

Tidal sand ridges are the largest mobile bedform in the English Channel and are present south-west of the Dover Strait resulting from the strong tidal current regime in this area (e.g. the Bassurelle Sandbank). These can be up to 40km long, and rise up to 40m from the seabed such that they may shoal to within 5m of the sea surface during low spring tides (James *et al.* 2007) and are overlain by sandwaves and mega ripples which are asymmetric and orientated normal to the current (Hamblin *et al.* 1992). Sandwaves studied in the Dover Straits are covered in megaripples which reach a vertical elevation of 2m and a wavelength of 10 to 20m, smaller ripples (20cm) with 2m wavelengths are observed on the lee of sandwaves, all orientated at 20° anti-clockwise to the sandwave crest orientation (Idier 2002). Idier (2002) proposes that short term sandwave variation is the result of megaripple movements which can reach 1mh^{-1} and generate avalanches of material when their slopes reach 34°. Smaller banner banks associated with headlands are found closer to the coast, with associated local sediment transport paths and gyres

Large sand and gravel waves (approximately 2km long, 0.25 to 2m high, 5 to 18m wavelengths) are found in the West Solent, with asymmetry indicating movement in different directions at either side of the channel (Hamblin *et al.* 1992). Smaller, irregular individual sandwaves are located within the Eastern Solent.

A1b.5.3 Reefs

A significant proportion of Regional Sea 3 contains potential stony and bedrock reef (see Figure A1b.3), related to the high proportion of coarse sediment and exposed bedrock noted above. A number of these reefs are recognised in conservation designations including, the South Wight Maritime SAC which represents 5% of Europe's chalk reef exposures, Studland to Portland SAC, Lyme Bay and Torbay SAC and Wight-Barfleur Reef SAC (also see Appendix 1j).

The largest site, Wight-Barfleur Reef, is located in the central English Channel between St Catherine's Point and Barfleur Point on the Contentin peninsula, and comprises an area of bedrock and stony reef at depths of 25-100m. The bedrock reef, generally sandstone, mudstone and siltstone, is characterised by a series of well-defined exposed bedrock ridges up to 4m high, with stony reef being present in the south east of the site, coinciding with part of the northern Palaeochannel described above. Studland to Portland has a large amount of geological and biological diversity. The Studland Nay to Ringstead Bay area includes limestone ledges (up to 15m across) protruding from shelly gravel at Worbarrow Bay; shale reefs extending from Kimmeridge; a unique reef feature, known as St Albans ledge, extending out over 10km offshore and subject to strong tidal action; and an area of large limestone blocks known as the "seabed caves". The Portland Reefs are characterised by flat bedrock, limestone ledges, large boulders and cobbles, with limestone boulders provide deep gullies and overhangs on the western side of Portland Bill. The Lyme Bay reefs comprise bedrock outcrop (mudstone, sandstone, limestone (which is commonly piddock bored) and igneous rock) and stony reef not connected to the coast.

A1b.5.4 Coastal geomorphology

The coastal geomorphology of the southern coast of England from Start Point to Dover is primarily cliffed, dominated by chalk exposures from the western extent of the Regional Sea to Poole Bay, moving into Tertiary sandstones in the lee of the Isle of Wight until east of Selsey Bill. The southern coast of the Isle of Wight is faced by chalk (primarily), limestone, clay and sandstone of Cretaceous and Jurassic age (BGS 1996). The southern coast of the Isle of Wight is flanked by narrow flint and chalk beaches supplied with material from ongoing coastal erosion. Cliffs are interspersed or accompanied by beaches and low lying estuarine areas, with the height of coastal land varying between 5m and 200m. The nature of the coastline in Regional Sea 3, the dominant sediment transport (including an update to this working taking place 2014-2016), its sources and sinks, have been systematically considered through the Standing Conference on Problems Associated with the Coastline (SCOPAC), which continues to contribute to funding for research into coastal management for the area between Lyme Regis and Shoreham-by-Sea, including the Isle of Wight. Outputs from SCOPAC studies have contributed to the summary below.

The dominance of coarse sediment which characterises offshore substrates is also evident at the coast, with the majority of beaches (e.g. at Hastings, Eastbourne, and an almost continuous stretch between Brighton and Chichester Harbour) or spits (e.g. Hurst Spit and at Shoreham and Pagham Harbour) comprising a dominant shingle rather than sand sediment fraction (see Barne *et al.* 1996a, b, c – an exception being Dawlish Warren). Notable shingle structures which are also recognised as GCR sites include Chesil Beach, formed during the marine transgression and now without a contemporary sediment source (May 2003b) and Dungeness, a large cuspate foreland with sediments likely derived from redistributed barrier beaches and containing a series of shingle ridges marking its evolution (May 2003b).

The coast from Selsey Bill to Dover is dominated by chalk cliffs with the exception of the Dungeness foreland, a large sand and gravel barrier consisting of several hundred storm beaches, dating to at least *c.* 4000 years BP (Long *et al.* 2006). Sediment supply to this barrier comes partly from offshore and longshore movements of material much of which is derived from soft chalk cliffs to the west (Selsey Bill-Dungeness sediment cell), but also through internal reworking of material (Long *et al.* 2006). Other shingle beach structures fringe the coastline at Weymouth, Lymington, Hurst Castle; and on the Isle of Wight, Newton and the shingle spit system of The Duver, at St. Helen's (BGS 1996).

Chichester, Langstone and Portsmouth have the largest intertidal areas on the south coast with substantial areas of saltmarsh present. Other areas such as Poole Harbour, Christchurch Harbour and numerous sites on the coasts of the Isle of Wight and the UK mainland fringing the Solent also have saltmarsh. These areas are generally less than 120 years in age and are found in harbours, embayments and small estuaries where they are often grazed (Hill 1996). These areas are often of importance for waders and waterfowl, particularly where large areas of sand and mudflat are exposed at low tide, and attain SPA designations as a result, such as at Poole, Chichester and Langstone Harbours. Like many intertidal areas in the UK, these are subject to 'coastal squeeze' which threatens the future viability of these habitats.

The east coast of the south inshore area from Dartmouth to the Isle of Purbeck is characterised by the large embayment of Lyme Bay, and smaller headland confined bays, particularly south of Teignmouth. Like much of the south coast, landforms are predominantly cliffs and large clastic beaches, with soft sediment features largely confined to estuarine areas. The area includes the Jurassic Coast World Heritage Site noted for its cliffs of Triassic to Cretaceous rocks, and substantial sediment inputs of both sand and larger boulders are derived from cliffs along its length. Littoral sediment transport direction in this area is predominantly from the west to the east, though drift divergence and convergence is seen in proximity to river and estuary mouths (e.g. the Teign, Exe and Axe). Offshore sediment transport converges around the Isle of Portland at a boundary at its southern tip, which has an almost symmetrical set of offshore sediment sandbanks and shoals (West Shoal and Portland Banks to the west and Shambles Bank and Adamant Shoal to the east). The Portland and Shambles Banks are comprised of mobile coarse sand in accumulations of up to 19m and 22m respectively, with sediment movement being largely clockwise and anti-clockwise around the banks respectively. The Banks and headland of Portland also play a role attenuating received wave energy in Weymouth Bay, where littoral drift direction and is poorly understood.

Shingle coastal structures are abundant on the southern coast, the largest being the barrier/tombolo of Chesil Beach, which extends southward to connect the mainland to Portland Island. The barrier beach is backed by cliffs to the west and the large lagoon of The Fleet further east. The genesis of the feature probably extends back to late glacial times when sea-level was much lower than at present, perhaps formed from eroded offshore and riverine gravels maintained by longshore sediment supply from west Dorset (May 2003b). The site is included in the Dorset and East Devon World Heritage Site designation of 2001.

Ringstead Bay to the east includes cliffs subject to landslides and a number of features derived from erosion of soft Wealden and chalk geology surrounding areas of Portland stone (e.g. Durdle Door, Lulworth Cove and Warbarrow Bay). Sediment transport is primarily in a west to east direction, and cliff derived sediment input is dominated by fine sediments with occasional larger limestone derived clasts, and small quantities of chert and flint. A dominant south westerly sediment movement also supplies sediment to the Adamant and Shambles Banks. Similarly, offshore sediment transport in Poole Bay is to the southwest and south. Sediment input to the coast of Poole Bay is limited from coastal sources, and is dominated by estuarine inputs and wave driven inputs onshore, and sediment deficits have resulted in several phases of beach nourishment at Bournemouth. The coast between Studland and Hurst spit in the east is dominated by shingle and sand beaches backed by low cliffs, and sand dunes are a feature at the Studland and Godlinston Heaths SSSI in the west.

The area of the Solent includes a complex of drowned estuaries which are now harbours (Southampton, Portsmouth) and that are partially sheltered by the Isle of Wight. Sediment inputs to the Solent are largely trapped by coastal and flood defence works leading to a depleted sediment budget and an associated requirement to offset erosion in certain areas through nourishment works, for instance at Hurst Spit[8]. Littoral and tidal sediment transport in the Solent tends to be is from west to east, with some wave driven sediment moving north and northwest into the East Solent and ebb tidal current meanders generating westward recirculation in the West Solent, transporting material to the Solent Bank.

The coast of the Isle of Wight has a varied geology including chalk (exposed at the Needles and Culver Cliff), and softer Wealden sediments in the south east, and Bembridge Limestone, which is more resistant to erosion than the other geology and is responsible the majority of headlands (SCOPAC 2004). The coast is subject to erosion, particularly in the south where exposure is greatest. Sediment transport movement is variously influenced by estuaries, headlands and nearshore subtidal features (e.g. St. Catherine's Deep). The dominant littoral sediment transport direction is from west to east, with substantial sediment inputs (in some cases >20,000m^3/year) to the coastal system being made on the south west and south coasts of the island from erosional inputs. In the north east, dominant transport is northeast from Bembridge Point to Ryde, and transport convergence occurs at estuary mouths including the Yar. In the Solent, sediments reach sinks including Brambles Bank and Ryde Sands.

To the east of the Solent, the topography is controlled by underlying Tertiary clays and sandstones resulting in a low-lying coast. The shoreline between the entrances to Portsmouth, Langstone and Chichester Harbour, is comprised of gravel barrier beaches interrupted by the narrow harbour entrances which generate strong tidal currents, and can move sediment offshore to sinks including Horse and Dean Sand. The harbour entrances include large spits and are characterised by muddy sediments and saltmarsh which are qualifying features for designations and are valuable habitats for associated species (e.g. Chichester and Langstone Harbours SPA).

The Tertiary rocks which make up Hayling Island continue to the low lying Selsey peninsula, which includes the well defined headland of Selsey Bill, which was formerly subject to high rates of erosion and now has extensive coastal defences (e.g. groyne fields, nearshore breakwaters). The headland separates two sediment transport cells, and sediment transport is influenced by a number of nearshore banks, shoals and reefs, for instance the Mixon, which has also influenced the formation of the triangular shape of Selsey Bill. To the east, Pagham Harbour resides in an embayment enclosed by spits that have been subject to stabilisation and include tidal flats and saltmarsh providing habitat for waterfowl populations. Shingle beaches backed by the low lying West Sussex Coastal Plain continue eastwards to Brighton which are subject to erosion and extensive coastal defence structures (e.g. at Elmer). Littoral sediment transport to the east of this section is predominantly west to east resulting from the south-westerly wave approach, with a local reversal in the lee of Dungeness.

To the East of Brighton coastal exposures of chalk form cliffs including the Seven Sisters which are a series of truncated hanging dry valleys, and Beachy Head which reaches 163m in height. Erosion rates on this section of coast are relatively high (~0.5m/year), particularly in the area around Birling Gap. Beachy Head and its chalk foreshore are of particular geological interest, and continue subtidally to provide subtidal chalk ridges which form habitats occupied by, *inter alia*, blue mussel and native oyster. Shingle ridges form the predominant coastal landform

[8] New Forest District Council (2010), North Solent Shoreline Management Plan.

between Eastbourne and Hastings, after which the wide shingle beach at Hastings is maintained by groynes. East of Hastings, the cliffs at Fairlight rise to approximately 150m, before reducing to the low lying Pett Levels.

The Dungeness foreland is the largest of its kind in Britain and is largely comprised of flint shingle likely derived from redistributed barrier beach sediments and containing a series of shingle ridges marking its evolution, and which are still prograding (May 2003c). The low-lying foreland, and sand and shingle coast to the east, is backed by the Denge, Romney and Walland Marshes. The section of coast encompassing the south marine plan areas ends at Hythe, which has a shingle beach defended by several rock groyne structures.

A1b.6 Features of Regional Seas 4 & 5

The seabed of the area of the western English Channel, like that further east, is significantly controlled by Eocene and Oligocene planation resulting in the levelling of the inner shelf. The shelf is largely featureless with the exception of some outcrops of igneous rocks where sand ridges and waves have developed (Jones *et al.* 2004b), and in the mid-shelf to the east of the south-west peninsula, Haig Fras crops out to just 38m below the seabed, from surrounding depths of 100-110m.

Water depths on the continental shelf gradually deepen away from the coast in a southwesterly direction to between 140 and 180m at the shelf break. Isolated deeps occur towards the shelf edge, and the varying topography here is partly controlled by major tidal sand ridges (discussed below). The Celtic Deep is a seabed depression at the southeastern end of St. George’s Channel which reaches a maximum depth of 127m, with an average depth of around 110m, and is overlain by significant thicknesses (in places up to 400m) of Quaternary material (Tappin *et al.* 1994). To the east of Regional Sea 4 between 4°W and 2°W, the Hurd Deep is an isolated channel reaching 172m depth, constituting part of the palaeovalley complex of the English Channel, thought to have been cut out in the mid-Pleistocene during a catastrophic flooding event which resulted from the breach of the Weald-Artois Anticline at the Dover Straits (Gibbard 1995).

In addition to this deep, palaeo-processes associated with the now extinct Channel River (see Regional Sea 3 above) generated a significant depositional sedimentary environment to the west of the English Channel, responsible for the Celtic Sea sandbanks and deep-sea fans at the shelf break and slope (Lericolais *et al.* 2003). The Channel River may have reached the shelf break in certain low stands (the most recent of which was the late glacial period within the Devensian) where the sea-level was reduced to below the -100m isobath (Lericolais *et al.* 2003). Erosional forces associated with multiple marine transgressions in the Pleistocene have also influenced the Quaternary sediment profile of the area, though this area would have been free from direct glacial reworking throughout the Pleistocene. A survey of the Explorer and Dangaard Canyons on the shelf slope revealed a number of features associated with slope failure (e.g. slumps, slide and slump scars) and dendritic patterns also derived from such sediment failures, but also due to fluvial processes dating back to the Pleistocene period (Davies *et al.* 2008). Erosional features at canyon margins highlight the presence of deep-sea currents transporting suspended material, and the proximity of canyon heads to sandwave fields on the continental shelf and in the Celtic Sea provides a conduit for sediment transport to the shelf slope (Davies *et al.* 2008).

A1b.6.1 Substrates

Sediments deposited in the Western Approaches during previous interglacial periods when sea levels were analogous to modern times would have been extensively eroded during subsequent low-stands and marine transgressions. Such Pleistocene sediments are only preserved in the west where the outer shelf was not as exposed (Jones *et al.* 2004b). Quaternary deposits as a whole are sparse and decline in thickness to the east. The Melville Formation – a deposit of Pleistocene material similar in composition to lodgement till, deposited by drifting ice – is located primarily in the middle and outer shelf. This formation is overlain by poorly sorted sand and shelly gravel and at the coast, coarse sand a few tens of centimetres thick which contains some ice-rafted erratics up to 0.5m in diameter (Evans 1990). Partly overlying this layer, sediments deposited following the wave erosion of the Devensian-Flandrian transgression (Late glacial-early Holocene) are present and are mobilised at their surface by modern bottom currents (Evans 1990).

The seabed sediments of the region primarily consist of deposits derived from either former terrestrial sediments and/or biogenic accumulations. Modern input of material from the coastal margins is extremely small and is derived from coastal erosion and riverine sources and much sediment is autochthonous, derived from reworking of seabed material (Reynaud *et al.* 2003). Almost all marine deposits in the channel can be connected with temperate conditions with the exception of ice-rafted clasts (Bates *et al.* 2003). The substrates to the east of the western channel are defined by an area of high tidal current velocities leaving almost no sandy cover (Reynaud *et al.* 2003) with gravel and sandy gravel dominating the seabed, particularly away from the coast. Sediments in the Western Approaches vary from biogenic sand, to gravelly sand, whereas to the north-west, in the Celtic Bank area, mud and sandy mud are present which may be glacially derived.

A1b.6.2 Sandbanks and sandwaves

Sandwaves cover the western English Channel, passing into ribbons where tidal stresses are greater, leaving bare rock or reef environments at the coast. Rippled sand sheets are present in the Western Approaches and Celtic Sea (Evans 1990). Reynaud *et al.* (1999a) provide a summary detailing various previous interpretations of the genesis of the Celtic Sea sand banks which include both erosional (e.g. Berné *et al.* 1998) and depositional beginnings (Reynaud *et al.* 1999b).

Larger tidal sand ridges (up to 200km long and 60m high) occur close to the shelf break, orientated normal to it in a north-easterly direction (Evans 1990, Dyer & Huntley 1999). The surfaces of these ridges are covered in sandwaves which continue to be modified, though the larger features themselves are moribund, relicts from the Devensian low-stand (e.g. the Celtic Banks, the Kaiser Bank). The Celtic Banks are a qualifying geological feature of the South-West Deeps (West) MCZ, constituting the largest known examples of tidal sand ridges (Scourse *et al.* 2009). Investigations of the Kaiser Bank flanks in the outer shelf of the Western Approaches revealed a tide-dominated regime promoting dune and ripple formation and, at depths of less than 145m, wave generated ribbons (Reynaud *et al.* 1999a). Lockhart *et al.* (2018) presented an interpretation of these mega ridges using high-resolution geophysical data correlated to sediment cores. The authors suggest the ridges comprise post-glacial tidal deposits (the Meville Formation, constraining their age to 24.3 to 14 kaBP) overlying a partially eroded Upper Little Sole Formation, and a surficial drape of fining-up sediments resulting from prolonged exposure to wave action as tidal currents reduced towards the end of the marine transgression.

Maerl beds are a feature of coastal parts of Regional Sea 4 and consist of free-living coralline red algae (Corallinaceae). These are categorised within the Annex I SAC habitat, *Sandbanks which are slightly covered by sea water all of the time*, and are a feature of the Fal and Helford (Cornwall) SAC designation, which hosts the largest maerl bed in England and Wales at 150ha (Jones *et al.* 2004a), and are also a UKBAP priority habitat and on the list of OSPAR threatened and/or declining species and habitats (see Appendix 1j).

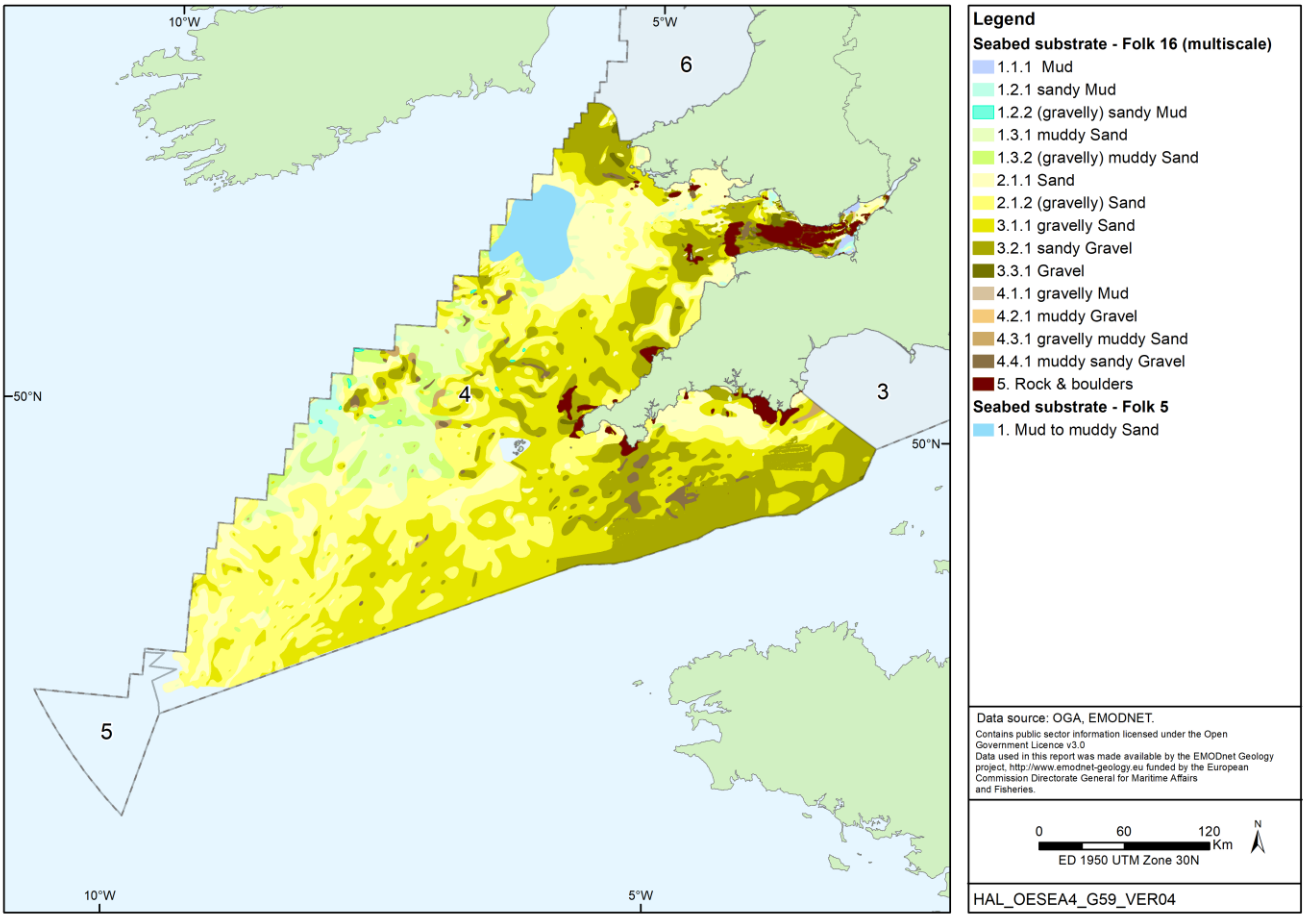
A1b.6.3 Reefs

There are several marine SACs within the 12nm limit which include reefs as a primary criteria for site selection (Isles of Scilly, Plymouth Sound and Estuaries, Lundy), and a few others where reefs are a secondary feature (Fal and Helford, Severn Estuary). Outside the 12nm limit, areas of bare rock and coarse sediment are present, or predicted to be present (see Figure A1b.3, Figure A1b.10), which may be suitable reef habitats.

The MESH survey of the South West Approaches set out with the prediction that canyons located within the South West Approaches on the shelf margin and continental slope may contain bedrock and cold water coral biogenic reefs (Davies *et al.* 2008), and Howell *et al.* (2010) collected biological data within an area of search as a possible SAC, which focussed on the flanks of the canyon features. The substrata and biological characteristics of two of these canyons (Explorer and Dangaard Canyon) were studied, revealing the presence of Annex I biogenic reef (*Lophelia pertusa* reef) and bedrock reef, though no stony reef. The Canyons area has been designated as a Marine Conservation Zone (MCZ) for deep-sea bed habitats and cold water coral reef (*Lophelia pertusa*) on the northernmost wall of the Dangaard Canyon.

The area of Haig Fras is designated as an offshore SAC, and is the only area of rocky reef in the Celtic Sea. Haig Fras is a shoal of three resistant granitic bodies at a distance of *c.* 150km north-west of Lands End (Evans 1990). The uppermost exposed bedrock pinnacle measures less than 1km across, with the overall exposure being approximately 15km by 45km (Rees 2000), covering a total area of *c.* 35,650ha (flat mapped), putting the reef into grade C for area (0-2% of total rocky reef resource), though for representativeness and structure the site is considered as grade A (JNCC 2008a). The areal extent which was designated covers 47,569ha. A further survey of the site was undertaken in 2012, with the full extent of rocky reef (176km^2) being mapped (along with benthic sampling), with approximately 26km^2 of this being outside of the present Haig Fras SAC boundary (Barrio Froján 2015). Ecological information relating to this site is provided in Section A1a.2. The wider Haig Fras geological feature is part of a MCZ, which has also been selected on the basis of a range of habitats types ranging from coarse sediment to muds and related faunal communities (see Appendix 1j).

Figure A1b.10: Seabed substrates in Regional Seas 4 & 5



A1b.6.4 Coastal geomorphology

The geological characteristics of the western peninsula produce a coastline which is more resistant to erosion than the soft chalk and Tertiary cliffs further east (Clayton & Shamoon 1998, also see Regional Sea 3). The Scilly Isles are made up of an igneous, granitic shoal (Evans 1990), with 5 inhabited isles and numerous others which are not inhabited. Some of the larger islands have been formed as a result of being linked by tombolos or low terraces (Mitchell & Orme 1967 in May 2003d) and constitute the largest British group of tied islands (May 2003d). Sandy beaches of till and weathered granite are present throughout the islands.

Devon and Cornwall are mostly backed by steep cliffs rising to 100m which are best developed on the northern coast of the peninsula (exemplified at Tintagel and Harland Quay), being more broken on the south coast by rias where the sea penetrates inland along mature valleys (Evans 1990). A number of features including dune systems, sand spits and shingle beaches are present. Sandy beach and dune systems are present along the Bristol Channel coast, for instance at Carmarthen and Oxwich Bay, and further south on the southwest peninsula at Upton and Gwithian Towans, where there is a sandy dune shore which gives way to an exhumed cliff line to the north (May 2003c). Further north at Braunton Burrows there is another example of an extensive dune system (6km in length) at the mouth of the Taw-Torridge estuary which accompanies a sand spit. The other significant sand spit feature on the English coast of Regional Sea 4 is at Dawlish Warren on the Exe Estuary.

Significant shingle structures in Regional Sea 4 include the gravel beaches at Loe Bar, Slapton Sands and Westward Ho! The two former sites, like Chesil Beach (Regional Sea 3), are backed by lagoons and cliffs, Slapton Sands having an excellent example of a cobble spit. At

Slapton Sands, the present gravel beach once extended south to Hallsands, an area which has suffered erosion of its shingle beach and the exhumation of former cliffs, as well as the loss of the village of Hallsands itself to erosion in 1917 (May 2003b).

Carmarthen Bay on the southern Welsh coast may have the most varied assemblage of coastal features anywhere in the British Isles, and has been relatively undisturbed by anthropogenic activities (May 2003e). Sitting at the mouth of the Taf, Twyi and Gwendraeth estuaries, the site includes major dunes, sand spits, barrier beaches, hard and soft-rock cliffs, rias, raised beaches, intertidal sandflats and saltmarshes. Further west, past St. Govan's Head is an active cliff coastline of Carboniferous limestone which has formed a complex of geo, stack, cave and arch, that is retreating into an area of karstic landscape (May 2003a).

A1b.7 Features of Regional Sea 6

Regional Sea 6 has a complex sea-bed topography with many static, relict, bedforms indicative of glacial and peri-glacial activity (e.g. rôche moutonnées, pingos). The wider bathymetry of the area varies from shallow near-shore to deeper waters in the Firth of Clyde (80m), with a number of active bedforms including sandbanks and smaller sandwaves and ripples. A prominent north-south trough extends from the North Channel (120m), reaching 275m depth in the Beaufort's Dyke passing the Manx Depression, St George's Channel (120m), and towards the Celtic Deep. The areas of Cardigan Bay and Caernarfon Bay are relatively shallow with depths typically ranging between 40 and 80m. A substantial area to the north of Northern Ireland has been mapped by the Joint Irish Bathymetric Survey (JIBS) using high resolution bathymetric data collected by the Marine Institute of Ireland and the Marine and Coastguard Agency. A comprehensive overview of the geology and geomorphology of the Irish Sea is presented in Mellett *et al.* (2015).

A1b.7.1 Substrates

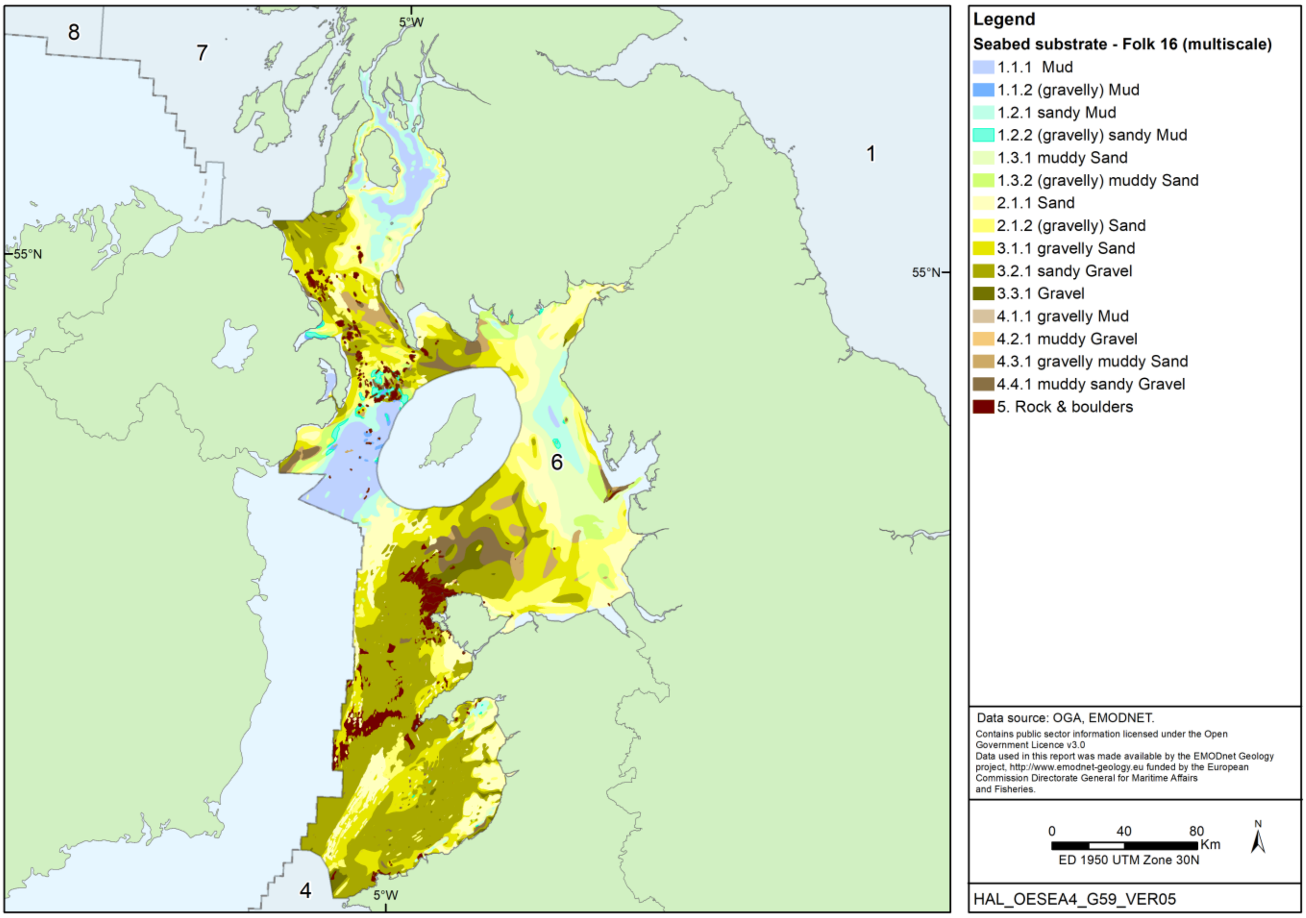
In the eastern Irish Sea there is a general transition south-east and east of the Isle of Man, towards the western English coast, from coarser-grained gravel and sand to mud (the Eastern Irish Sea Mud Belt) Belderson (1964). Along with the Western Irish Sea Mud Belt, the area is defined by depositional processes in the wider Irish Sea (see Coughlan *et al.* 2015, Murphy *et al.* 2016). The Eastern Irish Sea Mud Belt sediments have the potential to contain accumulations of shallow gas deposits (e.g. Judd & Hovland 1992, Judd 2005, Croker *et al.* 2005). Shallow gas has potential geotechnical implications and may also be represented at the surface by pockmark or methane derived authigenic carbonate (e.g. see Judd *et al.* 2019) which have the potential to be classified as the Annex I *submarine structures made by leaking gases* (see Section A1b.7.4 below).

To the east and south of Arran, muddy sediments range down to around 55°N in the Firth of Clyde. These muddy areas coincide with areas of weak bed stress, representing depositional environments. These areas were identified by Judd (2005) as potentially providing Holocene-based sources of methane – a key gas involved in the creation of MDAC habitats (see below).

Thin sandy, gravelly sediments generally less than 0.3m thick overly a layer of gravelly lag deposits comprising sandy, shelly and poorly sorted gravel, which makes up the floors of the St. George's Channel and North Channel (Jackson *et al.* 1995), the sand only thickening in areas of raised bedforms. Sand thickness increases towards the area of extensive mud to the west and east, varying in thickness from 0.5 to 40m, with surface variations accounted for by the development of sand waves and tidal sand ridges (Jackson *et al.* 1995).

The carbonate content of sediments is nearly 0% in the nearshore of Liverpool Bay, to the east of the Isle of Man, St. George's Channel and Cardigan Bay. Higher (10-25%) carbonate content occurs in sediments in the south-eastern lee of the Isle of Man, to the north and west of Anglesey and the Lleyn peninsula and south to Pembrokeshire.

Figure A1b.11: Seabed substrates in Regional Sea 6



A1b.7.2 Sandbanks and sandwaves

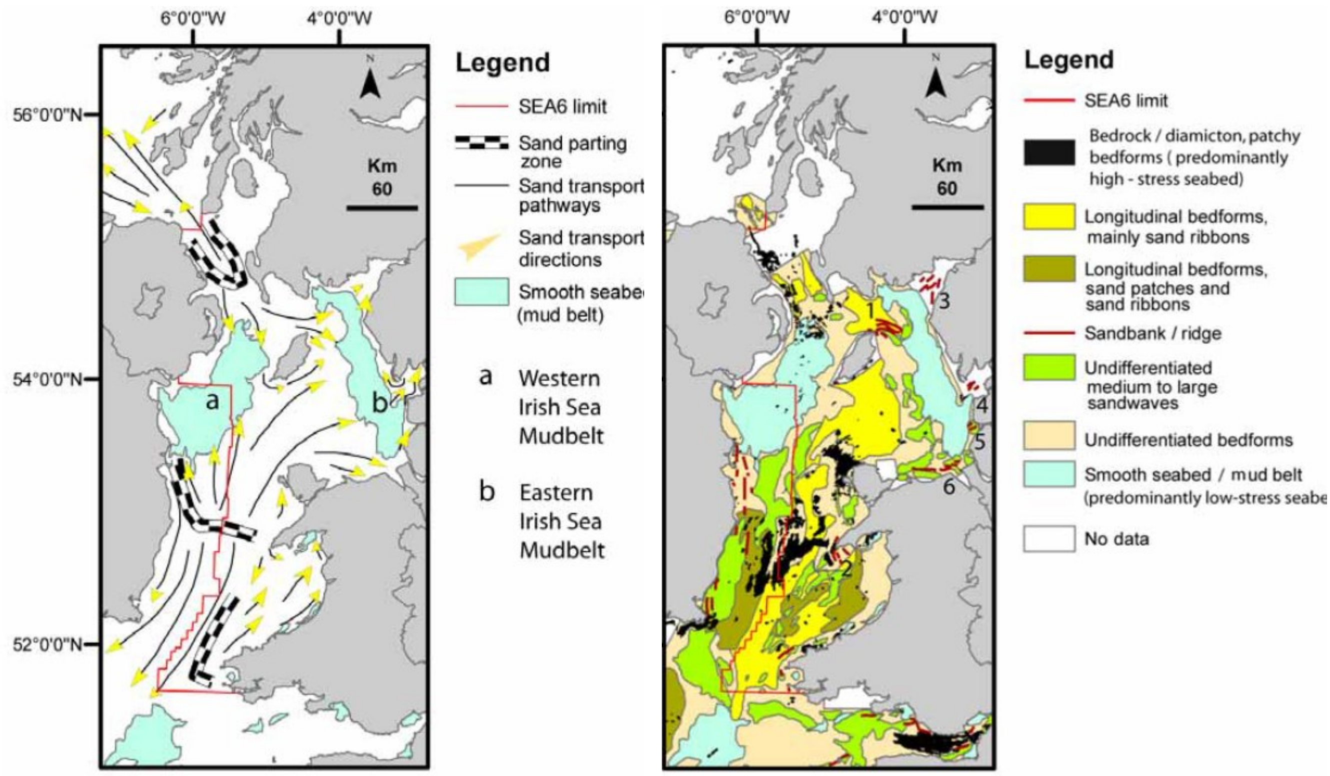
Substantial fields of sandwaves and sand ripple bedforms are present in Regional Sea 6, primarily south of 53°N, particularly between the Republic of Ireland and Welsh coasts (see the BGS regional reviews (Fyfe *et al.* 1993, Tappin *et al.* 1994, Jackson *et al.* 1995) and the technical reports for previous SEAs (Kenyon & Cooper 2005, Holmes & Tappin 2005). In the Irish Sea, sandbanks are located in the mouths of estuarine areas (Solway, Ribble, Morecambe Bay), around headlands (Llyn Peninsula), off North Wales, and to the east of the Isle of Man. These latter banks include the Bahama Bank, which is a combination of banner banks associated with erosion from the northern coast of the Isle of Man in the west, and a low bank extending to the south east by over 40km. The Ballacash and King William Banks are located to the north of these banks, showing an active surface with small to very large sandwaves are moving from west to east (Holmes & Tappin 2005). In the long term, the banner banks to the east of the Isle of Man leak sand to the shelf and are therefore only temporary sediment sinks (Holmes & Tappin 2005). The eastern extent of the Bahama Banks was subject to a 2004 MESH survey, which investigated the benthic fauna and sediments of the survey area.

The Shell Flat and Lune Deep SAC is located to the south of the entrance to Morecambe Bay and is partly designated for the Shell Flat banner bank, which forms a continuous structure

15km east to west at a depth of approximately 20m. The bank comprises a range of mud and sand sediments from silts and clays through to coarse sands (see Appendix 1j).

Other sand dominated bedforms range from tidal-parallel sand ribbons to larger transverse barchan-type sand waves and extensive sand patches with smaller sandwaves. These waves occur to the west of St. George's Channel, in the Nymphe Bank and to the west of Cardigan Bay, broadly coinciding with sandy seabed substrates. Sand ribbon features are often found downstream of small obstacles in relatively high shear stress conditions, and are therefore highly mobile (Holmes & Tappin 2005). Tidal stresses are moderate to strong (Connor *et al.* 2006) to the north and south of the Isle of Man, where sand ribbons are most abundant. Smaller linear sand streaks supplemented by linear sand ribbons occur across St. George's Channel and the Cardigan Bay area following a tide-parallel pattern, coinciding with sandy gravel deposits. Analysis of mobile and static bedforms has enabled the prediction of sediment transport pathways (Holmes & Tappin 2005) which are indicated in Figure A1b.12.

Figure A1b.12: Net sand transport and generalised mobile bedforms



Source: Holmes & Tappin (2005)

The abundance of sandwaves in the area has resulted in a number of SAC sites, for example at Menai Strait and Conwy Bay/Y Fenai a Bae Conwy, Cardigan Bay, Morecambe Bay, Murlough (Co. Down) and Pembrokeshire Marine/Sir Benfro Forol.

A1b.7.3 Reefs

A number of reefs were described in the 2004 DTI survey of the SEA 6 area and a number of locations in Regional Sea 6 have reefs as a qualifying feature in their designation as an SAC, for example, Pembrokeshire Marine, Lleyn Peninsula and the Sarnau, Strangford Lough (Co. Down) and Menai Strait and Conwy Bay, the Pisces Reef Complex, the Lune Deep aspect of Shell Flat and Lune Deep, and the Maidens SAC (see Figure A1b.3 for potential areas of hard ground/reef on the UKCS and related designations). Offshore, Pisces reef is a 1.4km outcrop of rock lying in an area of soft mud to the west of the Isle of Man, rising to about 60m above the seabed. Soft sediments infill hollows in the rock structure, and the area designated as an SAC comprises both bedrock and boulder-dominated stony reef at distances of between 5.5km and 14km from one another, though not covering the intervening muds. The three reef areas are tertiary igneous rock and boulders with a veneer of silty bedrock and muddy sediment.

Potential areas of biogenic reef have been identified off north-west Anglesey through surveys undertaken by Rees (2005) for SEA 6. These areas of horse mussel *Modiolus modiolus* reef are discussed further in Section A1a.2.

A1b.7.4 Methane-Derived Authigenic Carbonate (MDAC)

MDAC is formed close to the seabed and is closely associated with gas seeps (Judd *et al.* 2007) where calcite precipitates and fills pore spaces between sand grains forming hard ground (JNCC 2012). The resulting cemented material may have a high magnesium, calcite, dolomite or aragonite content (Judd *et al.* 2007, Milodowski *et al*, 2009).

Previous surveys undertaken as part of the SEA programme revealed the presence of MDAC in an area called Texel 11 located in the eastern Irish Sea close to the median line (Judd 2005, Judd *et al.* 2007), now the Croker Carbonate Slabs SAC designated for the qualifying habitat, *Submarine structures made by leaking gases*. A further survey of the area encompassing Texel 11 was undertaken in 2008 (Whomersley *et al*. 2010) which identified extensive MDAC structures at this location which were characterised as low relief pavements or slabs up to 20mm thick, and high relief structures greater than this thickness and up to 2m in height, surrounded by extensive areas of circalittoral coarse sediment. Following further survey and analysis in 2015, Judd *et al.* (2019) noted that MDAC has been forming at the site since the marine transgression at the end of the last ice age and is ongoing (e.g. as evidenced by bubbles in the water column, possible sulphidic sediments, and possible *Beggiatoa* mats). The topographic relief of the Croker Carbonate Slabs ranged from relatively flat, but in places was up 6m above the surrounding seabed, with the higher areas extensively colonised by diverse epifauna. Mineralogical analysis presented in Judd *et al.* (2019) and Field *et al.* (2016a, b) noted that the MDAC contained poorly compacted, quartz-dominated sandstones and siltstones with various quantities of bioclastic material and cemented carbonate minerals, with the later containing either high magnesium calcite, aragonite, or a combination of these. The distribution of MDAC for which there is a high confidence of presence was estimated to be 20km^2, with a further 37km^2 identified to be potential MDAC (Judd *et al.* 2019). The potential presence of MDAC outside the boundary of the Croker Carbonate Slabs is evidenced through MBES data, but these have not yet been investigated.

Holden's reef lies in the near-shore area of Cardigan Bay off Barmouth and was also found to contain cemented hard ground generated by MDAC, covering an area of approximately 40,000m^2. A few pockmark fields were identified in the muddy sediments to the west of St. George's Channel in the north-west Irish Sea, just south of 54°N in an area of high carbonate content. Other areas containing shallow gas identified by acoustic turbidity have no surface pockmark expressions, possibly due to the softness of the seabed sediments (Judd 2005). At the median line and western Irish Sea, the Codling Fault, a major strike-slip fault extending from the Kish Bank Basin, near the Irish Coast, south-east towards Cardigan Bay (Judd 2005). Though the presence of MDAC or shallow gas for an area in the UK sector could not be confirmed in the 2004 survey, evidence supports the presence of MDAC in the Irish sector (O'Reilly *et al.* 2014), including active seeps and stacked pavements.

It is considered probable that further areas of MDAC are located in the Irish Sea (e.g. due to the distribution of potential sources of methane of Holocene to Carboniferous ages, and the availability of fluid migration pathways), and though not confirmed Judd (2005) notes potential methane sources, gas migration pathways, shallow gas, elevated methane concentrations in sediment pore waters, elevated methane concentrations in seawater, and pockmarks, suggest the presence of MDAC at a range of other sites including Lune Deep, Wigtown Bay, the area of Yuan pockmarks, Peel Basin and St George’s Wall.

A1b.7.5 Glacigenic bedforms

Glacially influenced relict bedforms occur extensively throughout Regional Sea 6. Rôche Moutonnées occur between the eastern Irish coast and the Isle of Man; these are subglacial bedforms which are orientated to the south in the direction of ice flow. To the west of Anglesey and north to the Isle of Man, polygonal textured bedforms originally described by Wigfield (1987) are derived by periglacial ice-wedging, generating features ranging from 15-80m in diameter. Former pingos are also a feature of the area, generated in permafrost conditions when an ice wedge pushes sediment up from the surface to create a dome, which eventually collapses to leave a ridge representing the former dome edge – the diameter of domes can vary from 10-500m in diameter (Holmes & Tappin 2005).

A1b.7.6 Coastal geomorphology

The coast of south-west Wales is characterised by a series of cliffs and small sandy bays, the largest being Whitesand Bay (Evans 1996). North of Aberystwyth, Cardigan Bay supports a sequence of estuaries (e.g. Teifi, Dyfe and Glaslyn), cliffs (e.g. at Dinas Head and Cemaes Head) and sand dunes. The northern estuaries of Dyfi, Mawddach and Glaslyn are surrounded by saltmarsh, and dune covered spits extend northwards from the southern shores of the estuaries, leading to enclosure and of marshland (Evans 1996). Two spits are located between the Mawddach and Glaslyn estuaries, Morfa Dyffryn and Morfa Harlech, both shingle structures and indicating a northerly sediment transport direction (Evans 1996). The southern spit, Morfa Dyffryn, is really a large sand tombolo originally developed as a spit, with a narrow shingle beach and low dunes to the south and higher and larger dunes enclosing slacks and low glacial cliffs to the north (May 2003a). Morfa Harlech is a well developed spit and is a good example of a multi-phased, gravel based sand spit which remains active and relatively unspoilt (May 2003b).

Further north the Lleyn Peninsula and Anglesey have rockier coastlines though Anglesey supports several sand dune systems, for example at Newborough Warren (CEFAS 2000). The coast also includes exposures of glacial till (e.g. at Porth Dinallaen) and a series of spit complexes at the mouth of the Menai Strait (Evans 1996). The Menai Strait is generally just a few hundred metres wide, emerging in the east to a narrow sandy section of coast and sand dunes at the mouth of the Conwy, interrupted to the east by the near vertical cliffs of the Great Orme (Evans 1995). Further east, rocky headlands are interspersed with open bays backed by sand and shingle beaches, with much of the low landward area being covered by till which contributes to beach sediments (BGS 1995).

From Liverpool Bay to the Solway Firth the majority of the land is low-lying and includes a number of important estuaries containing areas of saltmarsh, sand or mud flats and sand dunes. Of the 14 major estuaries in this region, all except one are larger than 5,000ha, including Morecambe Bay which is the second largest area of intertidal mud and sand in the UK after the Wash. Much of the estuarine coast in the middle of the region has been highly developed with major industrial and port facilities on the River Mersey and on the Wirral, and to a lesser extent on the River Dee (CEFAS 2000). To the north, rocky shores dominate the coast running from the Solway Firth to the Mull of Galloway. The east and south-west coasts of the Isle of Man also consist of rocky shores with sandy beaches in the exposed north-west (CEFAS 2000).

The coast of Northern Ireland is extremely varied, incorporating high cliffs, extensive sand dunes, mudflats and rocky shores. The principal features are the three sea loughs (Larne, Strangford and Carlingford) which are characterised by fine sand and muddy sediments. Along much of the rest of the coast, sandy beaches and shingle are interspersed along rocky shores with rock outcrops and low cliffs more extensive towards the border with the Republic of Ireland (CEFAS 2000).

Coastal defence works occur widely around the Welsh coast though are concentrated in Carmarthen Bay, the Dyfi, Mawddach and Glaslyn estuaries (though almost all estuaries have been modified in some way) and Malltreath Bay on Anglesey (Dunbar *et al.* 1995).

A1b.8 Features of Regional Sea 7

Regional Sea 7 has a complex sea-bed topography varying from shallow coastal areas to isolated deeps of 200m or 300m (e.g. the Inner Sound between Raasay and the mainland), resulting from past glacial processes acting on rocks of differing strengths (Fyfe *et al.* 1993).

A1b.8.1 Substrates

Mud and sandy mud dominate the Little Minch and the Sea of the Hebrides with sandy material comprising much of the surficial sediments to the north in the Minch and south in the Malin Sea around Stanton Banks and Blackstones Bank (Figure A1b.13). Sediment sorting generally increases from Skye (unsorted) north towards the Butt of Lewis and Cape Wrath; the well-sorted material being lithic sand less than 10cm thick probably of periglacial origin (Bishop & Jones 1979). The biogenic fraction of sands varies widely from *c.* 5% in the Minch, 35% between Lough Foyle and Benbane Head, up to 55% southeast of Islay (Fyfe *et al.* 1993).

Coarse sediment (sandy gravel, gravel) is more abundant further south, e.g. to the west of Islay and the North Channel, due to strong currents. Further north, offshore gravelly sediments often reflect onshore geology, with clasts of Lewisian material making up assemblages off the Outer Hebrides, and Mesozoic Permo-Triassic and Jurassic material being found around Skye and Raasay.

The largest rock outcrop in the area is in the North Channel, with other areas including the Stanton Banks, Blackstones Bank, Hawes Bank and platforms extending from Canna, Tiree, south-west Mull and Islay (Fyfe *et al.* 1993, also see Gafeira *et al.* 2010, Baxter *et al.* 2011).

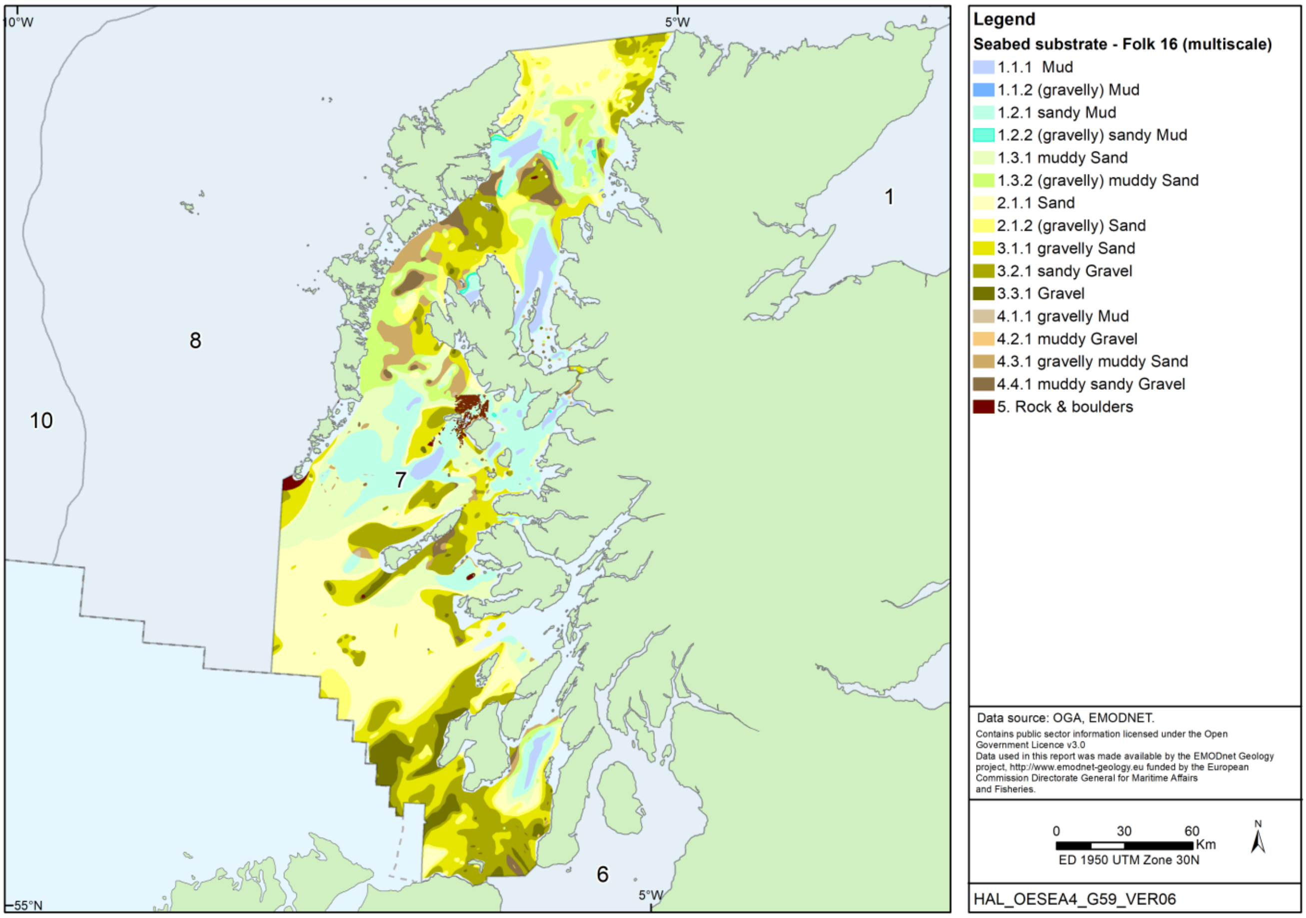
A1b.8.2 Sandbanks and sandwaves

Sandwaves, sand ribbons and sand ripples are all features of Regional Sea 7 and are consistent with tidal and residual currents which play a major part in the net transport of sand along the shelf, though features larger than sand ripples are largely absent from the Hebrides shelf due to a lack of modern inorganic sediment input (Holmes *et al.* 2006). Sand waves occur off the north east coast of Lewis in shell sands, in the Malin Sea, Inner Hebrides, south of Mull and the Firth of Clyde (Fyfe *et al.* 1993). Off the Northern Irish coast sandwaves reach a maximum height of 30m with a morphology suggesting eastwards migration. Smaller sand ripples occur between rock outcrops in the shell sand of the Stanton Banks and in gravelly and sandy sediments in the Passage of Oronsay and the north end of the Sound of Islay. Sand ribbons predominate in the north and between Islay and Malin Head, and the North Channel.

A1b.8.3 Reefs

To the west and south of the Outer Hebrides, there is a substantial area considered to be potential rocky reef owing to the seabed substrate there, which is primarily rock outcrop of Lewisian gneiss (see section on Regional Sea 8). There are a number of areas within Regional Sea 7 where reefs constitute an Annex I habitat in a designated SAC (e.g. Firth of Lorn, Loch Creran, Lochs Duich, Long and Alsh Reefs, Rathlin Island, Skerries and Causeway SAC, East Mingulay SAC, Sound of Barra SAC and Stanton Banks SAC), or where the Annex I habitat is a qualifying feature, but not a primary reason for SAC site selection (e.g. Loch Laxford, Loch nam Madadh, Sunart, Treshnish Isles). See Appendix 1j for more information on relevant conservation designations and Figure A1b.3 for a map of their location in relation to wider potential UKCS reef habitat/hard ground. In addition to these sites, zones where high carbonate input is associated with submarine bedrock outcrop might be regarded as fringing reefs (Holmes *et al*. 2006).

Figure A1b.13: Seabed substrates in Regional Sea 7



A1b.8.4 Glacigenic bedforms

The cyclic expansion of glaciers during the Pleistocene has led to erosion and sediment deposition of glacigenic material offshore. For instance, buried submarine moraines on the outer shelf mark the limit of the last glacial maximum in the area, in addition to relict, static bedforms such as drumlins and iceberg scour. Erosion has featured heavily, generating glacigenic troughs in weaker rocks, and islands, pinnacles and rock platforms on the Hebrides shelf which generally consists of more resistant igneous and/or metamorphic bedrock (Holmes *et al.* 2006).

A1b.8.5 Coastal geomorphology

The Regional Sea 7 coast consists largely of cliff and sand dune environments interspersed with small areas of shingle beach. The region has *c.* 29% of the British hard cliff coastline and therefore represents a significant resource (Barne *et al.* 1997c, f). Lewisian gneiss dominates the eastern coast of the Outer Hebrides with near-vertical cliffs (Dargie 1997), the west having more prolific sand dune formations partly due to the islands' west-east upward tilt, particularly in the south (BGS & Threadgould 1997). Elsewhere the coastal geology is more varied, with notable outcrops of Tertiary volcanics on Rum, Eigg, Skye and Mull, and Torridonian sandstones and Lewisian gneiss making up much of the mainland coast. Further south on Mull, igneous rocks dominate north of the Great Glen Fault, while further south Dalradian rocks make up much of the coastal geology. In addition to cliffs notable features include caves (e.g. Fingal's Cave, Staffa), raised beaches and fossil cliffs (e.g. Jura). These cliffs provide a substantial habitat resource for bird fauna recognised by a number of SPA designations in the area (e.g. Rum, Ardmeanach, Rinns of Islay).

Although numerous dune or machair sites occur in the area, almost all are of a small size and no large systems like those seen on the western coast of the Outer Hebrides occur on the western mainland. Tiree contains the largest dune system within the Inner Hebrides at 785ha, and is recognised as an SAC on account of its mobile and fixed dune, and machair which encompasses 24% of the island. The eastern coast of the Outer Hebrides largely lacks dune coverage (apart from in the far north and south) due to the dominance of cliff habitat discussed above. Many of the island dune systems are recognised in SSSI or SAC designations. Dune systems provide habitat for a significant floral resource (Dargie 1993 – cited in Dargie 1997). Wildfowl and wader populations are also of importance in relation to machair systems, though these are largely restricted to the western coast of the Outer Hebrides.

A1b.9 Features of Regional Sea 8

Regional Sea 8 covers the area of the West Shetland Shelf, Hebrides Shelf and parts of the West Shetland Slope (see Figure A1b.15). The West Shetland Shelf is relatively flat with depths of between 70 and 120m, the shelf break being located at between 120 and 250m (Stoker *et al.* 1993). Seabed morphology is strongly controlled by glacigenic deposits including moraine complexes running parallel to the shelf break and prograding Plio-Pleistocene wedges (Figure A1b.15, see Stevenson *et al.* 2011 and Clarke *et al.* 2017).

There is little modern sediment input to the continental shelf of Regional Sea 8 and the modern seabed environment now largely reflects the effects of reworking by near-bottom currents on the topography and sediments that originated during the former glaciations. The effects of glacial erosion are evident on the outer continental shelf and upper slope but there are also bedforms generated from sediment deposition as the ice sheets advanced and retreated. Inner shelf and nearshore sediments include a substantial component of carbonate fragments derived from benthic fauna during the Holocene.

A1b.9.1 Seabed substrates

There is much spatial variation in sediment grain size, sand and gravel tend to dominate the shelf deposits, whereas muds are located in deeper waters along part of the continental slope at depths greater than 500m (Figure A1b.14)[9]. Sediments in the region are mostly of glacigenic origin, having been reworked in the late glacial or Holocene, with terrestrial inputs to the area largely absent (Stevenson *et al.* 2011). Biogenic carbonate production has contributed to contemporary shelf sediments, and continues to do so (Stoker *et al.* 1993).

Outcrops of submarine rock consist of strong sedimentary material of more than 210Ma age and extremely strong crystalline metamorphic rock of more than 545Ma age. Coastal and mid-shelf areas underlain by these crystalline rocks have resisted repeated glacial erosion and are now mostly swept clean of mobile sediments by very strong near-bottom currents. The Outer Hebrides Platform is a significant outcrop of rock to the west of the Outer Hebrides consisting of the dominant Lewisian geology of the wider Foreland Province (Cotterill & Leslie 2013) – the Flannan Ridge and Islands are a northern extension of this platform (Cotterill & Leslie 2013), and the Lewisian sediments also make up North Rona and Sula Sgeir. On the Hebrides Shelf, St. Kilda is a feature of bedrock outcrop, though in this case it is of Tertiary igneous intrusive derivation (Stoker *et al.* 1993). The Outer Hebrides Platform has a glaciated topography similar to the terrestrial extension of this formation, with exposed bedrock highs and infilled hollows, and is also overlain in places by large mobile bedforms (Cotterill & Leslie 2013).

In many shelf locations, but particularly on topographic highs, gravel fields form lag deposits that are exposed or covered by thin mobile seabed sediments for example, extensive fields of seabed gravel occur on regional features such as the Otter, Papa, Stormy and Solan Banks situated to the north and west of Orkney. In contrast, ridges of lag gravel also occur on gravel berms formed by the seabed ploughing processes associated with iceberg scour. Coarse sediments (gravelly sand and sandy gravel) form a large part of the surficial, unconsolidated Holocene substrates in the Regional Sea 8 area. Inner shelf and nearshore areas of seabed rock and gravel support a diverse and prolific calcareous biota which contributes significantly to the proportion of calcium carbonate in nearshore sediments. These sediments represent major high-latitude centres of modern carbonate production (Farrow *et al.* 1984) consisting of bivalve and echinoid fragments, serpulid tubes, barnacle plates and bryozoans, the proportions and ages of which vary with location – ages of dated material varies from greater than 8,000 BP to 3,000 BP (Stoker *et al.* 1993). The carbonate component of the sand fraction of sediment in the area is generally 25-50%, rising to up to 100% between Orkney and Shetland. Carbonate content is tending to rise as inputs from local epifauna and infauna continue (Farrow *et al.* 1984).

West of Shetland, large areas of shelf are characterised by longitudinal sand patches overlying a gravel substrate. Individual sand patches are usually strongly elongate, typically a few tens to 200m wide by hundreds of metres to several km long. The predominant trend of the elongate patches is north-east to east-north-east. On the basis of sidescan sonar data, sand cover varies from <5% to >95%, but is typically in the 10-60% range (Masson 2003).

A baseline video survey of the Clair field in 2000 indicated that the seabed was tide scoured and varied from sand, through mixed sand, gravel and pebble, to cobble and boulder pavement, and PSA analysis of sediments including for the Lancaster field indicate the presence of mostly coarse sands and gravel. Topographic highs had a greater proportion of cobbles and boulders, although such rocks were ubiquitous over the survey area. The

[9] Seabed sediment data is now available as part of a harmonised map covering all European seas (http://www.emodnet-geology.eu/data-products/seabed-substrates/), however harmonisation across certain areas is limited by data availability and variations in sediment classification schemes used both within the UKCS and between adjacent states. More recently, geostatistical approaches to mapping have been proposed to produce such harmonised maps (e.g. Mitchell *et al.* 2019).

sediment pattern accorded with the BGS description of the area given by Stoker *et al.* (1993), with sediments arranged linearly, parallel to the tidal stream axis, with ribbons of sand alternating with coarser material. Over much of the area the layer of sand was thin and only partially covered the hard clay beneath (Hartley Anderson 2000, ERTSL 2001).

Muddy sediments are rare on the shelf with the exceptions of sheltered sea lochs and certain mid-shelf enclosed basins, generally as late-Pleistocene to early Holocene infill which has remained to due reduced currents (Stevenson *et al.* 2011). Muddy sand is not abundant and is found locally to the north west of Orkney (incorporating a pockmark field) and more extensively to the north-west of the Outer Hebrides and along the shelf slope. At other sites, thick sequences of sub-seabed mud occur under superficial sands and gravelly sands.

A1b.9.2 Sandbanks and sandwaves

Sand ripples are present along the outer shelf slope to the west of the Outer Hebrides, with a range of geometries that reflect the interaction of several currents, but with a predominant orientation parallel to bathymetric contours. These features are small (0.2m amplitudes) compared to larger sandwaves near the Outer Hebrides and sometimes overlying bedrock (Cotterill & Leslie 2013). Sand streaks, ribbons and ridges of varying sizes are orientated in parallel to inshore and tidal currents: the lack of significant modern sediment inputs to the Outer Hebrides shelf prevents more widespread large-scale bedforms (Cotterill & Leslie 2013).

Tidal sand banks, tidal sand ridges and fields of migrating sandy bedforms typically form in water depths ranging from 20-100m or more and in areas prone to the strongest wave and tide generated near-bottom currents. Sand waves occur along the northern Scottish mainland, to the south west of Orkney and north between the Northern Isles in the middle and inner shelf, often asymmetric indicating the net direction of sediment transport (Stoker *et al.* 1993), and are well developed in carbonate rich sediments between Orkney and Shetland Stevenson *et al.* 2011). Sandbanks occur to the north of Orkney reaching 30m in height and 10km in length, with well-developed sand waves on their flanks (Stevenson *et al.* 2011). What proportion of Holocene and glacigenic material these banks contain is uncertain (Stoker *et al.* 1993).

A1b.9.3 Pockmarks

Pockmarks appear to be rare in Regional Sea 8. Gafeira (2016) notes that more than 50 shallow pockmarks were identified on the seabed in a survey undertaken by Gardline in 2005 on behalf of the MCA to the west of Orkney. The surficial sediments (e.g. see Evans 1984) of slightly gravelly sand, sand and muddy sand do not reflect what would be expected in an area supporting pockmarks, however cores in the area reveal that these are underlain by silts and silty clays, and four showed the presence of hydrogen sulphide. All but two of the pockmarks are shallow, with only 15 deeper than 50cm. The two deeper pockmarks were 2.5m and 7m deep, with their morphology controlled by the deeper silt dominated sediment rather than the thin (generally 1m) upper muddy sand layer. Further investigation would be required to understand the processes involved in the formation of these pockmarks (Gafeira 2016).

A small area of apparently relict and extinct pockmarks appear to the north east of Rona, and the genesis of some similar features may result from other processes (e.g. plough marking, slope instability) (Stoker *et al.* 1993).

A1b.9.4 Glacigenic bedforms

Repeated glaciation and the advancement and retreat of ice sheets to the north west of Britain has generated a range of seabed features in this area (Figure A1b.15) including a number of

Plio-Pleistocene prograding wedge deposits which have extended the continental shelf break seaward (Stevenson *et al.* 2011, Dove *et al.* 2016) by up to 40km (Stoker & Varming 2011). These include the Sula Sgeir Fan (Bradwell & Stoker 2015) and the Rona and Foula Wedges which represent depositional trough-mouth fans, and also the North Sea Fan (Stoker & Varming 2011). This progradation has extended from the shelf to the floor of the Faroe-Shetland Channel since the mid-Pleistocene, with mass failure taking place on the West Shetland Slope in the form of the AFEN, Paleo-AFEN and Miller slides (Stoker & Varming 2011, Long *et al.* 2011 and references therein), and also on the Hebrides slope (e.g. associated with the Sula Sgeir Fan and Barra Fan) (see Cotterhill & Leslie 2013).

Moraine deposits are present across the Hebrides and West Shetland shelves (Figure A1b.15). Large arcuate ridges on the mid- and outer-shelves relate to the previous extent of ice grounded ice on the continental shelf (Stoker & Holmes 1991, Stoker *et al.* 1993, Bradwell *et al.* 2008), and large moraines show geographical association with glacially eroded troughs and trough-mouth fans (Dove *et al.* 2016). These features range in scale from tens of metres to more than 20km, with elevations of 20-50m above the seabed (Stevenson *et al.* 2011)

Partially infilled iceberg ploughmarks occur in Regional Sea 8 (Figure A1b.15) to the west of the Outer Hebrides on the upper shelf and slope at 200-500m depth (Cotterill & Leslie 2013), and north of Shetland at water depths of 200-450m (Masson 2001). These were generated by grounding of floating ice on the edge of the continental shelf during the late Pleistocene (Johnson *et al.* 1993, Stoker *et al.* 1993). These striating features extend for many kilometres in an overlapping path with a width of *c.* 20m and depth of *c.* 2m, flanked by ridges of gravelly material generating highly varied bed topography. This area coincides with an area defined by JNCC as the potential Annex I habitat; *rocky reef*. Ploughmarks were observed in areas including Rosemary Bank, the Wyville Thomson Ridge and Outer Hebrides Shelf, and also in water depths of less than 500m in the Faroe-Shetland Channel in the 2007 SEA 7 survey (Stewart & Davies 2007). They have also been observed in industry surveys, for example in the Penguins, Don North East (both Quad 211) and Lancaster (Quad 205) fields.

Together, the above features of Regional Sea 8, combined with those of the wider UKCS, contain much of the evidence relating to the nature of the British-Irish Ice Sheet, further research of which is important in understanding current information gaps in the dynamics of fast-moving ice streams (Bradwell & Stoker 2015, Gordon *et al.* 2018).

A1b.9.5 Reefs

Potential Annex I habitat reefs described as, rocky marine habitats or biological concretions that arise from the seabed, occur to the west of Shetland and the Outer Hebrides, and stony areas occur to the north and west of Regional Sea 8. Though not designated, these areas may contain the Annex I reefs habitat which results from animal and plant community development on rock or stable cobbles and boulders, or biogenic structures. Their distribution is partly controlled by underlying geology in addition to depth, oceanographic conditions, distance from the coast and geomorphological history, including past glacial episodes.

The Stanton Banks SAC and Wyville Thomson Ridge SAC were selected for designation partly due to the presence of the Annex I reef habitat. The Stanton Banks consist of bedrock mounds supporting communities typical of moderately exposed/circalittoral bedrock reef. Primarily in Regional Sea 8, but also with elements in Regional Seas 9 and 10, the Wyville Thomson Ridge forms part of the Greenland Scotland Ridge that extends from East Greenland to Scotland, forming a narrow north-westerly trending topographic barrier between the Faroe-Shetland Channel and the Rockall Trough, having a minimum depth of 400m (Cotterill & Leslie

2013). Both basaltic bedrock and extensive pebbles and cobble are present on the Wyville Thomson Ridge, and the area surveyed as part of the 2006 SEA 7 survey (Stewart & Davies 2007) identified biogenic material indicative of an extensive, but now dead, coral reef. This material is redistributed in the area by strong currents. The ridge also has iceberg ploughmarks which occur in more widely in Regional Seas 8 and 9 (see above).

A1b.9.6 Coastal geomorphology

High exposed cliffs formed from a variety of metamorphic, sedimentary and igneous rocks dominate much of the north coast of Scotland. Lewisian gneiss typically forms rounded and hummocky slopes, although in the vicinity of Cape Wrath it forms steep cliffs (Steers 1973). In Caithness, Old Red Sandstone forms high cliffs with stacks and geos, whereas the more intricate and indented coastline between Strathy Point and Loch Eriboll is largely formed of Moine rocks (Stoker *et al.* 1993). Loch Eriboll is one of three large sea lochs which cut into the western part of the coast in alignment with geological formations. Prominent headlands provide shelter for a number of beach and dune systems (Barne *et al*. 1996b).

The coast of the Outer Hebrides is composed of Lewisian gneiss, with many sea lochs of late Devensian origin and low cliffs commonly incised into the overlying glacial drift (BGS & Threadgould 1997). The west coast of the southern isles of North Uist, Benbecula and South Uist tend to be lower than in the east due to tilting, possibly associated with movement along the Minch fault in the Tertiary (BGS & Threadgould 1997). The west coasts of these islands also feature extensive beaches, machair, sand flats and dunes, the morphology of which is greatly controlled by the prevailing wind.

The Orkney Islands are generally low-lying with gentle slopes and rounded topography. Spectacular cliff and rock formations including sea stacks, arches, caves, geos and shore platforms characterise much of the western coastline, reflecting the dominant geological control of horizontally bedded sandstone and flagstone (Hansom 2003). The eastern coasts display predominantly rocky shorelines interspersed with sandy and shingle beaches and sand dunes. The islands are mostly composed of Devonian sedimentary rocks (410-360Ma), predominantly Middle and Upper Old Red Sandstone (Barne *et al*. 1997e).

A1b.10 Features of Regional Sea 9

The bulk of modern seabed sediments comprise substrates that are more than 10,000 years old and have been reworked from strata by currents generated by tides and waves. The slope area to the west of Shetland is characterised by a convex lower slope, possibly related to bottom-current erosion, and features related to slope instability, erosion (e.g. furrows and gullies), iceberg scouring and sediment transport (e.g. contourites). The Faroe-Shetland Channel separates the West Shetland Shelf and Faroes Shelf, being wider and deeper to the north east (190km wide and 2km deep) compared to the south west (90km wide and 1km deep), where it turns abruptly to the north west into the Faroe Bank Channel (Stevenson *et al.* 2011). Other major sedimentary bedforms on the West Shetland Slope and Faroe-Shetland Channel include sand waves, and the Judd Deeps.

A1b.10.1 Seabed substrates

Sediments in the region are mostly of glacigenic origin having been reworked in the late glacial or Holocene periods, with little Holocene sediment input. Modern sediment input to the continental slope and Faroe-Shetland Channel is limited, but biogenic accumulation has continued throughout the Holocene (Stoker *et al.* 1993).

North of the shelf break the seabed sediment grades from sand and gravelly sand into soft, silty clay with varying amounts of sand, larger clasts and shell fragments (Stevenson *et al.* 2011, see Figure A1b.14), also observed in industry survey for the area including for the Lyon and Cragganmore wells. Sampling of a southerly part of the Faroe-Shetland Channel NCMPA and adjacent areas in 2017 observed both sand and gravel sediment, and mixed sediments dominated by mud/clay (Taylor *et al.* 2019a). Similarly samples collected in 2018 from the Faroe-Shetland Sponge Belt NCMPA ranged from primarily mud, to muddy sand with gravel, with some samples containing large clasts (Taylor *et al.* 2019b). The grab samples from these surveys were sub-sampled for PSA analysis, but these results are not yet available.

The floor of much of the Faroe-Shetland Channel is characterised by relatively featureless mud and muddy sand with some gravel. The boundary between muddy sand and mud at the seafloor gradually moves deeper in the basin as it becomes narrower towards the south, reflecting the increasing importance of bottom currents.

Few to no rock outcrops are noted for Regional Sea 9 (see Stoker *et al.* 1993, Stevenson *et al.* 2011), however data coverage for some of the region to the north east is incomplete. The only area of potential hard ground in Regional Sea 9 is the area around the Judd Deeps, potentially of Eocene-Oligocene sediments (Stevenson *et al.* 2011). Any outcrops may consist of igneous and sedimentary Tertiary deposits.

Figure A1b.14: Seabed substrates in Regional Seas 8 and 9

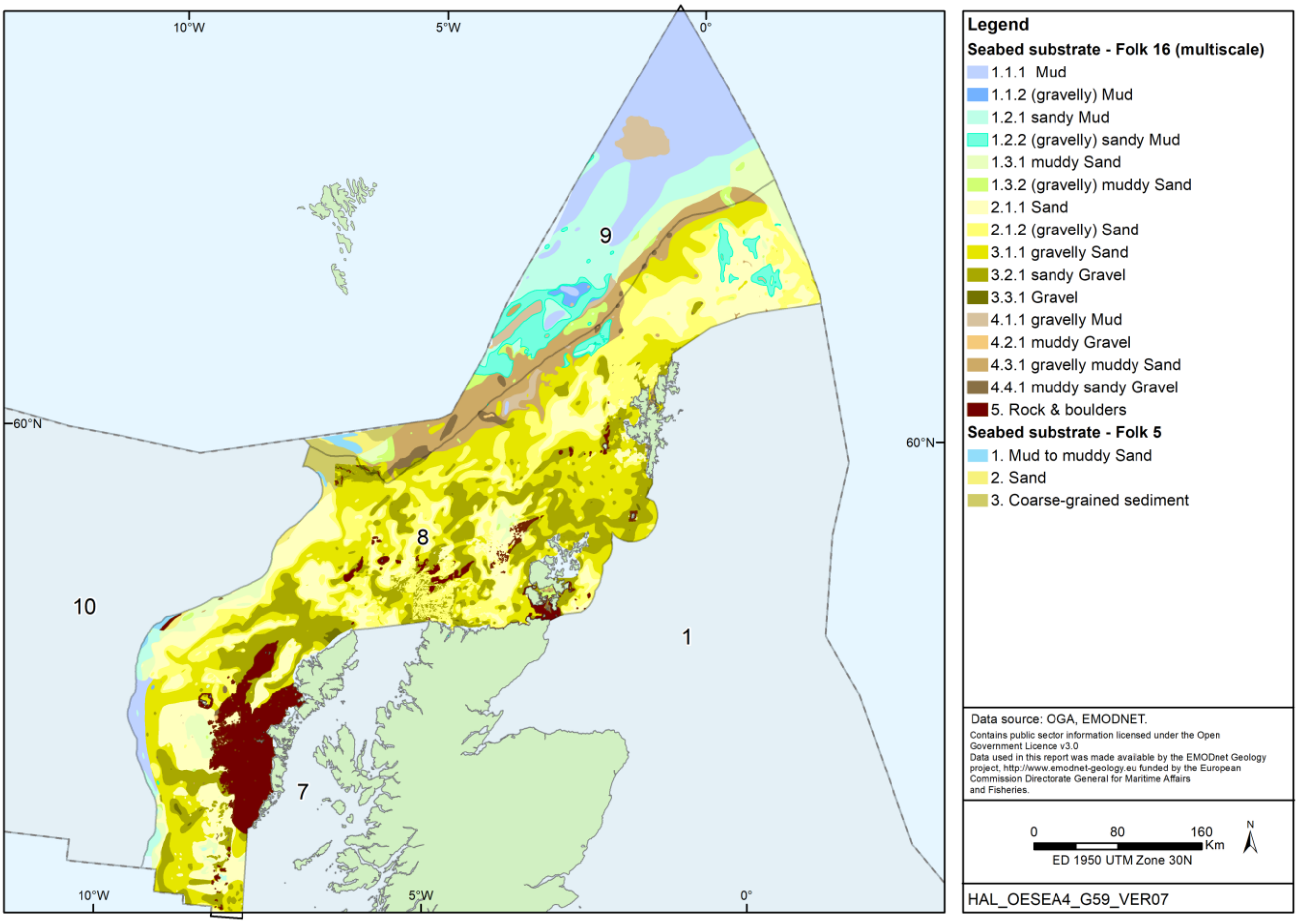
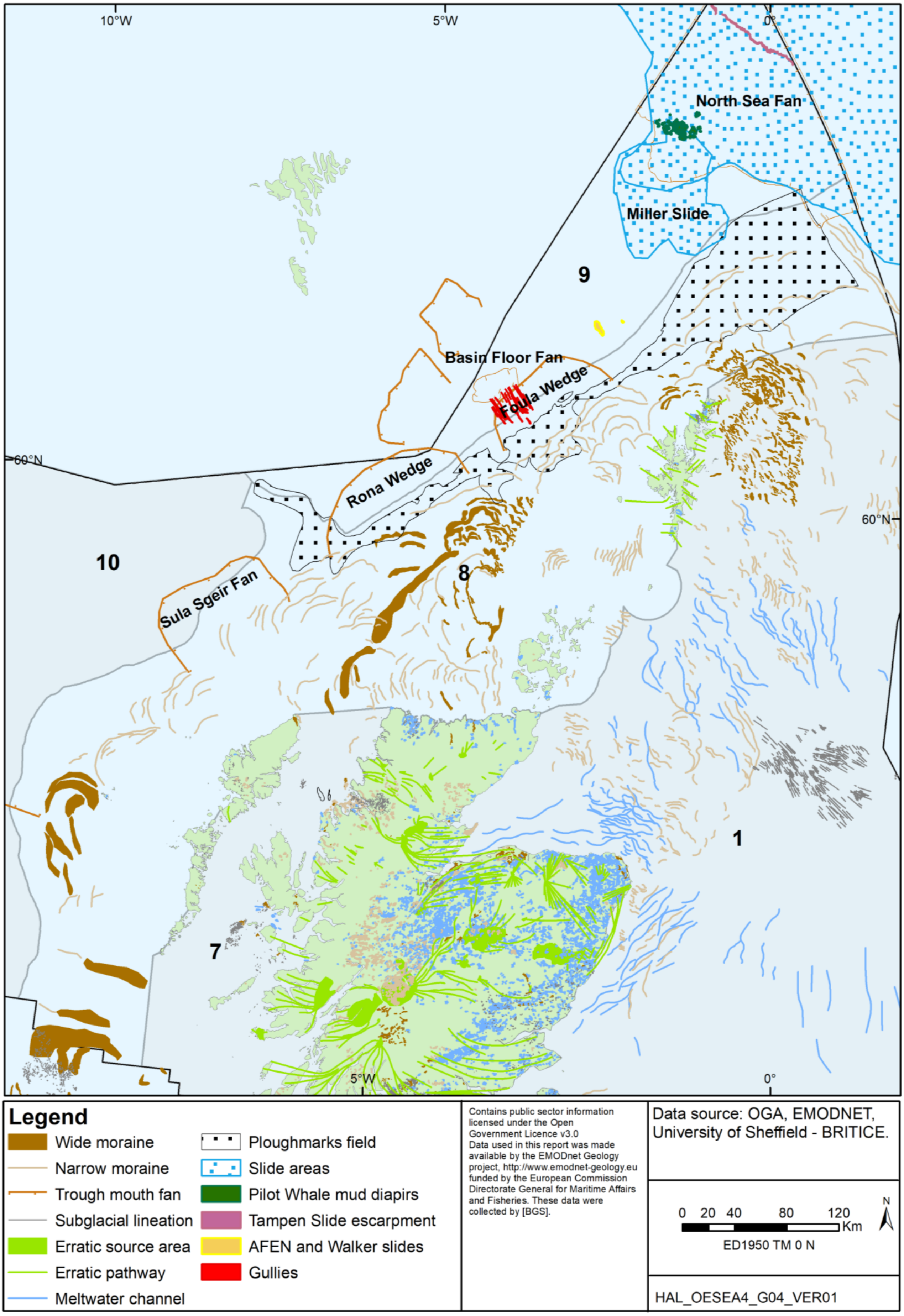


Figure A1b.15: Seabed features of Regional Seas 8 and 9 mentioned in the text



A1b.10.2 Seabed features

The West Shetland Slope and Faroe-Shetland Channel contain a number of features which reflect the deep geological and more recent glacial past combined with the hydrodynamic regime of the area throughout the Quaternary, including the most recent Holocene period. These features include debris flows and slope failures, fans, sediment waves, contourite mounds, polygonal faulting and bedrock ridges (Bulat & Long 2001, Stevenson *et al.* 2011, Long *et al.* 2011).

Deep cold water flow between the Norwegian Sea and the North Atlantic passes through the Faroe Bank Channel and Faroe-Shetland Channel generating strong bottom currents capable of eroding and transporting sediments including up to sand (Kenyon 1986) and gravel (Masson *et al.* 2004). These have formed a range of bedform features including scours, sand sheets (i.e. contourites, Masson *et al.* 2010, also see Brooks *et al.* 2011), furrows and barchan-type dunes detectable in side-scan sonar and high-resolution seismic profiles (Bulat & Long 2001, Wynn *et al.* 2002, Masson *et al.* 2004), at depths of 800-1,200m (Brooks *et al.* 2011). These barchan dunes occur at 1.1-1.2km depths on the floor of the southern Faroe-Shetland Channel, having "horn-to-horn" widths of up to 120m and extending for 25km with their orientation indicating long term south westerly flow (Wynn *et al.* 2002).

The slope area contains shallow along slope channels and sand ribbons down to 500m depth, and at depths between 900m and 1,400m, an extensive area of elongate mounds are present covering an area approximately 60km with length and between 5 and 15km in width which narrows to the south, interpreted as longitudinal sediment waves (Bulat & Long 2001, Stevenson *et al.* 2011).

The Judd Deeps are a small area of complex seabed on the southern Faroe-Shetland Channel created in Miocene times by erosional processes, forming scarps up to 200m high into Eocene bedrock (Stoker 1999, Stoker *et al.* 2003) and which are partly infilled by the Rona Wedge (Stewart & Long 2016). The features are now relict, but kept from infilling with sediment by modern bottom currents (Stevenson *et al.* 2011).

The North Sea Fan dominates much of the underlying sediment in the north eastern part of the Faroe-Shetland Channel, with other glacially-fed fans in Regional Sea 9 including the Rona and Foula wedges (Figure A1b.15), which are located on the West Shetland Slope, accompanied by a number of linear down slope gullies, debris lobes and fans extending on to the floor of the Faroe-Shetland Channel (Stoker & Varming 2011, Stevenson *et al.* 2011, see Figure A1b.15). A series of other submarine slides are located on the slopes of the Faroe-Shetland Channel, which include the following (after Long *et al.* 2011 and references therein):

- The Miller Slide is a series of debris flows up to 95km long, occurring on the western edge of the North Sea Fan. The slide has a surface expression covering 5,700km^2 and involved the movement of approximately 800m^3 of sediment, and is estimated to have an age of about 200,000 years.
- The Tampen Slide is located in the north east of Regional Sea 9 on the North Sea Fan which is likely of late Saalian age and extends into Norwegian waters, possibly having covered an area larger than the Holocene Storegga Slide.
- The AFEN Slide, covering approximately 45km^2, displaced approximately 0.4km^3 of sediment to a thickness of 10-20m. The slide has been dated to relatively recent times, of less than 2,880 yr BP. High-resolution seismic data suggesting the presence of an

underlying palaeo-AFEN slide similar is scale buried to approximately 50m below the seabed. Based on the sediment deposition rate in the area, the palaeo-AFEN slide is estimated to be several hundred thousand years in age. Both slides occur on the slope headwalls where there are well-developed contourite deposits, analysis of which suggests that ground motion amplification within shallow sediments could cause slope failure.

- The Walker Slide is located 20km to the north east of the AFEN Slide. This feature is small by comparison (1.5km^2) but at similar depth (850m) and with a likely similar genesis to the AFEN slide, though may predate its Holocene age.
- The Fugloy Slide (not mapped) occurs north of the AFEN slide, crossing the Faroes/UK Median line, extending 25km in a south easterly direction. The slide has a sediment lobe thickness of 50m and is probably one of many on the on the south-eastern flank of Fugloy Ridge.

These features also present potential geohazards and are discussed in Section A1b.13 below.

A surface veneer of mud covers the floor of the Norwegian Basin below 1,000m depth and glacigenic debris flow sediments of the North Sea Fan underlie much of the area. A field of mud diapirs, resulting from the upward migration of fluid/mud to the surface occur in Quadrant 217 of the southern Norwegian Basin (the Pilot Whale diapirs, see Figure A1b.15), which are the only known such diapirs in UK waters that breach the seabed surface (Brooks *et al.* 2013). No evidence for fluid escape (or possible associated biological communities) has yet been found but there remains the possibility that localised areas of fluid escape may be active in the area. Holmes *et al.* (2003) conducted a study of the evolution of the Pilot Whale diapirs, concluding that modern activity and fluid escape is most likely to occur where diapirs are underlain by shallow acoustic scatter. The surface expression of the mounds is approximately 350km^2 with mounds being extruded up to 50m from the seabed in an initial phase, reaching maturity at 100m height and with a smooth appearance (Nielson & Kuijpers 2004) – the overall area covered by the diapirs at depth is approximately 3,000km^2.

A1b.11 Features of Regional Seas 10 & 11

Current knowledge of seabed sediments only allows for a description of those deposits out to approximately 14°W, i.e. those in Regional Sea 10, though features have been described for the Hatton Bank area further west. The current array of sediments on the shelf of Regional Sea 10 are the result of reworking of glacigenic sediments by submarine processes which have created a seabed armour in areas winnowed by strong bottom-currents (DTI 2007). A number of areas within Regional Seas 10 and 11 were surveyed as part of SEA 7 (Hatton Bank, Rosemary Bank, Anton Dohrn Seamount). The results of this survey are presented in Stewart & Davies (2007) and are synthesised in the sections which follow.

A1b.11.1 Seabed features and substrates

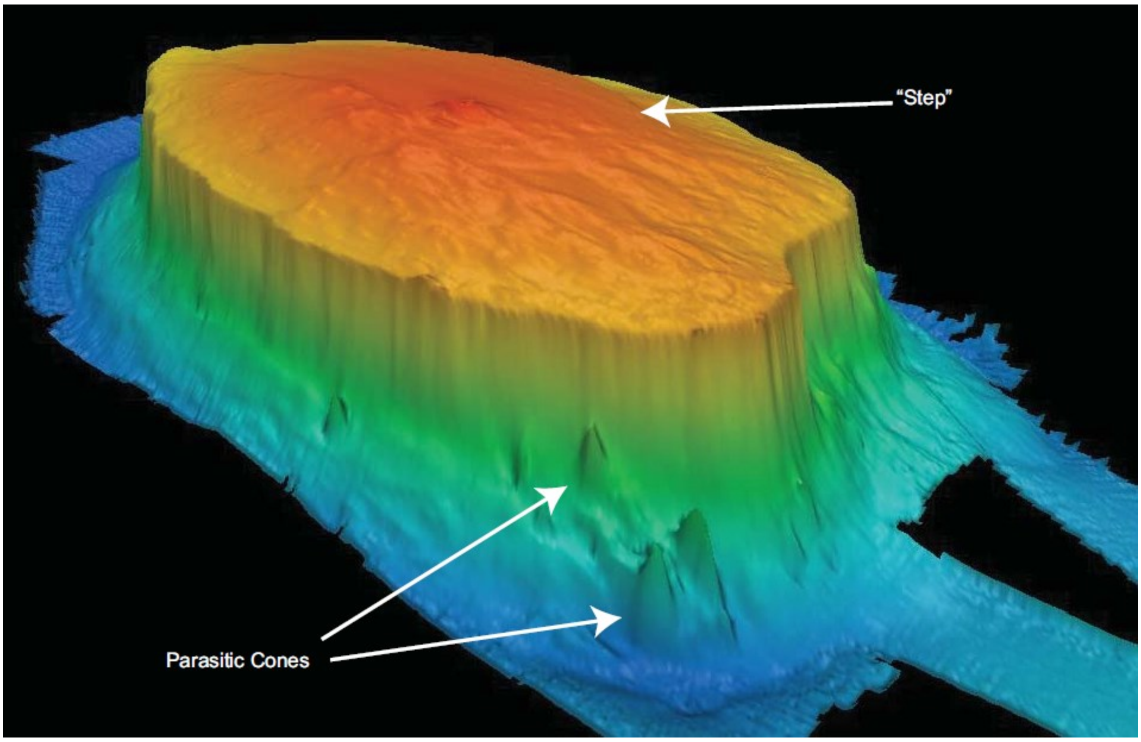
There are four notable areas in Regional Sea 10 and one in Regional Sea 11 which contain the Annex I *reef* habitat (see Figure A1b.3); The Darwin Mounds SAC, North West Rockall Bank SAC, East Rockall Bank SAC, Anton Dohrn Seamount SAC, and Hatton Bank SAC. The Darwin Mounds are at a depth of *c.* 1000m, around 160km northwest of Cape Wrath, covering an area of 137,726ha. The features of interest are sandy mounds formed by seabed expulsion (Cotterill & Leslie 2013), capped with the cold water coral *Lophelia pertusa* (JNCC 2008b). Each mound, of which there are hundreds, is approximately 100m in diameter and 5m in height. Unlike other reef areas, this population of *L. pertusa* is notable in that it colonises sandy rather than hard rock or gravel substrata. The North West Rockall Bank is located between 13 and 15°W and covers an area 488,569ha. This area is currently a draft SAC being considered under the Annex I *reefs* habitat.

Most of the seabed sediments in Regional Seas 10 and 11 are muds or sandy muds only interrupted by seamounts (see below) which tend to have a covering of gravel and gravelly sand, and at which bedrock closely subcrops. One of the largest inputs of modern material to the shelf is of biogenic carbonate, and the carbonate concentration of shelf muds is typically between 40 and 60%, increasing to 40-80% on and around Rockall Bank. Sediment waves are present in Regional Sea 10 on the Barra Fan, next to the Sula Sgeir Fan and in basinal parts of the Rockall Trough.

Rosemary Bank is a seamount 305km west of Cape Wrath with a diameter of 75km. The mound is thought to consist of basalt with localised phono-tephrite lavas and potassium rich tuffs (Stoker 1995) and extends from the seafloor to within 500m of the surface. The bank is of volcanic origin (70Ma) and has large pinnacles of later origin on its surface, extending to a maximum of 180m above the surrounding seafloor. A moat-drift complex surrounds the mount and sediment wave fields are located to the east and west (Howe *et al.* 2006). Medium to coarse grained sediments which include gravel and cobbles, and boulders in areas of iceberg ploughmarks cover the bank. Bedrock outcrops have also been observed.

The Anton Dohrn Seamount (Figure A1b.16) lies in the centre of the Rockall Trough, extending 1,500-1,600m above the seabed, with the surface at between 530 and 1,100m water depth, and is surrounded by a bathymetric moat at 2,300m depth (Heather *et al.* 2009). Sandy sediments surround this feature, extending into shallower water to the west, whereas the feature itself has a covering of gravelly and muddy coarse sands to gravels and broken shell fragments. A number of features are present at the edges of the feature, including sharp breaks in slope, radial ridges and gullies to the south east, a number of parasitic cones to the north west, and area of uneven topography which could be interpreted as a submarine landslide or rockfall to the west (Heather *et al.* 2009).

Figure A1b.16: 3D perspective of Anton Dohrn Seamount



Source: Jacobs (2006)

As the shelf floor rises towards the Rockall Bank and George Bligh Bank, the sediments become coarser, consisting principally of gravelly sandy mud, gravelly sand and gravel. The George Bligh Bank lies to the north and west of the Anton Dohrn Seamount, and has coral on its northern flank and iceberg ploughmarks on its surface. Its eastern flank is covered in coarse sands, gravels and boulders, and to the south there is evidence of scour from strong current flows (DTI 2007). The East Rockall Bank lies to the west of the Anton Dohrn Seamount at depths of between 190 and 2,175m and slopes of up to 48˚ at a bedrock escarpment at approximately the 500m depth contour. Late Palaeocene to Early Eocene volcanic basaltic lavas overly the basement geology with less basic lavas and tuffs having also been recovered (Heather *et al.* 2009). Major features imaged on the bank include three possible volcanic cones up to 200m high and 800m in diameter, in close proximity to smaller (50m diameter) biogenic/lithic gravel mounds; two canyons on the eastern flank of the bank, and iceberg ploughmarks on the bank crest (Heather *et al.* 2009).

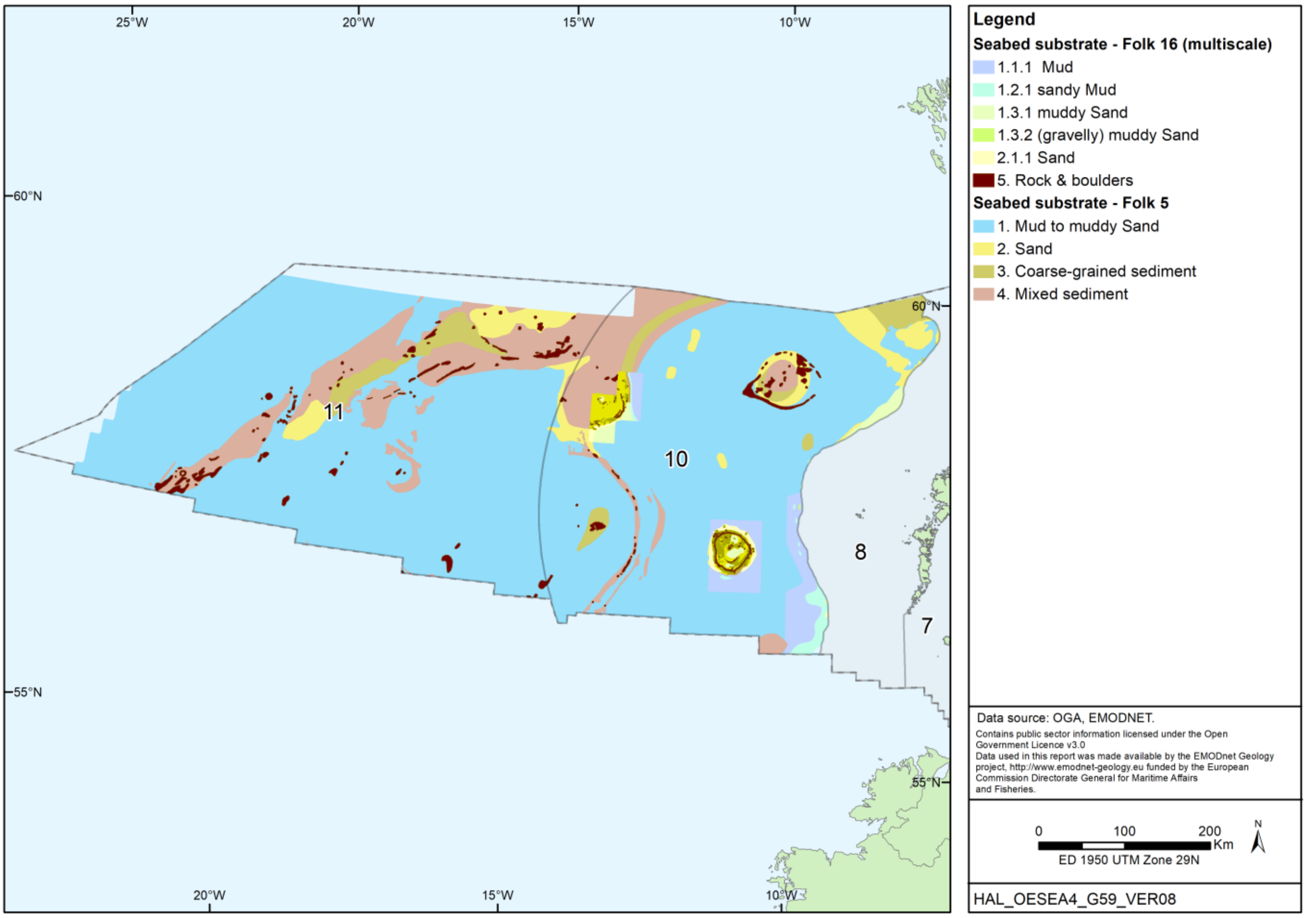
In the south east of Regional Sea 10, the Hebrides Terrace Seamount has a vertical relief of 650-1,000m, and its summit is at 1,000m water depth. The mount is elliptical, 27km by 40km and is partially buried by sediments from the Barra and Donegal fans (Cotterill & Leslie 2013).

Submarine slide complexes feature on the Hebrides slope. These occur in association with the Barra and Sula Sgeir fans which are debris flows that have developed over the last 4.7Ma (Cotterill & Leslie 2013). The potential for failures is connected with slope angle and sediment properties, and other forces such as seismicity (Cotterill & Leslie 2013), however in the absence of sea-bed stresses from tides, waves and earthquakes, the times of gravity-driven slope failures are unpredictable (Holmes *et al*. 2006). The largest area of slope failure is associated with the Peach Slide Complex generated by at least four events, and involving the displacement of over 1,800km^3 of material (Holmes *et al*. 1998, Owen *et al*. 2018).

The Hatton Bank area in Regional Sea 11 was surveyed in 2005 and 2006. The area is covered by Palaeogene lavas with the exception of a few areas which are suggested to be Upper Palaeozoic-Mesozoic sedimentary strata (Hitchen 2004). The central Hatton Bank was found to host diverse reef communities where strong currents are a key influence. Clean and often rippled sands were observed on top of colonised scarp slopes and washed gravel lag deposits were observed at their bases (DTI 2007). Several areas to the south of the Hatton Bank area surveyed in 2006 revealed superficial sediment primarily consisting of coarse sand and gravel, the latter of which often contained biogenic material derived locally from reefs (Stewart & Davies 2007). Pinnacles represent bedrock outcrops and in turn a reef bearing substrate which included the cold water coral *Lophelia pertusa*.

The only feature in Regional Sea 11 which reaches the water surface is Rockall, a small intrusion of granite notable for its unusual mineralogy. The small islet was probably formed during late Tertiary igneous activity. The seabed around Rockall is considered of conservation importance due to the presence of cold water corals (JNCC 2007).

Figure A1b.17: Seabed substrates in Regional Seas 10 and 11



A1b.12 Economic geology

A1b.12.1 Hydrocarbon prospectivity

The hydrocarbon prospectivity of the UKCS has been described in a number of regional reports for the UKCS (e.g. Cameron *et al.* 1992, Tappin *et al.* 1994, Gatliff *et al.* 1994, Ritchie *et al.* 2011, Hitchen *et al.* 2013), and has been summarised in DECC (2013, 2014). The principal regions of historical and ongoing interest on the UKCS cover four broad provinces (North Sea Oil, North Sea Gas, Irish Sea and Atlantic Margin), which encompass a number of basins and sub-basins (see Figure A1b.18). There continues to be little exploration in areas outside these provinces, with historic activity showing either dry holes or non-commercial discoveries. However, there ispotential for new discoveries and development in these provinces as extensions of existing plays or by targeting previously underexplored plays.

The location and prospectivity of hydrocarbon accumulations in the North Sea Oil and Gas provinces (Regional Seas 1 and 2 in Figure A1b.18) are relatively well-known given the maturity of exploration and development of these areas. The northern and central North Sea Oil fields are dominated by late Jurassic to early Cretaceous crustal extension which generated the Viking Graben, Moray Firth and Central Graben rift systems, with Upper Jurassic Kimmeridge Clay Formation source rocks being the source for most of the region's hydrocarbons. Source rocks are mature for oil over most of the flanks of the basin and adjacent to the main highs but are increasingly gas-prone in the deepest rift basins.

Within the central North Sea, the Mid-North Sea High remains relatively under explored and contains no producing fields or significant discoveries. The area was subject to recent seismic acquisition and interpretation, which indicated the potential for hydrocarbon prospectivity, with more work required to understand the consequences of Cenozoic uplift which reconfigured structures and formed potential migration pathways from Lower Carboniferous to Jurassic source rocks (Brackenridge *et al.* 2020).

Regional Sea 2 (the Southern North Sea basin) contains a gas province, with most production from resources reservoired within Lower Permian (Rotliegend) sandstones which dominate the southern half of the province, with Carboniferous sandstone reservoirs dominating the north of the area and minor areas with Triassic sandstone source rocks in both of these areas (DECC 2013). Gas and oil-prone Dinantian and Namurian aged source rocks are mature locally but oil accumulations are few and limited to the western and northern fringes of the basin. The basin is bounded to the north by the Mid-North Sea High.

Oil and gas production in Regional Sea 3 (the Anglo-Paris Basin) has been centred on the offshore extension of the Permian to Jurassic Wessex Basin, the largest oil field discovery being Wytch Farm in Poole Bay to the west of the Isle of Wight. This field has no offshore surface infrastructure and is produced from onshore facilities. Source rocks include Lias, Oxford Clay and Kimmeridge Clay (Jurassic), which are mature for oil, with reservoirs being Sherwood Sandstone (Triassic) and Bridport Sands (Lias) in the Central English Channel Basin and the Great Oolite (Middle Jurassic) in the offshore Weald Basin. A gas discovery was made a few kilometres south of Wytch Farm. No offshore development drilling has taken place in the English Channel.

No economic hydrocarbon accumulations have been discovered to date in the Western Approaches and western English Channel. Jurassic and Cretaceous rocks are the most likely sources for hydrocarbon deposits, though these formations were either never deposited in the west, or have undergone erosion during the late Jurassic to early Cretaceous, with thick sections only being found in the southern part of the Western Approaches Trough in the Brittany Basin (Evans 1990). Deformation may have resulted in the possible breaching of structural traps in these formations, reducing their prospectivity (Ruffell 1995).

No commercial hydrocarbons have been found in the Celtic Sea and Bristol Channel Basins (Regional Seas 4 and 5) where there is a general absence of organic source rocks. Potential reservoir intervals have been encountered (Sherwood Sandstone dominated groups over 50m thick were seen in Well 93/6-1) in the South Celtic Sea basin (Tappin *et al.* 1994), and though not in the UK sector, proven gas reserves in the North Celtic Sea Basin have led to the development of several gas fields (Shannon & Naylor 2012). Further North, the rocks beneath the St George's Channel contain gas and oil shows though economic accumulations are yet to be proven (Tappin *et al.* 1994). Permo-Triassic salt may have provided a suitable sealing interval in the area and prospects similar to the oil and gas fields of the east Irish Sea are possible at depth (Tappin *et al.* 1994).

The East Irish Sea basin is a mature production area, with production from fault-bounded Permo-Triassic reservoirs, with source rocks comprising gas and oil prone Namurian-Westphalian coals and shales, and oil prone Dinantian marine shales. Initial discoveries were made in the mid-1970s with the Morecambe gas field from which production started in 1985 following the completion of the 34km Morecambe to Barrow-in-Furness pipeline. Discoveries in Regional Sea 6 have primarily been gas in the Cardigan Bay and East Irish Sea Basin, the latter area also having oil discoveries in the Douglas and Lennox fields.

Future exploration in this area would likely concentrate on extending the Lower Triassic play fairway, and on the Carboniferous basinal mudstones and coal measures (oil- and gas-prone respectively) in the Solway Basins (Holmes & Tappin 2005). There are multiple potential source rocks in this area, though the most likely hydrocarbon source rocks are early Jurassic marine mudstones (Lias Group). These are fully mature for oil generation in the west of the UK sector, and are mature for gas generation nearby in the Irish sector. Gas-prone Westphalian pre-rift coal measures may also be present locally at depth. Conditions suitable for oil and gas production (reservoirs with viable seals and structural traps) is observed in basins from Larne-Lough Neagh, Solway, Peel, Kish Bank and Central Irish Sea basins however creation of an effective hydrocarbon system has been hampered by poor source rock preservation, locally poor seal integrity and unfavourable timing of hydrocarbon migration and trap formation (Naylor & Shannon 1999).

Very limited hydrocarbon exploration activity has taken place in Regional Sea 7, where Permo-Triassic and Mesozoic half-graben basins have been considered as potential sources of hydrocarbons. Carboniferous source rocks are thought more promising than Jurassic as the latter may be insufficiently mature (Fyfe *et al.* 1993). In the Malin Sea, North Channel and Irish Sea, the Triassic Sherwood Sandstone Group is considered to be a prospective, albeit high risk, hydrocarbon reservoir (Holmes *et al.* 2006). The highest likelihood of recovery is where Carboniferous rocks are overlain by Permo-Triassic material (e.g. south of Arran), though no successful exploration or development of this resource has yet occurred (Holmes *et al.* 2006).

To the north and west of Shetland, exploration effort has been small relative to the North Sea, though discoveries have culminated in the development of the Clair, Schiehallion/Loyal, Foinaven, Edradour, Glenlivet, Laggan-Tormore and Solan fields. The area of the Faroe-Shetland Channel has been relatively underexplored, however recent licensing rounds have attracted interest and the area continues to be actively explored.

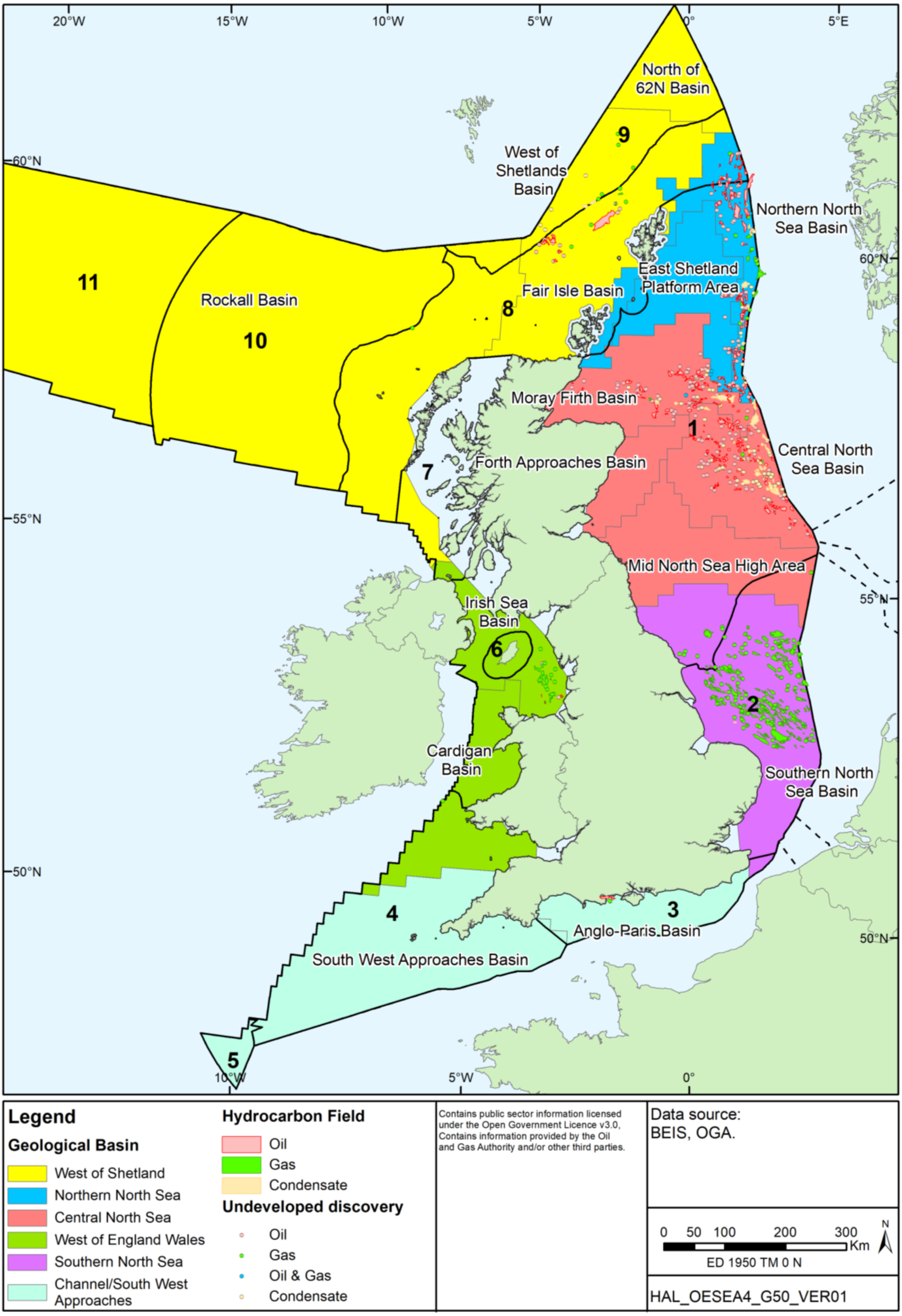
The hydrocarbon prospectivity of Regional Seas 8 and 9 have has been described in a number of regional reports (Ritchie *et al.* 2011, Hitchen *et al.* 2013), and has been summarised in DECC (2013). Relative to other areas of the UK continental shelf, exploration effort to the north and west of Shetland has been limited (part of Regional Sea 8 and Regional Sea 9), although around 200 wells have been drilled in the area within the past 30 years (Quinn *et al.* 2011, Austin *et al.* 2014). Despite drilling in the region commencing in 1972, activity in this area has continued at lower levels compared to the North Sea due to a combination of factors including the deep water, complex geology, lack of offshore infrastructure, and short summer weather window (Hitchen *et al.* 2003). There has been some success with the discoveries of the Schiehallion and Foinaven fields which have reserves of 250 and 500 million barrels of 24-27° API oil, and the Clair field which has an estimated 3-5 billion barrels. Additionally the Solan field commenced production in 2016 and the Lancaster field started producing in 2019. The latter is the first fractured basement field to be developed in the UK. This play is relatively underexplored on the UKCS, and Norwegian Continental Shelf (Belaidi *et al.* 2018, Trice *et al.* 2019) but comes with considerable risks. The reservoir pressure in the Lancaster field fell more rapidly than anticipated, and the estimated recoverable reserves have been substantially downgraded by the operator.

In addition to these developed fields, a number of discoveries are located to the north and west of Shetland including Rosebank/Lochnagar, Cambo, Suilven, Strathmore (oil) and Laxford, Victory, Tobermory and Tornado (gas). Other significant discoveries include Alligin, Arkle and Cuillin adjacent to Foinaven (Quinn *et al.* 2011). Nine potential oil and oil and gas prone source rocks are present in the north-east Atlantic Margin, with Middle Devonian, Lower, and Middle and Upper Jurassic rocks being correlated as active source rocks that have generated the hydrocarbons now being recovered from commercial accumulations (see Quinn *et al.* 2011 and references therein). Of these source rocks the upper Jurassic Kimmeridge Clay Formation is the main proven source rock.

Palaeogene lavas (largely comprising basalt) which characterise much of the recent outcropping and subcropping hard geology of the Faroe-Shetland Channel to the north and west of the UK-Faroe median line, and north of 62˚N in UK waters, have posed barriers to seismic surveys (Stoker *et al.* 1993, Hitchen *et al.* 2003) and drilling activity, which has resulted in a low seismic resolution and few exploratory wells. Due to the relatively poor resolution of seismic data, interpretation of hydrocarbon prospectivity is problematic in areas underlying these basalts. For example, the full distribution of Jurassic source rock is poorly understood (Quinn *et al.* 2011) below the basalts. More recent seismic methods such as deep-tow seismic survey and processing techniques (see Varming *et al.* 2012) have allowed better imaging of the sub-basalt Mesozoic strata, indicating that there may be reservoirs at drillable depths (Davison *et al.* 2010). Hardman *et al.* (2018) characterised the distribution of volcanics and intra-basaltic sedimentation in the Cambo-Rosebank region, interpreted from the integration of seismic survey and well data. There was considered to be significant exploration potential in the area, particularly in zones of thickening adjacent to the southern Corona Ridge.

Unlike the North Sea and East Irish Sea, Regional Seas 7, 10 and 11 have generated little interest in oil and gas exploration. Licensing rights for areas beyond 200nm of the mainland are under negotiation, so only Regional Seas 7 and 10 have short-term prospects for licensing in the north west Atlantic Margin province, and to date exploration has been concentrated in the east of this area (east of 10˚W) (Hitchen & Quinn 2013). Seven wells have been drilled in the Rockall Basin, however these licences have all now been relinquished. Two of these wells found hydrocarbons and the remaining five were dry holes. A single gas discovery (Benbecula) was made by Well 154/1-1 in the north east Rockall Basin (Regional Sea 10) from Palaeocene basin-floor sands (DTI 2006), and oil shows were found within the Vaila Formation in well 164/28-1A (DECC 2014). The Irish sector of the Rockall Basin contains the Dooish condensate discovery which also demonstrates the potential of a working hydrocarbon system within the south Rockall Basin of the UK sector (Hitchen & Quinn 2013, DECC 2014). It remains to be proven whether there is a viable system for the Hatton Bank to the west (DTI 2006).

Figure A1b.18: Major hydrocarbon basins of the UKCS, developed fields and significant* undeveloped discoveries



Note: * "significant" generally refers to the flow rates that were achieved (or would have been reached) in well tests (15 mmcfgd or 1,000 BOPD). It does not indicate the commercial potential of the discovery.

A1b.12.2 Aggregates resources

The Crown Estate has produced maps which indicate the aggregates resource of the UKCS developed by BGS (Figure A1b.19) which correspond with a number of key aggregate licence areas. Aggregate extraction is a major industry in south east England with areas between the Humber and the Wash, off the Suffolk coast and in the outer Thames Estuary all licensed for extraction (see Appendix 1h). Aggregate extraction takes place in Regional Sea 3 to the south-east and south-west of the Isle of Wight, in the Owers region and also in the wider east English Channel. The principal target for extraction is the Quaternary gravel and sand lag deposit which covers much of the central and eastern English Channel, but only where it exceeds 0.5m thickness, which mainly coincides with the palaeo-valley network (Hamblin *et al.* 1992). More information on the distribution of activity is provided in Appendix 1h.

A1b.13 Geohazards

A1b.13.1 Seismicity

The regional pattern of earthquake occurrence under the North Sea is related to deep geological structure. Expectations of earthquakes with magnitude of 4 or higher may require special structural design and are therefore also of environmental concern. In the North Sea as a whole the expected frequency of occurrence for a magnitude 4 natural seismic event is about every 2 years and a magnitude 5 natural seismic event every 14 years. The most recent earthquake was in August 2015 in the southern North Sea and had a magnitude of 4.1ML at a depth of 4km, being felt on nearby platforms and at Sheringham on the Norfolk coast[10].

The English Channel is subject to moderate seismic activity with few large (>5.5ML) events, though historic records indicate such sizeable movements (Lagarde *et al.* 2003). 233 events have taken place between 1962 and 2000 following pre-existing fault lines, and from this (brief) dataset it can be calculated that an earthquake of 5.2ML or greater may be expected once in 100 years. Over a longer period, though relying more heavily on observational reports than instrumental records, a number of earthquakes ranging from 4.0-4.9ML have been reported in the English Channel between 1700 and 1993, with particular foci in the central channel to the south of the Isle of Wight and in the Straits of Dover (Musson & Winter 1997).

Earthquakes in Regional Sea 6 have been largely coastal attaining a maximum magnitude of 5.0-5.9ML, with smaller earthquakes occurring off the Isle of Man (<3.0ML) and south eastern Irish coast (3.0-3.9ML) Musson (1994). A substantial cluster of events is centred on the area around Anglesey and Lleyn Peninsula, with a few scattered large events indicated near Whitehaven, off Barrow-in-Furness and Pembrokeshire (5.0-5.9ML). The earthquake hazard maps produced by Musson & Winter (1997) indicate that much of Regional Sea 6 has a 90%, 50 year return interval for an event of 5.0-6.0EMS (i.e. a return interval of 475 years).

Five earthquakes of magnitude 4.0ML have been recorded in the nearshore of Regional Sea 7 since 1970, though none are recorded for the Outer Hebrides shelf and areas further west. Earthquakes of magnitudes less than 4.0ML have been recorded 2-3 times per year in the nearshore since 1970, and these may pose risks for local geomorphological stability in bedrock

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[10] http://earthquakes.bgs.ac.uk/

or unconsolidated sediments. More work is required to fully classify the seismic risk for the nearshore in this region (Holmes *et al.* 2006).

The northern and easterly area of Regional Sea 8 also has a low incidence of seismic events on record, with a total of 25 known, the largest of which was 3.1 ML (Hitchen *et al*. 2003). The recording of earthquake events in the region is poor and so, therefore, is the understanding of their historical frequency. Instrumentation prior to 1970 was not focussed on collecting local data and therefore our understanding relies mainly on post-1970 data augmented with documentary evidence. It is debatable that any extrapolation can be made from a 30-year dataset though for the UK such estimates have proved reasonably reliable (with the exception of SW Wales) (Hitchen *et al.* 2003).

Seismic activity is largely absent in the west of Regional Sea 9, being mainly confined to the south and east. Any events that may have occurred are unlikely to have been recorded since a magnitude 5.5 ML earthquake to the north of the area would be felt weakly on Shetland and Faroes and imperceptibly elsewhere (Hitchen *et al.* 2003), however, there is good seismic network coverage for the area, and any earthquake of a magnitude =>3 ML is likely to be detected (Long *et al.* 2011). A number of earthquakes have been recorded in the north east of Regional Sea 9 towards the Møre Basin-Viking Graben active area, the largest of which was magnitude 3.1 ML, though the epicentre of this event is poorly constrained. Slope instabilities due to earthquake motion have been recorded to the north west of Shetland (Jackson *et al.* 2004), like those of much more northerly areas (Leynaud & Meinert 2003). The seismicity of the area is generally low and therefore the seismic hazard is also low though the possibility of an unusually large earthquake occurring at the passive margin of the modern continental shelf, running SW-NE, is unknown (Hitchen *et al.* 2003).

Seismic events in themselves may not represent a threat, but related mass movement events are hazardous (see below) and therefore understanding the history of such movements in relation to seismic events is important (Long *et al.* 2011).

A1b.13.2 Mass movements

Submarine mass movements pose geohazards for offshore developers. While landslides and debris flows are relatively few on the UK continental shelf, the eastern margin of Rockall Bank has evidence of landslides on its mid-lower slope and the Faroe-Shetland Channel has seabed features including landslides and debris flows (Long *et al*. 2004, also see Long *et al.* 2011 and characterisation of slides above).

The recent geological history of Europe's continental shelf regions has been important in determining the current sediment supply and characteristics of mass wasting features, resulting in mega-scale slides in the previously glaciated area to the north of 52°N, with smaller, large-scale debris flows in the non-glaciated but glacially-influenced margin further south (Leynaud *et al*. 2009). A number of slides are partly or wholly present in Regional Sea 9, for instance the AFEN, Walker, Fugloy, Miller and Tampen slides (Long *et al.* 2011, see above). Others (only partly in Regional Sea 8, to the west of the Hebrides), include the Barra Fan, which together with the Donegal Fan to the north of Northern Ireland (both are considered to be part of the same fan complex) cover an area of approximately 6,300km^2 Brooks *et al.* 2011). Sediments making up the Barra Fan have been displaced to the north-west, which is represented by the Peach Slide Complex. A radiocarbon based age model for the seismic stratigraphy constrains the occurrence of the two main periods of slope failure to ca. 21kya BP, and between 12 and 11kya BP (Owen *et al*. 2018). Additionally, there is evidence of sliding on the Sula Sgeir Fan (Baltzer *et al.* 1998, see Long 2013 for a synthesis).

Documented large-scale submarine mass movements are relatively few on the UK continental margin, though megascale slides (e.g. the Storegga Slide of the mid-Norwegian margin) probably had far reaching consequences for coastal settlements in the Norwegian and North Sea (Dawson *et al*. 1988, Long *et al.* 2016, Waddington & Wicks 2017, Gaffney *et al.* 2020) during the early Holocene (dating to *ca.* 7,900 cal. yr. BP).

A1b.13.3 Other

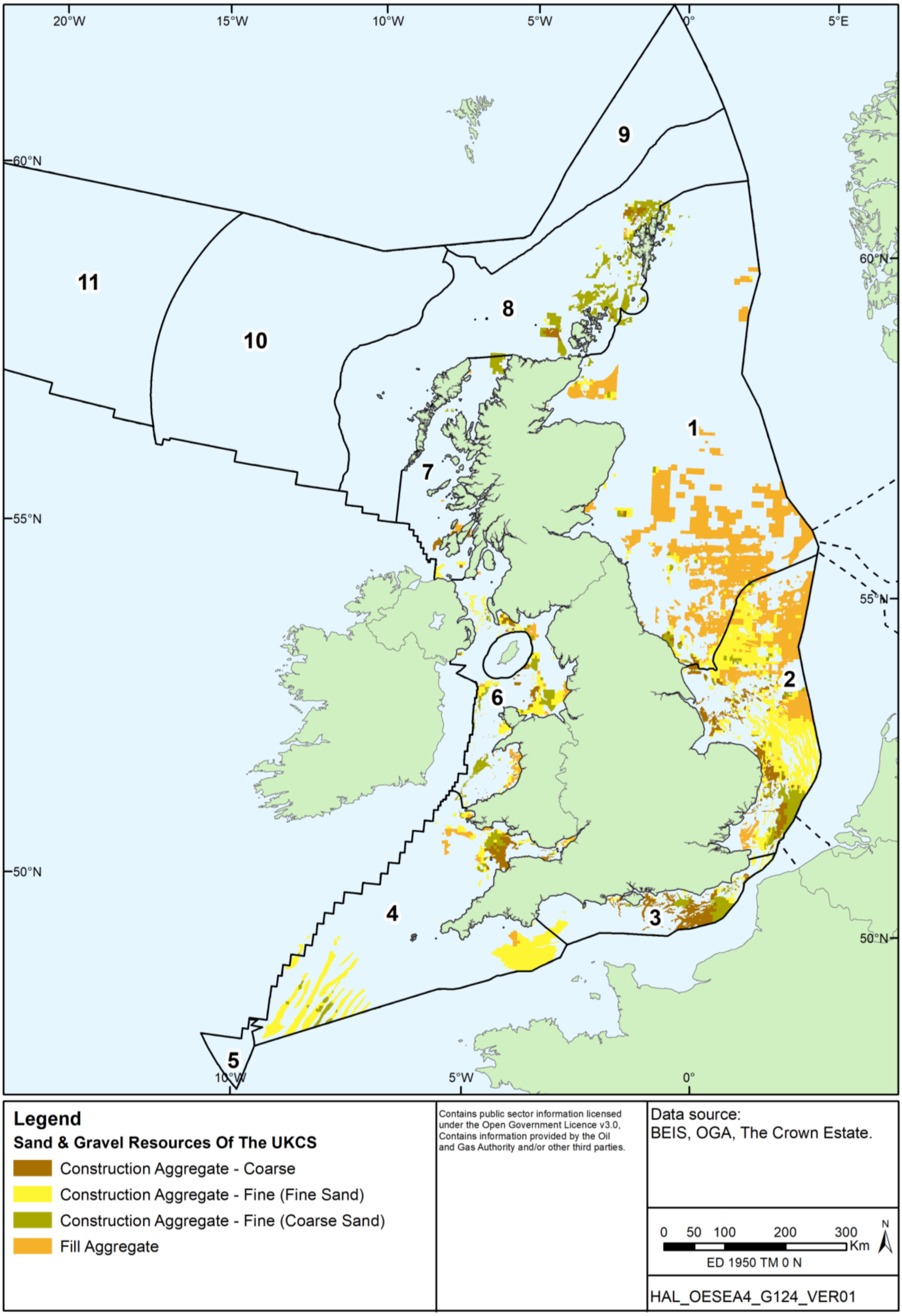
A number of other potential hazards on the UKCS are presented by geological processes such as the presence of shallow gas and diapirism or mud mounds. The former is relatively well understood and the latter are only known in the Faroe-Shetland Channel area (e.g. see Long *et al.* 2011).

A1b.14 Strategic information gaps

Despite advances in the interpretation of seabed data and improved understanding of the nature of the British-Irish Ice Sheet during the Pleistocene and into the early Holocene, the characterisation of the seabed both in terms of understanding local seabed features and sediment composition is based on relatively limited data for Regional Seas 8 and 9 compared to the wider North Sea, with recent conservation efforts (e.g. the designation of the Faroe-Shetland Sponge Belt and North East Faroe-Shetland Channel) still largely relying on data collected as part of previous offshore energy SEA sampling efforts and those on behalf of AFEN, however, some additional work has been undertaken (e.g. Eggett *et al.* 2012, Taylor *et al.* 2019a, b), and the monitoring of such sites should result in continued effort at least to map and characterise these areas. The relative lack of data for this area is clear on the resolution of broadscale sediment maps, and by association, habitat maps, which variably have a medium to low confidence.

While limited, survey data from industry survey (specifically oil and gas for Regional Seas 8 and 9) continue to provide a source of localised sediment data. The reporting of these data remain poor, often only being made available in the form of syntheses within project environmental statements, or partially through UKBenthos which only records a limit range of sediment parameters that limits further use. Bathymetry data is treated similarly, and therefore fails to make a contribution to wider mapping efforts of the UKCS. Arguably, the format of UKBenthos is dated and fails to recognise standards being applied within other repositories such as those under MEDIN which risks perpetuating a system where survey metadata is not recorded (particularly in relation to methodologies used), partial results are stored, and further use and comparability of results is limited. The storage of such data could more usefully be undertaken through the existing MEDIN framework, or else follow established metadata standards and expand the database fields to provide for more robust archiving that would allow for a wider range of future uses.

Figure A1b.19: Marine Sand and Gravel Resources of the UKCS



A1b.15 Environmental issues

A1b.15.1 Development activities

Development activities (e.g. aggregate extraction, fisheries, capital dredging, port expansion, cable and pipeline installation, renewable and other energy structures) have all had varying degrees of effect on the seabed and related habitats, with the potential to generate environmental issues. Aggregate extraction has been linked to potential changes in the wave, tidal and sediment regime, can alter the topography of the seabed through the removal of substrata and generate sediment plumes which could cause smothering of benthic habitats, but industry best practice and studies including the REC programme have improved the understanding of environments targeted for resource extraction (see Newell & Woodcock 2013).

Besides sediment contamination impacts on the geology and substrates (see Section A1b.12.4), impacts from oil and gas related activities are likely to be associated with sediment plumes and redistribution of sediments associated with seabed activities including pipe and cable lay and the placement of platforms (note that as these activities are directly related to the plan, they are not generically considered further here – see Section 5 of the Environmental Report), but possible legacy issues which provide context to the plan are discussed in Section A1b.12.4 below. Geological effects of hydrocarbon exploration and production may be regarded as local and small scale in the context of the long-term geological evolution of the UKCS, though in some instances wider scale changes have been noted, for example in a single North Sea case (Ekofisk, in the Norwegian sector), the extraction of oil and gas has led to production-related seabed subsidence. This process appears to be restricted to a single type of chalk reservoir.

A1b.15.2 Sea level change and flood risk

Sea-level change is likely to have a number of geomorphological effects. These include increased coastal erosion, particularly when considered in the context of possible enhanced storminess. The acceleration of coastal squeeze in intertidal areas is likely to lead to the loss of related habitat where these are constrained either naturally or by manmade defences, some of which will need to be maintained where they protect essential infrastructure. The rate and spatial variability of sea-level change around the UK and issues related to coastal change and its management are discussed further in Section A1b.17.

A1b.15.3 Existing contamination

There is a legislative framework in place for controlling pollution from contaminants, including consenting and monitoring programmes. Sources of contamination on the UKCS include terrestrial emissions and discharges (transported to the marine environment via rivers and from atmospheric deposition); shipping; military activities, and offshore industries including oil and gas production.

Knowledge of contaminant levels in the marine environment is generally good, particularly in coastal and inshore areas as a result of measures related to OSPAR and the WFD, which require the monitoring of specific contaminants and compliance with specific concentration limits to prevent pollution. Charting Progress 2 (Defra 2010) provided a useful summary of existing contamination in coastal and marine waters and sediments, and was also more widely used as the basis to provide the initial assessment in relation to the Marine Strategy Framework Directive (MSFD). This initial assessment was updated in 2019, and in advance of the target under the MSFD to achieve Good Environmental Status by 2020. The key points from that report in relation to contamination are noted below, and where relevant are augmented with information from the OSPAR Intermediate Assessment 2017, noting that many of the indicators of GES for relevant descriptors in this area are related to OSPAR:

- For contaminants, Defra (2019) note that that Good Environmental Status (GES) had been largely achieved but will not be fully achieved by 2020 due to the persistence of certain contaminants, which include PCBs in biota and marine sediments[11] (also see the OSPAR Intermediate Assessment 2017).
- GES has not been achieved for litter, nor was it expected to be achieved by 2020. Marine litter in UK waters is predominantly plastics from packaging and fishing related items, but include a range of other items. This includes litter on beaches and on the seabed, with higher amounts located in the English Channel than the Greater North Sea and Celtic Seas.

The main programme for monitoring the status of contaminants on the UKCS is the Clean Seas Environmental Monitoring Programme (CSEMP) which collects data at some 500 sites. Given the area of the UKCS this provides a relatively sparse coverage of stations. Defra (2019) noted few temporal changes in contaminant levels, the majority of which saw a downward trend, though the persistence of others (e.g. PCBs) means they will continue to be recorded for some time. As noted above, the OSPAR Intermediate Assessment 2017 similarly indicated that offshore, contamination in sediments for a number of metals and pollutants (cadmium, mercury, lead, PAHs, PCBs) was largely acceptable (e.g. below the Background Assessment Concentration or significantly below the Effects Range-Low concentration), though mercury and lead remained at or above the ERL for a significant number of the monitoring sites assessed.

Other surveys which have taken place on the UKCS that have contributed to knowledge on contaminant levels include those undertaken in relation to oil and gas activity. This has included a number of regional surveys of contaminant and ecological status in areas of oil industry activity (Figure A1b.20) which were summarised in 2008 for the OSPAR Joint Assessment and Monitoring Group and have been updated below. The conclusions of this summary are:

- Since the cessation of Oil Based Mud (OBM) discharges, the regional trends in sediment hydrocarbon concentrations in developed areas have been significant reductions and a return to background or near background concentrations. Mean hydrocarbon concentration in the Fladen Ground had reduced from 50.4 µg/g in 1989 to 19.3µg/g in 2001. In the East Shetland Basin, the mean hydrocarbon concentration reduced from 74.4µg/g in 1994 to 26.1µg/g in 2002.
- Regional scale benthic ecological perturbation attributed to oil industry activities has not been detected. In contrast to previous studies in the Norwegian sector (Olsgard & Gray 1995) – which appeared to indicate that stations 2 to 6km away from platforms showed measurable faunal effects after a period of 6 to 9 years development – available data from the Fladen Ground (2005, 2015) and East Shetland Basin (2007) showed no

[11] See: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/contaminants/pcb-fish-shellfish/ and https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/contaminants/pcb-sediment/

indications of ecological disturbance. This may be associated with the observed recovery in terms of contaminant concentrations and absence of anthropogenic changes to sediment size distribution in sediments (i.e. benthic community structure may have shown some degree of broadscale disturbance during the earlier period following development).

- Evidence from long term studies of single OBM wells indicates that a variety of degradation, redistribution and recovery processes are involved and that after 25 years recovery is almost complete at both diesel and low-toxicity OBM sites. Broadly similar processes and timescales were observed in the Fladen Ground and central North Sea (2004); in several cases a period of opportunist species colonisation is believed to have occurred as evidenced by the presence of numerous dead shells of the bivalve *Thyasira sarsi* in sediments from within 200m of the well.
- Relatively long monitoring time series (from the mid-1980s) have been established for multi-well production platforms in the east Shetland Basin and central North Sea. In several cases the data suggest little change over the period when there was active OBM drilling, followed by appreciable declines in THC contamination (considered as peak concentration at 500m from the platform and as the spatial extent over which 50µg/g concentration is exceeded) and also in far field concentrations by 2006.
- In deep water areas to the west of the UK conditions are sufficiently energetic and dispersive that North Sea monitoring approaches and strategies are of limited applicability. A managed programme of regional survey coverage and targeted investigation of specific habitat features has been conducted over a ten-year period, using a combination of seabed mapping and imaging followed by sampling the seabed sediments using a range of equipment to suit the sediment types identified.
- A regional survey covering parts of the central North Sea in 2009 indicated that no drill cuttings or other evidence of oil industry operations were observed in any samples and provided further information on the background concentration of seabed sediment contaminants for this area of the UKCS.

In general, sources of contamination from the offshore oil and gas industry (e.g. oil based muds, contaminated cuttings and oil and chemical discharges) have declined in line with OSPAR requirements in relation to the discharge of oil based contaminated cuttings, oil in produced water concentrations and other regulatory controls including the *Offshore Chemicals Regulations 2002* (as amended) – see Table A1b.1 and Appendix 2 for more details (also see OSPAR 2020).

Table A1b.1: Oil discharged with produced water 2006-2018

	2011	2012	2013	2014	2015	2016	2017	2018
No. of installations discharging oil in produced water	94	91	89	91	107	96	123	117
Total produced water discharged (million m^3)	174	156	149	156	165	155	143	139
Total dispersed oil in produced water discharged (tonnes)	2,494	2,268	2,176	2,004	2,412	2,017	2,139	2,241
Oil content (mg/l)	14.31	14.6	14.35	12.84	15.2	13.8	18.6	18.8
No. of installations re-injecting oil in produced water	28	27	26	24	22	27	27	25
Produced water re-injected (million m^3)	38.29	44.94	39.15	31.32	37	48	53	60

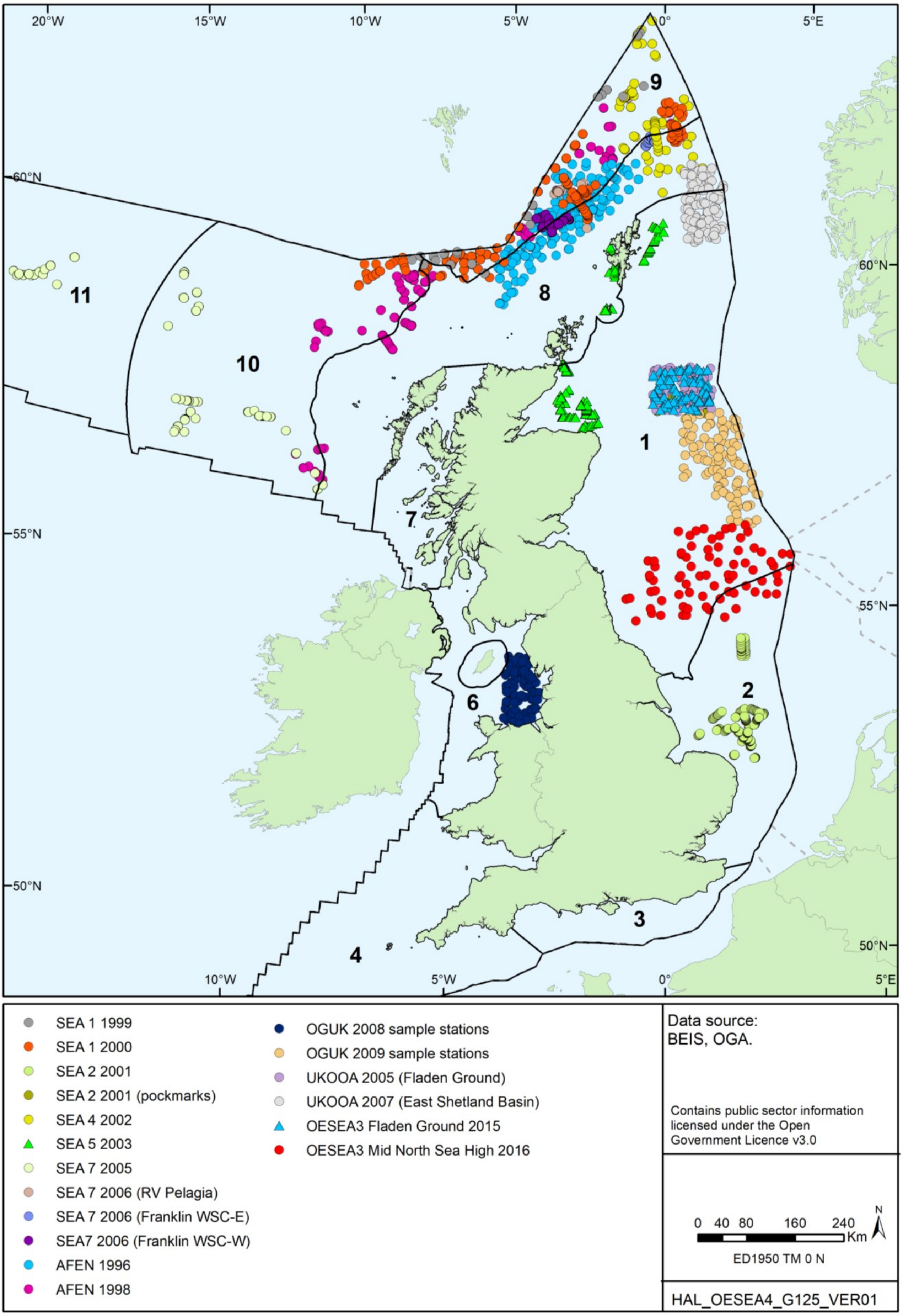
Source: DECC Oil and gas: field data website: https://webarchive.nationalarchives.gov.uk/20151109151730/https://www.gov.uk/guidance/oil-and-gas-uk-field-data (accessed: 04/11/2015), OSPAR (2018, 2019, 2020, 2021)

A1b.15.4 Radioactive material

Concentrations of NORM (naturally occurring radioactive material) are discharged into UK waters from offshore oil and gas platforms as a constituent of produced water and insoluble scale. Radionuclides found in these discharges include $_{226}$Ra (radium) and $_{228}$Ra, and their decay products such as $_{210}$Pb (lead) and $_{210}$Po (polonium).

OSPAR Contracting Parties have reported discharge data since 2005. The OSPAR (2020) report on discharges of radioactive substances from the non-nuclear sectors indicated that the UK offshore oil and gas industry discharged approximately 0.039TBq of $_{210}$Pb, 0.29TBq of $_{226}$Ra and 0.18TBq of $_{228}$Ra, in produced water primarily to the Greater North Sea area in 2018. With the exception of a peak in the discharge of $_{210}$Pb, $_{226}$Ra and 228Ra in 2011, the discharge of NORM has not significantly changed over the past decade. The Fourth Periodic Evaluation of Progress towards the objective of the OSPAR Radioactive Substances Strategy concluded that while a baseline period had been established for discharges from the oil and gas sector, there was still insufficient data to identify a period for comparisons to be made. More progress is expected in the Fifth Periodic Review, which is due to make a contribution to the OSPAR Quality Status Report 2023.

Figure A1b.20: UK regional and other seabed monitoring stations



Sazykina & Kryshev (2003) estimated that concentrations of each of the radionuclides $_{226}$Ra and $_{228}$Ra, due to the discharge of produced water, would be between 0.005 and 0.01Bq/l. This compares with a typical concentration of $_{226}$Ra in seawater of ~0.002Bq/l (Defra 2010). Naturally occurring background levels of $_{210}$Pb, $_{226}$Ra and $_{228}$Ra are variable and can make it difficult to detect signatures of these radionuclides from oil and gas discharges by conventional monitoring techniques (OSPAR 2016).

The OSPAR Radioactive Substances Committee has undertaken modelling to address this issue both close to discharge points and at some distance. Near-field modelling was undertaken for 16 UK installations and 7 Norwegian installations which were selected to be representative of a range of discharge scenarios and, which give rise to the largest the quantity of radionuclides discharged. Concentrations of $_{210}$Pb, $_{226}$Ra and $_{228}$Ra were predicted by comparing the specific activity of discharges with average dilutions at 500m. These were 10% or less of the Environmental Assessment Criteria (EAC), and two thirds of the results were <1% of the EAC. A correlation was found between discharge volume and dilution, but not depth. Far-field modelling predicted activity concentrations for the above radionuclides and $_{210}$Po in filtered seawater, with concentrations being higher closer to the discharge point, with those at distance being several orders of magnitude lower (range 10^{-15} to 10^{-5} Bq/l). Activity concentrations close to the discharge point were found to reach a steady state after 10 years and be dominated by the discharged radionuclides. Those at distance took longer to reach equilibrium, though with much lower overall activity concentrations, and some radioactive progeny became relatively more important with increasing time and distance depending on their behaviour in the environment and half-life. The modelled additional concentrations were far less than the variations in background levels and far lower than typical low-end background levels; this means that any additional concentrations would likely be indistinguishable from background levels measured by routine analytical techniques for environmental monitoring purposes. The radiological impact of annual doses of the modelled concentrations in seawater was found to be below the trivial annual dose of 10 μSv and a small fraction of the concentrations at which effects on biota have been observed.

A1b.16 Evolution of the baseline

A1b.16.1 Sea-level change

Sea-level across the UKCS has varied between lowstands during glacial periods and subsequent marine transgression during interglacial periods, as the vast quantity of water held in terrestrial ice sheets melts. A number of marine transgressions have taken place on the UKCS, the most recent beginning at the end of the last glacial maximum (~26-19kya, Clarke *et al.* 2009, 2012), with sea-levels broadly reaching modern levels by ~6,000BP). In addition to this barystatic sea-level rise, isostatic readjustment has also been taking place – a change in the elevation of the land surface of the UK following the removal of the weight of the British-Irish Ice Sheet which is regionally variable (see Section A1b.2). Generally, this has resulted in positive adjustment over much of the Highlands, central and western Scotland, and negative adjustment in south west England, the southern North Sea coast and Shetland, which is ongoing at a range of between +1.4 to -0.9mm/year (see Shennan *et al.* 2009, 2012, 2018, Bradley *et al.* 2011, Smith *et al.* 2011), and is the principal contributor to the spatial variation in sea-level rise projections around the UK (see below, and Horsburgh *et al.* 2020).

Sea-level change is regionally and locally variable, both at decadal and multi-decadal timescales (see the summary in Horsburgh *et al.* 2020), and in the longer-term as part of larger climatic cycles (see Appendix A1i), and more recently, due to anthropogenically augmented climate change. The latter is attributed to the reduction in the size of valley glaciers and ice sheets which has dominated recent rises, with a significant proportion also attributable to the thermal expansion of the ocean associated with increased global temperatures (Church *et al.* 2013, Pörtner *et al.* 2019).

At a regional scale, sea-level change is also affected by gravitational adjustment in response to ice melting in Greenland and the Antarctic (Mitrovica *et al.* 2011, see Palmer *et al.* 2018), and is superimposed on a range of other parameters controlling relative sea level, for example, salinity, temperature, and atmospheric pressure, and the tidal and wave climate at a given time. It is virtually certain that the rate of global mean sea level rise has increased in the last two centuries from tenths of mm/yr in the late Holocene, to several mm/yr at present (Pörtner *et al.* 2019, Woodruff *et al.* 2013), with a high confidence that the majority of this change is attributable to GHG emissions. The scale of the change globally has been in the order of 1.5-1.9mmyr^{-1} (total of 0.17-0.21m) between 1901 and 2010 (Church *et al.* 2013), though recent changes interpreted from satellite altimetry indicate a rate of 3.6±0.3mmyr^{-1} for the period 2006-2015 (Ablain *et al.* 2019).

There remain questions concerning non-linear accelerations from ice sheet contributions, for example, the contribution that the Antarctic ice sheet is likely to play, and the potential role of marine ice sheet instability (MISI) and marine ice cliff instability (MICI), although there is a high degree of uncertainty associated with the latter (see Edwards *et al.* 2019, Oppenheimer *et al.* 2019, Garbe *et al.* 2020, Wang *et al.* 2021). The basis of MICI is that the disappearance of ice shelves could allow formation of ice cliffs which may be inherently unstable (see DeConto and Pollard 2016), but there is limited evidence to support the theory. Oppenheimer *et al.* (2019) note that a great deal of progress has been made since the publication of the IPCC Fifth Assessment Report (AR5) on understanding the dynamics of the Antarctic ice sheet, but that complex interactions between the ice sheet, ocean, atmosphere and underlying bedrock remain difficult to simulate collectively. Oppenheimer *et al.* (2019) note that modelling studies (e.g. Favier *et al.* 2014, Joughin *et al.* 2014, Seroussi *et al.* 2017) since AR5 increases confidence that observed retreat of Amundsen Sea outlet glaciers is driven by processes consistent with marine ice sheet instability theory, that this will continue and, could accelerate (all medium confidence). Ultimately, continental-scale simulations are needed to understand the potential contribution of Antarctica to global mean sea level rise.

The rate of sea-level rise has now outpaced the positive isostatic adjustment being experienced in certain areas of the UK, and therefore all UK coasts may be expected to be influenced by the projected increases (see Rennie & Hansom 2011, Hansom *et al.* 2017), and unless global greenhouse gas reductions in keeping with the Paris Agreement are met, positive isostatic adjustment will certainly be outpaced, with sea-level rise compounded where this is negative. The sea-level projections of Palmer et al. (2018) provide an update to those of UKCP09 (e.g. Lowe et al. 2009). These are based on the Representative Concentration Pathways (RCPs) of AR5 (e.g. Church et al. 2013, also see Appendix A1f), and use the Coupled Model Intercomparison Project Phase 5 (CMIP5) model which provides improved projections including the inclusion of ice dynamics, such that values for sea-level rise for the UK are systematically larger than previous projections (Horsburgh *et al.* 2020). Projections for sea-level rise around the UK at 2100 relative to the 1981-2000 average are presented in Figure A1b.21 for three RCP scenarios. Increases of 0.15-0.61m for Edinburgh and 0.37-

0.83m for London for the central estimate under RCP 4.5[12], are projected (Table A1b.2; see Palmer et al. 2018).

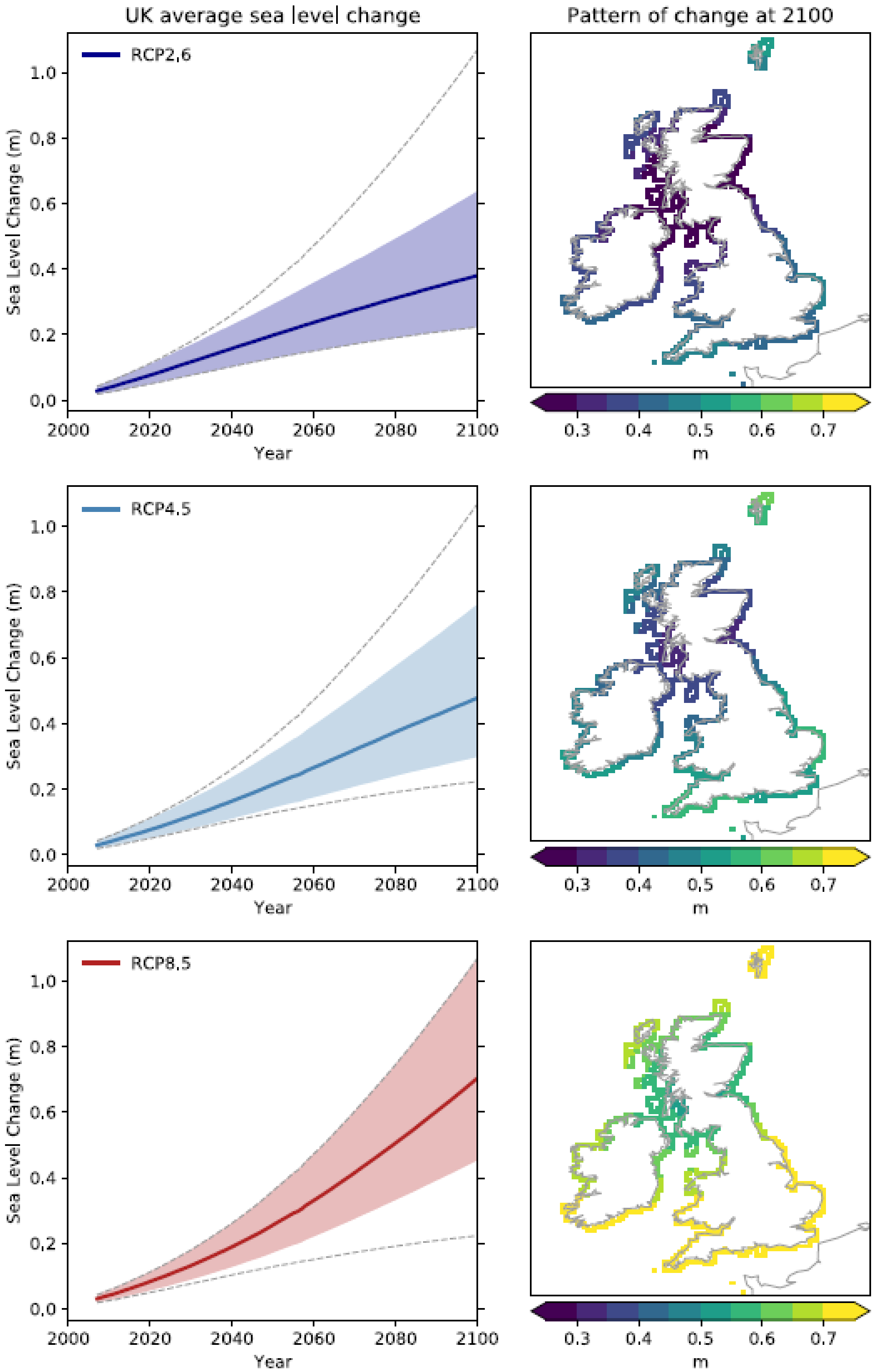
Table A1b.2: Projected ranges of sea level rise (m) at UK capital cities under RCP2.6, 4.5 and 8.5

	London			Cardiff			Edinburgh			Belfast		
	R2.6	R4.5	R8.5	R2.6	R4.5	R8.5	R2.6	R4.5	R8.5	R2.6	R4.5	R8.5
2020	0.07-0.13	0.07-0.13	0.07-0.13	0.06-0.12	0.06-0.12	0.07-0.13	0.01-0.07	0.01-0.07	0.02-0.07	0.02-0.08	0.02-0.08	0.03-0.08
2040	0.13-0.26	0.14-0.27	0.16-0.29	0.12-0.25	0.13-0.26	0.15-0.28	0.04-0.16	0.05-0.17	0.06-0.20	0.05-0.18	0.06-0.18	0.08-0.21
2060	0.19-0.40	0.22-0.44	0.26-0.52	0.18-0.39	0.21-0.43	0.25-0.51	0.06-0.27	0.08-0.30	0.13-0.38	0.08-0.29	0.10-0.32	0.15-0.40
2080	0.24-0.55	0.30-0.63	0.39-0.80	0.23-0.53	0.28-0.62	0.38-0.79	0.07-0.37	0.12-0.45	0.21-0.62	0.10-0.40	0.15-0.48	0.23-0.65
2100	0.29-0.70	0.37-0.83	0.53-1.15	0.27-0.69	0.35-0.81	0.51-1.13	0.08-0.49	0.15-0.61	0.30-0.90	0.11-0.52	0.18-0.64	0.33-0.94

The potential for any of the sea-level projections outlined above to be realised is directly related to the success, or otherwise, of greenhouse gas reductions at a global level.

[12] RCP4.5 is an intermediate pathway, consistent with an increase in global mean surface temperature of 2.4°C averaged over 2081-2100 (Collins *et al.* 2013). If the UK, and other countries, reduced their emissions to be consistent with the ambitions of the Paris Agreement to limit temperature rise to 1.5°C, they would have to reach net zero GHG emissions by 2050, which would be equivalent to the Shared Socioeconomic Pathway of 1.9W/m^2 (Rogelj *et al.* 2018).

Figure A1b.21: UK sea level rise projections at 2100 under RCPs 2.6, 4.5 and 8.5



Note: The sold line and shaded areas in each plume plot represent the central estimate and ranges for each RCP. The maps relating to these RCPs represent the central estimate.

A1b.16.2 Coastal change and its management

Coastal change is widespread and is subject to local factors relating to geology and exposure to prevailing waves (Masselink *et al.* 2020). Research is continuing into the possible change in wave conditions which may arise due to the anthropogenic climate change. There is generally low level of agreement in projections of future storm and wave conditions, as future projections are sensitive to model projections for the North Atlantic storm track which remains an area of considerable uncertainty (Wolf *et al.* 2020). The response of coasts to sea-level rise will depend on local conditions (prevailing solid and drift geology, wave and tidal conditions and sediment processes), however, beach steepening and a loss of intertidal habitat where adjoining landward areas are constrained to adjustment (i.e. coastal squeeze), and potentially enhanced flooding and erosion of soft-rocked coasts are possible (e.g. see Walkden & Dickson 2006, Brooks & Spencer 2012, Masselink *et al.* 2020 and Brooks & Spencer 2014 for decadal scale influences). Erosion presently affects approximately 17% of the UK coast, but is variously distributed (30% in England, 23% in Wales, 20% in Northern Ireland, 12% in Scotland), with geology having a strong role in this variation (see Clayton & Shamoon 1998, May & Hansom 2003, Masselink *et al.* 2020), having a general gradient in rock strength from highly resistant in the north west to very weak in the south and southeast.

Engineered structures are present along much of the UK coast (Table A1b.3, Figure A1b.23) which have sought to limit coastal erosion in certain areas, typically where important infrastructure would otherwise be threatened. Though sometimes controversial, in many instances managed realignment is recommended as the course of action for some eroding coasts, particularly where this is both economically and environmentally justified (for instance where intertidal area is being lost such as in the Severn), and where erosion may actually lead to improved defence against coastal flooding (Dawson *et al.* 2009, in Masselink & Russell 2010). Erosion may be undesirable due to the loss of land, property or infrastructure, but in some cases can be essential in providing sediment to the nearshore area which may be redistributed in the longshore direction and contribute to accreting beaches, fine sediment sinks and other sedimentary features, for example Spurn Head and the Dungeness Foreland.

Current Shoreline Management Plans (SMPs) include policy recommendations for a number of local coastal sub-cells based on a consideration of local geomorphological issues and anthropogenic use of the coast considered over the timescale of the next ~100 years, covering three “epochs” at 20, 50 and 100 year intervals (see Figure A1b.22). These policies take the form of hold the line, advance the line, no active intervention or managed realignment. Coastal change management areas may be defined where rates of shoreline change are significant. The CCC (2018), however, note that SMPs are not being effectively implemented in many areas. Furthermore, the policies and actions they contain are non-statutory and largely untested, such that the practicalities of their implementation are not fully know, and their costs may render them unlikely to be viable such that alternative plans are needed.

Table A1b.3: Coastal erosion and protection in the UK

Area	Coast length (km)	Coast length that is eroding (%)	Coast length with defence works and artificial beaches (%)
England	4,273	29.8	45.6
Wales	1,498	23.1	27.7
Scotland	11,154	11.6	6.6
Northern Ireland	456	19.5	19.7
United Kingdom	17,381	17.3	18.3

Source: From EUROSION 2004, cited by Masselink & Russell (2013)

Though a high level of confidence in the recent MCCIP report card (Masselink *et al.* 2020) is attached to the current knowledge with regard to coastal processes and erosion, a medium level of confidence is applied to what could happen, mainly due to uncertainties about the effect of climate change, rate of sea-level rise and changes in the wave climate, and their interactions with a complex coastal system. Projections of future flood risk in the UK (Sayers *et al.* 2020) produced as part of the third Climate Change Risk Assessment (CCRA 2022, see Betts & Brown 2021) [13], use the latest versions of the UKCP18 climate projections (Palmer *et al.* 2018, see above) to indicate the potential relative change in sea level with an increase of 2˚C and 4˚C in global mean temperature in 2100. Following a number of assumptions, these are used to indicate the standard of protection that would be offered by certain types of coastal defences (i.e. the change in flood return interval the defence could accommodate) in 2100. Sayers *et al.* (2020) note the uncertainty in sea-level rise values highlighted for example, by Pörtner *et al.* (2019, also see above) associated with ice sheet loss that are not taken into account by UKCP18. In addition to the CCRA, and though now dated, the National Coastal Erosion Risk Mapping (NCERM) project has indicated the potential cumulative extent of retreat around the English and Welsh coast along SMP frontages. The mapping includes projections covering the short term (0-20 year), medium term (20-50 year) and long term (50-100 year), with figures presented at the 5th, 50th and 95th percentile[14]. In Scotland, the Dynamic Coast project[15] has mapped past changes and has projected these forward to 2050 and 2100.

Many of the coastal and estuarine environments around the UK are defined as heavily modified or artificial for the purposes of the WFD due to the incidence of, amongst other pressures, land reclamation, coastal and flooding defences, aggregate extraction, use for marine fisheries, and navigation and port activity (see Appendix 1h for more details on many of these activities). Work is underway in order to achieve "Good Ecological Potential" (GEP) in such areas – i.e. encouraging those elements of the natural environment in these areas recognising the physical changes and restrictions applied through the current conditions of use (e.g. navigation). The Environment Agency, NRW, SEPA and DAERA have responsibility for reporting and achieving GEP for their respective areas. The WFD set the objective that

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[13] See: https://www.ukclimaterisk.org/
[14] Details of geologically "complex cliffs" are, in general, not included within the dataset due to the inherent uncertainties associated with predicting the timing and extent of erosion at these locations.
[15] http://www.dynamiccoast.com/ also see: http://marine.gov.scot/information/national-coastal-change-assessment-ncca-2017

modified/artificial water bodies should aim to achieve GEP by 2015[16], however, for many coastal and estuarine water bodies, targets have instead been set for 2021 or 2027. The geographical coverage of the MSFD overlaps with WFD coastal waters. Whilst the implementation of WFD and MSFD may be complementary in these areas in terms of their objectives (e.g. particularly in relation to water chemical quality and some aspects of ecological quality and hydromorphological quality), for coastal waters MSFD will only cover those aspects of GES not already covered by the WFD.

A1b.16.3 Contamination

One of the descriptors of good environmental status in Annex I of the MSFD is that "*concentrations of contaminants are at levels not giving rise to pollution effects*". The implementation of the Marine Strategy Framework Directive and the Water Framework Directive through River Basin Management Plans will likely reduce further existing contamination in estuarine, coastal and marine waters and sediments, in combination with a range of other legislative controls (e.g. in relation to urban waste water treatment and the use and discharge of certain chemicals (see Appendix 2).

[16] Note that where managed realignment contributes to the management of a site which is part of the National site network (e.g. where an SPA is threatened due to intertidal loss), such modification is not considered to be incompatible with achieving GEP.

Figure A1b.22: SMP areas and related policies (20 year epoch)

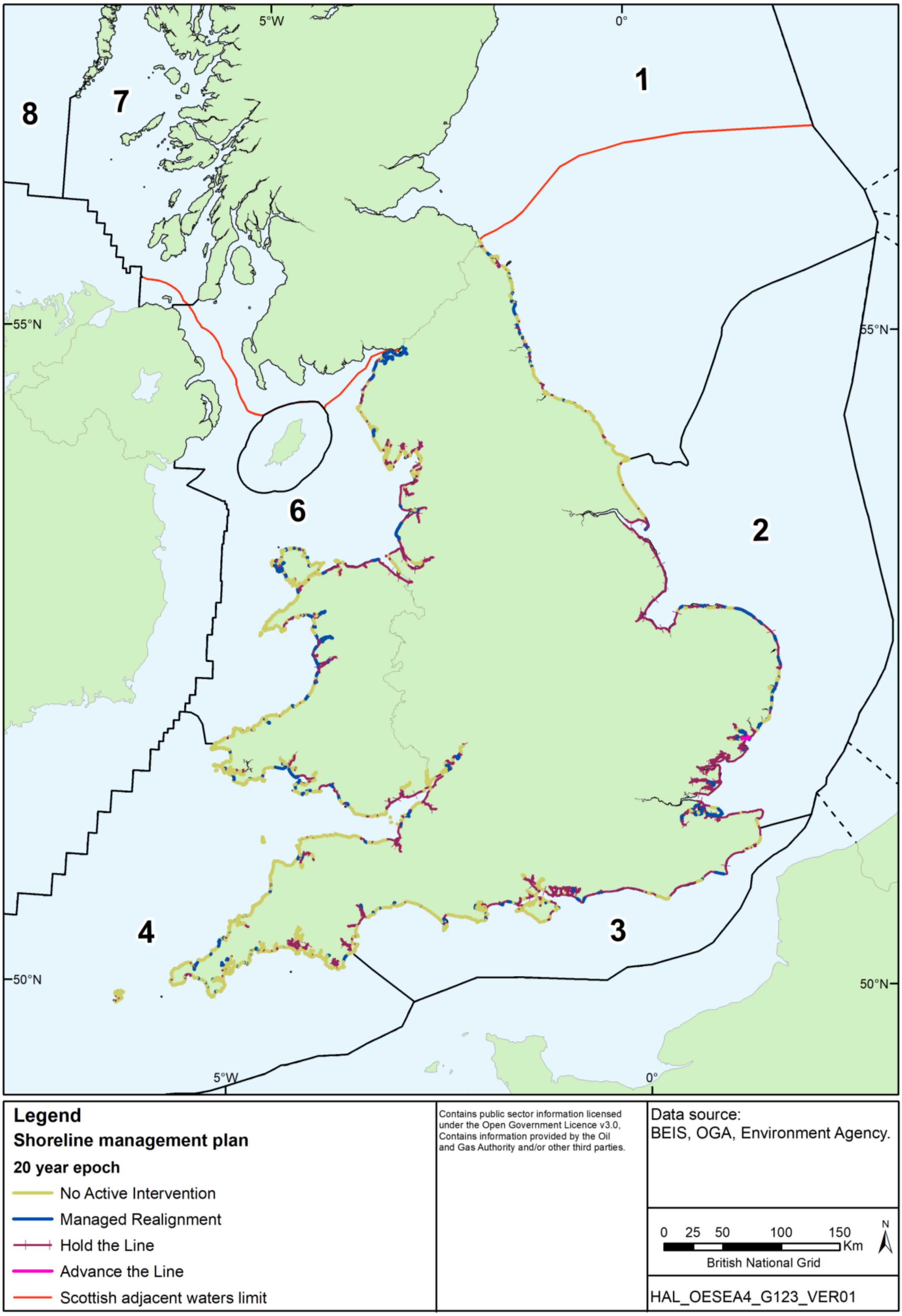
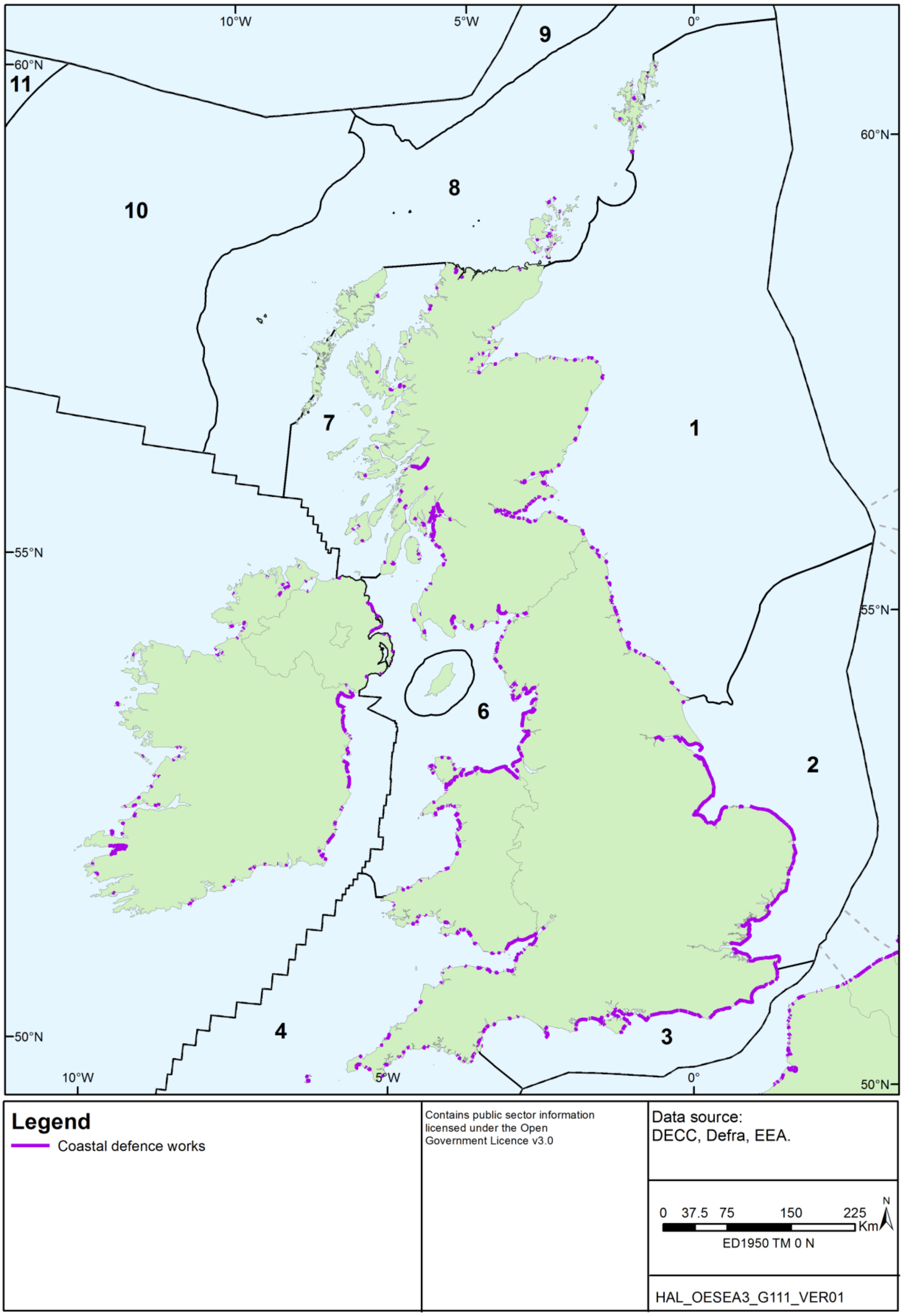


Figure A1b.23: Areas of coastal protection in the UK



Notes: Coastal defence based on output of the EUROSION project and depicts presence/absence of works including sea walls, quays, rocky strands, embankments or groynes.

References

ABPmer (2005). Historical analysis of the Inner Gabbard and the Galloper sand banks; 1833 to 2005. Report to Greater Gabbard Offshore Winds Ltd.

ABPmer (2006). London Array Offshore Wind Farm: Coastal Process Investigation. ABP Marine Environmental Research Ltd, Southampton, 192pp.

Andrews IJ, Long D, Richards PC, Thomson AR, Brown S, Chesher, JA & McCormac M (1990). United Kingdom offshore regional report: the geology of the Moray Firth. HMSO for the British Geological Survey, London, 96pp.

Anthony EJ (2004). Offshore bedload segregation and coastal sand transport pathways in the English Channel: Implications for shoreline development in a mixed tide-, wind- and wave-influenced epicontinental sea. *Proceedings Int. Workshop HWK Delmenhorst* 15-18 April 2004 – From Particle Size to Sediment Dynamics Delmenhorst, Germany.

Austin JA, Cannon SJC & Ellis D (2014). Hydrocarbon exploration and exploitation West of Shetlands. In: Cannon SJC & Ellis D (Eds.) Hydrocarbon Exploration to Exploitation West of Shetlands. *Geological Society, London, Special Publications* **397**: 1-10.

Balson P, Butcher A, Holmes R, Johnson H, Lewis M, Musson R (2002). North Sea Geology. Technical report produced for Strategic Environmental Assessment – SEA2 & SEA3. British Geological Survey. Report to the DTI, 49pp.

Balson P, Tragheim D & Newsham R (1998). Determination and prediction of sediment yields from recession of the Holderness coast, Eastern England. Proceedings of the 33rd MAFF Conference of River and Coastal Engineers: London, Ministry of Agriculture, Fisheries and Food, pp. 451-462.

Barne JH, Robson C, Kaznowska S, Doody J & Davidson N (Eds.) (1995c). Coasts and seas of the United Kingdom. Region 6 Eastern England: Flamborough Head to Great Yarmouth. Joint Nature Conservation Committee, Peterborough, UK, 220pp.

Barne JH, Robson CF, Kaznowska SS & Doody JP (Eds.) (1995a). Coasts and Seas of the United Kingdom. Region 12 Wales: Margam to Little Orme. Joint Nature Conservation Committee, Peterborough, UK, 239pp.

Barne JH, Robson CF, Kaznowska SS, Davidson NC & Doody JP (Eds.) (1995d). Coasts and Seas of the United Kingdom. Region 13: Northern Irish Sea: Colwyn Bay to Stranraer, including the Isle of Man. Joint Nature Conservation Committee, Peterborough, UK, 280pp.

Barne JH, Robson CF, Kaznowska SS, Davidson NC & Doody JP (Eds.) (1997a). Coasts and Seas of the United Kingdom. Region 17 Northern Ireland. Joint Nature Conservation Committee, Peterborough, UK, 217pp.

Barne JH, Robson CF, Kaznowska SS, Davidson NC & Doody JP (Eds.) (1997b). Coasts and Seas of the United Kingdom. Region 4 South-east Scotland: Montrose to Eyemouth. Joint Nature Conservation Committee, Peterborough, UK, 224pp.

Barne JH, Robson CF, Kaznowska SS, Davidson NC & Doody JP (Eds.) (1998a). Coasts and seas of the United Kingdom. Region 7 South East England: Lowestoft to Dungeness. Joint Nature Conservation Committee, Peterborough, UK, 258pp.

Barne JH, Robson CF, Kaznowska SS, Davidson NC, Doody JP & Buck AL (Eds.) (1996a). Coasts and Seas of the United Kingdom. Region 11 The Western Approaches. Joint Nature Conservation Committee, Peterborough, UK, 262pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP & Davidson NC (Eds.) (1996b). Coasts and Seas of the United Kingdom. Region 3 North-east Scotland: Cape Wrath to St. Cyrus. Joint Nature Conservation Committee, Peterborough, UK, 219pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP & Davidson NC (Eds.) (1996c). Coasts and Seas of the United Kingdom. Region 9 Hayling Island to Lyme Regis. Joint Nature Conservation Committee, Peterborough, UK, 249pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP & Davidson NC Eds (1995b). Coasts and Seas of the United Kingdom. Region 5 North-east England: Berwick-upon-Tweed to Filey Bay. Joint Nature Conservation Committee, Peterborough, UK, 194pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP, Davidson NC & Buck AL (1996d). Coasts and seas of the United Kingdom Region 10 South-west England: Seaton to the Roseland Peninsula. Joint Nature Conservation Committee, Peterborough, UK, 217pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP, Davidson NC & Buck AL (Eds.) (1997c). Coasts and Seas of the United Kingdom. Region 14 South-west Scotland: Ballantrae to Mull. Joint Nature Conservation Committee, Peterborough, UK, 229pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP, Davidson NC & Buck AL (Eds.) (1997d). Coasts and Seas of the United Kingdom. Region 1 Shetland. Joint Nature Conservation Committee, Peterborough, UK, 207pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP, Davidson NC & Buck AL (Eds.) (1997e). Coasts and Seas of the United Kingdom. Region 2 Orkney. Joint Nature Conservation Committee, Peterborough, UK, 195pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP, Davidson NC & Buck AL (Eds.) (1997f). Coasts and Seas of the United Kingdom. Regions 15 & 16 North-west Scotland: The Western Isles and west Highland. Joint Nature Conservation Committee, Peterborough, UK, 261pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP, Davidson NC & Buck AL (1997g). Coasts and seas of the United Kingdom Region 15 & 16 North-west Scotland: the Western Isles and west Highland. Joint Nature Conservation Committee, Peterborough, UK, 261pp.

Barne JH, Robson CF, Kaznowska SS, Doody JP, Davidson NC & Buck AL (Eds.) (1998b). Coasts and Seas of the United Kingdom, Region 8: Rye Bay to Chichester Harbour. Joint Nature Conservation Committee, Peterborough, UK, 220pp.

Barrio Froján C, Diesing M & Curtis M (2015). Mapping of the Haig Fras Site of Community Importance (SCI). JNCC/Cefas Partnership Report Series, No. 4002.

Bates MR, Keen DH & Lautridou J-P (2003). Pleistocene marine and periglacial deposits of the English Channel. *Journal of Quaternary Science* **18**: 319-337.

Baxter JM, Boyd IL, Cox M, Donald AE, Malcolm SJ, Miles H, Miller B & Moffat CF (Eds.) (2011). Scotland's Marine Atlas: Information for the national marine plan. Marine Scotland, Edinburgh, 191pp.

Belaidi A, Bonter DA, Slightam C & Trice RC (2018). The Lancaster Field: progress in opening the UK's fractured basement play. *In: Bowman M & Levell B (Eds.) Petroleum Geology of NW Europe: 50 Years of Learning.* Proceedings of the 8th Petroleum Geology Conference, 358-398.

Belderson RH (1964). Holocene sedimentation in the western half of the Irish Sea. *Marine Geology* **2**: 147-163.

Belderson RH (1986). Offshore tidal and non-tidal sand ridges and sheets: differences in morphology and hydrodynamic setting. *In: RJ Knight & JR McLean (Eds.) Shelf Sands and Sandstone. Canadian Society of Petroleum Geologist Memoirs **11**: 293-301.*

Belderson RH, Kenyon NH & Wilson JB (1973). Iceberg plough marks in the Northeast Atlantic. *Palaeogeography, Palaeoclimatology, Palaeoecology* **13**: 215-224.

Bentham M, Mallows T, Lowndes J & Green A (2014). CO_2 STORage Evaluation Database (CO_2 Stored). The UK's online storage atlas. *Energy Procedia* **63**: 5103-5113.

Berné S, Marsset T, Lericolais G, Bourillet J-F & de Batist M (1998). Erosional offshore sand ridges and lowstand shorefaces: examples from tide and wave dominated environments around France. *Journal of Sediment Research* **68**: 540-555.

BGS & Threadgould (1997). Coastal Geology. *In: JH Barne, CF Robson, SS Kaznowska, JP Doody, NC Davidson & AL Buck (Eds.) Coasts and Seas of the United Kingdom. Regions 15 & 16 North-west Scotland: The Western Isles and west Highland.* Joint Nature Conservation Committee, Peterborough, UK, pp. 19-24.

BGS (1995). Coastal landforms. *In: Barne JH, Robson CF, Kaznowska SS, Davidson NC & Doody JP (Eds.). Coasts and Seas of the United Kingdom. Region 13: Northern Irish Sea: Colwyn Bay to Stranraer, including the Isle of Man.* Joint Nature Conservation Committee, Peterborough, UK, pp. 39-41.

BGS (1996). Coastal landforms. *In: Barne JH, Robson CF, Kaznowska SS, Doody JP & Davidson NC (Eds.) Coasts and Seas of the United Kingdom. Region 9 Hayling Island to Lyme Regis.* Joint Nature Conservation Committee, Peterborough, UK, pp. 35-36.

Bishop P & Jones EJW (1979). Patterns of glacial and post-glacial sedimentation in the Minches. *In: FT Banner, MB Collins & KS Massie (Eds.) The North-West European shelf seas: the sea bed and the sea in motion - 1.* Geology and sedimentology, Elsevier, Amsterdam, pp. 18-25.

Black K (2004). SEA5 Analysis: Particle size and organic matter. Report to the Department of Trade and Industry.

Blewett J & Huntley D (1998). Measurement of suspended sediment transport processes in shallow water off the Holderness Coast, UK, *Marine Pollution Bulletin* **37**: 134-143.

Brackenridge RE, Underhill JR, Jamieson R & Bell A (2020). Structural and Stratigraphic Evolution of the Mid North Sea High Region of the UK Continental Shelf. *Petroleum Geoscience* **26**: 154-173.

Bradley SL, Milne GA, Shennan I & Edwards R (2011). An improved Glacial Isostatic Adjustment model for the British Isles. *Journal of Quaternary Science* **26**: 541-552.

Bradwell T, Small D, Fabel D, Clark CD, Chiverrell RC, Saher MH, Dove D, Callard SL, Burke MJ, Moreton SG, Medialdea A, Bateman MD, Roberts DH, Golledge NR & Finlayson A (2019). Pattern, style and timing of British-Irish Ice Sheet retreat: Shetland and northern North Sea sector. *Journal of Quaternary Science*. https://doi.org/10.1002/jqs.3163

Brooks AJ, Kenyon NH, Leslie A, Long D & Gordon JE (2013). Characterising Scotland's marine environment to define search locations for new Marine Protected Areas. Part 2: The identification of key geodiversity areas in Scottish waters. Scottish Natural Heritage Commissioned Report No. 432, 197pp.

Brooks SM & Spencer T (2010). Temporal and spatial variations in recession rates and sediment release from soft rock cliffs, Suffolk Coast, UK. *Geomorphology* **14**: 26-41.

Brooks SM & Spencer T (2012). Shoreline retreat and sediment release in response to accelerating sea-level rise: measuring and modelling cliffline dynamics on the Suffolk Coast, UK. *Global and Planetary Change* **80-81**: 165-179.

Brooks SM & Spencer T (2014). Importance of decadal scale variability in shoreline response: examples from soft rock cliffs, East Anglian coast, UK. *Journal of Coastal Conservation* **18**: 581-593.

Brown LS, Green SL, Stewart HA, Diesing M, Downie A-L, Cooper R & Lillis H (2017). Semi-automated mapping of rock in the Irish Sea, Minches, western Scotland and Scottish continental shelf. JNCC Report No. 609, JNCC, Peterborough.

Bulat J & Long D (2001). Images of the seabed in the Faroe-Shetland Channel from commercial 3D seismic data. *Marine Geophysical Researches* **5**: 345-367.

Burden A, Garbutt A & Evans CD (2019). Effect of restoration on saltmarsh carbon accumulation in Eastern England. *Biology Letters* **15**: 20180773.

Burden A, Garbutt RA, Evans CD, Jones DL & Cooper DM (2013). Carbon sequestration and biogeochemical cycling in a saltmarsh subject to coastal managed realignment. *Estuarine, Coastal and Shelf Science* **120**: 12-20.

Burningham H & French JR (2008). Historical changes in the seabed of the greater Thames estuary. The Crown Estate, 54pp.

Cameron TDJ, Crosby A, Balson PS, Jeffrey DH, Lott GK, Bulat J & Harrison DJ (1992). United Kingdom Offshore Regional Report: the geology of the southern North Sea. HMSO for the British Geological Survey, London, 152pp.

Caston VND & Stride AH (1970). Tidal sand movement between some linear sand banks in the North Sea off northeast Norfolk. *Marine Geology* **9**: 38-42.

Caston VND (1972). Linear sandbanks in the southern North Sea. *Sedimentology* **18**: 63-78.

CEFAS (2000). Quality Status Report of the Marine and Coastal Areas of the Irish Sea and Bristol Channel 2000. DETR, London, 258pp.

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D & Unnikrishnan A (2013). Sea Level Change. *In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1137-1216.

Ciavola P (1997). Coastal dynamics and impact of coastal protection works on the Spurn Head spit (UK). *Catena* **30**: 369-389.

Clarke CD, Ely JC, Greenwood SL, Hughes ALC, Meehan R, Barr ID, Bateman MD, Bradwell T, Doole J, Evans DJA, Jordan CJ, Monteys X, Pellicer XM & Sheehy M (2017). BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet. *Boreas* https://doi.org/10.1111/bor.12273

Clayton K & Shamoon N (1998). New approach to the relief of Great Britain II. A classification of rocks based on relative resistance to denudation. *Geomorphology* **25:** 155-171.

Coggan R, Barrio Froján CRS, Diesing M & Aldridge J (2012). Spatial patterns in gravel habitats and communities in the central and eastern English Channel. *Estuarine, Coastal and Shelf Science* **111**: 118-128.

Coggan R, Diesing M & Vanstaen K (2009). Mapping Annex I Reefs in the central English Channel: evidence to support the selection of candidate SACs. Scientific Series Technical Report, Cefas Lowestoft, 145: 116pp.

Collins M, Knutti R, Arblaster K, Dufresne J.-L,Fichefet T, Friedlingstein P,Gao X, Gutowski WJ,Johns T, Krinner G,Shongwe M, Tebaldi C, Weaver AJ & Wehner M (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In: In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1029-1136.

Collins MB, Shimwell SJ, Gao S, Powell H, Hewitson C & Taylor JA (1995). Water and sediment movement in the vicinity of linear sandbanks: the Norfolk Banks, southern North Sea. *Marine Geology* **123**: 125-142.

Connor DW, Gilliland PM, Golding N, Robinson P, Todd D & Verling E (2006). UKSeaMap: the mapping of seabed and water column features of UK seas. Joint Nature Conservation Committee, Peterborough, UK, 107pp.

Cooper KM (2005). Cumulative effects of marine aggregate extraction in an area east of the Isle of Wight. A fishing industry perspective. Science Series Technical Report No. 126. Centre for Environment, Fisheries & Aquaculture Science, Lowestoft, 28pp.

Cooper NJ & Pontee NI (2006). Appraisal and evolution of the littoral ‘sediment cell concept in applied coastal management: Experiences from England and Wales. *Ocean & Coastal Management* **49**: 498-510.

Copper ES, Townend IH & Balson PS (2008). A synthesis of current knowledge on the genesis of the Great Yarmouth and Norfolk Bank Systems. The Crown Estate, 69 pages, February 2008. ISBN: 978-0-9553427-8-3, 74pp.

Cotterill C & Leslie A (2013). Physiography and Seabed Sediments. *In: Hitchen K, Johnson H & Gatliff RW (Eds.) (2013). Geology of the Rockall Basin and Adjacent Areas.* British Geological Survey Research Report RR/12/03, 144-159.

Cotterill CJ, Phillips E, James L, Forsberg CF, Tjelta TI, Carter G & Dove D (2017). The evolution of the Dogger Bank, North Sea: A complex history of terrestrial, glacial and marine environmental change. *Quaternary Science Reviews* **171**: 136-153.

Cox (2002). Appendix 9 Report on mineralogical tracers. In: HR Wallingford. Southern North Sea Sediment Transport Study, Phase 2, 14pp.

D’Olier B (2002). Appendix 10 A geological background to sediment sources, pathways and sinks. In: HR Wallingford. Southern North Sea Sediment Transport Study, Phase 2, 24pp.

Dargie TCD (1993). *Sand dune vegetation survey of Great Britain. Part 2 – Scotland.* Joint Nature Conservation Committee, Peterborough, UK.

Dargie TCD (1997). Cliffs and cliff-top vegetation. *In: JH Barne, CF Robson, SS Kaznowska, JP Doody, NC Davidson & AL Buck (Eds.) Coasts and Seas of the United Kingdom. Regions 15 & 16 North-west Scotland: The Western Isles and west Highland.* Joint Nature Conservation Committee, Peterborough, UK pp. 49-52.

Davies J, Guinan J, Howell K, Stewart H & Verling E (2008). MESH South West Approaches Canyons Survey (MESH Cruise 01-07-01) Final Report. MESH Partnership, 2008.

Davis RA & Balson PS (1992). Stratigraphy of a North Sea tidal sand ridge. *Journal of Sedimentary Petrology* **62**: 116-122.

Davison I, Stasuik S, Nutall P & Keane P (2010). Sub-basalt hydrocarbon prospectivity in the Rockall, Faroe-Shetland and Møre basins, NE Atlantic. *Geological Society, London. Petroleum Geology Conference series* **7**: 1025-1032.

Dawson AG, Long D & Smith DE (1998). The Storegga Slides: evidence from eastern Scotland for a possible tsunami. *Marine Geology* **82**: 271-276.

DECC (2012). Elgin gas release, environmental aspects update. Government Interest Group, 16 May 2012.

DECC (2013). Petroleum prospectivity of the principal sedimentary basins on the United Kingdom Continental Shelf. Department of Energy and Climate Change, 39pp.

DECC (2014). Potential future exploration 2014 opportunities, UK Rockall Basin. Promote United Kingdom, Department of Energy and Climate Change, 7pp.

Defra (2010). Charting Progress 2 Feeder Report: Clean and safe seas. Draft published by the Department for Environment Food and Rural Affairs on behalf of the UK Marine Monitoring and Assessment Strategy community, London, 358pp.

Defra (2019). Marine Strategy Part One: UK updated assessment and Good Environmental Status. 107pp.

Diesing M, Green SL, Stephens D, Cooper R & Mellett CL (2015). Semi-automated mapping of rock in the English Channel and Celtic Sea. Peterborough, UK. 19pp.

Diesing M, Thorsnes T & Bjarnadóttir LR (2021). Organic carbon densities and accumulation rates in surface sediments of the North Sea and Skagerrak. *Biogeosciences* **18**: 2139–2160.

Diesing M, Ware S, Foster-Smith R, Stewart H, Long D, Vanstaen K, Forster R & Morando A (2009). Understanding the marine environment – seabed habitat investigations of the Dogger Bank offshore draft SAC. Joint Nature Conservation Committee Peterborough. JNCC Report No. 429, 89pp + Appendices.

Dixon T (2013). Advisory Committee on Protection of the Sea. Annual survey of reported discharges attributed to vessels and offshore oil and gas installations operating in the United Kingdom pollution control zone 2013. A survey conducted on behalf of the Maritime and Coastguard Agency, 83pp.

Dolphin TJ, Silva TAM & Rees JM (2011). Natural Variability of Turbidity in the Regional Environmental Assessment (REA) Areas. MEPF-MALSF Project 09-P114. Cefas, Lowestoft, 41

Doody JP (1996). Overview. Introduction to the region. *In: JH Barne, CF Robson, SS Kaznowska, JP Doody & NC Davidson (Eds.) Coasts and Seas of the United Kingdom. Region 3 North-east Scotland: Cape Wrath to St. Cyrus.* Joint Nature Conservation Committee, Peterborough, UK, pp. 13-18.

Downie AL, Dove D, Westhead RK, Diesing M, Green SL & Cooper R (2016) Semi-automated mapping of rock in the North Sea, JNCC Report No. 592, JNCC, Peterborough, ISSN 0963-8091.

DTI (2006b). Petroleum prospectivity of the principal sedimentary basins on the United Kingdom Continental Shelf. Unpublished report. Department of Trade and Industry, London, 41pp.

Duarte CM, Losanda IJ, Hendriks IE, Mazarrasa I & Marbà N (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change* **3**: 961-968.

Dunbar MJ, Everett SJ & Fowler SL (1995). Coastal defence. *In: Barne JH, Robson CF, Kaznowska SS & Doody JP (Eds.). Coasts and Seas of the United Kingdom. Region 12 Wales: Margam to Little Orme.* Joint Nature Conservation Committee, Peterborough, UK, pp. 183-185.

Dunbar MJ, Everett SJ & Fowler SL (1996). Land use, infrastructure and coastal defence. *In: JH Barne, CF Robson, SS Kaznowska, JP Doody & NC Davidson (Eds.) Coasts and Seas of the United Kingdom, Region 9: Hayling Island to Lyme Regis.* Joint Nature Conservation Committee, Peterborough, UK pp. 185-188.

Dyer KR & Huntley DA (1999). The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research* **19**: 1285-1330.

Eggleton J, Dolphin T, Ware S, Bell T, Aldridge J, Silva T, Forster R, Whomersley P, Parker R, Rees J (2011). Natural variability of REA regions, their ecological significance & sensitivity. MEPF-MALSF Project 09-P114. Cefas, Lowestoft, 171pp.

Eggleton J, Stephens D, Diesing M, Ware S & Curtis M (2015). Farnes East rMCZ post-survey site report. Report No. 3 to Defra under contract MB0120. Version 10, March 2015, 86pp.

Ellwood H (2013). Method for Creating a Composite Map of Annex I Reef in UK Waters. Available from: http://jncc.defra.gov.uk/pdf/20130607_AnnexI_Reef_Map_Methodology_v2.pdf

Emery AR, Hodgson DM, Barlow NLM, Carrivick JL, Cotterill CJ, Mellett L & Booth AD (2019). Topographic and hydrodynamic controls on barrier retreat and preservation: An example from Dogger Bank, North Sea. *Marine Geology* **416**: 105981.

Emu Ltd & University of Southampton (2009). Outer Thames Estuary Regional Environmental Characterisation. Published by Marine Aggregate Levy Sustainability Fund, 129pp.

Environment Agency (2010). The Wash Shoreline Management Plan 2: Gibraltar Point to Hunstanton. 112pp + Appendices.

ERTSL (2001). BP Clair field development (UKCS Block 206/8), seabed environmental survey April/May 2000. ERTSL report R00/203 for BP.

Evans CDR (1990). The Geology of the English Channel and its Western Approaches. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, UK, 93pp.

Evans CDR (1995). Coastal landforms. *In: Barne JH, Robson CF, Kaznowska SS & Doody JP (Eds.). Coasts and Seas of the United Kingdom. Region 12 Wales: Margam to Little Orme.* Joint Nature Conservation Committee, Peterborough, UK, 38-40.

Farrow GE, Allen NH & Akpan ET (1984). Bioclastic carbonate sedimentation on a high-latitude, tide dominated shelf: Northeast Orkney Islands, Scotland. *Journal of Sedimentology and Petrology* **54**: 373-393.

Fitch S, Thomson K & Gaffney V (2005). Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research* **64**: 185-196.

Flavell B, Carr H, Robson L, Byford S, Chaniotis P, Last E, Long M, Matear L & Novak E (2020). Developing the evidence-base to support climate-smart decision making on MPAs. JNCC Report No. 648. JNCC, Peterborough, ISSN 09638091.

Foster-Smith R, Benson A & Foster-Smith J (2009). Biological data interpretation of the Reef East of Shetland Isles Area of Search. JNCC Report No. 433, 67pp.

Fyfe JA, Long D, Evans D & Abraham DA (1993). United Kingdom Offshore Regional Report: the geology of the Malin-Hebrides sea area. HMSO for the British Geological Survey, London 91pp.

Gafeira J & Long D (2015a). Geological investigation of pockmarks in the Scanner Pockmark SCI area. JNCC Report No. 570, Joint Nature Conservation Committee, Peterborough, UK, 80pp.

Gafeira J & Long D (2015b). Geological investigation Braemar Pockmarks SCI and surrounding area. JNCC Report No. 571, Joint Nature Conservation Committee, Peterborough UK, 53pp.

Gafeira J, Green S, Dove D, Morando A, Cooper R, Long D & Gatliff RW (2010). Developing the necessary data layers for Marine Conservation Zone selection - Distribution of rock/hard substrate on the UK Continental Shelf. Final Report. Project Code: MB0103, 72pp.

Games KP & Gordon DI (2015). Study of sand wave migration over five years as observed in two windfarm development areas, and the implications for building on moving substrates in the North Sea. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* **105**: 241-249.

Garbe J, Albrecht T, Levermann A, Donges GF & Winkelmann R (2020). The hysteresis of the Antarctic Ice Sheet. *Nature* **585**: 538-544.

Gatliff RW, Richards PC, Smith K, Graham CC, McCormac M, Smith NJP, Long D, Cameron TDJ, Evans D, Stevenson AG, Bulat J & Ritchie RD (1994). The geology of the central North Sea. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, 118pp.

GGOWL (2005). Greater Gabbard Offshore Wind Farm Environmental Statement. 2005. Greater Gabbard Offshore Winds Ltd (Airtricity/Fluor).

Gibbard PL & Lautridau JP (2003). The Quaternary history of the English Channel: an introduction. *Journal of Quaternary Science* **18**: 195-199

Gibbard PL (1995). The formation of the Strait of Dover. *In: RC Preece (Ed.) Island Britain: a Quaternary Perspective.* Special Publication Geological Society Publishing House, Bath pp. 15-26.

Gordon JE, Brooks AJ, Rennie AG, James BD, Chaniotis PD, Kenyon NH, Leslie AB & Long D (2013). The selection of Nature Conservation Marine Protected Areas (MPAs) in Scotland – assessment of geodiversity interests. Scottish Natural Heritage Commissioned Report No. 633, 74pp.

Graham AGC, Lonergan L, Martyn S (2009). Seafloor glacial features reveal the extent and decay of the last British Ice Sheet, east of Scotland. *Journal of Quaternary Science* **24**: 117-138.

Gregg R, Elias JL, Alonso I, Crosher IE, Muto P & Morecroft MD (2021). Carbon storage and sequestration by habitat: a review of the evidence (second edition). Natural England Research Report NERR094. Natural England, York.

Hamblin RJO, Crosby A, Balson PS, Jones SM, Chadwick RA, Penn IE & Arthur MJ (1992). The Geology of the English Channel. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, 106pp.

Hansom (2003). Forvie. Geological Conservation Review. Volume 28: Coastal Geomorphology of Great Britain, Chapter 7: Sandy beaches and dunes, 9pp.

Hartley Anderson (2000). An analysis of the seabed fauna and sediments of the Clair Field from photographs and video. Report to BP, 45pp. plus appendices.

Heather S, Davies J, Long S, Strömberg H & Hitchen K (2009). JNCC Offshore Natura Survey. Anton Dohrn Seamount and East Rockall Bank Areas of Search. 2009/03-JNCC Cruise Report: Report Number CR/09/113. 90pp.

Hill MA (1996). Terrestrial Coastal Habitats: Salt Marsh. In: JH Barne, CF Robson, SS Kaznowska, JP Doody & NC Davidson Eds. Coasts and Seas of the United Kingdom, Region 9: Hayling Island to Lyme Regis. Joint Nature Conservation Committee, Peterborough, UK pp. 57-60.

Hitchen K & Quinn M (2011). Economic Geology. *In: Hitchen K, Johnson H & Gatliff RW (Eds.) (2011). Geology of the Rockall Basin and Adjacent Areas*. British Geological Survey Research Report RR/12/03, 138-143.

Hitchen K, Holmes R, Musson RMW, Cooper RM & Jones SM (2003). DTI Strategic Environmental Assessment Area 4 (SEA4): Sub-seabed Geology. Report No. CR/03/080. Report to the Department of Trade and Industry. British Geological Survey, UK, 14pp.

Hitchen K, Johnson H & Gatliff RW (Eds.) (2013). Geology of the Rockall Basin and Adjacent Areas. British Geological Survey Research Report RR/12/03, 192pp.

Hobbs PRN, Jones LD, Kirkham MP, Pennington CVL & Dashwood MC (2019). Coastal landslide monitoring at Aldbrough, East Riding of Yorkshire, UK. *Quaternary Journal of Engineering Geology & Hydrogeology* https://doi.org/10.1144/qjegh2018-210

Holloway S, Vincent CJ & Kirk KL (2006). Industrial carbon dioxide emissions and carbon dioxide storage potential in the UK. Report No. COAL R308 DTI/Pub URN 06/2027. October 2006, 56pp.

Holmes R & Tappin DR (2005). DTI Strategic Environmental Assessment Area 6, Irish Sea, seabed and surficial geology and processes. Report No. CR/05/057. Report to the Department of Trade and Industry. British Geological Survey, UK, 72pp.

Holmes R, Bulat J, Henni P, Holt J, James C, Kenyon N, Leslie A, Long D, Musson R, Pearson S & Stewart H (2004). DTI Strategic Environmental Assessment Area 5 (SEA5): Seabed and superficial geology and processes. Report to the Department of Trade and Industry. British Geological Survey, UK, 86pp.

Holmes R, Hitchen K & Ottemoller L (2006). Strategic Environmental Assessment Area 7: hydrocarbon prospectivity, earthquakes, continental shelves and Rockall Trough surficial and sea-bed geology and sea-bed processes. British Geological Survey Commissioned Report, CR/06/063, 89pp.

Holmes R, Long D & Dodd LR (1998). Large-scale debrites and submarine landslides on the Barra Fan, west of Britain. *Geological Society London, Special Publications* **129**:67-79.

Horsburgh K & Lowe J (2013). Impacts of climate change on sea level. *MCCIP Science Review 2013*, pp. 27-33.

Houbolt JJHC (1969). Recent sediments in the southern bight of the North Sea. *Geological Mijnbouw* **47**: 245-273.

Howell KL, Davies JS & Narayanaswamy BE (2010). Identifying deep-sea megafaunal epibenthic assemblages for use in habitat mapping and marine protected area network design. *Journal of the Marine Biological Association of the United Kingdom* **90**: 33-68.

HR Wallingford (1997). Coastal cells in Scotland: Scottish Natural Heritage Research. Survey and Monitoring Report No. 56, 136pp.

HR Wallingford (2002). Southern North Sea Sediment Transport Study, Phase 2. Report EX 4526 August 2002, 94pp. plus appendices.

Hughes ALC, Gyllencreutz R, Lohne ØS, Mangerud J & Svendsen JI (2016). The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas* **45**: 1-45.

Huuse M & Kristensen TB (2016). Pleistocene tunnel valleys in the North Sea Basin. Geological Society, London, Memoirs **46**: 207-208.

Idier M, Ehrhold A & Garlan T (2002). Morphodynamique d’une dune sous-marine du détroit du pas de Calais. *C. R. Geoscience* **334**: 1079-1085.

IPCC (2013). Summary for Policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V & Midgley PM (Eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson DI, Jackson AA, Evans S, Wingfield RTR, Barnes RP & Arthur MJ (1995). The Geology of the Irish Sea. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, 123pp.

Jackson PD, Gunn DA & Long D (2004). Predicting variability in the stability of slope sediments due to earthquake ground motion in the AFEN area of the western UK continental shelf. *Marine Geology* **213**: 363-378.

Jacobs CL (2006). An Appraisal of the Surface Geology and Sedimentary Processes within SEA7, the UK Continental Shelf. National Oceanography Centre, Southampton. Research & Consultancy Report No. 18, 62pp + Figures.

James JWC, Coogan RA, Blyth-Skyrme VJ, Morando A, Birchenough SNR, Bee E, Limpenny DS, Verling E, Vanstaen K, Pearce B, Johnston CM, Rocks KF, Philport SL & Rees HL (2007). Eastern English Channel Marine Habitat Map. Science Series Technical Report no. 139, 191pp.

James JWC, Pearce B, Coggan RA, Arnott SHL, Clark R, Plim JF, Pinnion J, Barrio Frojan C, Gardiner JP, Morando A, Baggaley PA, Scott G, Bigourdan N (2010). The South Coast Regional Environmental Characterisation. British Geological Survey, 249pp.

JNCC (2007). 2007 consultation on the selection of UK offshore Special Areas of Conservation. Joint Nature Conservation Committee, Peterborough, UK, 51pp.

JNCC (2008a). Offshore Special Area of Conservation: Haig Fras. SAC Selection Assessment Version 4 (1st July 2008). Joint Nature Conservation Committee, Peterborough, UK, 14pp.

JNCC (2008b). Offshore Special Area of Conservation: Darwin Mounds. SAC Selection Assessment Version 4 (1st July 2008). Joint Nature Conservation Committee, Peterborough, UK, 14pp.

JNCC (2010). Offshore Special Area of Conservation: Dogger Bank. SAC Selection Assessment Document. Version 9.0 (26th August 2011), 32pp.

JNCC (2012). Offshore Special Area of Conservation: Croker Carbonate Slabs. SAC Selection Assessment Document. Version 5.0 (5th September 2012), 18pp.

JNCC (2014). Method for Creating a Composite Map of Annex I Sandbanks slightly covered by seawater all of the time. Version 1.1, revised 23/01/2014, 12pp.

JNCC (2018a). Offshore Special Area of Conservation: Scanner Pockmark. SAC Selection Assessment Document. Version 6.0, 14pp.

JNCC (2018b). Offshore Special Area of Conservation: Braemar Pockmarks. SAC Selection Assessment Document. Version 6.0, 15pp.

JNCC (2019). Method for creating version 8 of the UK Composite Map of Annex I Reefs. 19pp. https://hub.jncc.gov.uk/assets/992dfef7-3267-43db-b351-5927bf0621d4

JNCC (2020). Method for Creating version 3 of the UK Composite Map of Annex I Sandbanks slightly covered by seawater all of the time. 14pp.

Johnson H, Richards PC, Long D & Graham CC (1993). The geology of the northern North Sea. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, 110pp.

Johnston C, Turnbull CG & Tasker M (2002). Natura 2000 in UK Offshore Waters: Advice to support the implementation of the EC Habitats and Birds Directives in UK offshore waters. Report No. 325. Joint Nature Conservation Committee, Peterborough, UK, 162pp.

Jones LA, Coyle MD, Evans D, Gilliland PM & Murray AR (2004a). Southern North Sea Marine Natural Area Profile: A contribution to regional planning and management of the seas around England. English Nature, Peterborough, UK, 102pp.

Jones LA, Irving R, Coyle MD, Evans D, Gilliland, PM & Murray AR (2004b). Western Approaches Marine Natural Area Profile: A contribution to regional planning and management of the seas around England. English Nature, Peterborough, UK, 76pp.

Judd A, Croker P, Tizzard L & Voisey C (2007). Extensive methane-derived authigenic carbonates in the Irish Sea. *Geo-Marine Letters* **27**: 259-267.

Judd A, Noble-James T, Golding N, Eggett A, Diesing M, Clare D, Silburn B, Duncan G, Field L & Milodowski A (2019) The Croker Carbonate Slabs: extensive methane-derived authigenic carbonate in the Irish Sea—nature, origin, longevity and environmental significance. *Geo-Marine Letters.* doi: https://doi.org/10.1007/s00367-019-00584-0

Judd AG (2001). Pockmarks in the UK Sector of the North Sea. Report to the Department of Trade and Industry. University of Sunderland, UK, 70pp.

Judd AG (2005a). The distribution and extent of methane-derived authigenic carbonate. DTI Strategic Environmental Assessment, Area 6 (SEA6), 69pp.

Judd AG (2005b). The distribution and extent of 'submarine structures formed by leaking gas' and other seabed features (reefs) relevant to the 'Habitats Directive'. Technical Report produced for SEA6 Strategic Environmental Assessment of the Irish Sea.

Kenyon (2005). Internal Structure and Potential Movement of the Inner Gabbard and Galloper Banks, Southern North Sea. Kenyon MarineGeo.

Kenyon NH & Cooper W (2005). Sandbanks, sand transport and offshore wind farms. Report for the Department of Trade and Industry. Kenyon MarineGeo and ABP Marine Environmental Research Ltd, UK.

Lagarde JL, Amorese D, Font M, Laville E & Dugué O (2003). The structural evolution of the English Channel area. *Journal of Quaternary Science* **18**: 201-213.

Lambeck K (1995). Predicted shoreline from rebound models. *Journal of the Geological Society* **152**: 437-448.

Lericolais G, Auffret J-P & Bourillet J-F (2003). The Quaternary Channel River: seismic stratigraphy of its palaeo-valleys and deeps. *Journal of Quaternary Science* **18**:245-260.

Leynaud D, Mienert J & Vanneste M (2009). Submarine mass movements on glaciated and non-glaciated European continental margins: A review of triggering mechanisms and preconditions to failure. *Marine and Petroleum Geology* **26**: 618-632.

Leynaud DJ & Meinert J (2003). Slope stability assessment of the Trænadjupet Slide area offshore the mid-Norwegian margin. In: Submarine mass movements and their consequences. Dordrecht, Boston, London: Kluwer Academic Publishers, p.255-266.

Limpenny SE, Barrio Froján C, Cotterill C, Foster-Smith RL, Pearce B, Tizzard L, Limpenny DL, Long D, Walmsley S, Kirby S, Baker K, Meadows WJ, Rees J, Hill J, Wilson C, Leivers M, Churchley S, Russell J, Birchenough AC, Green SL & Law RJ (2011). The East Coast Regional Environmental Characterisation. Cefas Open report 08/04. 287pp.

Lonergan L, Maidment SCR & Collier JS (2006). Pleistocene subglacial tunnel valleys in the central North Sea basin: 3-D morphology and evolution. *Journal of Quaternary Science* **21**: 891-903.

Long AJ, Waller MP & Plater AJ (2006). Coastal resilience and late Holocene tidal inlet history: The evolution of Dungeness Foreland and the Romney Marsh depositional complex (U.K.). *Geomorphology* **82**: 309-330.

Long D (1986). Seabed Sediments: Fladen Sheet 58°N-00°. British Geological Survey, 1:250,000 Series.

Long D (2011). Geohazards. *In: Ritchie JD, Ziska H, Johnson H & Evans D (Eds.) (2011). Geology of the Faroe-Shetland Basin and Adjacent Areas.* British Geological Survey/Jarðfeingi Research Report RR/11/01, 239-253.

Long D (2013). Geohazards. *In: Hitchen K, Johnson H & Gatliff RW (Eds.) (2013). Geology of the Rockall Basin and Adjacent Areas*. British Geological Survey Research Report RR/12/03, 160-164.

Lovelock CE & Duarte CM (2019). Dimensions of Blue Carbon and emerging perspectives. *Biology Letters* **15**: 20180781.

Luisetti T, Turner RK, Andrews JE, Jickells TD, Kroger S, Diesing M, Paltiguera L, Johnson MT, Parker ER, Bakker, DCE & Weston K (2019). Quantifying and evaluating carbon flows and stores in coastal and shelf ecosystems in the UK. *Ecosystem Services* **35**: 67-76.

Luisetti, T., Ferrini, S., Grilli, G., Jickells, T. D., Kennedy, H., Kröger, S., et al. (2020). Climate action requires new accounting guidance and governance frameworks to manage carbon in shelf seas. *Nature Communications* **11**: 4599–4610. doi:10.1038/s41467-020-18242-w

Masselink G & Russell P (2010). Coastal erosion in MCCIP Annual Report Card 2010-11, MCCIP Science Review, 18pp.

Masselink G & Russell P (2013). Impacts of climate change on coastal erosion. MCCIP Science Review 2013, 71-86.

Masselink G, Russell P, Rennie A, Brooks S & Spencer T (2020). Impacts of climate change on coastal geomorphology and coastal erosion relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 158-189.

Masson DG (2001). Sedimentary processes shaping the eastern slope of the Faroe-Shetland Channel. *Continental Shelf Research* **21**: 825-857.

Masson DG, Bett BJ, Billet DSM, Jacobs CL, Wheeler AJ & Wynn RB (2003a). The origin of deepwater, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. *Marine Geology* **194**: 159-180.

Masson DG, Le Bas TP, Bett BJ, Hühnerbach V, Jacobs CL & Wynn RB (2003b). Seafloor sediments and sedimentary processes on the outer continental shelf, continental slope and basin floor. Report to the Department of Trade and Industry. Southampton Oceanography Centre, Southampton, UK.

Masson DG, Wynn RB & Bett BJ (2004). Sedimentary environment of the Faroe-Shetland and Faroe Bank Channels, north-east Atlantic, and the use of bedforms as indicators of bottom current velocity in the deep ocean. *Sedimentology* **51**: 1207-1241.

May VJ & Hansom JD (2003). *Coastal Geomorphology of Great Britain*, Geological Conservation Review Series, No. 28. Joint Nature Conservation Committee, Peterborough, UK, 754pp.

May VJ (2003a). Chapter 3: Hard-rock cliffs – GCR site reports. *In: VJ May & JD Hanson (Eds.) Coastal Geomorphology of Great Britain. Geological Conservation Review Series: No. 28.* Joint Nature Conservation Committee, Peterborough, UK.

May VJ (2003b). Chapter 6: Gravel and ‘shingle' beaches – GCR site reports. *In: VJ May & JD Hansom Eds. Coastal Geomorphology of Great Britain. Geological Conservation Review Series: No. 28.* Joint Nature Conservation Committee, Peterborough, UK.

May VJ (2003c). Chapter 7: Sandy beaches and dunes – GCR site reports. *In: VJ May & JD Hansom Eds. Coastal Geomorphology of Great Britain. Geological Conservation Review Series: No. 28.* Joint Nature Conservation Committee, Peterborough, UK.

May VJ (2003d). Chapter 8: Sand spits and tombolos – GCR site reports. *In: VJ May & JD Hansom Eds. Coastal Geomorphology of Great Britain. Geological Conservation Review Series: No. 28.* Joint Nature Conservation Committee, Peterborough, UK.

May VJ (2003e). Chapter 11: Coastal assemblage GCR sites – GCR site reports. *In: VJ May & JD Hansom. Coastal Geomorphology of Great Britain. Geological Conservation Review Series: No. 28.* Joint Nature Conservation Committee, Peterborough, UK.

McBreen F, Askew N, Cameron A, Connor D, Ellwood H & Carter A (2011). UKSeaMap 2010: Predictive mapping of seabed habitats in UK waters. JNCC Report No. 466, Joint Nature Conservation Committee, Peterborough, UK, 103pp.

Mellett C, Hodgson DM, Plater AJ, Mauz B, Selby I & Lang A (2013). Denudation of the continental shelf between Britain and France at the glacial–interglacial timescale. *Geomorphology* **203**:79-96.

Mellett C, Long D, Carter G, Chiverell R & Landeghem K (2015). Geology of the seabed and shallow subsurface: The Irish Sea. British Geological Survey Commissioned Report, CR/15/057. 52pp.

Milodowski AE, Lacinska A & Sloane H (2009). Petrography and stable isotope geochemistry of samples of methane-derived authigenic carbonates (MDAC) from the Mid Irish Sea. British Geological Survey commissioned report, cr/09/051, 18pp.

Montreuil AL & Bullard JE (2012). A 150 year record of coastline dynamics within a sediment cell: eastern England. *Geomorphology* **179**: 168-185.

Murphy PK, Coughlan MJ, Wheeler AJ & Tóth Z (2016). Irish Sea Suitability Mapping for Novel Offshore Foundations (ISSMaNOF). University College Cork, Gaelectric Developments Ltd and the Irish Centre for Research in Applied Geosciences, 189pp.

Musson RMW & Winter PW (1997). Seismic Hazard maps for the UK. *Natural Hazards* **14**: 141-154.

Musson RMW (1994). A catalogue of British earthquakes. BGS Technical Report No. WL/94/04.

Naylor D & Shannon PM (1999). The Irish Sea region: why the general lack of exploration success? *Journal of Petroleum Geology* **22**: 363-370.

Newell RC & Woodcock TA (2013). Aggregate dredging and the marine environment: an overview of recent research and current industry practice. The Crown Estate, 165pp ISBN: 978-1-906410-41-4, 164pp.

Nielson T & Kuijpers A (2004). Geohazard studies offshore the Faroe Islands: slope instability, bottom currents and sub-seabed sediment mobilisation. *Bulletin of the Geological Survey of Denmark and Greenland* **4**: 57-60.

Noy DJ, Holloway S, Chadwick RA, Williams JDO, Hannis SA & Lahann RW (2012). Modelling large-scale carbon dioxide injection into the Bunter Sandstone in the UK Southern North Sea. *International Journal of Greenhouse Gas Control* **9**: 220-233.

O’Reilly SS, Hryniewicz K, Little CTS, Monteys X, Szpak MT, Murphy BT, Jordan SF, Allen CCR & Kelleher BP (2014). Shallow water methane-derived authigenic carbonate mounds at the Codling Fault Zone, western Irish Sea. *Marine Geology* **357**: 139-150.

Olsgard F & Gray JS (1995). A comprehensive analysis of the effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf. *Marine Ecology Progress Series* **122**: 277-306.

Oreska MPJ, McGlathery KJ, Aoki LR, Berger AC, Berg P & Mullins L (2020). The greenhouse gas offset potential from seagrass restoration. *Scientific Reports* **10**: 7325.

OSPAR (2010a). Quality Status Report 2010. OSPAR Commission, London, 176pp.

OSPAR (2010b). The OSPAR system of Ecological Quality Objectives for the North Sea, a contribution to OSPAR’s Quality Status Report 2010. OSPAR Commission, 16pp.

OSPAR (2019). Discharges of Radionuclides from the Non-nuclear Sectors in 2013. Radioactive Substances Series. 20pp.

OSPAR (2020). OSPAR discharges, spills and emissions from offshore oil and gas installations - 2017. Offshore Industry Series, 53pp.

Ottesen D, Batchelor CL, Dowdeswell JA & Løseth H (2018). Morphology and pattern of Quaternary sedimentation in the North Sea Basin (52–62°N). *Marine and Petroleum Geology* **98**: 836-859.

Ottesen D, Stewart M, Brönner M & Batchelor CL (2020). Tunnel valleys of the central and northern North Sea (56°N to 62°N): Distribution and characteristics. *Marine Geology* **425**: 106199.

Owen MJ, Maslin MA, Day SJ & Long D (2018). Sediment failures within the Peach Slide (Barra Fan, NE Atlantic Ocean) and relation to the history of the British-Irish Ice Sheet. *Quaternary Science Reviews* **187**: 1-30.

Pantin HM (1991). The seabed sediments around the United Kingdom; their bathymetric and physical environment, grain size, mineral composition and associated bedforms. British Geological Survey Research Report SB/90/1.

Pethick (1994). Humber Estuary & Coast. University of Hull, 47pp.

Phillips E, Cotterill C, Johnson K, Crombie K, James L, Carr S & Ruiter A (2018). Large-scale glacitectonic deformation in response to active ice sheet retreat across Dogger Bank (southern central North Sea) during the Last Glacial Maximum. *Quaternary Science Reviews* **179**: 24-47.

Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Algería A, Nicoli M, Okem A, Petzold J, Rama B and Weyer NM (eds.) (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Poulton CVL, Philpott SL & James JJC (2005). Greater Gabbard Wind Ltd Offshore Wind Farm Study: A Geological Review. British Geological Survey Commissioned Report, CR/04/168.

Queirós AM, Stephens N, Widdicombe S, Tait K, McCoy SJ, Ingels J, Rühl S, Airs R, Beesley A, Carnovale G, Cazenave P, Dashfield S, Hua E, Jones M, Lindeque P, McNeill CL, Nunes J, Parry H, Pascoe C, Widdicombe C, Smyth T, Atkinson A, Krause-Jensen D & Somerfield PJ (2019). Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. *Ecological Monographs* **89**(3): e01366.

Quinn JD, Philip LK & Murphy W (2009). Understanding the recession of the Holderness Coast, east Yorkshire, UK: a new presentation of temporal and spatial patterns. *Quarterly Journal of Engineering Geology & Hydrogeology* **42**: 165-178.

Quinn M, Varming T & Ólavsdottir J (2011). Petroleum Geology. *In: Ritchie JD, Ziska H, Johnson H & Evans D (Eds.) (2011). Geology of the Faroe-Shetland Basin and Adjacent Areas.* British Geological Survey/Jarðfeingi Research Report RR/11/01, p254-280.

Rance J, Frojan CB & Schinaia S (2017). CEND 19x/12: Offshore seabed survey of Braemar Pockmarks SCI and Scanner Pockmark SCI. Centre for Environment, Fisheries & Aquaculture Science, Leeds, UK. 60pp + appendices.

Rees EIS (2000). Preliminary Observations on benthic biotopes at Haig Fras: an isolated submerged rock in the Celtic Sea. Paper for OSPAR/ICES/EEA Second workshop on Habitat Classification, Southampton, 18-22 September 2000, 9pp.

Rees EIS (2005). Assessment of the status of horse mussel (*Modiolus modiolus*) beds in the Irish Sea off NW Anglesey. A report for the Department of Trade and Industry, UK.

Rennie AF & Hansom JD (2011). Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. *Geomorphology* **125**: 193-202.

Reynaud J-Y, Tessier B, Auffret J-P, Berné S, Batist M, Marsset T & Walker P (2003). The offshore Quaternary sediment bodies of the English Channel and its Western Approaches. *Journal of Quaternary Science* **18**: 361-371.

Reynaud J-Y, Tessier B, Berné S, Chamley H & Debatist M (1999). Tide and Wave dynamics on a sand bank from the deep shelf of the Western Channel approaches. *Marine Geology* **161**: 339-359.

Ritchie JD, Ziska H, Johnson H & Evans D (Eds.) (2011). Geology of the Faroe-Shetland Basin and Adjacent Areas. British Geological Survey/Jarðfeingi Research Report RR/11/01, 317pp.

Rogelj J, Popp A, Calvin K, Luderer G, Emmerling J, Gernaat D, Fujimori S, Strefler J, Hasegawa T, Marangoni Krey V, Kriegler E, Riahi K, van Vuuren D, Doelman J, Drouet L, Edmonds J, Fricko O, Harmsen M, Havlík P, Humpenöder F, Stehfest E & Tavoni M (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change* **8**: 325-332.

Ruffel A (1995). Evolution and hydrocarbon prospectivity of the Brittany Basin (Western Approaches Trough), offshore north-west France. *Marine and Petroleum Geology* **12**: 387-407.

Sayers PB, Horritt MS, Penning-Rowsell E & McKenzie A (2015). Climate Change Risk Assessment 2017 Projections of future flood risk in the UK: Project A: Report prepared for the Committee on Climate Change, UK, 125pp.

Scafidi J, Wilkinson M, Gilfillan SMV, Heinemann N & Haszeldine SR (*in press*). A quantitative assessment of the hydrogen storage capacity of the UK continental shelf. *International Journal of Hydrogen Energy.*

Scott Wilson (2009). Humber Estuary Coastal Authorities Group: Flamborough Head to Gibraltar Point Shoreline Management Plan – Consultation Draft. Prepared for Humber Estuary Coastal Authorities Group, 182pp. plus appendices.

Scott Wilson Resource Consultants (1997). Coastal landforms. *In: JH Barne, CF Robson, SS Kaznowska, NC Davidson & JP Doody (Eds.) Coasts and Seas of the United Kingdom. Region 4 South-east Scotland (Montrose to Eyemouth).* Joint Nature Conservation Committee, Peterborough, UK, pp. 36-38.

Scourse J, Uehara K & Wainwright A (2009). Celtic Sea linear tidal sand ridges, the Irish Sea Ice Stream and the Fleuve Manche: Palaeotidal modelling of a transitional passive margin depositional system. *Marine Geology* **259**: 102-111.

Shannon PM & Naylor D (2012). Petroleum Geology of Ireland. Search and Discovery Article #10395 (2012) Posted February 27, 2012, 9pp.

Shennan I & Horton B (2002). Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science* **17**: 511-526.

Shennan I, Milne G & Bradley S (2012). Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. *Journal of Quaternary Science* **27**: 64-70.

Smeaton C, Austin W & Turrell WR (2020). Re-Evaluating Scotland's Sedimentary Carbon Stocks. *Scottish Marine and Freshwater Science* **11** No 2

Smeaton C, Austin WE, Davies A, Baltzer A, Howe JA and Baxter JM (2017). Scotland's forgotten carbon: a national assessment of mid-latitude fjord sedimentary stocks. *Biogeosciences* **14**: 5663-5674.

Smeaton C, Hunt CA, Turrell WR & Austin WEN (2021). Marine Sedimentary Carbon Stocks of the United Kingdom's Exclusive Economic Zone. *Frontiers in Earth Science* **9**: 593324. doi: 10.3389/feart.2021.593324

Smith DE, Hunt N, Firth CR, Jordan JT, Fretwell PT, Harman M, Murdy J, Orford JD & Burnside NG (2012). Patterns of Holocene relative sea level change in the North of Britain and Ireland. *Quaternary Science Reviews* **54:** 58-76.

Smith DJ, Bentham M, Holloway S, Noy DJ & Chadwick RA (2010). The impact of boundary conditions on CO_2 capacity estimation in aquifers. Ninth Annual Conference on Carbon Capture and Sequestration - May 10-13, 2010, 6pp.

Steers JA (1973). *The Coastline of Scotland.* Cambridge University Press, Cambridge, 335pp.

Stewart HA & Davies JS (2007). Habitat investigations within the SEA7 and SEA4 areas of the UK continental shelf (Hatton Bank, Rosemary Bank, Wyville Thomson Ridge and Faroe-Shetland Channel). British Geological Survey Commissioned Report, CR/07/051, 85pp.

Stewart MA, Lonergan L & Hampson G (2013). 3D seismic analysis of buried tunnel valleys in the central North Sea: morphology, cross-cutting generations and glacial history. *Quaternary Science Reviews* **72**: 1-17.

Stoker M & Varming T (2011). Cenozoic (sedimentary). *In: Ritchie JD, Ziska H, Johnson H & Evans D (Eds.) Geology of the Faroe-Shetland Basin and Adjacent Areas.* British Geological Survey/Jarðfeingi Research Report RR/11/01, 151-208.

Stoker MS, Hitchen K & Graham CC (1993). The geology of the Hebrides and West Shetland shelves, and adjacent deep-water areas. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, 149pp.

Stoker MS, Long D & Bulat J (2003). A Record of Mid-Cenozoic Strong Deep-Water Erosion in the Faroe-Shetland Channel. *In: Meinart A & Waver P (Eds.), European Margin Sediment Dynamics*, Springer Berlin Heidelberg, pp. 145-148.

Stride AH, Belderson RH, Kenyon NH & Johnson MA (1982). Offshore tidal deposits: sand sheet and sand bank facies. In: *AH Stride (Ed.) Offshore tidal sands: processes and deposits.* Chapman & Hall pp. 95-125.

Sturt F, Garrow D & Bradley S (2013). New models of North West European Holocene palaeogeography and inundation. *Journal of Archaeological Science* **40**: 3963-3976.

Tappin DR, Chadwick RA, Jackson AA, Wingfield TRT & Smith NJP (1994). The geology of Cardigan Bay and the Bristol Channel. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, UK, 107pp.

Tappin, DR, Pearce B, Fitch S, Dove D, Geary B, Hill JM, Chambers C, Bates R, Pinnion J, Diaz-Doce D, Green M, Gallyot J, Georgiou L, Brutto D, Marzialetti S, Hopla E, Ramsay E, & Fielding H (2011). The Humber Regional Environmental Characterisation. British Geological Survey Open Report OR/10/54.

Toucanne S, Zaragosi S, Bourillet JF, Gibbard PL, Eynaud F, Giraudeau J, Turon JL, Cremer M, Cortijo E, Martinez P, Rossignol L (2009). A 1.2 Ma record of glaciation and fluvial discharge from the West European Atlantic margin. *Quaternary Science Reviews* **28**: 2974–2981.

Trice R, Hiorth C & Holdsworth R (2019). Fractured basement play development on the UK and Norwegian rifted margins. *In: Chiarella D, Archer SG, Howell JA, Jackson CA-L, Kombrink H & Patruno S (Eds) Cross-Border Themes in Petroleum Geology II: Atlantic Margin and Barents Sea.* Geological Society, London, Special Publications **495**.

Van de Velde S, Van Lancker V, Hidalgo-Martinez S, Berelson WM & Meysman FJR (2018). Anthropogenic disturbance keeps the coastal seafloor biogeochemistry in a transient state. *Scientific Reports* **8**: 5582. doi:10.1038/s41598-018-23925-y.

Van Veen J (1935). Sand waves in the North Sea. *Hydrographic Review* **12**: 21-28.

Van Veen J (1936). *Onderzoekingen in de Hoofden.* Algemeene Landsdrukkerij, ’s-Gravenhage, 252pp.

Varming T, Ziska H & Ólavsdóttir J (2012). Exploring for hydrocarbons in a volcanic province – A review of exploration on the Faroese Continental Shelf.

Walkden M & Dickson M (2006). The response of soft rock shore profiles to increased sea-level rise. Tyndall Centre for Climate Change Research Working paper 105, 22pp.

Wang J, Chirch JA, Zhang X & Chem X (2021). Reconciling global mean and regional sea level change in projections and observations *Nature Communications* **12**: 990 https://doi.org/10.1038/s41467-021-21265-6

Weninger B, Schulting R, Brandtmöller M, Clarke L, Collard M, Edinborough K, Hilpert J, Jöris O, Niekus M, Rohling EJ & Wagner B (2008). The catastrophic final flooding of Doggerland by the Storegga tsunami. *Documenta Prehistorica* **XXXV**: 1-24.

Whomersley P, Wilson C, Clements A, Brown C, Long D, Leslie A & Limpenny D (2010). Understanding the marine environment – seabed habitat investigations of submarine structures in the mid Irish Sea and Solan Bank Area of Search (AoS). JNCC Report No. 430, Joint Nature Conservation Committee, Peterborough, UK.

Wolf J, Woolf D & Bricheno L (2020). Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK. MCCIP Science Review 2020, 132–157.

Wynn RB, Masson DG & Brett BJ (2002). Hydrodynamic significance of variable ripple morphology across deep-water barchan dunes in the Faroe–Shetland Channel. *Marine Geology* **192**: 309-319.