Appendix 1B: Geology, Substrates & Coastal Processes

A1b.1 Introduction

The present geology and substrates of the UKCS reflect a combination of processes taking 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 hydrocarbon gas or carbon dioxide storage. 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, feeder reports for Charting Progress 2, peer-reviewed publications and other relevant “grey” sources of literature.

A1b.2.1 Seabed topography and substrates

The JNCC UKSeaMap (Connor *et al.* 2006) and UKSeaMap 2010 (McBreen *et al.* 2011) are also instructive, presenting oceanographic, bedform 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 (Figure A1b.2). These were identified on the basis of bathymetry and derived slope data, and data compiled by BGS (shelf troughs, ploughmarks, and pockmarks), and more recently reviews such as Brooks *et al* (2013) in relation to marine geological conservation sites, have contributed to categorising marine geological features. The seabed habitat data presented by McBreen *et al.* (2011) is relevant to this topic 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).

A number of bathymetric studies of the UKCS have been carried out since 2003 by the MCA as part of the Civil Hydrography Programme, which is ongoing. 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 and changes in bathymetry made to new charts. The Maritime Environment Mapping Programme (MAREMAP) was launched in 2010 and is jointly led by the British Geological Survey (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 Maritime and Coastguard Agency (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 made available via the MAREMAP website and have also contributed to peer-reviewed publications. The MESH INTERREG programme conducted more than 40 surveys in UK waters with the principle 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. The data from JIBS and INIS Hydro are freely available.

Further surveys have been undertaken in relation to the aggregates industry under the Marine Aggregate Levy Sustainability Fund (ALSF), including 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 on the UKCS coverage, particularly for multibeam coverage. 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.

Figure A1b.1 and Figure A1b.2 display seabed substrates and notable topographic features for the UK continental shelf respectively. Seabed sediment maps for the UKCS are generally available at a scale of 1:250:000 and have limited coverage of Regional Seas 10 and 11. BGS is presently working on an updated seabed sediment map for the UKCS alongside other initiatives which are enhancing the resolution of seabed mapping, for example MAREMAP is making its mapping available at a scale of 1:50,000, and the data collected as part of their mapping programme shows both correspondence to earlier broadscale sediment maps, but also significantly more local variation (see: http://www.maremap.ac.uk/view/search/searchMaps.html).

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 problems for seabed site developments. The three main types of hard substrate occurring at or near seabed comprise unconsolidated gravel spreads, hard cohesive sediments which were formed during the 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 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 help 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) and sandbanks[1] (JNCC 2014) that have been used to inform conservation site selection (e.g. see Figure A1b.5, where the interpretation of potential "bedrock reef" largely corresponds to the BGS mapped extent of hard substrate, defined as areas of rock or hard substrate outcropping or within 0.5m of the seabed).

JNCC have mapped wider sandbank areas on the UKCS potentially qualifying as Annex I habitat[2] 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). More recently, 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 (Figure A1b.6). 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 Figures A1b.3 and A1b.4.

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)

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[1] 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, for example see Figure A1b.6.

[2] 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.

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 deployment. The location and importance of these industries is discussed in Appendix 1h, however their geological basis is discussed in this section.

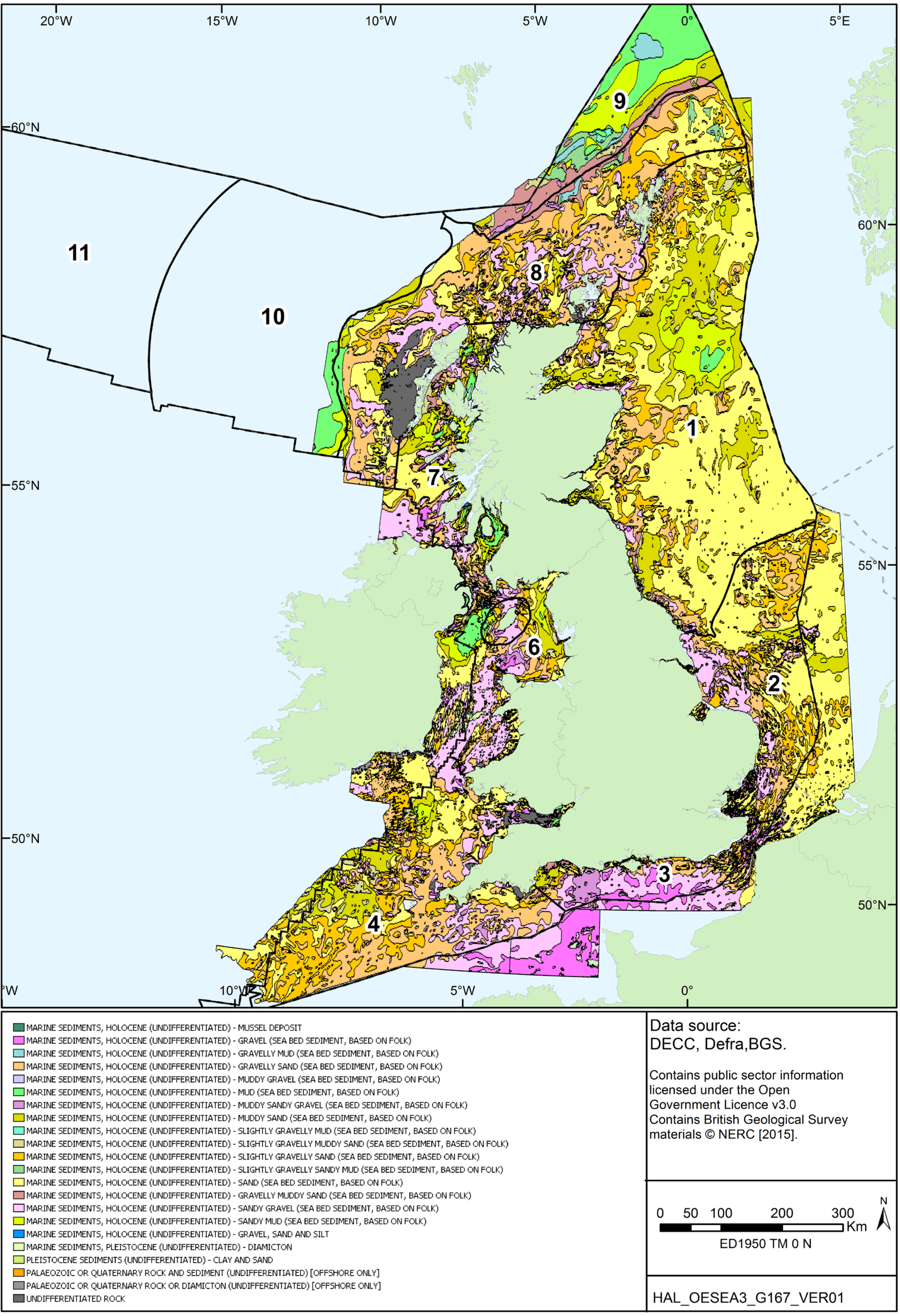
Below surficial sediments and at depth, the underlying hard geology of the North Sea, eastern Irish Sea, Faroe-Shetland Basin and to some extent the English Channel, has given rise to hydrocarbon prospectivity ranging from reserves of primarily oil and condensate in the central and northern North Sea and Faroe-Shetland Basin (with the exception of Wytch Farm and oil shows in the St. George's Channel) and 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 recent discoveries have culminated in the Clair, Schiehallion/Loyal and Foinaven oil fields, with the Solan and Edradour oil fields, and the Laggan, Tormore and Glenlivet condensate fields under development. The area of the Faroe-Shetland Channel has been relatively underexplored and other areas such as the Celtic Sea, Bristol Channel and Western Approaches have proved to be dry due to a general lack of source rocks.

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.

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 2010*). 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.

Figure A1b.1: UKCS seabed substrates, based on the BGS 1:250,000 scale data



Data source:
DECC, Defra,BGS.

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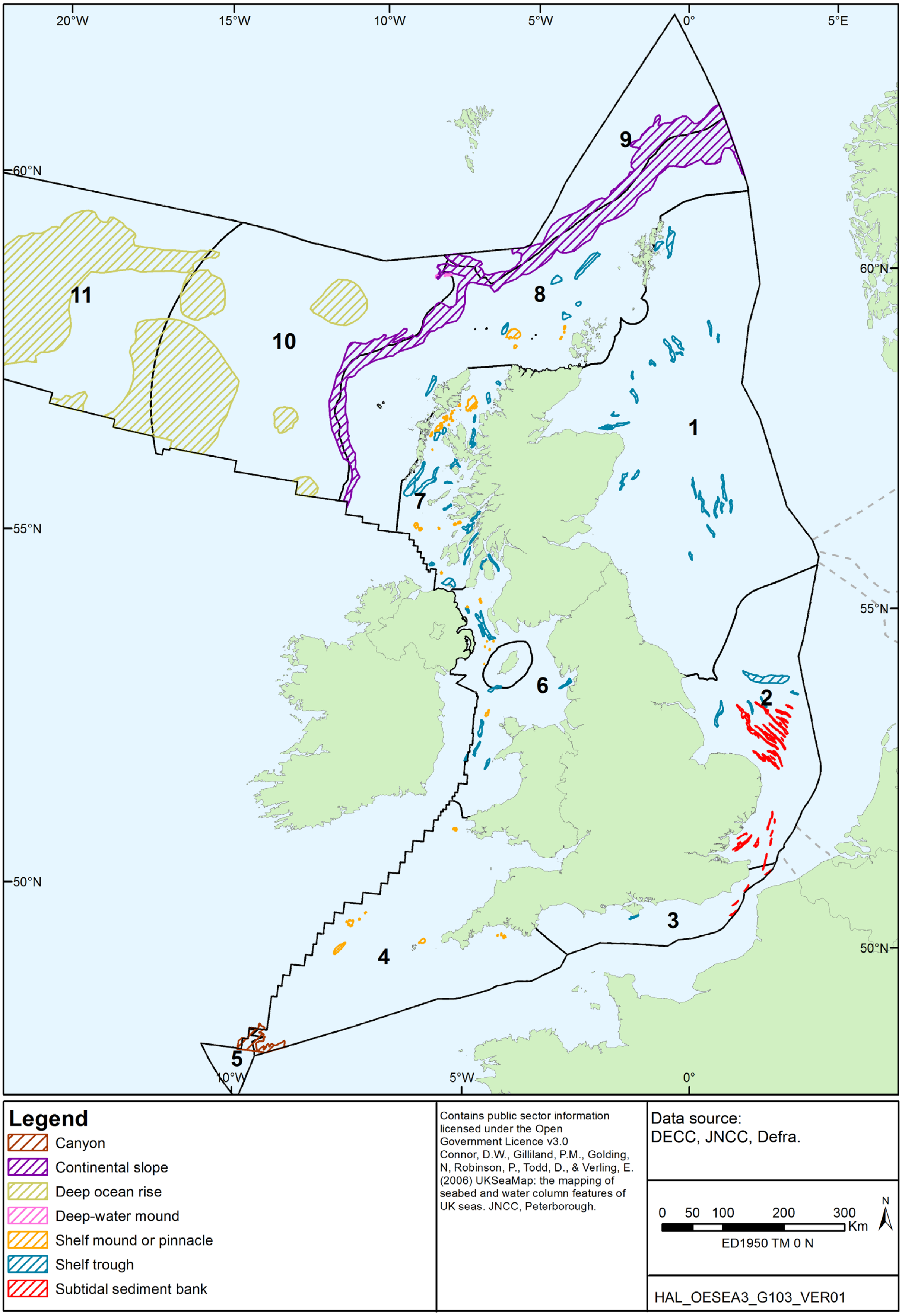
Contains British Geological Survey materials © NERC [2015].

Note: more detailed 1:50,000 scale data is available for some areas through MAREMAP, including additional areas over the George Bligh Bank and Anton Dohrn seamount.

Figure A1b.2: Major seabed topographic features



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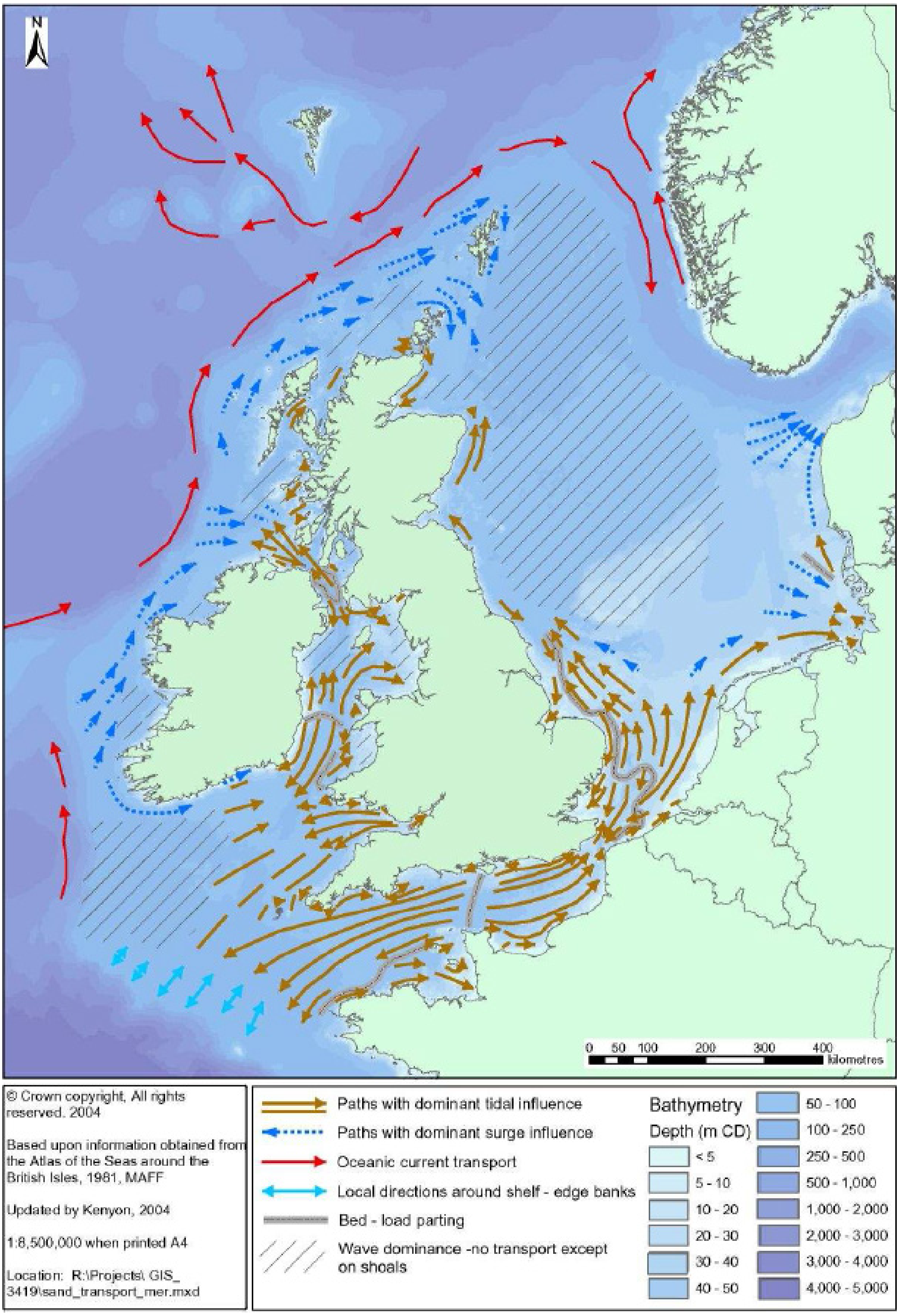
Connor, D.W., Gilliland, P.M., Golding, N, Robinson, P., Todd, D., & Verling, E. (2006) UKSeaMap: the mapping of seabed and water column features of UK seas. JNCC, Peterborough.

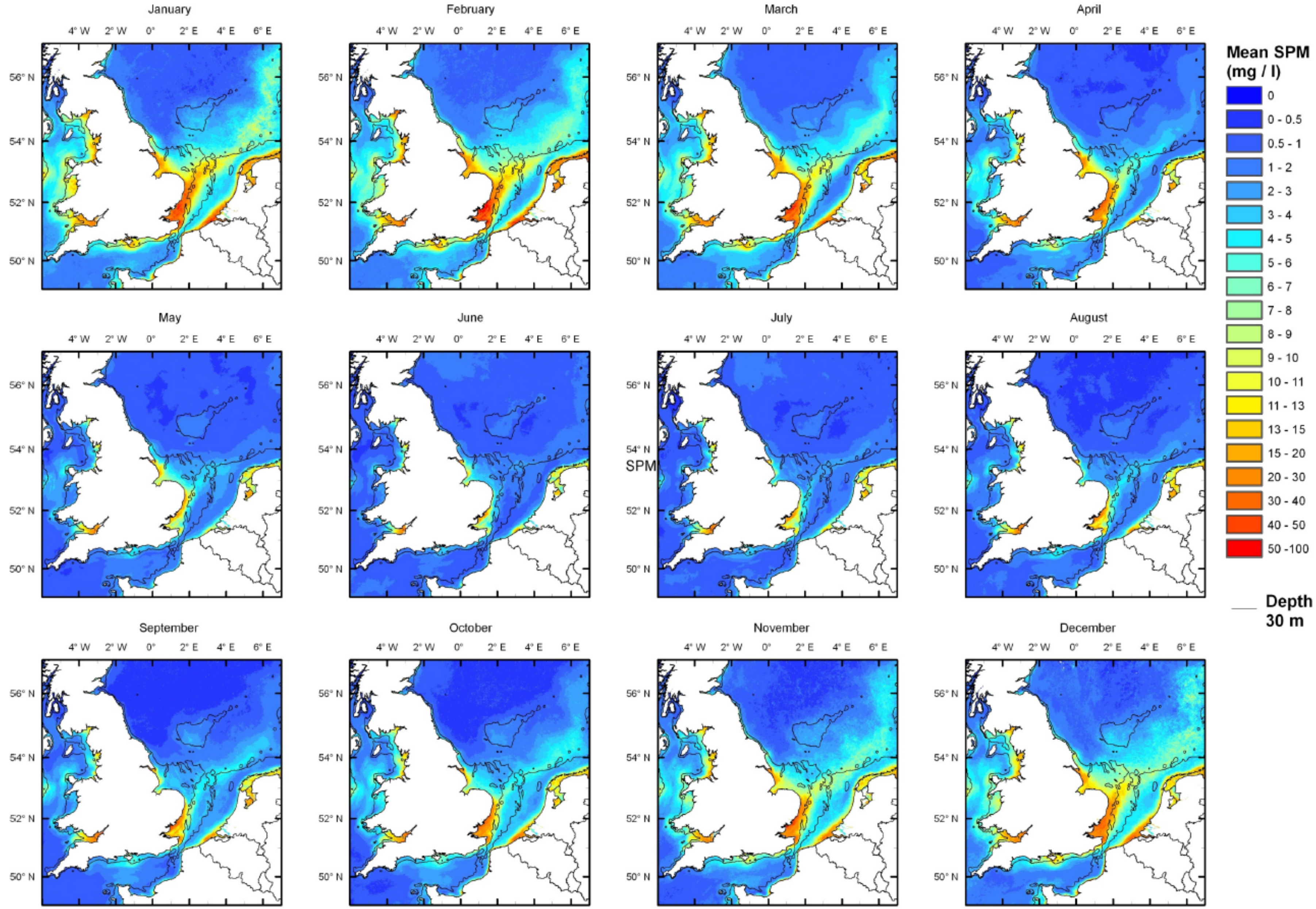
Data source:
DECC, JNCC, Defra.

Figure A1b.3: Major sand transport paths around the British Isles



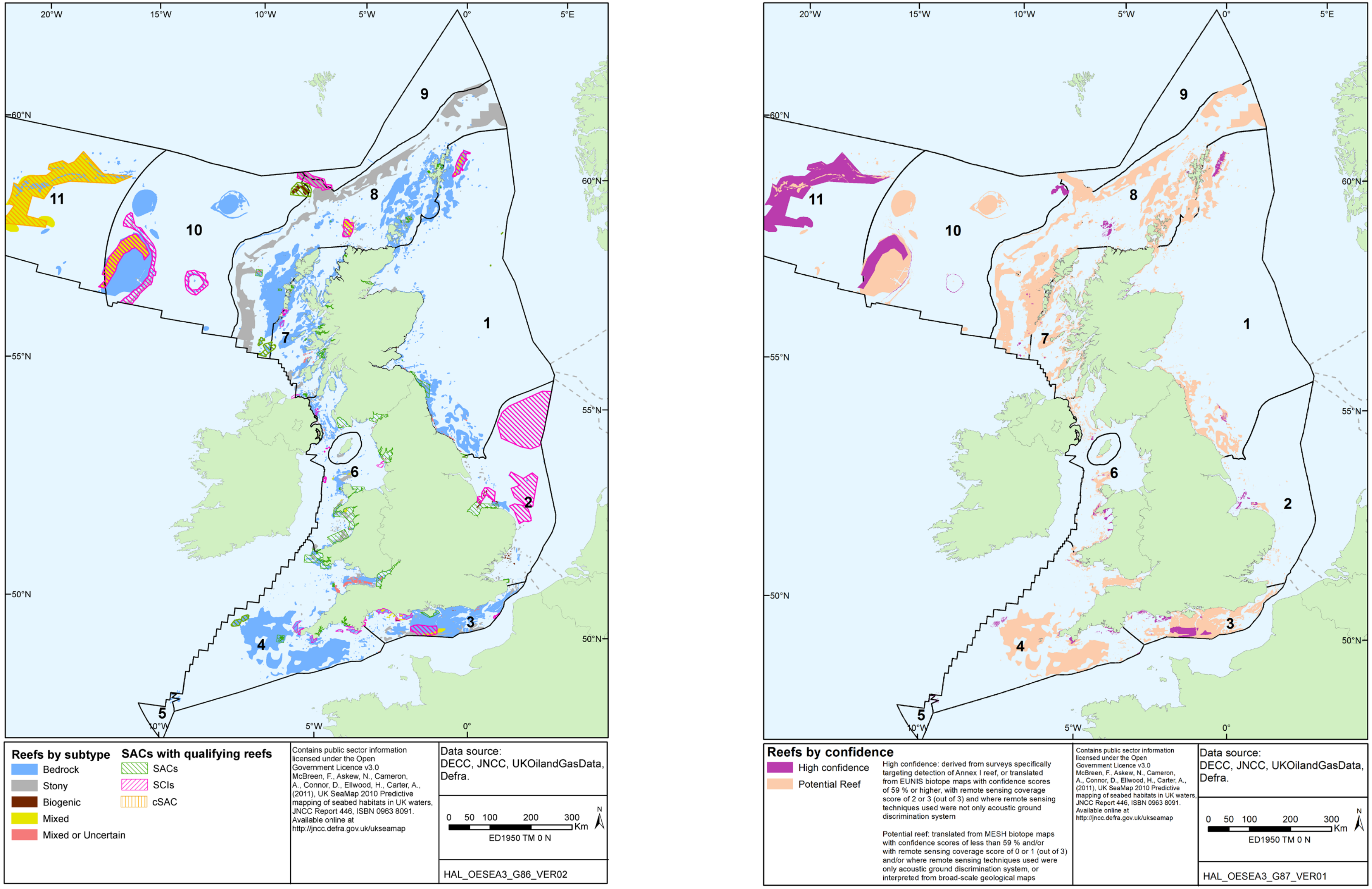
Source: Kenyon & Cooper (2005)

Figure A1b.4: Climatological mean of Suspended Particulate Matter derived from MODIS satellite images, 07/02 - 05/10



Source: Dolphin et al. (2011)

Figure A1b.5: Interpreted hard ground and reef on the UKCS



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

b: confidence in assessment of reef

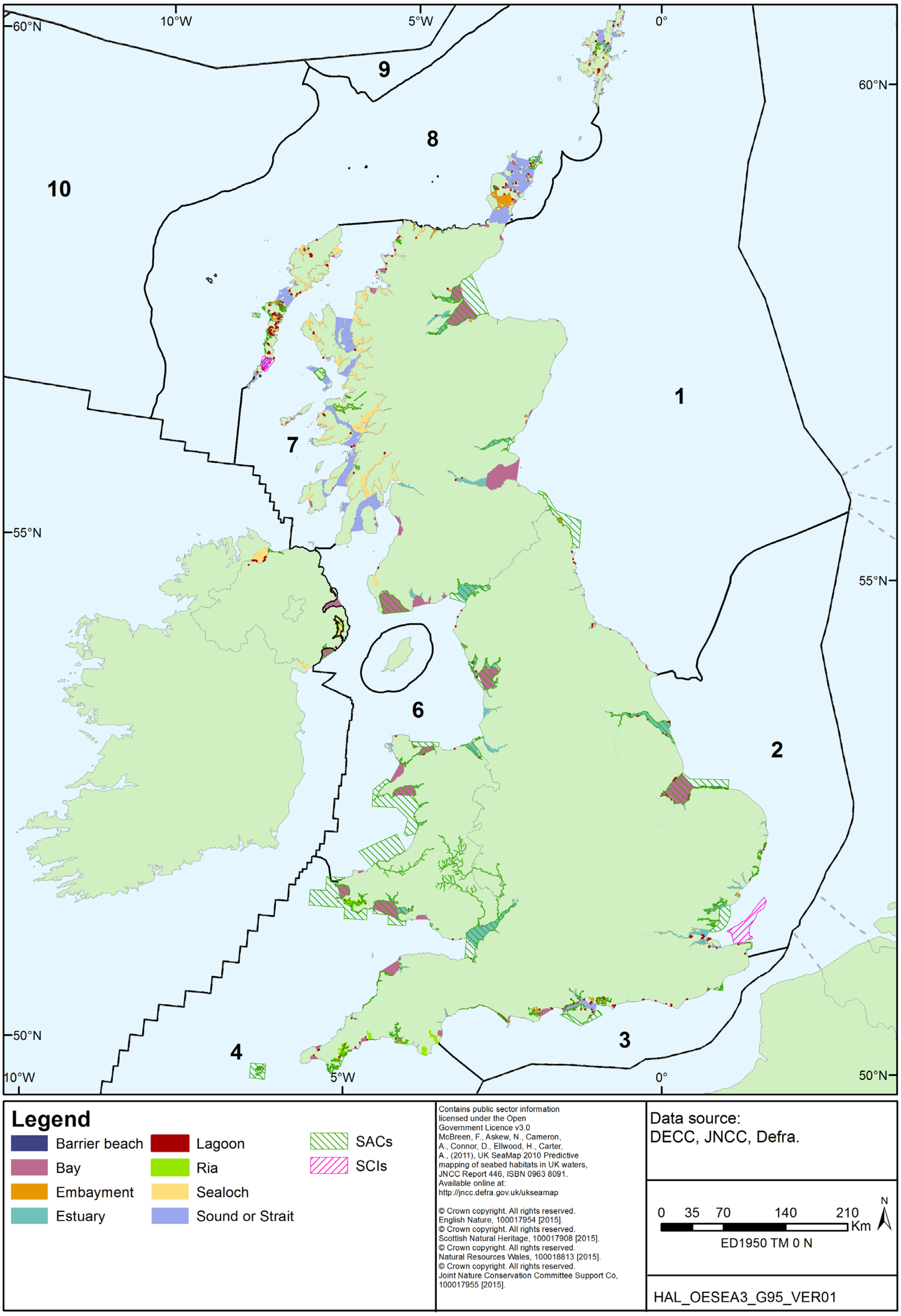
High confidence: derived from surveys specifically targeting detection of Annex I reef, or translated from EUNIS biotope maps with confidence scores of 59 % or higher, with remote sensing coverage score of 2 or 3 (out of 3) and where remote sensing techniques used were not only acoustic ground discrimination system

Potential reef: translated from MESH biotope maps with confidence scores of less than 59 % and/or with remote sensing coverage score of 0 or 1 (out of 3) and/or where remote sensing techniques used were only acoustic ground discrimination system, or interpreted from broad-scale geological maps

Contains public sector information licensed under the Open Government Licence v3.0 McBreen, F., Askew, N., Cameron, A., Connor, D., Ellwood, H., Carter, A., (2011), UK SeaMap 2010 Predictive mapping of seabed habitats in UK waters, JNCC Report 446, ISBN 0963 8091. Available online at http://jncc.defra.gov.uk/ukseamap

Data source: DECC, JNCC, UKOilandGasData, Defra.

Figure A1b.6: Coastal physiographic features and related conservation sites*



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McBreen, F., Askew, N., Cameron, A., Connor, D., Ellwood, H., Carter, A., (2011), UK SeaMap 2010 Predictive mapping of seabed habitats in UK waters, JNCC Report 446, ISBN 0963 8091. Available online at: http://jncc.defra.gov.uk/ukseamap

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© Crown copyright. All rights reserved. Joint Nature Conservation Committee Support Co, 100017955 [2015].

Data source:
DECC, JNCC, Defra.

*Notes: *includes SACs designated for Annex I habitat types: estuaries, mudflats and sandflats not covered by seawater at low tide, coastal lagoons and large shallow inlets and bays. It should be noted that these and other coastal features including dunes, machair, spits, tombolos, cliffs and saltmarsh may also be UK BAP priority habitat types and protected through other designations such as SSSIs, however SAC sites are often coincident with the occurrence of these. All relevant designations are considered in Appendix 1j.*

A1b.3 Features of Regional Sea 1

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 reworked sediments typically form large areas of seabed sand and gravel, and may also form large-scale sandbanks and ridges and smaller sand waves.

A number of features including moraines are present to the north and east of the UK which evidence past glacial activity at the seabed in the area, and have been used to construct scenarios of the pattern and timing of the retreat of the last British-Irish Ice Sheet (BIIS) (Clark *et al.* 2012) which has extended the traditionally held coverage of the ice sheet during the last glacial maximum. Additionally, the northern North Sea contains a large area of mud and sandy mud centred over the Fladen Ground. The area includes a range of seabed features including pockmarks (see below) and subglacial tunnel valleys, represented in the Fladen Deeps, the Devil's Hole to the south and Southern Trench off the north east coast. 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) and hold potentially valuable information in reconstructing the past extent and geometry of the BIIS (Brooks *et al.* 2013). Other Quaternary features of glacigenic origin located in Regional Sea 1 include Bosies Bank and Wee Bankie, which are large moraine features that have contributed to the debate on the extent of Late Devensian ice in the North Sea, and iceberg ploughmarks located at the edge of the continental shelf.

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). 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 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 located in the outer Moray Firth and estuarine areas including the Forth, though muds have their primary distribution in Regional Sea 1 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 part of a survey undertaken for SEA 2, and was resurveyed as part of the OESEA3 programme in 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.4).

A1b.3.2 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, a thick area of 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 Natura 2000 sites where they contain the Habitats Directive Annex I 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 Special Area of Conservation (SAC) (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). Interpretation of sidescan and multibeam backscatter suggests that MDAC may be present at or near the seabed in a number of pockmarks, however further investigation would be required to confirm this.

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). MDAC was either recorded directly or else inferred from sidescan and multibeam backscatter, and acoustic anomalies also inferred gas bubble streams, evidencing active gas seepage.

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*. More recently, 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 Annex I habitat is present.

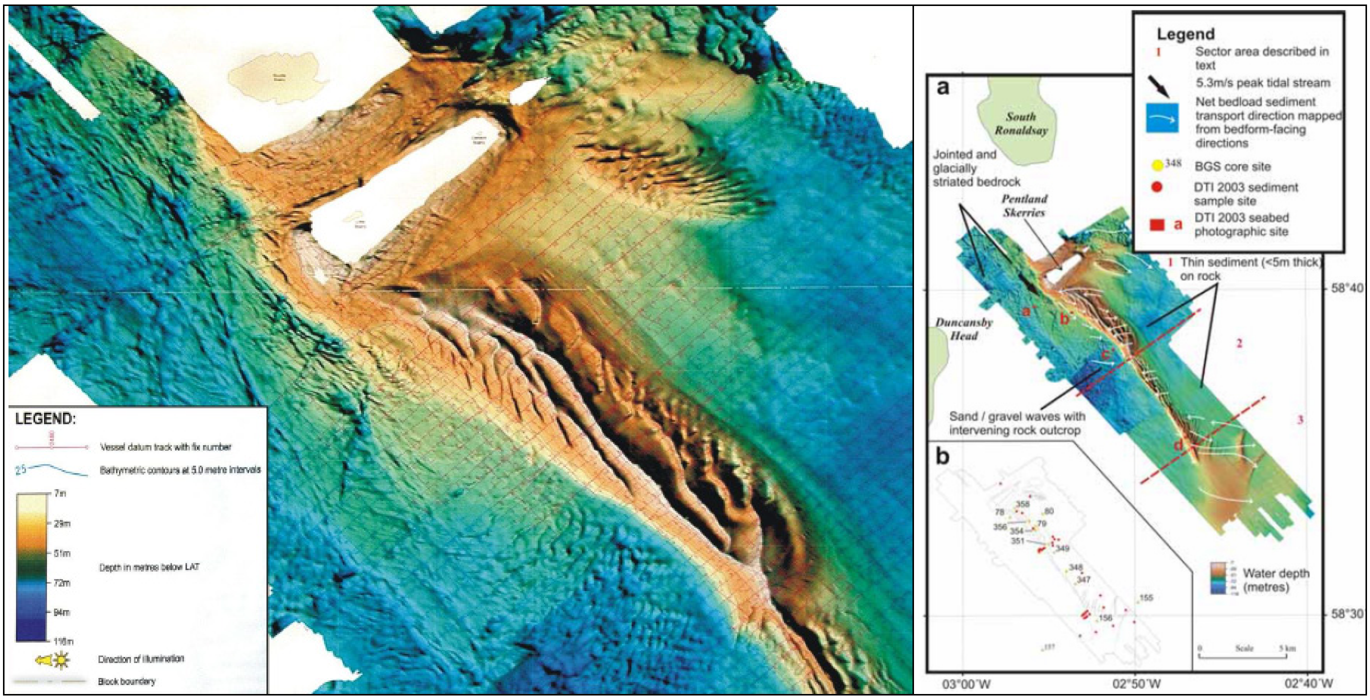
A1b.3.3 Sandbanks and sandwaves

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). To the south of Fair Isle a very large-scale sediment wave appears to be prograding towards shallower water. It is disconnected from the shallower bedrock adjacent to Fair Isle and appears to be part of a large shoal area in the east lee of the island.

The Sandy Riddle is a large carbonate gravel and sandbank set at the east end of the Pentland Firth (Figure A1b.7). 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 a qualifying Annex I habitat, *Sandbanks which are slightly covered by sea water all the time* (see Appendix 1j).

Figure A1b.7: Sandy riddle – shaded relief and net sediment transport direction



The 2003 DTI survey indicated that low sediment waves were present on the northern flanks of the Smith Bank, 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).

A1b.3.4 Tidal sand ridges

The East Bank Ridges are a group of sub-parallel ridges aligned north-east to south-west in relatively deep water to the north west of the Dogger Bank. The banks are up to 50km in length, 3-4km wide and range in height between 10 and 30m (Gatliff *et al.* 1994). These banks were believed by Stride *et al*. (1982) to be features which initially formed early in the Holocene transgression but which are now in water depths too great and with tidal currents too weak for their active maintenance. They are therefore considered to be ‘moribund’. 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.

A1b.3.5 Iceberg ploughmarks

Partially infilled iceberg ploughmarks occur to the north of Regional Sea 1 (and in 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.

A1b.3.6 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. 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 20km 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. Swath bathymetry collected as part of the previous SEA 5 survey programme indicated a bank crest with features interpreted as bedrock outcrops. 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 also been designated due to the occurrence of Annex I reef habitat and is presently a SCI (see Appendix 1j, Figure A1b.5).

A1b.3.7 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 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. Several coastal sediment cells (and subcells) have been identified by HR Wallingford (1997) which indicate the net direction of sediment movement in the littoral zone of the UK, though these cells provide a limited explanation of coastal processes where there is a heavy estuarine or offshore influence and where there are strong geological controls (Cooper & Pontee 2006).

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, but where exposures exist, these are usually chalk (Cameron *et al.* 1992, Jones *et al.* 2004a). Chalk bedrock is the dominant characteristic of the coast around Flamborough Head, and at Thanet in Kent. The exposure at Flamborough Head represents 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 up to 6km or 30m water depth from the headland. Shallow sub-cropping chalk is also found further offshore where surficial sediments are thin, for example in the troughs of large sandwaves.

South of the Humber, isolated outcrops of hard substrate are formed mainly of glacial tills. However, isolated 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).

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. To the west 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 near coast of 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).

A1b.4.2 Sandbanks and sandwaves

Both active sandbanks maintained by the modern tidal current regime, 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).

Connor *et al.* (2006) published seabed bathymetry data for the North Sea based on Digital Elevation Model (DEM) interpretation. Areas of 'subtidal sandbanks' were identified off the southeast coast of England ranging from the Thames estuary in the south to just north of the Wash, which approximately coincide with the sandbanks of the Thames estuary and the Norfolk Banks (see below). 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 for the 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 SCI.

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

- 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 and have amplitudes of 15-30m. These banks are considered to be inactive (moribund), formed approximately 9,000 years ago (Diesing *et al.* 2009), and are composed of very fine to fine sand which contrasts with the fine to coarse sand composition of other banks in shallower water within the area. Their surface is smooth and lacks the cover of mobile sandwaves seen on other sandbanks in the area.

- The Sand Hills are a group of parallel ridges to the south west of the Dogger Bank. Some of these banks are seen to be covered by sandwaves so their surface may in part be presently active, though the larger ridges are considered to be moribund.
- 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 SCI. Other banks in the area offshore of the Humber and Wash includes 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, and a linear, comparatively stable offshore group of probably older derivation (Cameron *et al.* 1992). They form part of the North Norfolk Sandbanks and Saturn Reef SCI and comprise the Leman, Ower, Inner, Well, Broken and Swarte banks and four banks termed the Indefatigables, and a number of smaller banks. The banks are mostly parallel, and the largest bank is Well Bank which is over 50 km long, 1.7 km wide and rises 38 m above the sea floor (Tappin *et al.* 2011). The banks are considered to be active, progressively elongating in a north-easterly direction and are generally asymmetric with a steeper face to the northeast (Cooper *et al.* 2008).
- The sandbanks or sandwaves in the 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 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 of lacustrine clays (the Dogger Bank Formation) generated in a proglacial environment during the last glacial recession which began c. 18,000 years BP, differing from the characteristic boulder clays of this part of the southern North Sea (Cameron *et al.* 1992). The deposit is up to 42m thick and would have constituted an island 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). 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, Marklams Hole and Silver Pit) located in close proximity (Diesing *et al.* 2009). Holocene sands and modern sandwaves with a depth of 1-5m (Fitch *et al*. 2005) overly earlier glaciogenic deposits (Cameron *et al*. 1992) and the extensive fluvial network which followed glacial retreat (Fitch *et al*. 2005). 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*) falls 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 therefore been designated as an offshore SCI (Diesing *et al.* 2009, JNCC 2011).

A1b.4.3 Coastal geomorphology

The geomorphology of the English coastline which meets the southern North Sea 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 and Figure A1b.4) – 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[3], 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). 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 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

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[3] http://www.eastriding.gov.uk/coastalexplorer/documents.html (accessed: 02/11/2015)

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.4.4 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 SCI, Inner Dowsing, Race Bank and North Ridge, and North Norfolk Sandbanks and Saturn Reef SCI (Figure A1b.5).

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 enclosure of the Channel until the Anglian glaciation has also meant that... 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).

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.5), 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 SCI, Lyme Bay and Torbay SCI and Wight-Barfleur Reef SCI (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 and process

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)[4]. 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.

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[4] See mapping here: http://www.dorsetwildlifetrust.org.uk/page283.html (accessed: 2/11/2015)

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[5]. 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 is characterised by 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

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

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 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 (Figure A1b.5).

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).

Maerl beds are a feature of coastal parts of Regional Sea 4 and consist of free-living 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.5), 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 biogenic reefs formed by cold water corals (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*), which is located 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).

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 to the 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.

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). 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.

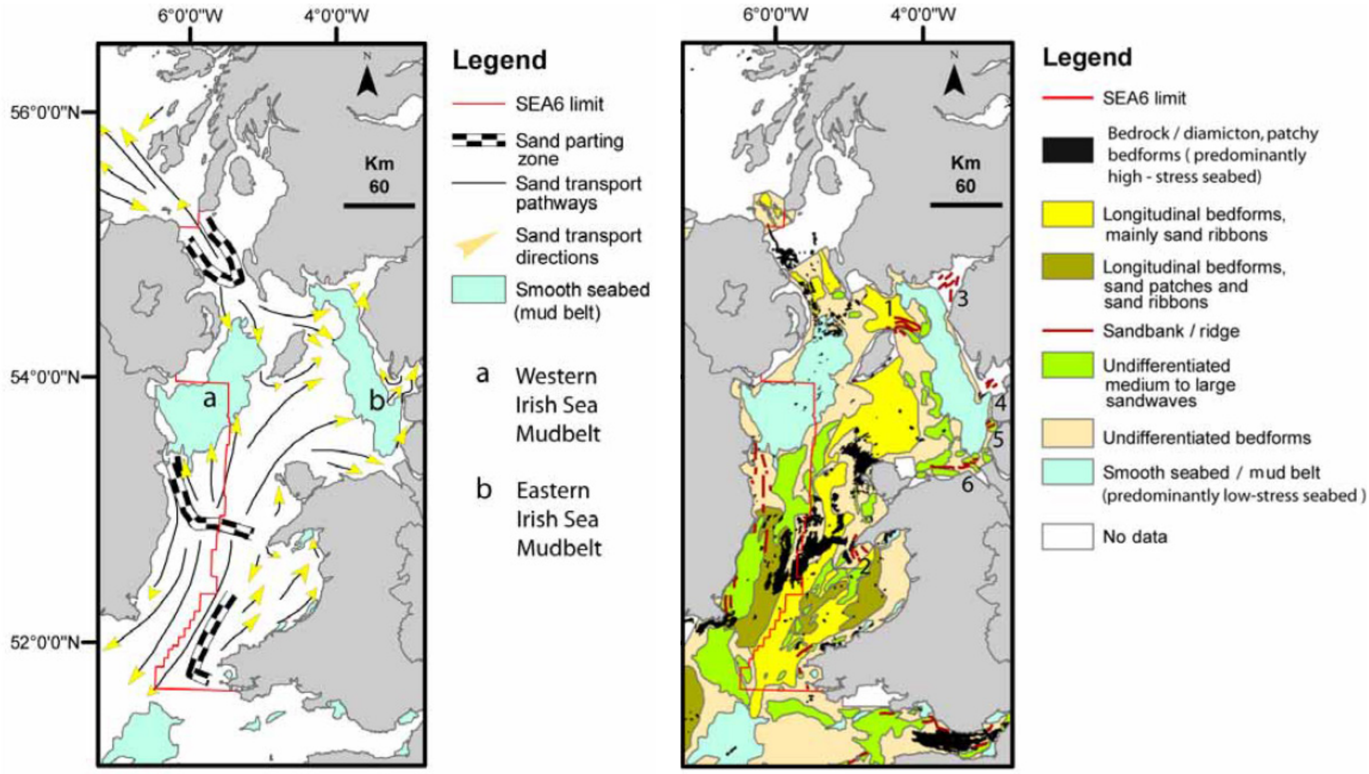
A1b.7.2 Sandbanks and sandwaves

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 SCI 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.8.

Figure A1b.8: 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 instance Pembrokeshire Marine/Sir Benfro Forol, Lleyn Peninsula and the Sarnau/Pen Llyn a`r Sarnau, Strangford Lough (Co. Down) and Menai Strait and Conwy Bay/Y Fenai a Bae Conwy, the Pisces Reef Complex SCI and the Lune Deep aspect of the Shell Flat and Lune Deep SCI, the Maidens SCI (see Figure A1b.5 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 SCI 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 composed of 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). 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. The coverage of MDAC was estimated to be 8km^2, with underlying geology suggesting this could extent further to the west. The resulting area has been designated as the Croker Carbonate Slabs SCI for the qualifying habitat, Submarine structures made by leaking gases.

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 are located along 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.1). 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 in the area varies widely from *c.* 5% in The Minch, 35% between Lough Foyle and Benbane Head, up to 55% to the 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 which extend 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 SCI, East Mingulay SCI, Sound of Barra SCI 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.5 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).

A1b.8.4 Glacigenic bedforms

The cyclic expansion of glaciers during the Pleistocene has led to erosion and sediment deposition of glaciogenic 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 glaciogenic 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

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. The most recent bathymetric survey relevant to Regional Sea 8 was conducted by the MCA Civil Hydrography Programme in 2005-2006, detailing the area from Cape Wrath to Solan Bank, and Solan Bank to the Fair Isle Channel.

A1b.9.1 Seabed substrates

There is a great deal of 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. Carbonate rich material is likely to be associated with gravels and bedrock in the inner and middle shelf and towards coastal areas. Sediments in the region are mostly of glaciogenic origin, having been reworked in the late glacial or Holocene periods.

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 is located 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 also 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 8000 BP to 3000 BP (Stoker *et al.* 1993) and contributions presumably continue in the modern environment. Fragments of the cold-water coral *Lophelia pertusa* have been found on positions of elevated seabed on moraines and rockhead to the north-west of Shetland.

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 two hundred metres 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. Topographic highs had a greater proportion of cobbles and boulders, although such rocks were ubiquitous over the survey area. The 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).

The carbonate component of the sand fraction of sediment in the area is made up of biogenic deposits broken down by hydraulic action and bio-erosion. The result is carbonate contents of generally 25-50%, rising to 100% between Orkney and Shetland. Carbonate content is tending to rise as inputs from local epifauna and infauna continue (Farrow *et al.* 1984).

Muddy sediments are rare on the shelf with the exceptions of sheltered sea lochs and certain mid-shelf enclosed basins. 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. 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, having 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 located 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, with a lack of significant modern sediment inputs to the Outer Hebrides shelf preventing 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 that are 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 glaciogenic material these banks contain is uncertain (Stoker *et al.* 1993).

A1b.9.3 Pockmarks

Pockmarks appear to be rare in Regional Sea 8. 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 Iceberg ploughmarks

Partially infilled iceberg ploughmarks occur in Regional Sea 8 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 the potential Annex I habitat; *rocky reefs*. 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).

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 (e.g. see Figure A1b.5). Their distribution is partly controlled by underlying geology in addition to depth, oceanographic conditions, distance from the coast and geomorphological history.

The Stanton Banks SAC and Wyville Thomson Ridge SCI 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.

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 characterise much of the western coastline with eastern coasts displaying 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, possible related to bottom-current erosion, and features related to slope instability, erosion (e.g. furrows and gullies) and iceberg scouring. 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 glaciogenic origin having been reworked in the late glacial or Holocene periods. There is little modern sediment input to the continental shelf and Faroe-Shetland Channel, however there biogenic accumulation has continued throughout the Holocene (Stoker *et al.* 1993). The amount of biogenic carbonate is low compared with midshelf and coastal areas to the south, with most of the area having 0-20% by weight, presumably as habitat for carbonate forming fauna reduces. Higher carbonate concentrations (20-40%) are more likely to occur in muddy sediments for this area.

Little 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.

North of the shelf break the West Shetland Shelf seabed sediment grades from sand and gravelly sand into soft, silty clay with varying amounts of sand, larger clasts and shell fragments (Stevenson). Mud is centred on the continental slope and tends to increase with depth, generally overlying late Pleistocene to early Holocene muds where accumulation has probably continued throughout the Holocene due to a reduced current compared with the surrounding shelf (Stoker *et al.* 1993, also see Connor *et al.* 2006). Slope processes are associated with much of the sediment between 500-1,000m depth, with associated slope failures including the AFEN, Miller, Tampen and Walker slides (Stevenson *et al.* 2011, Long *et al.* 2011).

A veneer of sand or muddy sand covers much of the Faroe Bank Channel floor, deposited by bottom currents during the Holocene. However, much coarser sediments occur along the northern edge of the floor and grain-size generally increases towards and onto the lower slope of the Faroe platform. 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 up to gravel size, evidenced by bedform features including scours, furrows and barchan-type dunes detectable in side-scan sonar and high-resolution seismic profiles (Bulat & Long 2001, Masson *et al.* 2004). 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.

A1b.10.2 Seabed features

Some features characteristic of more southerly regions are missing from Regional Sea 9 (e.g. reef and pockmark features) which is most likely an outcome of substrate types, bed topography and bathymetry. The West Shetland Shelf and Faroe-Shetland Channel contain a number of features which characterise the slope and channel areas, including iceberg ploughmarks, moraines, 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).

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). The features are now relict, but kept from infilling with sediment by modern bottom currents (Stevenson *et al.* 2011).

Barchan dunes occur at 1.1-1.2km depths on the floor of the southern Faroe-Shetland Channel and east of the Wyville Thomson Ridge, 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 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, 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). A series of other submarine slides are located on the slopes of the Faroe-Shetland Channel, which include (after Long *et al.* 2011):

- the Miller Slide, a series of debris flows up to 95km long
- the Tampen Slide, located in the north east of Regional Sea 9 on the North Sea Fan which is likely of 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, displacing about 0.4km^3 of sediment to a thickness of 10-20m. The slide has been dated to relatively recent times – 2,880 yr BP – with seismic data suggesting the presence of an underlying palaeo-AFEN slide several hundred thousand years in age
- the Walker Slide, located 20km to the north east of the AFEN Slide, this feature is small by comparison (1.5km2) but at similar depth (850m) and with a likely similar genesis to the AFEN slide

These features also present potential geohazards and are discussed in Section A1b.11.

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, the earliest of which are probably of early Pliocene age (5Ma), resulting from the upward migration of fluid/mud to the surface occur in Quadrant 217 of the southern Norwegian Basin (the Pilot Whale diapirs), which are they are the only known diapirs in the 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 glaciogenic 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.5); The Darwin Mounds SAC, North West Rockall Bank SCI, East Rockall Bank SCI, Anton Dohrn Seamount SCI, and Hatton Bank cSAC. The former located in the north of the Rockall Trough 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, 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.

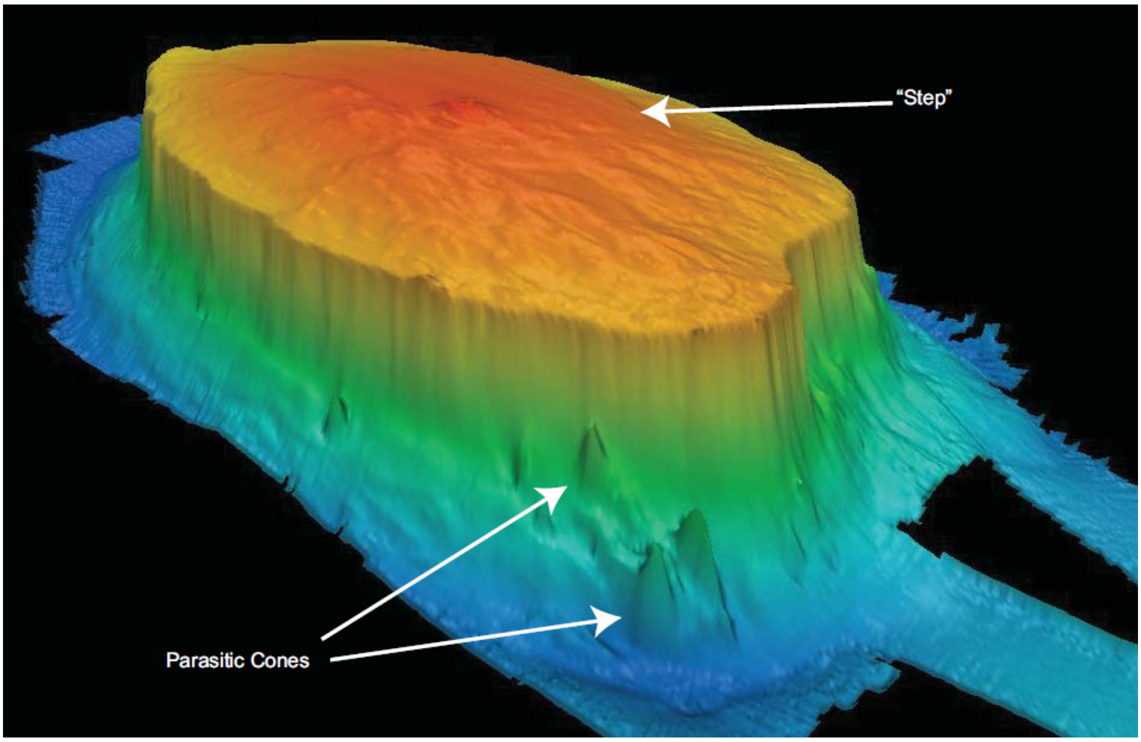
Most of the seabed sediments in Regional Seas 10 and 11 are muds or sandy muds only interrupted by Seamount features (see below) which tend to have a covering of gravel and gravelly sand and at which bedrock closely subcrops. One of the largest inputs of modern material to the shelf is from sources of 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.

The Darwin Mounds are located to the south west of the Wyville Thomson Ridge, between 900 and 1,000m depth, and contain communities including the cold water coral, *Lophelia pertusa*, and being more widely designated as an area of reef under the habitats directive. The mounds have dimensions of approximately 100m in diameter and 5m in height, and are thought to have formed as a result of the expulsion of sand in buoyant fluid or gas, supported by pockmarks and shallow gas in proximity to the features (Cotterill & Leslie 2013).

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 (Figure A1b.5). 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.9) 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.9: 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, being 27km by 40km and is partially buried by sediments from the Barra and Donegal fans (Cotterill & Leslie 2013).

Submarine slide compexes 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 five events, and involving the displacement of 1,830m^3 (Holmes *et al*. 1998).

The Hatton Bank area in Regional Sea 11 was subject to survey 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 area 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 which is 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).

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 are covered by 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.10). There continues to be little exploration in areas outside these provinces, which former activity showing either dry holes or discoveries being non-commercial, however there is remains considerable potential for new discoveries and development in extensions to existing plays or by targeting previously underexplored formations.

The location and prospectivity of hydrocarbon reserves in the North Sea Oil and Gas provinces (Regional Seas 1 and 2) 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 developed the Viking Graben, Moray Firth and Central Graben rift systems, with Kimmeridge Clay Formation source rocks being the source for most of the region’s hydrocarbons (DECC 2013). Within the central North Sea, the area of the mid-North Sea High remains relatively underexplored and has no producing fields or significant discoveries, but the area does have potential Palaeozoic plays.

Regional Sea 2 contains a gas province, with most production having been from Lower Permian (Rotliegend) sandstones which dominate the southern half of the province, with Carboniferous sandstones dominating the north of the area and minor areas with Triassic sandstone source rocks in both of these areas (DECC 2013). Future exploration is expected to focus on stratigraphic plays such as the northward pinch-out of the Leman Sandstone and on increasing the proportion of production from Carboniferous reservoirs.

Oil and gas production in Regional Sea 3 has been centred on the offshore extension of the 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 onshore. A gas discovery is also located a few kilometres to the south of this field. Bridport Sands and the more productive Sherwood Sandstone Group are the two main prospective reservoirs in the area (Hamblin *et al.* 1992). No offshore development drilling has taken place in the English Channel.

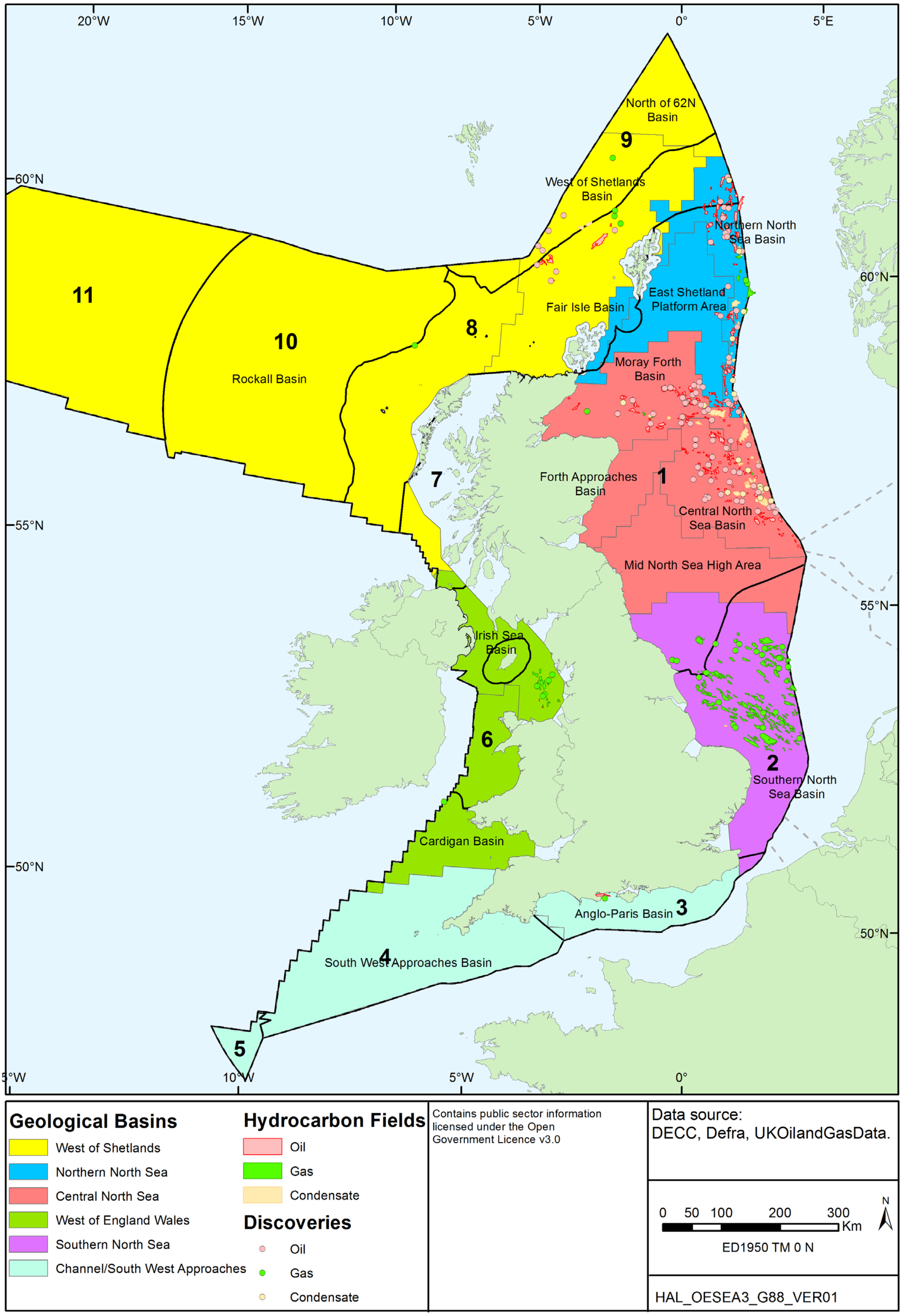
No economically exploitable hydrocarbon stores have been discovered to date in the Western Approaches and western English Channel. Jurassic and Cretaceous rocks are the most likely sources for hydrocarbon deposits, though these formations were either never deposited in the west, or have been depleted by late Jurassic to early Cretaceous erosion, 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).

The Celtic Sea and Bristol Channel Basins (Regional Seas 4 and 5) have proved to be dry with a general absence of organic source rocks (all wells drilled in the area have been either suspended or abandoned). The most promising were the Sherwood Sandstone dominated groups which were observed to be over 50m thick in Well 93/6-1 from 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 St George's Channel has shown oil though economic accumulations are yet to be proven (Tappin *et al.* 1994). Permo-Triassic salt may have provided a suitable reservoir cap 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 being from fault-bounded Lower Triassic reservoirs (principally Sherwood Sandstone). Initial discoveries were made in the mid-1970s with the Morecambe gas field, and later discoveries included the Hamilton, Douglas and Lennox fields. Discoveries in Regional Sea 6 have primarily been gas, located in the Cardigan Bay and East Irish Sea Basin, the latter area also having oil discoveries in the Douglas and Lennox fields. Production started in this location in 1985 following the completion of the 34km Morecambe to Barrow-in-Furness pipeline. Operators estimate that 8.3tcf of gas and 209 million barrels of oil are ultimately recoverable from the 12 producing fields in the East Irish Sea Basin. Future exploration is likely to concentrating on extending the Lower Triassic play, 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 at depth locally. Criteria suitable for oil and gas reclamation (reservoirs with viable seals and structural traps) is observed in basins from Larne-Lough Neagh, Solway, Peel, Kish Bank and Central Irish Sea basins, though recovery has been hampered by poor source rock preservation, locally poor seal integrity and unfavourable timing of hydrocarbon migration and trap formation (Naylor & Shannon 1999).

Unlike the North Sea and East Irish Sea, Regional Seas 7, 10 and 11 have experienced little interest in oil and gas prospecting. Areas beyond 200nm of the mainland are under negotiation for licensing rights, 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, licences relating to which have all been released. Two have 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.10: Major hydrocarbon basins of the UKCS, developed fields and significant* 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.*

In Regional Sea 7, Permo-Triassic and Mesozoic half-graben basins have been considered as potential sources of hydrocarbons. Carboniferous rocks are considered 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 hold potential hydrocarbon resources (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 prospecting or development of this resource has been carried out to date (Holmes *et al.* 2006).

Relative to other areas of UK continental shelf, exploration effort to the north and west of Shetland has been small (part of Regional Sea 8 and Regional Sea 9), though still having approximately 200 wells drilled in the area within the past 30 years (Quinn *et al.* 2011, Austin *et al.* 2014). Drilling in the region began in 1972 but activity since has continued at a low level 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. In addition to these developed fields, a number of important discoveries are located to the north and west of Shetland including Rosebank/Lochnagar, Cambo, Suilven, Strathmore and Solan (oil), and Laxford, Victory, Tobermory and Laggan (gas). Other significant discoveries (also see Figure A1b.10) 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 to commercial wells (see Quinn *et al.* 2011 and references therein). 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 survey (Stoker *et al.* 1993, Hitchen *et al.* 2003) and drilling, which has resulted in a low seismic resolution and few exploratory wells. Interpretation of hydrocarbon prospectivity is therefore also limited in some areas, for instance the full distribution of Jurassic source is poorly understood (Quinn *et al.* 2011). More recent seismic methods such as deep-tow seismic survey and processing techniques (see Varming *et al.* 2012) have been able to provide better imagery of the sub-basalt Mesozoic strata, indicating that there may be reservoirs at drillable depths (Davison *et al.* 2010).

A1b.12.2 Aggregates resources

The Crown Estate has produced a series of maps which indicate the aggregates resource of the UKCS developed by BGS (Figure A1b.11) 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 principle 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 distribution patterns of earthquakes occurring under the North Sea are 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 approximately 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 Sheringham on the Norfolk coast[6].

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

To the west in the area of Outer Hebrides, five events of 4.0 or greater have occurred since 1970. Smaller events of <4.0 have been recorded 2-3 times a year since 1970 and are restricted to the nearshore (Holmes *et al*. 2006). The northern and easterly area of Regional Sea 8 has a much lower 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 reasonable 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

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

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).

A1b.13.2 Mass movements

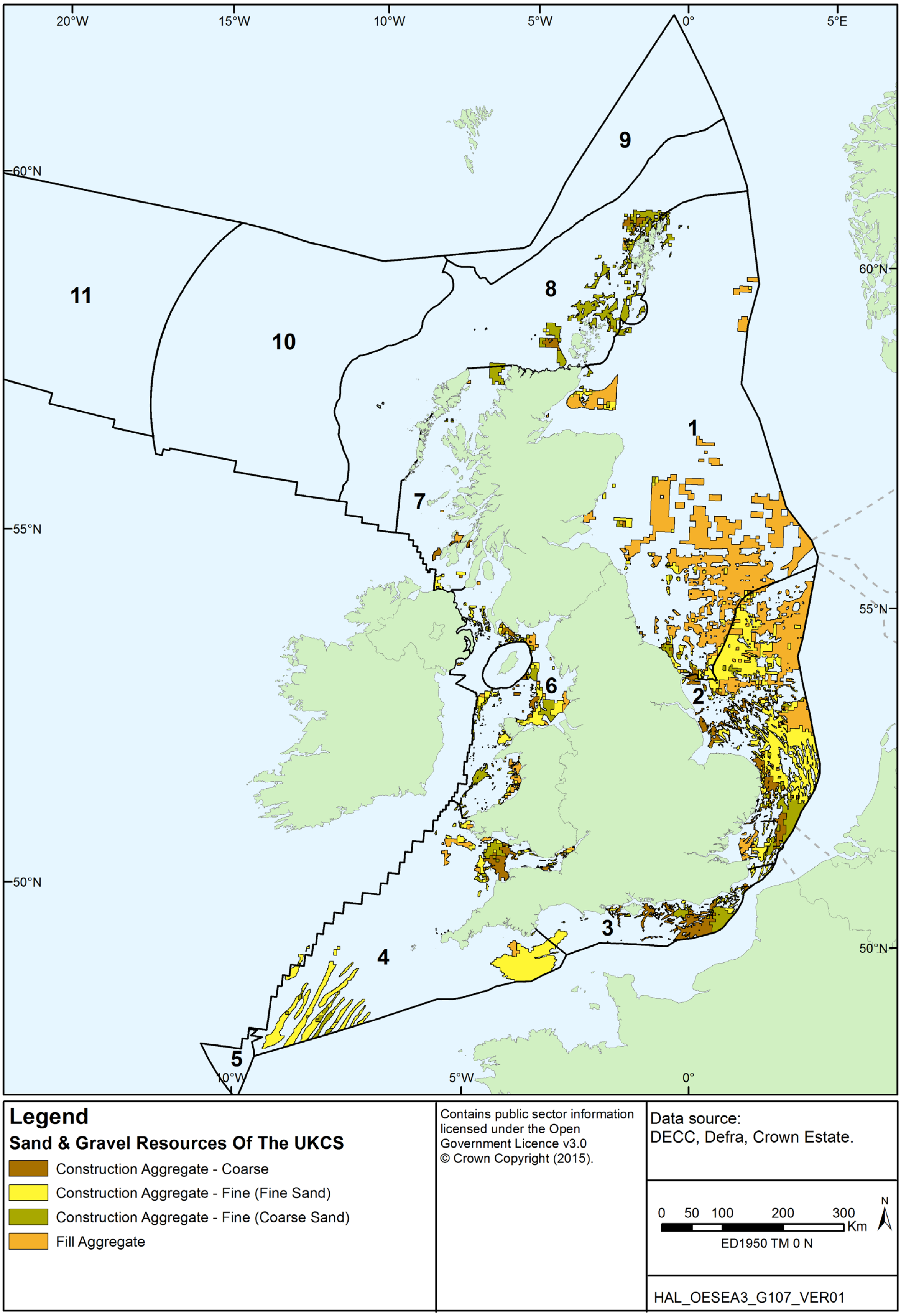
Submarine mass movements pose geohazards for offshore developers. Landslides and debris flows are relatively few on the UK continental shelf, though the eastern margin of Rockall Bank has evidence of landslides on its mid-lower slope and the Faroe-Shetland Channel displays seabed features including landslides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

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), with others including the Donegal (to the north of Northern Ireland) submarine mass movements both took place on the UK continental margin during the Holocene (Long *et al*. 2003, Holmes *et al*. 2003, cited in Leynaud *et al*. 2009), with the area around the Peach slide (to the north and west of Northern Ireland) which dates to the Pleistocene, receiving two recent seismic events suggesting a possible long-term history of movement in the area. 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 (e.g. eastern Scotland; Dawson *et al*. 1988) during the early Holocene (dating to *ca.* 7900 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).

Figure A1b.11: Marine Sand and Gravel Resources of the UKCS



A1b.14 Environmental issues

A1b.14.1 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 which have 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 might in turn lead to smothering of benthic habitats, however industry best practice and studies including those of 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), however possibly 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 and (to date) does not appear to have had detectable environmental impact. Sea level change and flood risk

Sea-level change potentially has a number of geomorphological effects including increased coastal erosion, particularly when considered in the context of possible enhanced storminess, the acceleration of coastal squeeze in intertidal areas and 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 (also see Section A1b.15). 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.15.2.

A1b.14.2 Aquifers

There is a potential local risk of groundwater contamination if developments are superimposed on areas with aquifers and if normal aquifer measures are not followed. There is a negligible risk of contamination of onshore supplies of freshwater from the mature areas of the oil and gas development provinces in the central and northern North Sea. Overall, the risk of onshore aquifer contamination decreases with increasing distance from the offshore to developments.

A1b.14.3 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 the atmospheric); 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). Key points include:

- The open seas are still little affected by pollution and levels of monitored contaminants continue to fall, albeit slowly in many cases. This reflects reductions in riverine inputs of a range of contaminants and in atmospheric deposition of some heavy metals and polycyclic aromatic hydrocarbons (PAHs) to UK seas. However, a range of persistent chemicals appear in deep-sea fish and marine mammals off UK coasts, and litter has been found at a depth of 1,000m.
- Some “legacy” contaminants are present at high concentrations in estuaries historically contaminated by industrial processes. For example, in the northeast of England, PAHs are present in sediments at concentrations which may be toxic to organisms living in or on the seabed, and may take many tens to hundreds of years to degrade.
- Levels of oil in produced water discharged by the offshore oil and gas industry are falling in response to regulatory controls. Doses of radioactivity received by people and wildlife continue to be well within regulatory limits. There have been no major marine oil or chemical spills in UK waters since the publication of Charting Progress in 2004[7].

The main programme for monitoring the status of contaminants on the UKCS is the Clean Seas Environmental Monitoring Programme (CSEMP) which collects data at approximately 500 sites, which given the area of the UKCS provides a relatively sparse coverage of stations. As indicated above, Charting Progress 2 observed 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. The OSPAR Quality Status Report (OSPAR 2010a) similarly indicated that offshore, contamination in sediments for a number of metals and pollutants (cadmium, mercury, lead, PAHs, PCBs) was largely acceptable, with problem areas being concentrated around the coast.

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.12) which were summarised in 2008 for the OSPAR Joint

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[7] Note that Charting Progress 2 was published prior to the Elgin condensate spill of 2012 – see DECC (2012).

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 to 19.3µg/g in 2001. In the East Shetland Basin, the mean oil 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 section (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) and East Shetland Basin (2007) showed no 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 and 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 2015a).

Table A1b.1: Oil discharged with produced water 2006-2014

	2006	2007	2008	2009	2010	2011	2012	2013	2014
No. of installations discharging oil in produced water	105	101	96	99	95	94	91	89	91
Total produced water discharged (million m^3)	219	203	198	197	197	174	156	149	156
Total dispersed oil in produced water discharged (tonnes)	4,356	2,960	3,160	2,901	3,008	2,494	2,268	2,176	2,004
Oil content (mg/l)	19.9	14.6	15.99	14.75	15.24	14.31	14.6	14.35	12.84
No. of installations re-injecting oil in produced water	20	23	24	26	28	28	27	26	24
Produced water re-injected (million m^3)	30.7	40.5	39.6	40.4	33	38.29	44.94	39.15	31.32

Source: DECC Oil and gas: field data website: https://www.gov.uk/guidance/oil-and-gas-uk-field-data (accessed: 04/11/2015)

A1b.14.4 Radioactive material

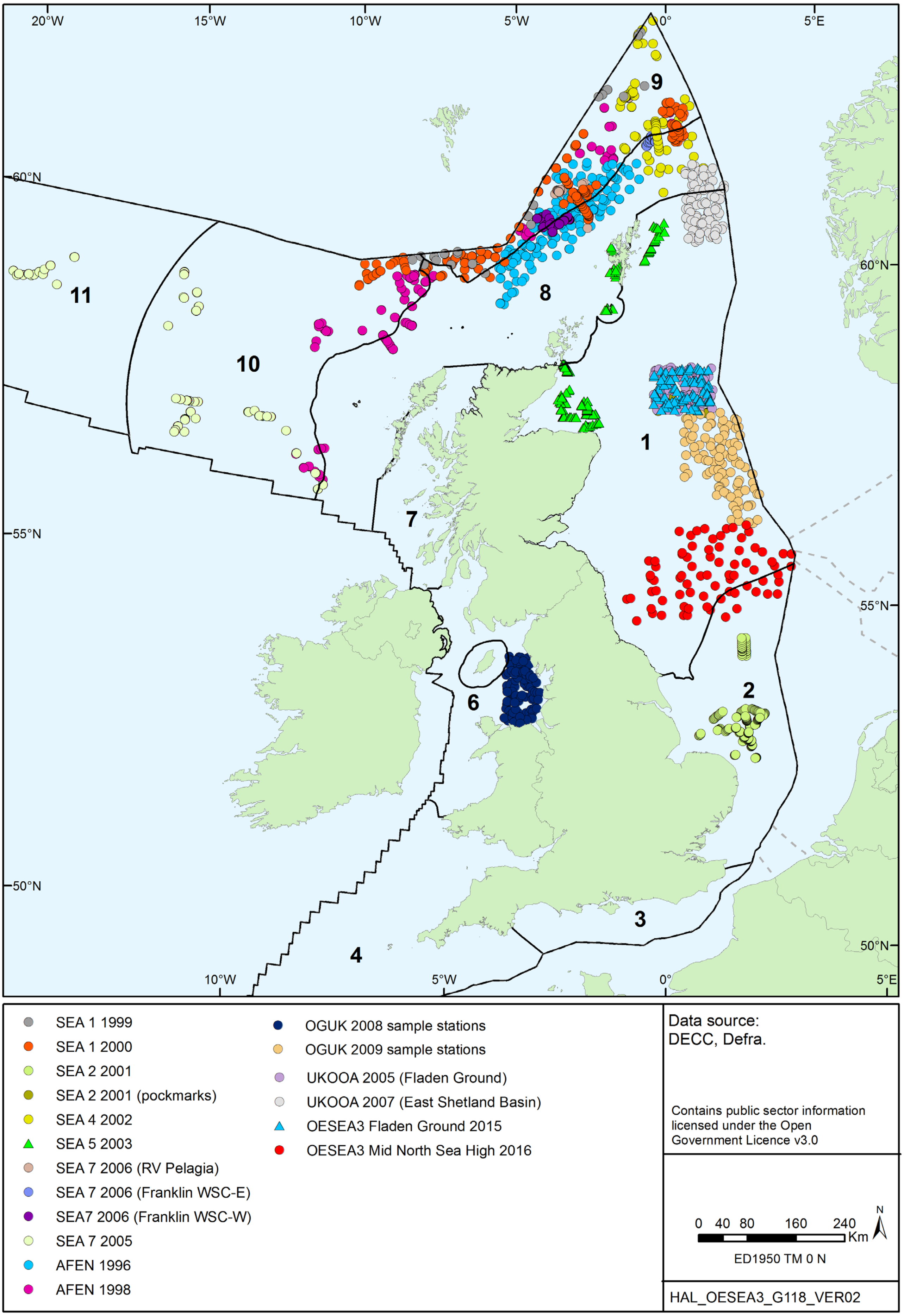
Concentrations of TNORM (Technologically-enhanced naturally occurring radioactive material) are discharged into UK waters from offshore oil and gas platforms as a constituent of produced water and insoluble scale. Radionuclides found in these discharges include $_{226}$Ra (radium) and $_{228}$Ra, and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

Estimates of the total radioactivity discharged per annum into UK waters from offshore platforms vary considerably. The MARINA II project (van Weers 2003) calculated that as much as 4.6TBq of both α- and β-emitting activity was discharged during the late 1990s, while more recent assessments (DEFRA 2008), put the annual discharge at around 0.75TBq of $_{226}$Ra (an α-emitter) and 0.25TBq of $_{228}$Ra (a β-emitter) over the period 2004–2005, with future projections of an increase in discharges due to operational and decommissioning sources (Defra 2010).

The OSPAR (2015b) report on discharges of radioactive substances from the non-nuclear sectors indicated that the UK offshore oil and gas industry discharged approximately 0.0147TBq of $_{210}$Pb, 0.289TBq of $_{226}$Ra and 0.199TBq of $_{228}$Ra, in produced water primarily to the Greater North Sea area in 2013.

The enhancement of radium in the local zone around an oil platform has been considered as part of the MARINA II project. 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).

Figure A1b.12: UK regional and other seabed monitoring stations



Data source:
DECC, Defra.

A1b.15 Evolution of the baseline

A1b.15.1 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 eustatic 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 BIIS. 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, at a range of between +1.4 to -0.6mm/year (see Shennan *et al.* 2009, 2012, Bradley *et al.* 2011, Smith *et al.* 2011).

More recently, sea-level rise has been connected with anthropogenically augmented climate change, primarily through freshwater input from the reduction in the size of valley glaciers and ice caps, and the thermal expansion of the ocean associated with increased global temperatures (Church *et al.* 2013). 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), and projections of future change vary depending on which emissions scenario and model is considered (see Appendix 1f for an overview of these scenarios), however it is considered very likely that rates for all scenarios will exceed those observed for the period 1971-2010 – using process based models (for which there is greatest confidence), mean ranges of global sea-level rise are 0.6m (0.42-0.8) for the SRES A1B scenario used in AR4 (UKCP09 medium emissions scenario), and 0.74m (0.52-0.98) for the RCP8.5 scenario (which has the highest radiative forcing). The change in sea-level will also vary regionally and locally (including due to variability in isostatic adjustment), and projections of sea-level change on a 5x10km grid around the UK have been produced as part of UKCP09 (note that these do not yet consider the latest IPCC 2013 input. See http://ukclimateprojections-ui.metoffice.gov.uk/). 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), with figures from UKCP09 indicating an increase of 0.07-0.54m for Edinburgh and 0.21-0.68m for London (medium emission scenario) (Horsburgh & Lowe 2013).

Sayers *et al.* (2015) provides an overview of the projections of future flood risk for the UK as part of the wider UK Climate Change Risk Assessment (CCRA), including the potential impacts of sea-level rise. The report presents future flood risks for a range of population and climate change adaptation scenarios, considering 2˚C and 4˚C changes in mean global temperatures by 2080.

A1b.15.2 Coastal change and its management

Coastal change is a widespread though spatially local phenomenon, and any general prediction of UK coastal response to variables such as relative sea-level rise or wave conditions (i.e. those associated with climate change), are likely to be of low confidence (Masselink & Russell 2010), and research is continuing into the possible change in wave conditions which may arise due to the anthropogenic climate change – there is generally low confidence in projections of future storm and wave conditions (Woolf & Wolf 2013), with recent changes in significant wave height likely attributable to natural variations in wind forcing (Church *et al.* 2013). 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 on 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 & Russell 2013 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), 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.2, Figure A1b.14) 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 and associated 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.

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.15). 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.

Table A1b.2: 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 & Russell 2013) 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.* 2015) produced as part of the Climate Change Risk Assessment 2017, use modified versions of the UKCP09 projections of sea-level rise to indicate the potential relative change in sea level with an increase of 2˚C and 4˚C in global mean temperature by the 2080s. 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) by the 2080s. Other aspects considered are the potential outcome for flood defences depending on the level of adaptation (e.g. continuing at current levels, or a higher or lower level of adaptation), however this does not seem to consider in detail where changes in defence are being identified through individual local flood risk management strategies. For England, where more detail on flood defences is available through the continuous defence line dataset, the identification of vulnerable coastal defences assuming a 2˚C temperature rise. The estimates reveal a similar length of coast at risk when compared to that identified in SMPs for managed realignment, and similarly when undertaken for the present day, identify that vulnerable defences spatially coincide with some areas identified for managed retreat. Modelling is undertaken in relation to these defences for a range of sea level rise scenarios (0-5m) connected with a 1:200 year tidal surge. This analysis assumes no adaptation work is undertaken, but for the present day scenario identified a number of areas which could be inundated. Overall, the report indicates that by the 2080s, the greatest increase in annual damages from flooding will increase most significantly for coastal sources.

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 try and 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 DOENI have responsibility for reporting and achieving GEP for their respective areas. The WFD set the objective that modified/artificial water bodies should aim to achieve GEP by 2015[8], however it is likely that many of these water bodies will not achieve this status. A second cycle of river basin planning will cover the period 2015-2021. Consultation on the updated plans was held by the UK and its devolved administrations between 2014 and 2015 which was also timed to coincide with consultations on draft flood risk management plans. 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.

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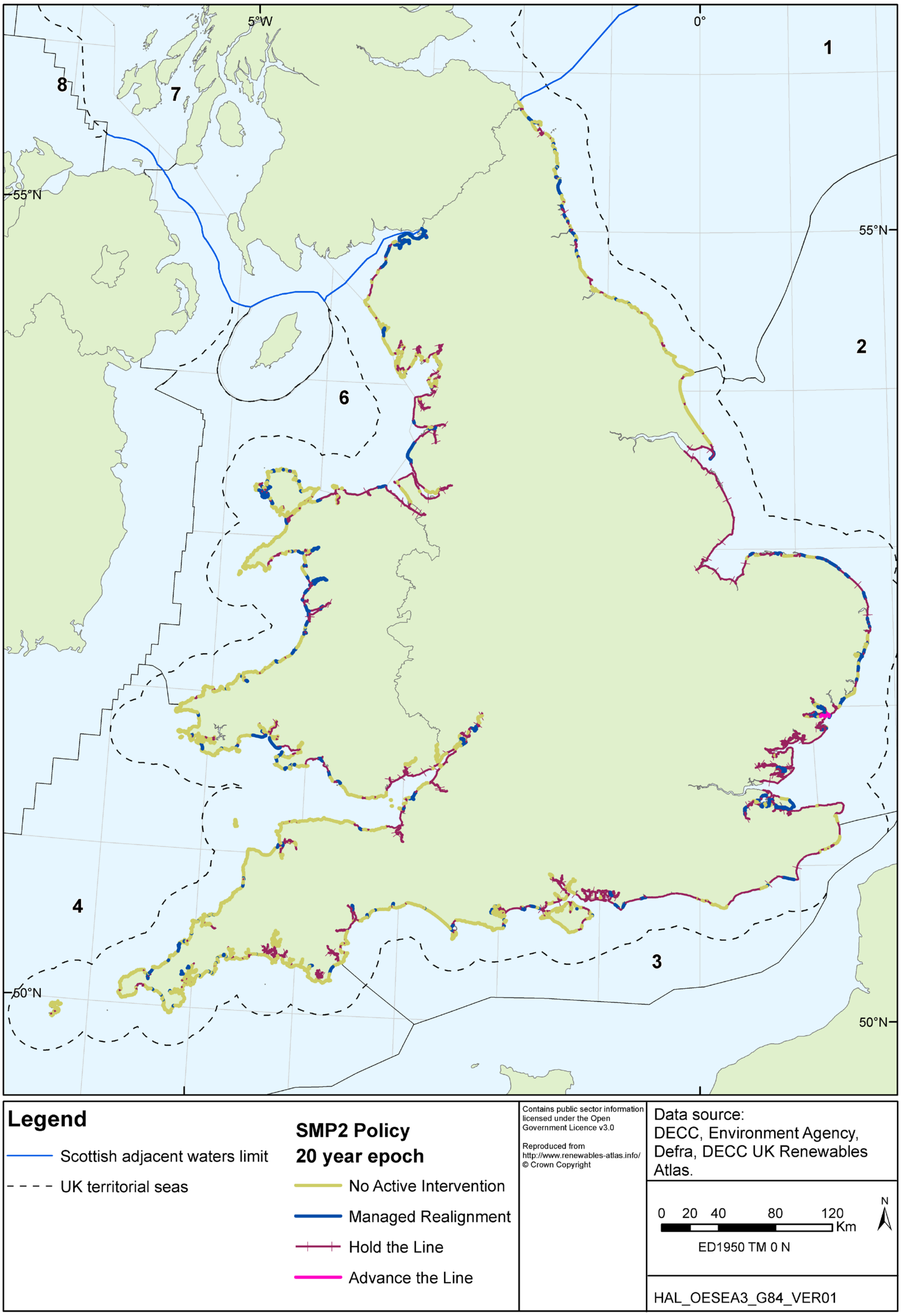
[8] Note that where managed realignment contributes to the management of a Natura 2000 site (e.g. where an SPA is threatened due to intertidal loss), such modification is not considered to be incompatible with achieving GEP through the WFD.

Figure A1b.13: SMP areas and related policies (20 year epoch)



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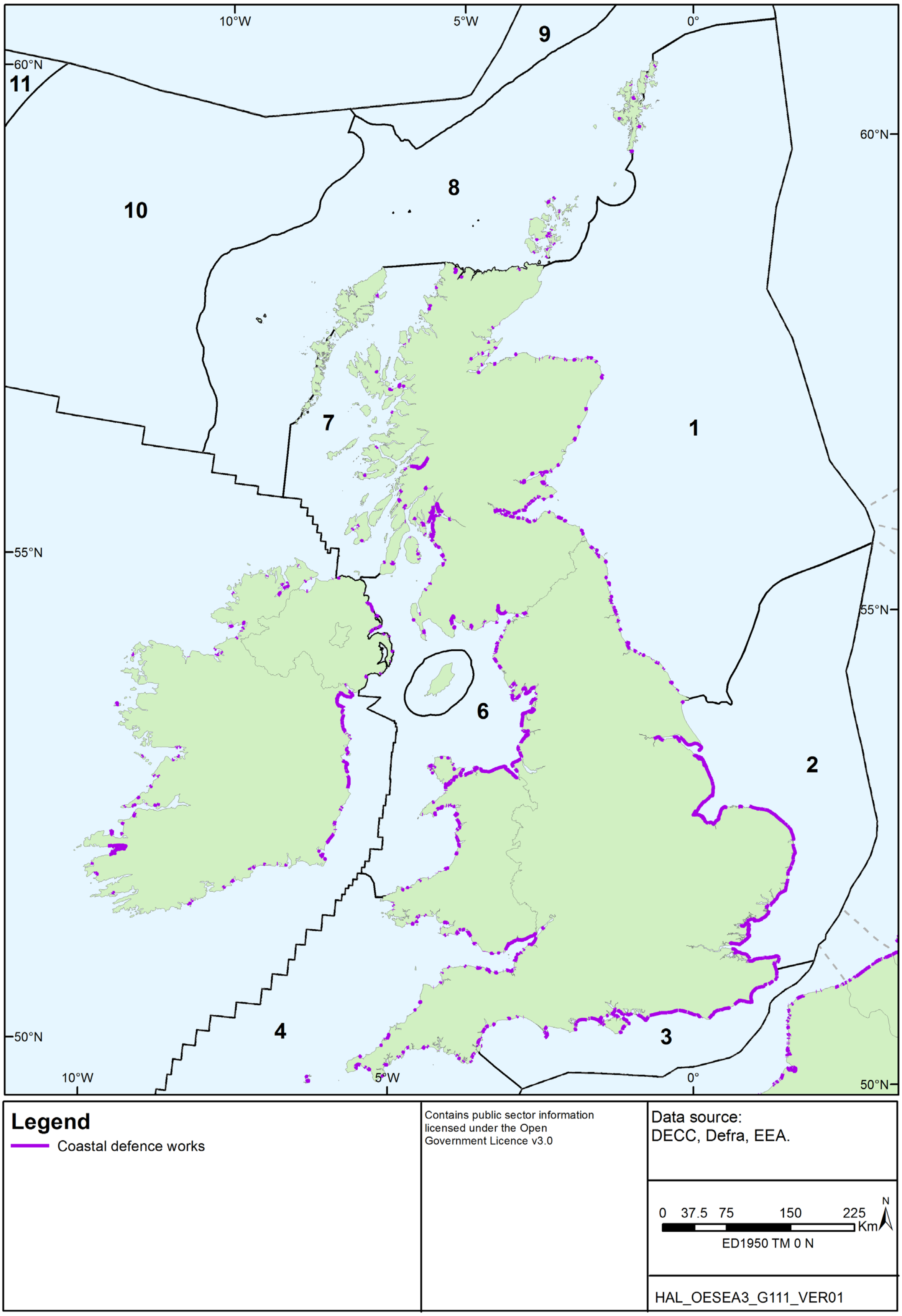
Data source: DECC, Environment Agency, Defra, DECC UK Renewables Atlas.

Figure A1b.14: 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.

A1b.15.3 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).

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