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Understanding the marine environment – seabed habitat investigations of the Dogger Bank offshore draft SAC

Markus Diesing
Suzanne Ware
Bob Foster-Smith
Heather Stewart
David Long
Koen Vanstaen
Rodney Forster
Angela Morando

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For further information please contact:

Marine Protected Sites Team
Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough
PE1 1JY
offshoresurvey@jncc.gov.uk

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Summary

This report details work carried out by the Centre for Environment, Fisheries and Aquaculture Science (Cefas), British Geological Surveys (BGS) and Envision Ltd. for the Joint Nature Conservation Committee (JNCC). It has been produced to provide the JNCC with evidence on the distribution and extent of Annex I habitat (including variations of these features) on the Dogger Bank in advance of its possible designation as a Special Area of Conservation (SAC). The report contains information required under Regulation 7 of the Conservation (Natural Habitats, &c.) Regulations 2007 and will enable the JNCC to advise the Department for Environment, Food and Rural Affairs (Defra) as to whether the site is deemed eligible as a SAC. The report provides detailed information about the Dogger Bank and evaluates its features of interest according to the Habitats Directive selection criteria and guiding principles. This assessment has been made following a thorough analysis of existing information combined with newly acquired field survey data collected using 'state of the art' equipment.

In support of this process acoustic (sidescan sonar and multibeam echosounder) and ground-truthing data (Hamon grabs, trawls and underwater video) were collected during a 19-day cruise on RV *Cefas Endeavour*, which took place between 2-20 April 2008. Existing information and newly acquired data were combined to investigate the sub-surface geology, surface sediments and bedforms, epifaunal and infaunal communities of the Dogger Bank. Results were integrated into a habitat map employing the EUNIS classification. Key results are as follows:

- The upper Pleistocene Dogger Bank Formation dictates the shape of the Dogger Bank.
- The Dogger Bank is morphologically distinguishable from the surrounding seafloor following the application of a technique, which differentiates the degree of slope.
- A sheet of Holocene sediments of variable thickness overlies the Dogger Bank Formation. At the seabed surface, these Holocene sediments can be broadly delineated into fine sands and coarse sediments.
- Epifaunal and infaunal communities were distinguished based on multivariate analysis of data derived from video and stills analysis and Hamon grab samples. Sediment properties and depth were the main factors controlling the distribution of infauna and epifauna across the Bank.
- Epifaunal and infaunal community links were explored. Most stations could be categorised according to one of four combined infaunal/epifaunal community types (i.e. sandy sediment bank community, shallow sandy sediment bank community, coarse sediment bank community or deep community north of the bank).
- Biological zones were identified using modelling techniques based on light climate and wave base data. Three biological zones, namely infralittoral, circalittoral and deep circalittoral are present in the study site.
- EUNIS level 4 habitats were mapped by integrating acoustic, biological, physical and optical data. Eight different habitats are present on the Dogger Bank.

This report also provides some of the necessary information and data to help the JNCC ultimately reach a judgement as to whether the Dogger Bank is suitable as an SAC. In support of this process the encountered habitats and the ecology of the Dogger Bank are compared with other SACs known to contain sandbank habitats in UK waters. The functional and ecological importance of the Dogger Bank as well as potential anthropogenic

impacts is discussed. A scientific justification underlying the proposed Dogger Bank dSAC boundary is also given (Appendix 1). This is followed by a discussion of the suitability and cost-effectiveness of techniques utilised for seabed investigations of the Dogger Bank. Finally, recommendations for strategies and techniques employed for investigation of Annex I sandbanks are provided.

Contents

1 Introduction

This document presents the findings of the JNCC contract F90-01-1221: "Understanding the marine environment-seabed habitat investigations of the Dogger Bank offshore draft SAC". It presents detailed geomorphological and biological information pertaining to the Dogger Bank along with discussion of the underlying context and justification for the proposed dSAC boundary. The report provides some of the necessary information to enable the JNCC to advise Defra as to the eligibility of the Dogger Bank as a SAC. Additionally, recommendations are made regarding strategies and techniques for the investigation of the Annex I habitat described in the European Commission's 2007 Guidance (Commission of the European Community, 2007) as 'sandbanks which are slightly covered by sea water all the time'.

Findings regarding the delineation of the dSAC boundary are detailed in a separate report (Cefas, 2008), which is attached as Appendix 1. The derived boundary is used throughout this report. This report details the subsurface geology, surface sediments, benthic biota and habitats, according to EUNIS and Annex I of the Habitats Directive, present on the Dogger Bank.

1.1 Geography of the area

The Dogger Bank is a large topographic feature that covers an area of approximately 17,600 km^2 in the centre of the North Sea (Figure 2.1) with its maximum dimension being approximately 260 km from northeast to southwest and 95 km from northwest to southeast. The name derives from *dogge* an Old Dutch word for a fishing boat, reflecting the importance of the area for fishing, formerly for cod and herring. Several shipwrecks lie on the bank, many of them fishing boats. Bottom trawling on the bank often dredges up peat, remains of prehistoric animals and even human artefacts, a reminder that the Dogger Bank was once an exposed and important landmass situated between Britain and continental Europe.

The area studied in this report is located in the southern North Sea between: 54°15' 50''N and 55°30'41''N in latitude and 1°6'00"E and 3°14'00'' E in longitude (Figure 2.2). The study area extends from approximately 60 nautical miles off the east coast of Yorkshire to an eastern boundary along the median line separating UK and Dutch waters. The Dogger Bank itself continues north-eastwards across the Dutch sector and into the German sector of the North Sea. The majority of the area lies in shallow waters, and constitutes the north-eastern prolongation of the platform in the southern part of the North Sea extending from the Dutch coast.

The Dogger Bank is the largest area of shallow water, rising to less than 20 m water depth, not contiguous with the UK landmass. The depth increases rapidly from the edge of the bank from 20 m to 50 m water depth and the 50 m isobath surrounds the perimeter of the dSAC area and the limit of the deep Outer Silver Pit. To the north the isobaths increase more gradually reaching a deeper area to the north. The climate of the region is conditioned from strong winds over much of the year and the temperature of the waters varies between 9 and 13º C annually. The tidal elevations lie within the 1-2 meters interval and the mean wave height in the region varies seasonally from 1-2 m in July to 3 m in January (IACMST, 2005).

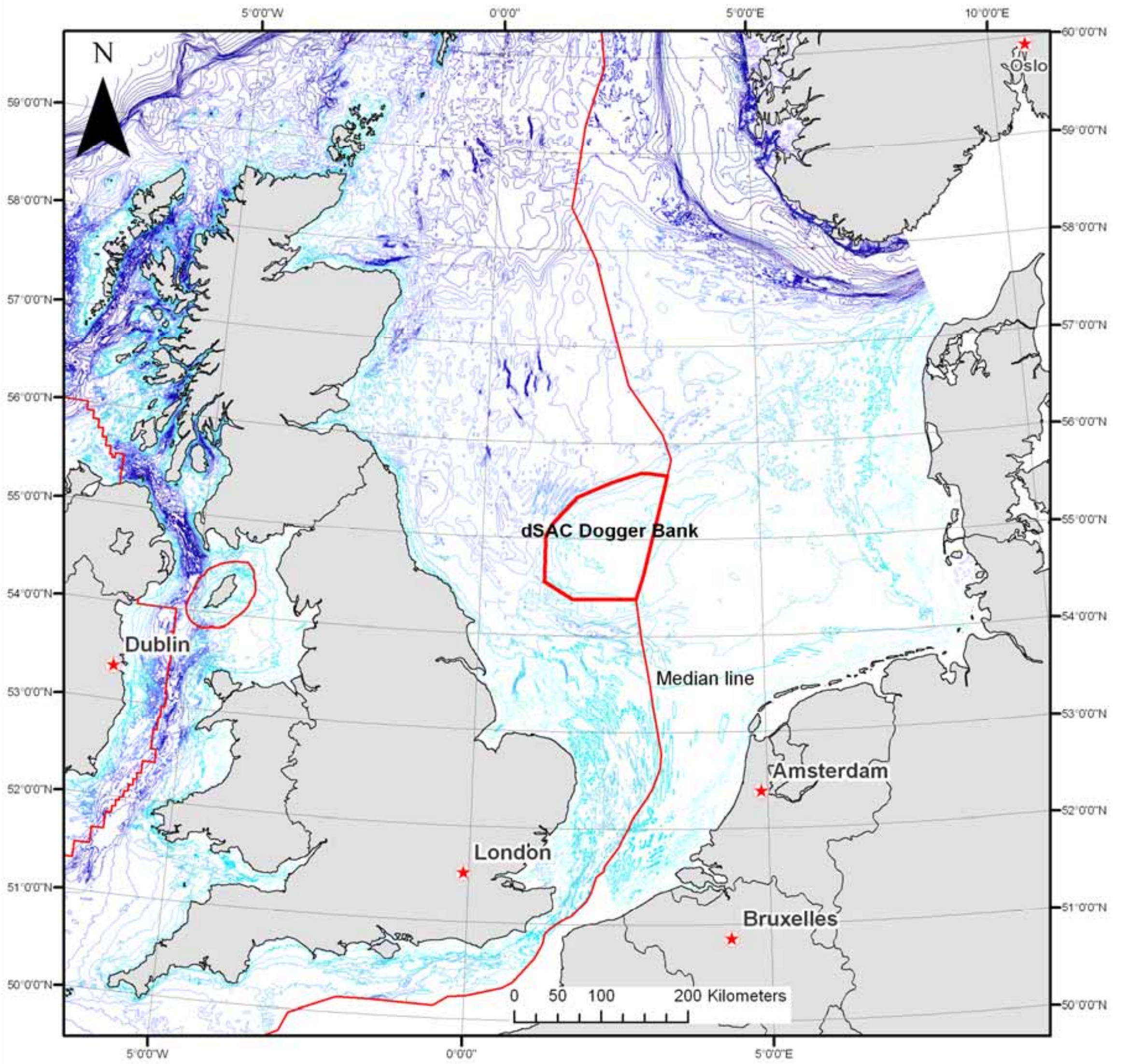

Figure 2.1. Location of the report area and position of the proposed Dogger Bank dSAC Bathymetric contours at 10 m intervals taken from DigBath250. (©BGS, licence no. 2009/0370B)

In the area, a few major features surrounding the Dogger Bank can be described. To the south a series of sandbanks and sand ridges extend from Norfolk to the median line with northwest-southeast crest orientation (Figure 2.2). They are considered to be tidal sand ridges and are up to 40 m amplitude and between 20 to 60 km in length. The ridges are up to 16 m high and the crests of the major sand waves rise to less than 10 m below the sea level. These features are called Norfolk Sand Banks in Figure 2.2. They are separated from Dogger Bank by the Outer Silver Pit, a narrow deep with an east-west trend that extends to a depth of 60 m. Elsewhere, the southern part of the area is formed by a gently undulating seabed with low gradient and increasing depth from 20 m to 80 m below sea level. The seabed is locally incised by narrow deeps such as Sole Pit, Marklams Hole and the Silver Pit. To the northwest of Dogger Bank are a series of large linear ridges known as the East Bank Ridges. They trend north-northeast to south-southwest, are between 17 and 60 km length and stand 15-30 m above the surrounding seafloor (Jansen, 1976). These are moribund tidal sand ridges formed when sea level was much lower (Davis and Balson, 1992). To the north the seafloor falls steadily to the main plain of the North Sea.

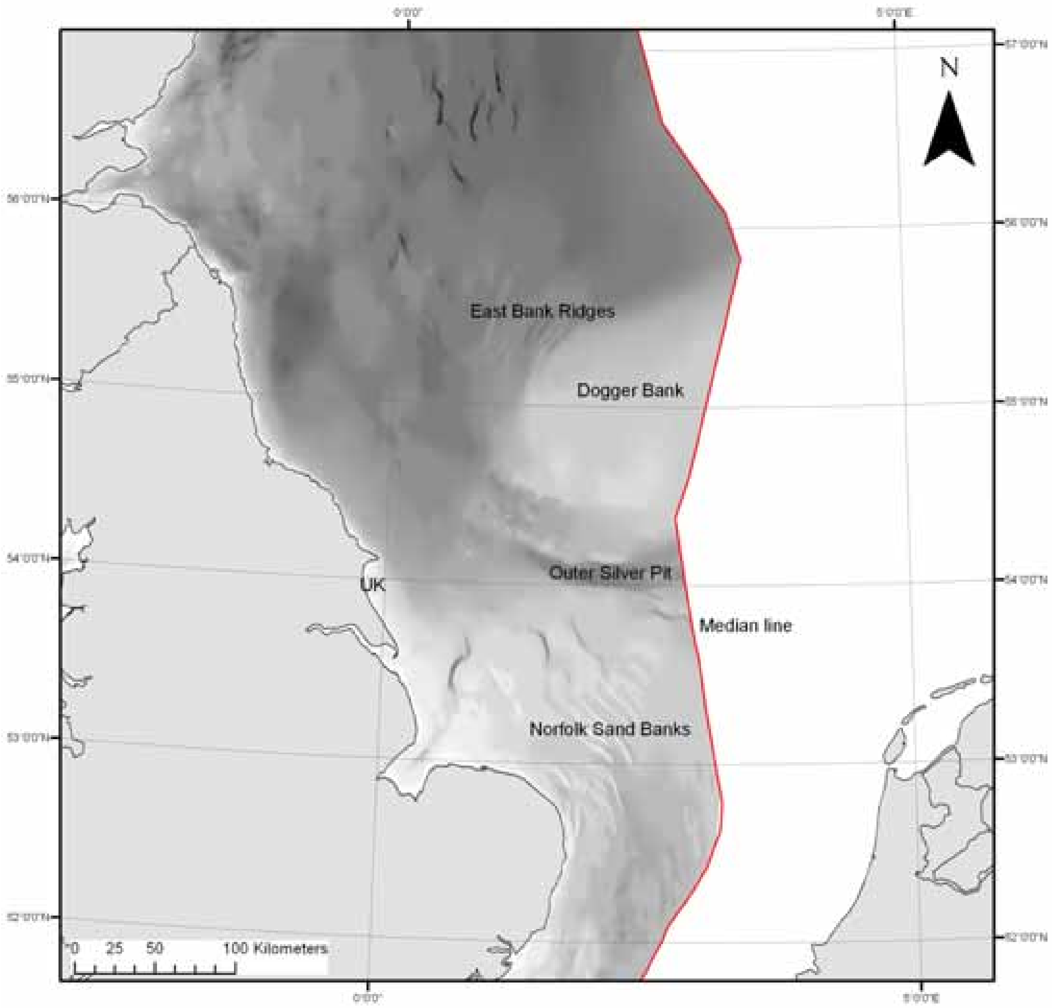

Figure 2.2. Gridded bathymetry of the area with indication of major features. (© British Crown and SeaZone Solutions Limited. All rights reserved. Products licence no. PGA042006 DO3. This product has been derived in part from material obtained from the UK Hydrographic Office with the permission of the Controller of Her Majesty's Stationery Office and UK Hydrographic Office (www.ukho.gov.uk).

1.2 Geological context[1]

The North Sea has been an area of active subsidence since the Pliocene. Together with global sea level fluctuations associated with climatic changes during the Quaternary, this has resulted in dramatic changes in the geometry and morphology of the North Sea seafloor. In addition glacial isostacy has influenced the area since the mid Quaternary and in the southern part of the Dogger Bank between 53° 50'N and 54°30'N salt movement has had a local effect. A series of synclines and anticlines have developed within the Pleistocene deposits due to salt movement (known as halokinesis) in the deeper bedrock. These structures are related to a series of pre-existing faults in the Dogger Fault Zone.

[1] A comprehensive summary of the underlying pre-Pleistocene geology of the Dogger Bank is given in Appendix 2.

While onshore the subdivision of the Quaternary is based on lithostratigraphic and biostratigraphic evidence the offshore stratigraphy is based on seismostartigraphic information and a different set of terms is more appropriate (Table 2.1). The entire Quaternary succession has recently been divided into three major subdivisions (Stoker *et al*, in press):

- Southern North Sea Deltaic Group, from Lower Pleistocene to Lower Middle Pleistocene.
- Dunwich Group – delta top sequence of Lower Middle Pleistocene age.
- Californian Glacigenic Group from Middle Pleistocene to Holocene.

1.2.1 Pleistocene Geology

Deltaic Division

This division is considered to be a regressive division composed of two different elements named for simplicity as Element A and Element B (see Appendix 2), but equating respectively to the proposed Southern North Sea Deltaic Group and the Dunwich Group. The sediment in this division is thick and extensive and was deposited under relatively stable climatic conditions. The lithofacies and the gradational nature of the deposit suggest a deposition in a prograding delta in the direction of a vast central basin positioned to the north of Dogger Bank. The two elements are interpreted as two parts of the same deltaic system. This system was presumably constituted by two amalgamated deltas: a smaller delta bordering East Anglia that received sediments from Britain in the west and a larger eastern delta that extended from the Netherlands. The latter delta was receiving sediments from the European Mainland from both a palaeo-Baltic river system and from the Rhine system. Element A is considered to be the marine part of this succession whilst Element B is the non-marine part.

Sediments of the Southern North Sea Deltaic Group (Element A) change through time from “pro delta” to “delta front” to “delta top” depositional environments. They are formed by sigmoid sedimentary bodies lying against each other and are indicated by a progradation of the deltas towards north–northwest. A vertical section through these formations would indicate a variation of the lithology from silty clays intercalated with fine bioturbated sands (Pro Delta formation), to sandier deposits with shelly bioturbated subtidal sands and mud (Front Delta Formation), and finally an intertidal fine sand dominated unit representing the Top Delta Formation.

The Dunwich Group (Element B) is separated from the Southern North Sea Deltaic Group by a strong reflector that probably represents the transition from fully marine conditions to a sequence representing a low energy shallow water environment. It is a unit with a chaotic acoustic signature with sporadic sub-horizontal reflectors (Cameron *et al,* 1992). It comprises the Yarmouth Roads Formation that can reach 160 m in thickness. This formation is characteristic of a delta top environment with different depositional local origins. In the area south of Dogger Bank the Yarmouth Road Formation can be subdivided into three different acoustic groups comprising lagoonal clays at the bottom and two upper members with fine sand and plant remains. These members of the formation show a transition to more terrestrial conditions and also contain beach deposits (BGS Silver Well Quaternary Geology sheet). The formation has been deposited in a delta top environment when the UK shoreline was probably in the vicinity of 55° N, during early Pleistocene times.

Table 2.1. Synthesis of Pleistocene formations (modified from Cameron *et al*, 1992).

Seismostratigraphic elements and lithogenic division		Formation	Depositional environment	Inferred chrono-stratigraphy
Californian Glacigenic Group	J	Various Formation	Marine	HOLOCENE
Californian Glacigenic Group	H	Sunderland Ground (SG)	Subglacial to Proglacial: Glaciolacustrine to Glaciomarine	UPPER WEICHSELIAN
Californian Glacigenic Group	H	Botney cut (BCT)	Subglacial: Glaciolacustrine to Glaciomarine	
Californian Glacigenic Group	G	Kreftenheye (KR)	Periglacial: Fluvial	
Californian Glacigenic Group	G	Twente (TN)	Periglacial: Aeolian	
Californian Glacigenic Group	G	Well Ground (WLG)	Proglacial: Fluvial	
Californian Glacigenic Group	G	Dogger Bank (DBK)	Proglacial: Glaciomarine to Glaciolacustrine	
Californian Glacigenic Group	G	Bolders Bank (BDK)	Subglacial: Terrestrial	
Californian Glacigenic Group	F	Brown Bank (BNB)	Marine to Lacustrine	LOWER WEICHSELIAN
Californian Glacigenic Group	F	Eem (EE)	Marine	EEMIAN
Californian Glacigenic Group	E	Tea Kettle Hole (TKH)	Periglacial Aeolian	SAALIAN
Californian Glacigenic Group	E	Cleaver Bank (CLV)	Proglacial Glaciomarine	HOLSTENIAN
Californian Glacigenic Group	D	Egmond Ground (EG)	Marine	
Californian Glacigenic Group	D	Sand Hole (SH)	Marine (lagoonal)	
Californian Glacigenic Group	C	Swarte Bank (SBK)	Subglacial: Glaciolacustrine to glaciomarine	ELSTERIAN
Dunwich Group	B	Yarmouth Roads (YM)	Non- Marine Fluvial to intertidal	LOWER PLEISTOCENE TO MIDDLE PLEISTOCENE
Southern North Sea Deltaic Group	A	Aurora (AA)	Marine	LOWER PLEISTOCENE
Southern North Sea Deltaic Group	A	Outer Silver Pit (OSP)	Marine	
Southern North Sea Deltaic Group	A	Markham's Hole (MKH)	Marine	
Southern North Sea Deltaic Group	A	Winterton Shoal (WN)	Marine	
Southern North Sea Deltaic Group	A	Ijmuiden Ground (IJ)	Marine	
Southern North Sea Deltaic Group	A	Smith's Knoll (SK)	Marine	
Southern North Sea Deltaic Group	A	Westkapelle Ground (WK)	Marine	PLIOCENE
		Red Crag (**RCG**)	Marine	

The Californian Glacigenic Group

The Californian Glacigenic Group consists of a number of formations (Elements C to J, see Appendix 2) deposited under a varied range of climatic conditions, that often comprise fragmented, variable lithologies reflecting transgressive and regressive episodes within a series of glacial episodes (Table 2.1). For example, Elements C and H contain infilled "tunnel valleys" cut into the lower Pleistocene succession and are related to the Elsterian and the Weichselian glaciations respectively. Not all elements are present within the Dogger Bank study area but are geographically close reflecting the oscillation of the glacial-interglacial-glacial cycles.

During the early Holocene rising eustatic sea level coincident with isostatic changes of the UK landmass occurred and glaciomarine deposition and the erosion of the scaphiform valleys gave way to the deposition of intertidal mud, silt and peats.

1.2.2 Holocene deposits and seabed sediments

During the early Holocene there was a rapid rise in global sea levels leading to a marine transgression in the southern North Sea causing the Dogger Bank to become an island shortly after 9000 yrs before present (BP) (Jelgersma *et al,* 1979) and eventually submerging it about 7500 yrs BP (Fitch *et al,* 2005). Several suites of relict tidal sand ridges are located around the Dogger Bank. These are indicative of higher current speeds that would have occurred as the sea level rose, thereby infilling passageways around the Dogger Bank. The oldest are the East Bank Ridges located northwest of Dogger Bank and formed about 9000 yrs BP. There is no evidence of active sand waves on the flanks of these ridges indicating that they are now moribund. They are located in 60-90 m water depths with heights of up to 30 m above the surrounding sea floor; the lengths of the ridges can be up to 60 km. To the southeast of Dogger Bank are the Sand Hills, which comprise moribund sandbanks 10-20 m in height. Holocene sediment in the area usually forms a thin veneer covering the older Pleistocene formations. Generally, the Holocene deposits are not very thick in the North Sea area, except within the estuaries of the major rivers and in some areas of sand bank and ridge accumulations.

The Dogger Bank is formed mostly by a core of Pleistocene sediment as described earlier in this section, but is surrounded and covered by a thin veneer of mobile Holocene sediment up to 10 m thick. Figure 2.3 is derived from the BGS regional mapping project undertaken during the 1980s and is a useful reference source to delineate the broad distribution of the seabed sediment across the region. Section 4.3 discusses in more detail the distribution of seabed sediments in the Dogger Bank area and presents an updated interpretation of their distribution taking into account seabed samples collected since the publication of the BGS seabed sediment map sheets and data collected during the course of this project. There is a distinctive association of coarser sediment (slightly gravelly sand, gravelly sand, sandy gravel and gravel) located inside the perimeter of Dogger Bank dSAC indicating that a major source of the Holocene sediment is from reworking the underling coarser sediments of glacial origin.

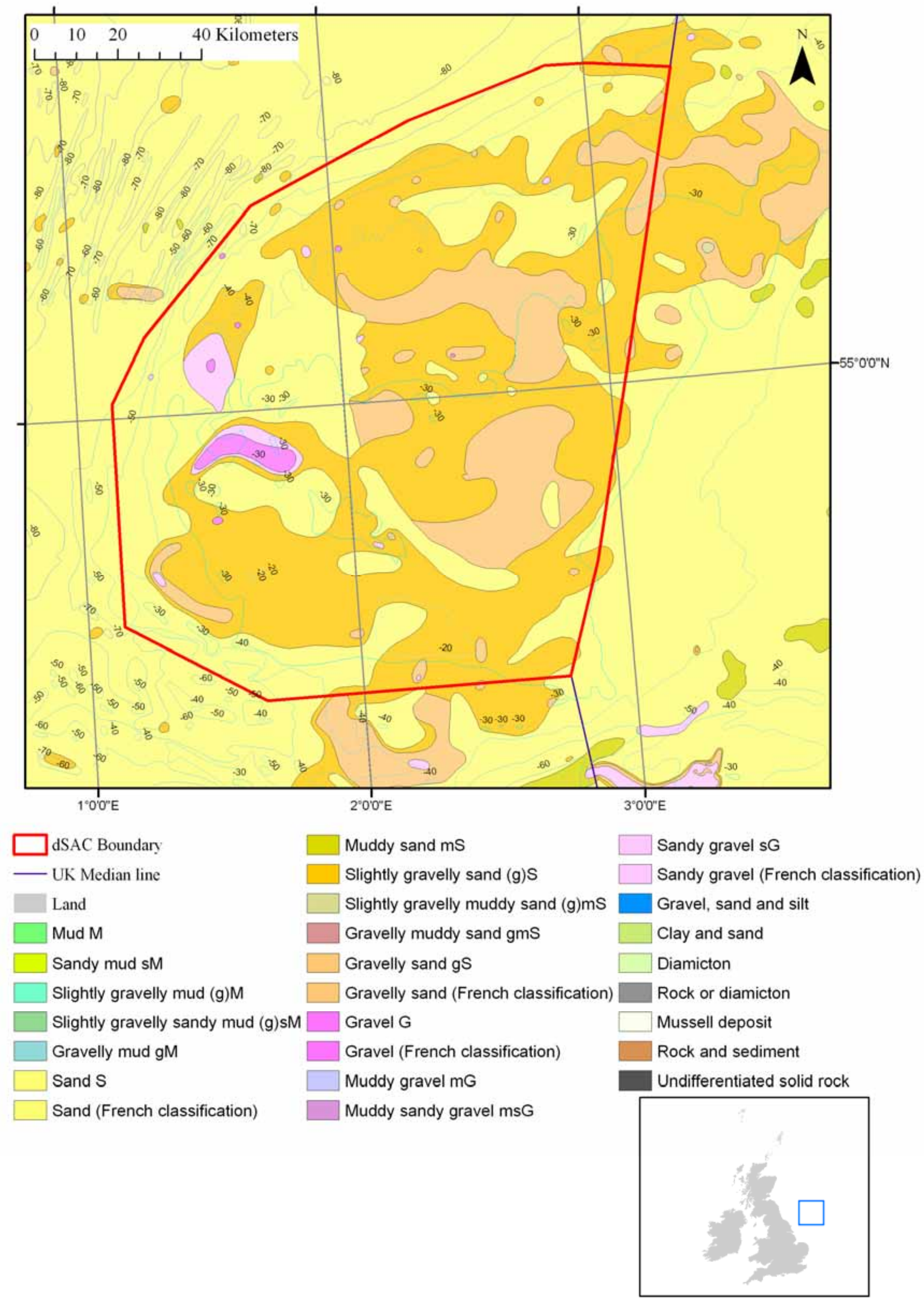

Figure 2.3. Distribution of seabed sediments across the Dogger Bank area derived from BGS report (Cameron *et al*, 1992). For an updated interpretation of the seabed sediments of the area see Chapter 4.3 and Figure 4.5. Depth contours © British Crown and SeaZone Solutions Limited. All rights reserved. Products licence No. PGA042006DO3. This product has been derived in part from material obtained from the UK Hydrographic Office with the permission of the Controller of Her Majesty's Stationery Office and UK Hydrographic Office (www.ukho.gov.uk).

The application of the regional study of 3D Seismic data acquired by the petroleum industry was utilised by Fitch *et al* (2005) to study the palaeogeographic reconstruction within the Dogger Bank area. This study demonstrated how the use of high-resolution bathymetric data is insufficient to accurately map detailed features of early Holocene or Holocene age, especially structures such as channels or fluvial, dendritic systems that do not have topographic expression. The study proposed that during the late Weichselian stage the area of Dogger Bank was dominated by the presence of tunnel valleys (which can be correlated to the tunnel valleys in Element H). Fitch *et al* (2005) studied one tunnel valley in detail. Located just under Dogger Bank, it has a "U" shaped profile and it is approximately 2.4 km wide and 23 km long. Overlying this tunnel valley is a system of fluvial channels with relatively well-developed sinuosity intercalated with lakes and marsh like features. The position of the fluvial channels and the lake system over the tunnel valley may suggest that the infilling material of the tunnel valley acted as a permeability barrier for the water bodies (Fitch *et al,* 2005).

Sea level rise generated marine conditions in the area that continued from the last glacial maximum, but dated peat samples suggest that the Dogger Bank was still dry land between 9000 and 9500 yrs BP and was completely submerged only 7500 yrs ago (Fitch *et al*, 2005). Until that time, a system with meandering fluvial channel and lakes connected with tributaries was active in the area. They were most likely infilled with mud and they were part of a postglacial fluvial plain. Subsequently the major meandering system was abandoned and the area was dominated by a dendritic channel system that may still considered to be of a fluvial origin or belonging to a distal estuarine environment (Fitch *et al,* 2005). Following the complete flooding of the area around 7500 yrs ago the deposition has remained conditioned by a shallow marine environment and Dogger Bank has behaved as a structured sandbank ever since.

1.3 Biological context

The Dogger Bank, and the faunal communities it supports, has historically received significant attention due to a variety of unusual attributes that the bank exhibits along with its importance in terms of commercial fisheries for both groundfish species and sandeels. The sediments on the bank range from fine sand and shell in the shallow areas to muddy fine sands in the deeper regions. The Dogger Bank has also been identified as a region of high annual phytoplankton production, a large proportion of which remains unconsumed and thus settles to the sediment surface where it is available to fauna that feed in the benthic boundary layer (Nielson and Richardson, 1989, Nielson *et al,* 1993, Wieking and Krönke, 2001).

1.3.1 Infaunal communities

Spatial patterns of infaunal communities on the Dogger Bank, and the factors that influence these, have received considerable attention in the recent literature (Krönke, 1990, Krönke and Rachor, 1992, Heip and Craeymeersch, 1995, Krönke and Knust, 1995, Wieking and Krönke, 2001, Krönke *et al,* 2004, Reiss and Krönke, 2005). Heip and Craeymeersch (1995) investigated broadscale benthic community structures in the North Sea and identified that, in general, the North Sea macrofauna consists of northern species extending south to the northern margin of the Dogger Bank and southern species extending north to the 100 m depth contour. Overlap in the distribution of species comprising northern and southern communities is evident around the 70 m depth contour. More detailed examination of macrofaunal communities on the Dogger Bank has identified relatively distinct spatial patterns in infaunal species distributions (Krönke, 1990, Krönke and Rachor, 1992, Wieking and Krönke, 2001, Reiss and Krönke, 2005).

Numerous factors have been identified as influencing spatial and temporal variability in infaunal communities on the Dogger Bank and these include natural variables such as depth, sediment type, climate variability, hydrographic regime, temperature and supply of organic matter (Krönke, 1990, Krönke and Rachor, 1992, Wieking and Krönke, 2001, Reiss and Krönke, 2005) along with anthropogenic influences such as increasing pollution and commercial fishery activities (Krönke, 1990, Krönke and Rachor, 1992, Wieking and Krönke, 2001). Surveys reported by Wieking and Krönke (2001) identified four main infaunal communities present on the Dogger Bank. These comprised a 'Bank Community', a 'Southern Community', a Western Community' and a 'Northeastern Community'. The 'Bank Community' was restricted to the top of the bank and was typified by shallow, fine sandy habitats that were inhabited by a *Bathyporeia-Fabulina* association. The 'Southern Community' generally exhibited higher faunal abundance than the 'Bank Community' and was largely dominated by the brittlestar *Amphiura* sp. The 'Northeastern Community' was described as a transitional association where the *Bathyporeia-Fabulina* assemblage at the top of the bank converges with the *Amphiura* assemblage present in deeper waters. Finally, the 'Western Community' was typified by increased dominance of species described from the northern part of the North Sea including the echinoderms *Leptopentacta elongata* and *Brissposis lyrifera* along with the sipunculid *Golfingia* spp. Observed temporal variability in the relative dominance of the species, and trophic structure, typifying the communities described above were attributed to variability in the hydroclimatic regime of the North Sea which in turn influences temperature, primary production and the hydrodynamics of the Dogger Bank region (Wieking and Krönke, 2001).

Such observations relating to spatial patterns in infaunal communities are supported in the wider literature, which identify a transition of species assemblages across the bank with depth (AUMS, 1989a, b, Daan and Mulder, 2001, 2006, Emu Ltd. 2003, 2007, Metoc 2004, DTI, 2005). In shallower regions, Emu Ltd. (2003 and 2007) describes the communities as being characterised by the presence of the polychaete *Nephtys cirrosa* and amphipods of the genus *Bathyporeia* sp. This is replaced, at increasing depths by species better adapted to living in more silty locations such as *Fabulina fabula* and the polychaete *Magelona mirabilis* and finally the habitats in the deepest locations on the edge of the bank are inhabited by species such as the brittlestar *Amphiura filiformis* and the bivalve *Mysella bidentata*. Deeper water areas tend to support comparatively greater varieties and densities of fauna due to the greater stability of the substrate and reduced environmental disturbance. Mixed heterogeneous substrates, where they occur, also support elevated diversity owing to the greater availability of micro-niches. The gravelly sand substrates in the north-western region of the bank support the polychaetes, *Glycera lapidum, Chone dunneri, Aonides paucibranchiata, Nereis longissima* and *Pholoe balthica* (Emu Ltd., 2003, 2007).

1.3.2 Epifaunal communities

Epifaunal species on the Dogger Bank have also received considerable attention in the literature with studies largely examining spatial distribution and diversity of epifaunal communities across the Dogger Bank region (Jennings *et al,* 1999, Callaway *et al,* 2002). Investigations carried out as part of a multinational, collaborative 2 m beam trawl survey of the North Sea identified three geographically distinct communities in the vicinity of the proposed Dogger Bank dSAC and these were characterised by species including the echinoderms *Asterias rubens*, *Astropecten irregularis*, *Ophiura* spp. and *Psammechinus miliaris* along with the crustacean *Pagurus bernhardus* (Callaway *et al,* 2002). Prior to this study, Jennings *et al* (1999) had previously identified a similar array of species as being characteristic of their 'Central' and 'Southern' North Sea communities.

Site specific 2 m trawl sampling and seabed video surveying at North West Rough, at the northern edge of the bank, and Southermost Rough to the south of the bank (Emu Ltd, 2003, 2007) identified commonly occurring epibenthic species within the boundaries of the dSAC. These included *Alcyonium digitatum*, *Pagurus bernhardus*, *Liocarcinus holsatus, Astropecten irregularis*, *Asterias rubens* and *Limanda limanda*, consistent with the wider array sampling completed by Callaway *et al* (2002) and Jennings *et al* (1999). Other widely recorded species during the site specific surveys included the long-clawed porcelain crab *Pisidia longicornis*, the whelk *Buccinum undatum*, the green sea urchin *Psammechinus miliaris*, the dragonet *Callionymus lyra* and gobies. Isolated patches of mixed coarse sandy gravel and cobble substrata at the northwest of the Dogger Bank supported the epifaunal brittlestar, *Ophiothrix fragilis*, which occurred in densities of up to 1,300 individuals/m^2 (Emu Ltd, 2003).

1.3.3 Fisheries

The distribution of sandeels (*Ammodytes* spp.) within the North Sea is highly localised and they are abundant in the Dogger Bank region. The sandeel population on the Dogger Bank is concentrated along the edges in water depths of around 20-30 m. Their distribution is linked to local hydrography and higher levels of food resource with increased plankton abundance where fronts meet (Cefas, 2007). Sandeels are most active during the spring when they are thought to undertake diurnal migrations of up to 5-10 km moving from the seabed where they are buried at night to the water column over deeper areas of the seabed during the day to feed (Cefas, 2004). Sandeel nursery areas are even more geographically localised than general sandeel distributions and the North West Riff area to the west of the Dogger Bank is regarded as a crucial sandeel nursery to the wider area (Cefas, 2007). Importantly, this high degree of site attachment exhibited by sandeels indicates low recolonisation potential of areas denuded by fishing.

Sandeels are a significant prey resource for various predators including other commercial fish species, seabirds (such as fulmar and kittiwake) and cetaceans, in particular the harbour porpoise (Cefas, 2007). Predatory fish species present on the Dogger Bank include whiting *Merlangius merlangus*, plaice *Pleuronectes platessa*, mackerel *Scomber scombrus* and cod *Gadus morhua* (Emu, 2003, 2007; Cefas, 2007, Fox *et al,* 2008) with dab *Limanda limanda* and grey gurnard *Eutrigla gurnardus* being particularly abundant (Cefas, 2007). In a survey of cod distribution and their spawning grounds throughout the North Sea, Fox *et al* (2008) found a high abundance of both mature cod and stage I cod eggs in the southern Dogger Bank region. These fish species consume a wide variety of prey types and therefore are not as dependent upon a constant sandeel population as seabird and cetacean species. However, a link between higher sandeel abundance and improved condition of these commercial fish species has been recorded indicating the importance of maintaining a healthy sandeel stock to the wider fish community on the Dogger Bank (Cefas, 2007).

1.3.4 Marine mammals

Satellite telemetry work has identified that common and grey seals are present in the area (Matthiopoulos *et al,* 2004, Matthiopoulos, 2007). There are known to be large haul-out populations of common seals along the Lincolnshire and North Norfolk coastline with the species travelling long distances on foraging trips and regularly visiting offshore sites (SCOS, 2007). Both species prey on a wide variety of fish species including white fish, flatfish, gadoids (e.g. saithe, cod), clupeids (e.g. herring, whiting, sprat), cephalopods (e.g. octopus and squid) and sandeel populations (Hammond *et al,* 1994a, b, Hall *et al,* 1998, Hall and Walton, 1999, SCOS, 2007). The contribution of each prey species is known to vary by area and season. However, for grey seals, sandeels can comprise up to 50% of the diet.

2 Survey design and methods

Acoustic seabed mapping techniques produce remotely sensed images of the seabed morphology and texture, and allow interpretation on the nature of the seabed surface. To facilitate the characterisation of seabed habitats on the Dogger Bank, simultaneous sidescan sonar and multibeam echosounder surveys were conducted to inform the position of ground-truth locations. The fieldwork was undertaken aboard RV *Cefas Endeavour* between 2-20 April 2008.

Due to the large extent of the area of interest and the limited resource available to undertake the survey, it was not possible to cover the entire area using acoustic techniques. Based on a review of existing data, a survey plan was developed that would allow a broadscale characterisation of the entire Dogger Bank. The majority of broadscale survey lines were chosen in a north - south orientation, and were initially spaced 10 km apart. During the data review stage, survey lines were selected to complement existing seismic data held by the BGS.

All data acquired during the survey was, in general, processed and available for inspection within 24 hours. The ability to review data during the course of the fieldwork allowed the identification of areas where finescale surveys of more complex sedimentary environments were required. This comprised an area of approximately 2 km by 3 km, which was covered using multibeam and sidescan sonar.

The acoustic survey included both broadscale and finescale components. The broadscale survey is shown in Figure 3.1, and consisted of a 14 north - south survey lines and five east-west lines. The location of the finescale survey is also shown in Figure 3.1, and full bottom coverage using multibeam bathymetry was achieved in this area.

The locations of ground-truthing stations were selected following interrogation of the acoustic data (Figure 3.2). Ground-truth stations were assigned into two categories; namely areas dominated by uniform sediments determined from sidescan records and areas at the boundary of different sediment or habitat types. Ground-truthing was required to further examine sediment composition along with infaunal and epifaunal community characteristics that typify these regions. Typically a single video tow and a single Hamon grab sample were collected from each of these 'uniform' stations. Boundary stations were similarly identified from the acoustic records and consisted of distinct boundaries between what appeared to be two different sediment or habitat types. At these stations, the camera tow was positioned to travel at a right angle to the boundary in order that the sediments on either side of the boundary could be examined. Additionally, grab samples were collected from the sediments on either side of the boundary in order that infaunal composition of the two habitat types could be determined. Beam trawl samples were collected to validate epifaunal species identification carried out from the video tow footage and were restricted to uniform areas of substrate.

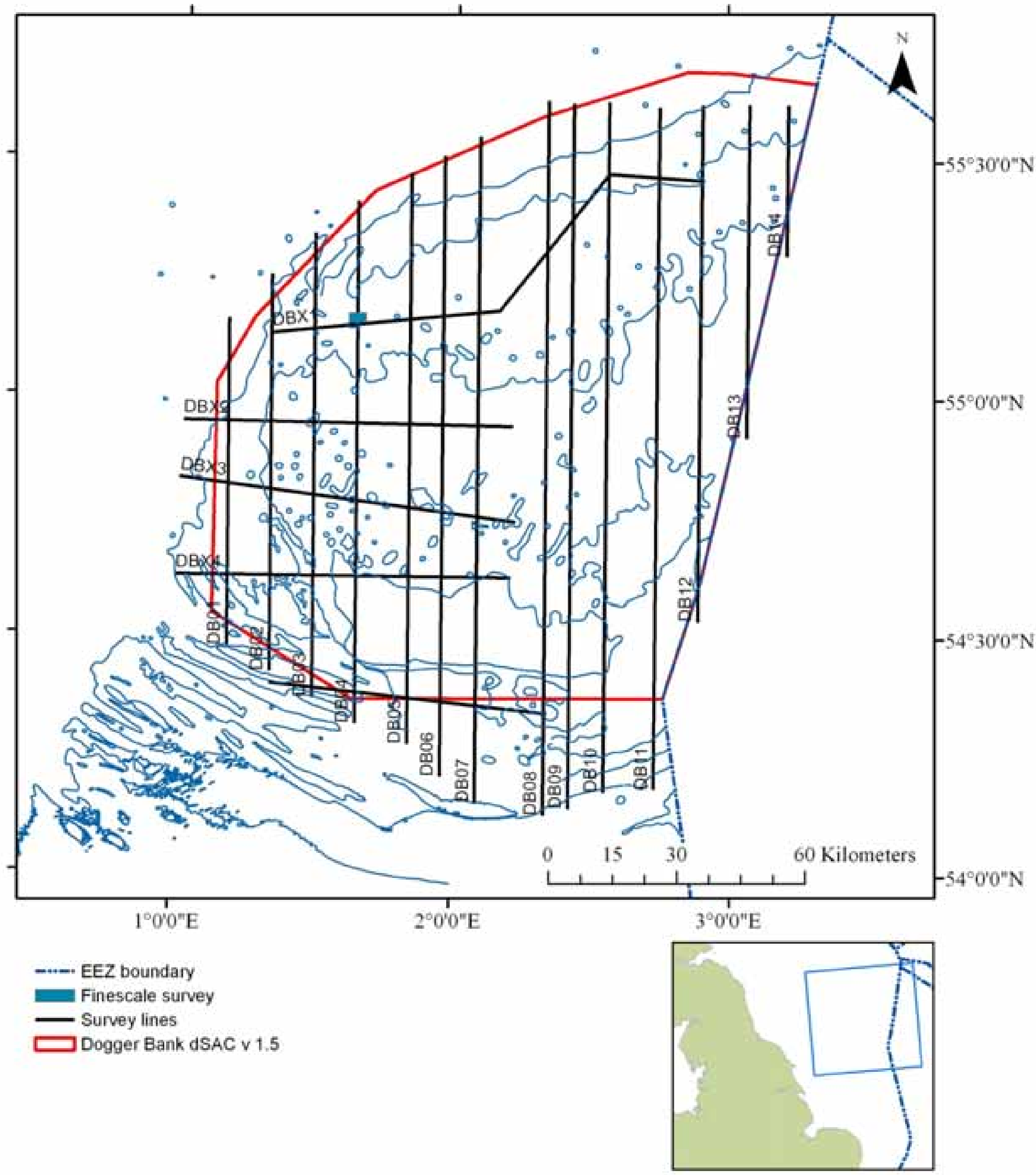

Figure 3.1. Acoustic (Sidescan sonar and multibeam bathymetry) lines surveyed.

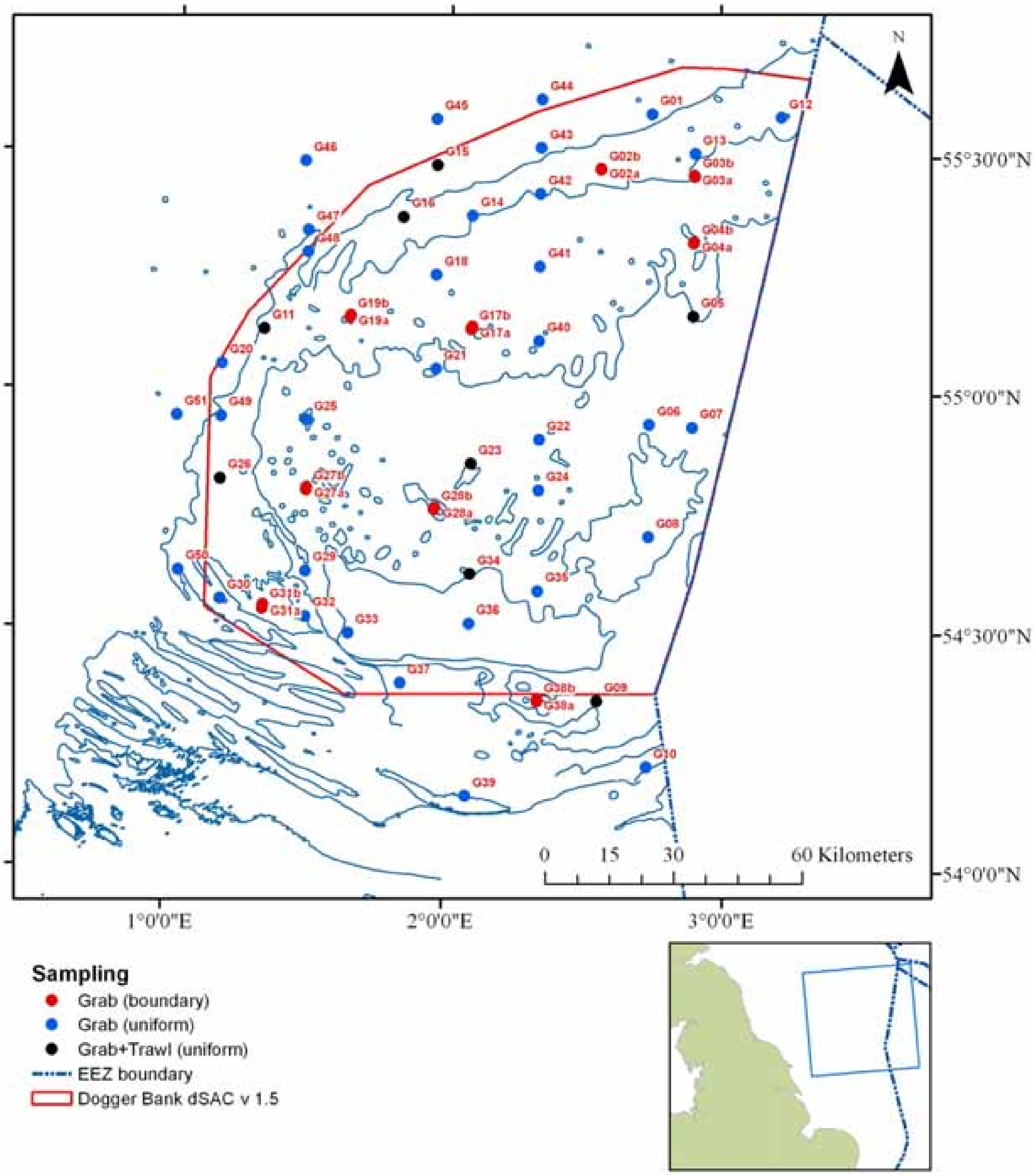

Figure 3.2. Ground-truthing/biological stations sampled. 'Boundary' denotes pairs of stations located at substrate boundaries as inferred from interpretation of backscatter data. 'Uniform' indicates stations located amidst uniform substrate.

2.1 Acoustic Tools

2.1.1 Sidescan sonar

For many years, sidescan sonar has been used in seabed characterisation studies (Boyd *et al,* 2006, Brown *et al,* 2002, Brown *et al,* 2004, Friedlander *et al,* 1999, Humborstad *et al,* 2004). Sidescan sonar produces an image of the seabed using acoustic energy. The emitted acoustic wave interacts with the seabed and the strength of the returned acoustic signal is used to produce a map of the seabed. The strength of the returned signal is a result of two main interactions at the seabed surface: direct reflection on features such as rock outcrops or wrecks, and backscattering of energy related to the seabed texture and character. Coarse substrates or features facing the sidescan sonar fish result in high backscatter intensities, whereas finer sediments or acoustic shadows behind seabed features result in low backscatter strength (Figure 3.3) (Blondel and Murton, 1997, James, 2007, Seabeam Instruments, 2000).

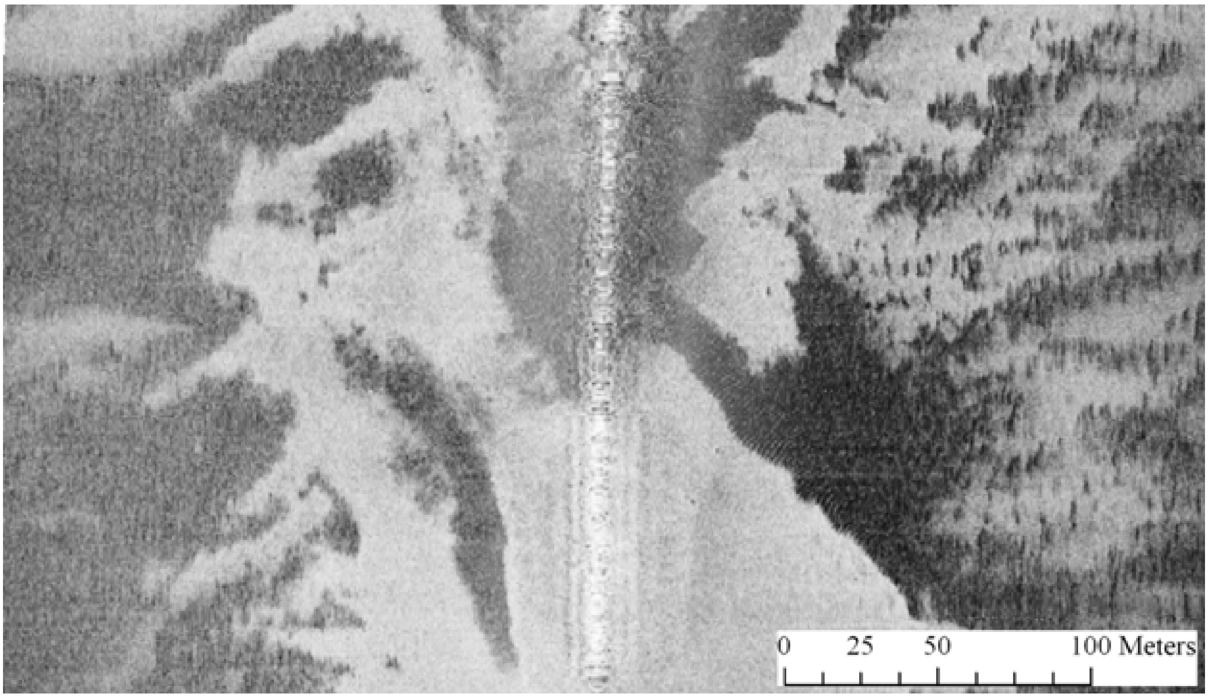

Figure 3.3. Sidescan sonar image showing difference in backscatter between soft (light tones) and hard substrates (dark tones).

The ability of the sidescan sonar to resolve fine details of the seabed surface is related to the frequency of the system, the acoustic pulse width and the sonar's horizontal beam width (Blondel and Murton, 1997). High frequency sidescan sonar systems (e.g. 500 kHz) have a small acoustic footprint, which allows the identification of smaller features, but will only have a limited range (e.g. 100 m). The acoustic footprint of a low frequency system (e.g. 100 kHz) will be larger, limiting its ability to detect small features, but the wider range (e.g. 200 m) allows coverage of larger areas in the same time.

Dual frequency sidescan sonar (Benthos SIS-1624) was used during this project to gather information on the nature of the seabed. This sidescan sonar can operate simultaneously at frequencies of 100 kHz and 400 kHz. Generally, the system was optimised for collecting data at the 100 kHz frequency with a range of 200 m from nadir. Triton Imaging ISIS v7.0 software was used during this survey to acquire all sidescan sonar data.

2.1.2 Multibeam echosounder

Multibeam echosounders were initially developed for hydrographic survey applications, but found a variety of applications in scientific research (Boyd *et al,* 2006, Butler *et al,* 2006, Kostylev *et al,* 2001, Kostylev *et al,* 2003, Pickrill and Todd, 2003, Roberts *et al,* 2005, Ryan *et al,* 2007, Szuman *et al,* 2006, Todd, 2005). Multibeam echosounders use a large number (>100) of narrow acoustic beams to measure the water depth along a swathe on the seabed.

The swathe width is a function of the water depth. Although manufacturers often suggest figures of 10 times water depth for the swathe width, experience shows that good quality data is only achieved up to four to five times the local water depth. Data from the multibeam survey can be combined to produce a digital terrain model of the seabed.

Accurate depth soundings can only be obtained when a number of factors are compensated for (i.e. ray bending as a result of sound velocity variations in the water column, tide and vessel movements such as heading, heave, pitch and roll). This can be achieved by taking regular Conductivity Temperature Depth (CTD) casts to estimate the sound velocity profile in the water column, and integrating a motion reference unit (MRU) and gyrocompass with the multibeam echosounder. To achieve seamless integration of adjacent multibeam swathes, detailed knowledge of the local tidal regime is also required. This can be obtained by deploying local tide gauges or by using tidal predication software.

The ability to resolve fine details of the seabed morphology depends on the frequency and beam angle of the multibeam system. Shallow water, high frequency (e.g. 300 kHz) systems can achieve a resolution at centimetre level, whereas deep water, low frequency (e.g. 12 kHz) multibeam echosounders will only be able to resolve features of several metres (Lurton, 2002, White *et al,* 2007).

In addition to detailed depth measurements, multibeam echosounders can also record sidescan sonar-like backscatter strengths. However, the hull mounted multibeam system will be less effective in feature detection than a sidescan sonar towed close to the seabed surface.

Multibeam echosounders were used in this project for their ability to provide detailed morphological information from the seabed surface. Multibeam data was collected using the Kongsberg EM3000D echosounder on the drop keel of the RV *Cefas Endeavour*. The system operates at a frequency of 300 kHz, ideally suited to the water depth encountered in the survey area. The data was acquired using Kongsberg SIS software and data recorded in the Kongsberg proprietary "ALL" file format.

2.2 Acoustic data processing

2.2.1 Sidescan sonar

Initial sidescan sonar data processing was undertaken during the survey onboard the vessel, whilst further processing was undertaken after completion of the survey. All sidescan sonar data was processed using Triton Imaging Inc. ISIS Sonar v7.0 and Delphmapv3.1 software suite. GeoTiff mosaics of the sidescan sonar imagery were produced with a resolution of 50 cm. These mosaics were imported in ArcGIS for further integration with other datasets and expert interpretation. Additionally, a pre-agreed list of seabed descriptors was drawn up and each descriptor assigned a number. A descriptor number was logged against a ping number every 15 minutes to provide a time-series of seabed descriptions. This aided data review for the purpose of finescale acoustic surveys and ground-truthing.

2.2.2 Multibeam echosounder

Initial processing was undertaken in the CARIS HIPS v6.1 hydrographic data processing software. The advanced Combined Uncertainty and Bathymetry Estimator (CUBE) algorithm was used for data cleaning in CARIS HIPS. Fully corrected soundings were imported in the Fledermaus v6.7 software suite for data visualisation. GeoTiff images were produced in Fledermaus to be included in the project GIS.

Tidal predication software was used to account for the effect of tide on the depth soundings. An in-house developed and verified software packaged, TSTide, was used to provide tidal predications at 157 virtual stations across the survey area. Performance of the tidal model was generally found to be very good, with no noticeable offsets at intersections between survey lines.

2.3 Ground-truthing tools

2.3.1 Video data collection

Sample video tows were conducted using a camera sledge (Shand and Priestly, 1999) fitted with a forwardly inclined, combined digital video and stills camera, with a downward pointing flash unit and appropriate flood lighting. Camera tows were conducted with the purpose of either characterising a homogenous seabed or to characterise and define habitat boundaries inferred from the acoustic data. Tows were conducted over a minimum of 15 minutes. Still images were taken every 30 seconds and additionally at points of particular interest. The lighting angle for the video was experimented with and it was considered that a strong, unidirectional light from one side with a weaker infill from the other gave the best results in terms of showing the small features on the sand surface. During the video tow, the position of the vessel was mapped in real time over a georeferenced image of the sidescan data collected earlier in the cruise. This assisted the finer scale interpretation of the acoustic data. A description of the habitat and fauna was made during the video tow.

At the end of each site, a large A0 map of the ground-truthing array plotted over the broadscale bathymetry data were annotated with notes from the video. This was useful when reviewing the ground-truthing progress and considering whether the current array was sufficient to meet the aims of the survey or whether additional sites were required. As a result, the requirement for extra video sites was agreed with the final number of video stations totalling 60.

Additionally, the Hamon grab was fitted with a vertically mounted video camera and a light source in order that an image of the sediment surface immediately adjacent to where the benthic/sediment sample was collected could be obtained. This information was important as it provided a visual impression of the seabed in an undisturbed state, which proved useful for informing subsequent acoustic and biological interpretations.

2.3.2 Beam trawls

A ‘Jennings’ type 2 m beam trawl (Jennings *et al,* 1999) was used for the semi-quantitative collection of epifaunal samples at ten stations. Beam trawl samples were collected to provide voucher samples for the video data and also enhance the epifaunal species list constructed from video surveys at the sites.

2.3.3 Hamon grabs

A single grab sample was collected from each uniform ground-truthing station and two grab samples were collected from boundary stations in order to sample the two different habitat types present on either side of the boundary. Grab sampling was conducted using a 0.1 m^2 Hamon grab fitted with a video camera and light. The grab was also fitted with a CTD probe to collect additional data to aid subsequent acoustic/biological interpretations. Grab samples were collected from within a 100 m radius range ring, centred on the target station. The Hamon grab was lowered to within a few metres of the seabed and the vessel was asked to move 20 m in order to provide an overview of the habitat on video ahead of sampling. This meant that the sample could be placed in context with the substrates surrounding it, which was particularly important in heterogeneous sediments. After the 20 m drift, the grab was lowered to the seabed to collect the sample.

On retrieval of the grab sample a representative 500 ml sub-sample of sediment was removed and frozen for subsequent particle size analysis (PSA) back at the laboratory. The sample was then photographed and the volume measured and recorded. It was then washed over a 1 mm sieve and the >1 mm fraction was retained and fixed in a 4-6% buffered Formaldehyde solution.

2.4 Ground-truth sample processing and data analyses

2.4.1 Video data processing

The decision was made to combine the data from the video tow, the stills and the Hamon grab video to create a single record that was located centrally along the video tow or video clip representing a single habitat type. The video and stills from the tow each provided complementary information: the lighting for the video created shadows from features on the seabed which were useful in identifying biogenic structures (holes, tubes, casts and burrows) and it was often easier to confirm the presence of certain species (e.g., *Ensis* from their spouts) from a moving image than from stills. Video also gave a more complete coverage of the habitat than the stills. The stills were used for confirming the identification of species where there was any doubt. The video attached to the Hamon grab was used to supplement the records, but often the clarity of the video was poor and, in practice, was only used as confirmation of sediment.

The procedure adopted was to view the video and to divide the tow into video clips for each habitat type. Many tows were uniform throughout their duration but others were designed to cross boundaries identified from the sidescan images. These clips were then viewed to record the habitat features and species. The format for the recording form was provided by the JNCC and was based on the fields in Marine Recorder. Thus, percent cover of different sediment types and the presence/absence of surface sediment features were recorded. Sediment size and percentage cover were estimated by the analyst with the aid of pre-determined prompt sheets.

Species were counted where possible. However, many species were given a SACFOR abundance score where counting proved difficult. For example, the abundance of *Echinocardium* was estimated from the distinctive keyhole burrow openings in the sand. It was likely that these were easily overlooked, depending upon the lighting, and counts would not be reliable. Another notable example where the SACFOR scale was employed was determining the abundance of *Lanice concheliga* since this species was often observed in dense carpets making individual counts difficult.

The stills associated with the video clips were then viewed and the same data recorded as for the video. One record was made for all the stills associated with a video clip rather than one record per still. All stills (60 or 30 second intervals and operator-selected stills) were viewed. Percent cover and abundance was estimated from all stills and a cumulative species count recorded. This strategy for the analysis of stills was justified since 1) the purpose of the analysis of the video/stills data was to provide a semi-quantitative description of the whole habitat rather than a quantitative analysis of frames and 2) the video was to be the main source of representative data for the sample station and stills were primarily to provide supplementary data.

The data from video, stills and Hamon grab video were combined into one record and the data from each source were placed in adjacent columns in a spreadsheet. A third column was used to enter the final record summarising the site. It was to be expected that species counts from the stills would be lower than for the video. In most cases the correlation between the video and the stills was good and deriving a representative count was straightforward. In cases where there was a significant disparity, the video and stills were viewed again to resolve the conflict. For some types of statistical analysis (SIMPROF/SIMPER) the final species counts were replaced by a SACFOR abundance estimate so that all records were of the same data type.

2.4.2 Infaunal sample processing and data analysis

Infaunal samples were processed by Unicomarine Ltd. following their procedural guidelines and quality control systems detailed in Worsfold *et al* (2005). All specimens were identified to the lowest possible level with solitary specimens enumerated and colonial species recorded on a presence/absence basis. Resulting data consisted of a species abundance matrix and total biomass of each taxon identified.

Infaunal species abundance data were investigated using both multivariate and univariate techniques. For multivariate analyses, the Bray Curtis similarity measure was applied to square root transformed species abundance data. The SIMPROF routine was then employed to examine genuine clustering within the samples. SIMPER analysis was subsequently utilised to identify the sub-set of species that were predominantly responsible for similarity within the genuine clusters identified using SIMPROF. Additionally, the BIO-ENV routine was employed to examine whether the suite of measured abiotic variables (i.e. sediment particle size and depth) are responsible for structuring the infaunal communities. Multivariate analyses were carried out using PRIMER v6 (Clarke and Gorley, 2006).

The univariate measures of species number (S), number of individuals (N), Shannon-Wiener diversity index (H') and total Ash Free Dry weight (AFDW) were calculated from the infaunal species abundance and biomass data and values for each station were mapped in order to investigate any patterns or gradients in their values.

2.4.3 Particle size analysis (PSA) and data interpretation

The sediment samples, collected during the field sampling, were split at 1 mm (0.5 ϕ) using wet sieving. The sediment greater than 1 mm was analysed using dry sieving at 0.5 ϕ-intervals between 1 mm and 63 mm (0.5 ϕ to –6 ϕ). A subsample of the sediment less than 1 mm was analysed using the Malvern Mastersizer 2000 laser sizer. The dry sieve and laser results were combined to give the full particle size distribution at 0.5 ϕ-intervals between

0.1 μm and 63 mm (11.5 ϕ to –6 ϕ). Sediment statistics derived from this full particle size distribution included mean, sorting, skewness, kurtosis, gravel (%), sand (%) and mud (%).

BGS have been acquiring sample data in the area as part of its regional mapping programme supported primarily by the Department of Energy in the 1980s (Fannin, 1989). A total of 563 BGS samples have undergone particle size analysis (PSA) within a 25 km buffer zone around the proposed Dogger Bank dSAC. Figure 2.3 shows the distribution of seabed sediments within the Dogger Bank area as published in Cameron *et al* (1992) and Gatliff *et al* (1994). During the current investigation, a further 51 PSA samples were acquired. In addition, a further 156 PSA samples from previous Cefas studies within a 25 km buffer zone around the proposed Dogger Bank dSAC were utilised (Figure 3.4).

All the samples were visualised within a GIS along with the multibeam and sidescan sonar data acquired during the course of this study. The existing seabed sediment distribution was then revised as necessary to take into account the complete database of PSA samples within the area and the associations between sediment type, seabed morphology and bedforms as interpreted from multibeam and sidescan sonar data. A revised seabed sediment interpretation has been produced for the Dogger Bank dSAC area (Figure 4.5).

Additionally, 51 newly gathered samples were analysed using the software EntropyMax 1.0 (Orpin and Kostylev, 2006). The software was used for grouping sediments based on their grain-size distributions, thereby minimising the variability (also known as entropy) within a group and maximising the variability between groups. This approach was pioneered by Shannon (1948) and more recently adapted to sedimentological applications by Woolfe and Michibayashi (1995). The software employs two statistics, the Rs statistic and the C-H criterion, to assist in determining the optimum number of groups. Optimum grouping is achieved where the C-H criterion reaches its maximum and where the Rs curve exhibits an inflection.

2.5 Satellite data interpretation

A series of daily satellite-derived maps (MODIS) of the attenuation coefficient (Kd) for the North Sea was obtained. These maps are a derived product calculated from knowledge of the surface sediment load and the chlorophyll concentration, both of which are determined from space. The Kd maps are an experimental product, and have not been properly tested against *in situ* data, but values are thought to be realistic and close to the true Kd. Spatial resolution is around 1 km.

All of the maps for August 2007 were averaged in order to produce a complete coverage with no gaps due to clouds. The average number of valid days for the Dogger region was around seven, which is higher than in most months. The Kd values in summer are likely to be lower than the year as a whole due to less suspended sediment and less chlorophyll. Average Kd for the Dogger region lies around 0.13. From the average map we calculated the 1% irradiance depth for each pixel as :

$$Z = \ln(100)/Kd.$$

The value of 1% was chosen as this is commonly used to describe the lower limit of the euphotic zone, although it is known that some seaweeds and benthic microalgae can grow at light levels much lower than this.

The map of 1% depth was compared to a bathymetric model of the Dogger Bank (see Appendix 1 for further details of the bathymetric model). Raster Calculater in ArcGIS 9.2 was used to make this comparison, resulting in a pixel value of one if the 1% depth was deeper than the seabed, or otherwise 0.

2.6 EUNIS classifications and habitat map

Each sampling station was assigned to a level 5 EUNIS classification, where possible, based on its habitat characteristics and dominant species. EUNIS classes at level 4 were assigned based on available physical data, i.e. sediment type, light climate from satellite data and relation to wave base as modelled for UKSeaMap (Connor *et al*, 2006). A habitat map was finally constructed based on all available information, i.e. mapped surface sediments and bedforms from acoustic and PSA data, modelled biological zones from light climate and wave base and EUNIS assignments from sampling stations as mentioned above.

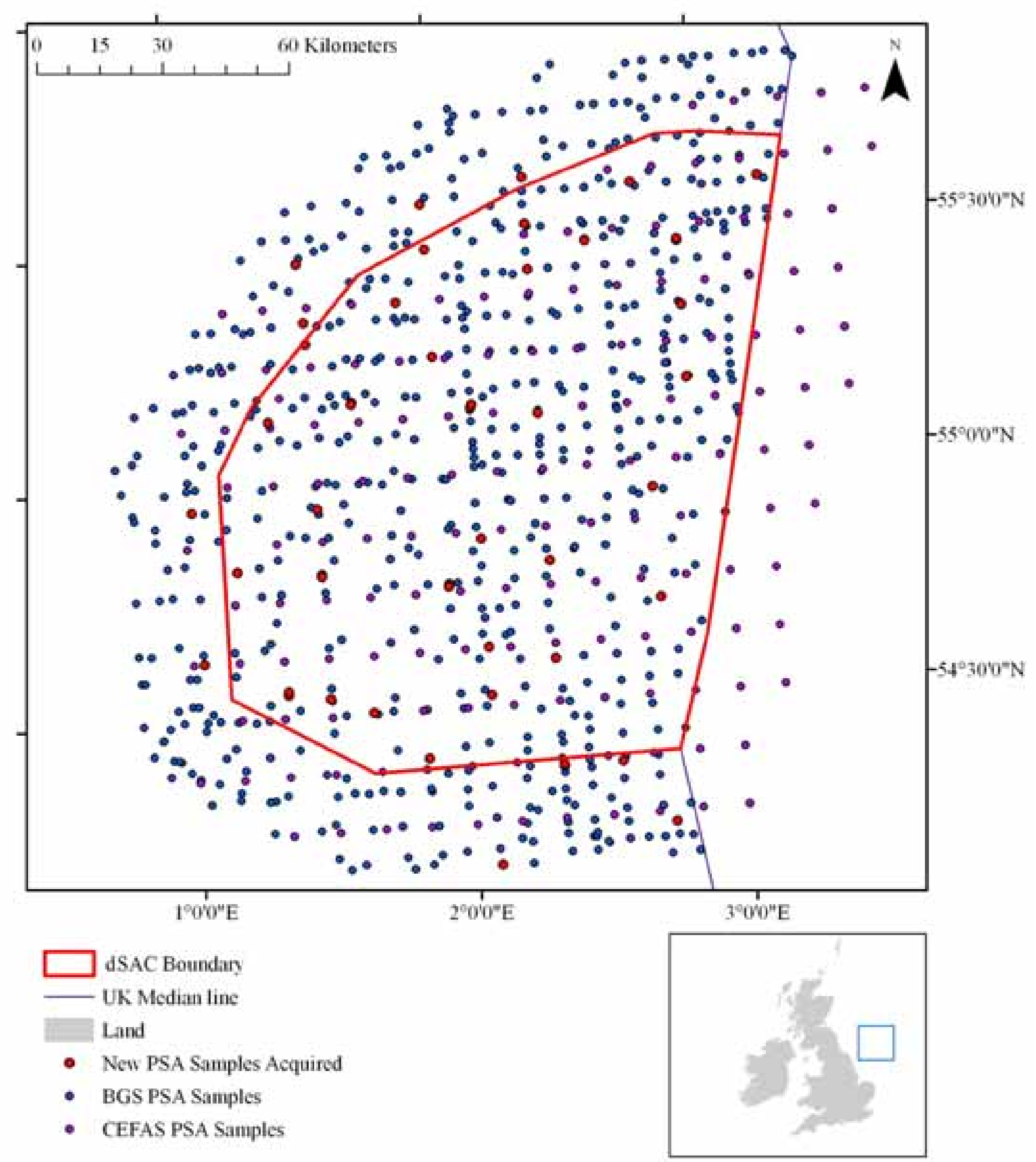

Figure 3.4. Positions of the stations sampled for PSA.

2.7 Quality control

2.7.1 Positioning

The primary system utilised for the survey was the Fugro Seastar Network. This system calculates a virtual base station for the vessel location and does not use differential corrections from actual base stations. The GPS mask angle was 5°. All steering nodes (offsets) were defined for the vessel's central reference point (CRP) (Table 3.1).

Table 3.1. Gear types and their associated steering node.

Gear	Steering node used
Sidescan sonar	Stern gantry. Cable counter on winch. Layback applied during acquisition.
MBES	Drop keel reference point. Correction applied in real-time by acquisition software.
AGDS	Hull mounted transducer reference point. Correction applied post acquisition.
Towed video and stills	Stern gantry. Cable counter on winch. Layback applied post acquisition.
Grab	Side gantry. Position logged during acquisition using the commercial hydrographic survey package Tower.

2.7.2 Bathymetry

The multibeam heads and sound velocity meter were mounted on a retractable blade which reduced noise caused by bubble blowdown and wave blanking around the hull's immediate interface with the water. The blade places the heads approximately 9 m down, or 3.2 m below the hull of the vessel. This also has the advantage of removing the top 9 m of sound velocity. Sound velocity at the heads was measured using a Reson sound velocity meter. Measurements are filtered over a 60 second period and applied in real-time in the Kongsberg SIS multibeam acquisition software. Realtime sound velocity measurements ensure appropriate corrections are applied for beam-forming at the multibeam heads. The blade is lowered fully to the fixed depth as surveyed, and fixed at calibration check time during the voyage. Additional CTD casts for sound velocity profiles were also carried out upon arrival and at intervals during the survey.

Vessel draft was measured by Druck PTX 1830 Depth/Level sensor (SN2069034) located in the blade space. The sensor, which resolves draft to millimetres, was connected via a 4-20 mA current loop to the shipboard logging system and was logged with navigation and parametric data in the general log file. It is also displayed in real-time on the logging displays as waterline level (distance between MRU and waterline as defined by Kongsberg's SIS multibeam acquisition package). Readings are made when the vessel is stationary in the water to eliminate any offsets introduced through water suckdown within the blade space whilst underway. The vessel draft was applied in the Kongsberg SIS acquisition software at the start of the survey. Where appropriate, the change in vessel draft over time was applied as a “delta draft” during multibeam post processing in Caris HIPS.

The Kongsberg EM3000D swathe bathymetry system was used to collect multibeam echo sounder data. A patch test was carried out during the mobilisation transit to verify calibration values previously determined for the system. QC of data was carried out during and following acquisition. Surveyors monitored all real-time data closely and notes were made regarding features of interest for subsequent review. Processing was started almost immediately after a line was complete as the bathymetric data were required to inform the fine-scale acquisition and ground-truthing programmes.

2.7.3 Sidescan sonar

The sidescan sonar data were collected using a Benthos SIS 1624 system. Data were stored digitally. All real-time data were monitored by surveyors and notes made in the sidescan sonar log regarding data quality and features of interest for subsequent review.

QC of data was carried out during and post acquisition. Processing of sidescan sonar data was also carried out almost immediately in order that the data could inform the design of subsequent fine-scale surveys and ground-truthing. Sidescan sonar data were reviewed at regular intervals with respect to quality, resolution and spatial coverage to ensure that the acquisition programme would provide adequate data to meet the objectives of the survey.

2.7.4 Seabed video and stills

The video and stills overlay included position, date, time, station number, station code and survey code. Real time video footage was monitored for quality and footage recorded simultaneously to HDD and miniDV. Real-time logs were kept for all video deployments and real-time notes were also made pertaining to substrate type and conspicuous biota. Stills were taken every 30 seconds and stored on the cameras internal memory. These were downloaded onto HDD and DVD.

2.7.5 Grab sampling

A maximum of three attempts were made at each station to achieve a sample of 5 l or more. Where it was not possible to obtain a sample of 5 l, due to the compact nature of the sediment, the sample of greatest volume was retained. Conspicuous fauna were noted from any grab samples that were rejected. Logs were kept for all grab samples including notes on sample quality and volume along with sediment type.

2.7.6 Trawling

Logs were kept for all trawl stations and these included positional information, sample volume and details of fauna present. Trawls were repeated where it was suspected that the net had not fished effectively. The trawls were towed for a nominal distance of 200 m. On retrieval of the beam trawl, sample volume was measured and the sample was washed over a 5mm sieve. All specimens were identified down to the lowest possible taxonomic level, usually species, and enumerated with the exception of colonial taxa, which were recorded on a presence/absence basis.

2.7.7 Metadata

All survey activities were recorded on Cefas' bespoke metadata database DigiLog.

For each acoustic survey line a number of fields were recorded as shown below:

- Cruise code
- Operator
- System
- Operating frequency
- Survey area
- Project name
- Line name or code
- Start and end date/time
- Start and end position
- Filename
- Swathe width (sidescan only)
- Towed gear positioning (sidescan only)
- Vessel draft (multibeam only)
- Sound velocity profile (multibeam only)

For each ground-truthing station a number of fields were recorded as shown below:

- Cruise code
- Operator
- Survey area
- Station number
- Station code
- Gear type
- Water depth
- Position (single point for grabs; start and end for towed gear)
- Cable out (for towed gear only)
- Sample volume (Hamon grabs and beam trawls only)
- Storage container volume and location (Hamon grabs only)
- Faunal and habitat notes (camera sledge only)

3 Results

3.1 Sub-surface geology

3.1.1 BGS Seismic Survey Database

A total of eight seismic surveys conducted between 1978 and 1994 fall within the proposed Dogger Bank dSAC boundary (Figure 4.1). Approximately 11,200 line kilometres of seismic data exist for the proposed dSAC and its surrounding area, comprising pinger, sparker and boomer data. The typical distance between these seismic lines is between 7 and 20 km, providing a regional framework. These data were interpreted for this study to examine the sub-surface geological formations associated with the Dogger Bank bathymetric feature.

Seismic Characteristics and Relationships

The Lower-Middle Pleistocene age Yarmouth Roads Formation (see Section 2.2.1) is the oldest formation identified in the BGS shallow seismic dataset and comprises inter-bedded clays and sands with scattered pebbles (Cameron *et al,* 1992). This formation is characterised by discontinuous horizontal reflectors, which reflect depositional surfaces related to changes in sea level within this delta-top formation (Figure 4.2). The Yarmouth Roads Formation forms a deposit of more than 100 m in thickness in the area of the Dogger Bank proposed dSAC, thinning to the west of the study area, although the base of the formation is beyond the maximum penetration of the sparker dataset and has therefore not been mapped during the course of this study. Although the boundary between this formation and the overlying formations is clear on the flanks of the Dogger Bank, directly underneath the Dogger Bank the Yarmouth Roads Formation becomes undistinguishable from the overlying formations (Cameron *et al,* 1992).

The Swarte Bank Formation is the first record of ice in the southern North Sea (Cameron *et al,* 1992) during the Elsterian glaciation. The formation forms a series of valleys incised into the Pleistocene deltaic and older lithologies formed through erosion by glacial meltwaters. The formation comprises diamictons with intermittent fluvial sands (Cameron *et al,* 1992).

In seismic records the Swarte Bank Formation is identified as infilled palaeovalleys, which are difficult to trace from seismic line to seismic line due to the anatomising character of the palaeovalleys. Internal reflectors of the infilling sediments can be well developed due to the presence of clays as can be seen in line 1983/3-18 (Figure 4.2), but evidence of multi-phase infill is elusive.

The Dogger Bank Formation forms the core of the bathymetric feature of the same name (Figures 4.2 and 4.3). The Dogger Bank Formation overlies the thin Egmond Ground and Cleaver Bank formations, which are not always acoustically distinguishable from the underlying Yarmouth Roads Formation and overlying Dogger Bank Formation. The two formations, which combined are 10 m in thickness, form a discontinuous seismic reflector represented by a dashed line at the top of the Yarmouth Roads Formation in seismic line 1983/3-18 in Figure 4.2. The younger of the two formations, the Cleaver Bank Formation, comprises pro-glacial clay whilst the Egmond Ground Formation comprises silty sand with clay laminae (Cameron *et al,* 1992; Gatliff *et al,* 1994). Where these two formations have suffered erosion the overlying Dogger Bank Formation is directly underlain by the Yarmouth Roads Formation.

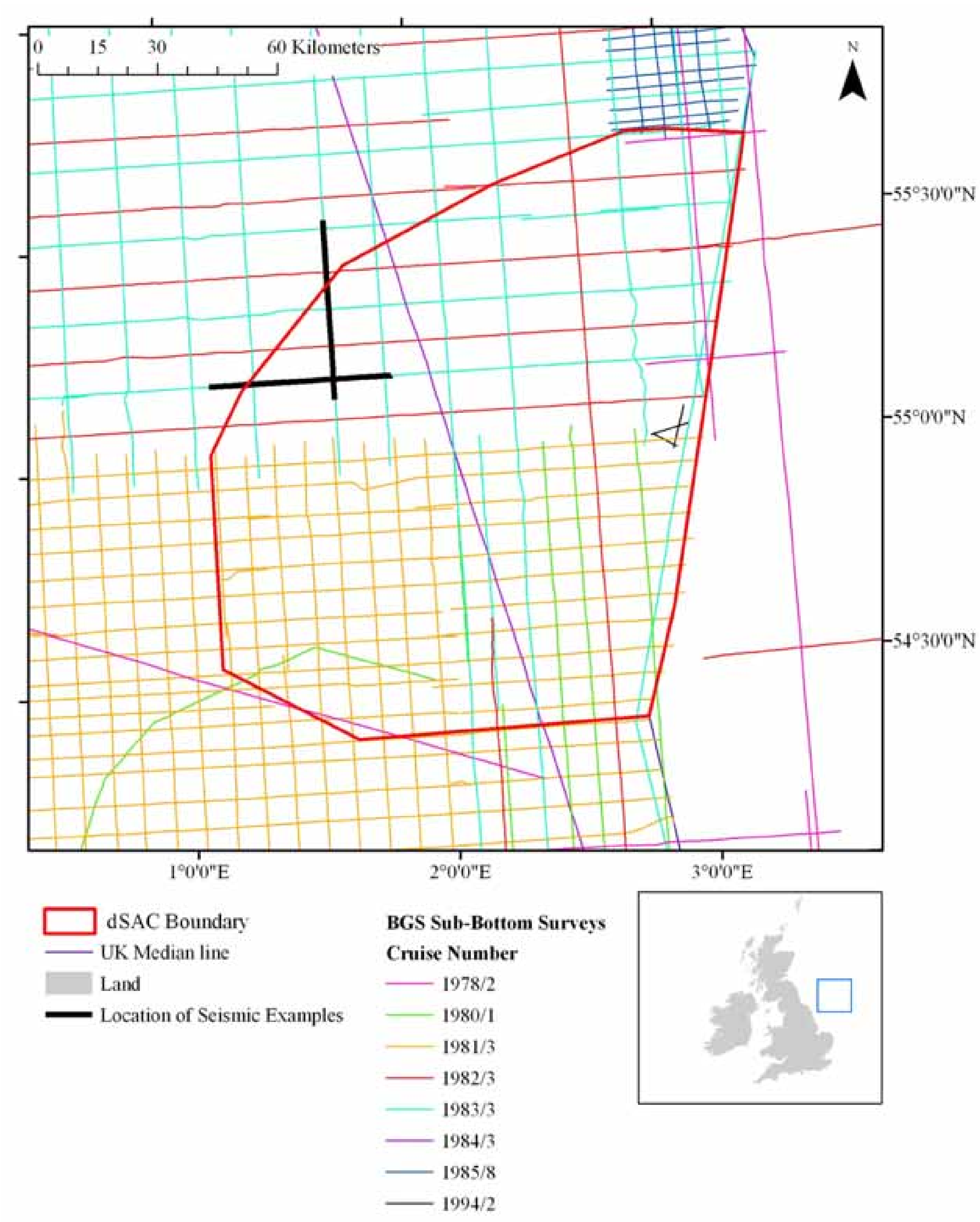

Figure 4.1. BGS seismic survey database over the proposed Dogger Bank dSAC.

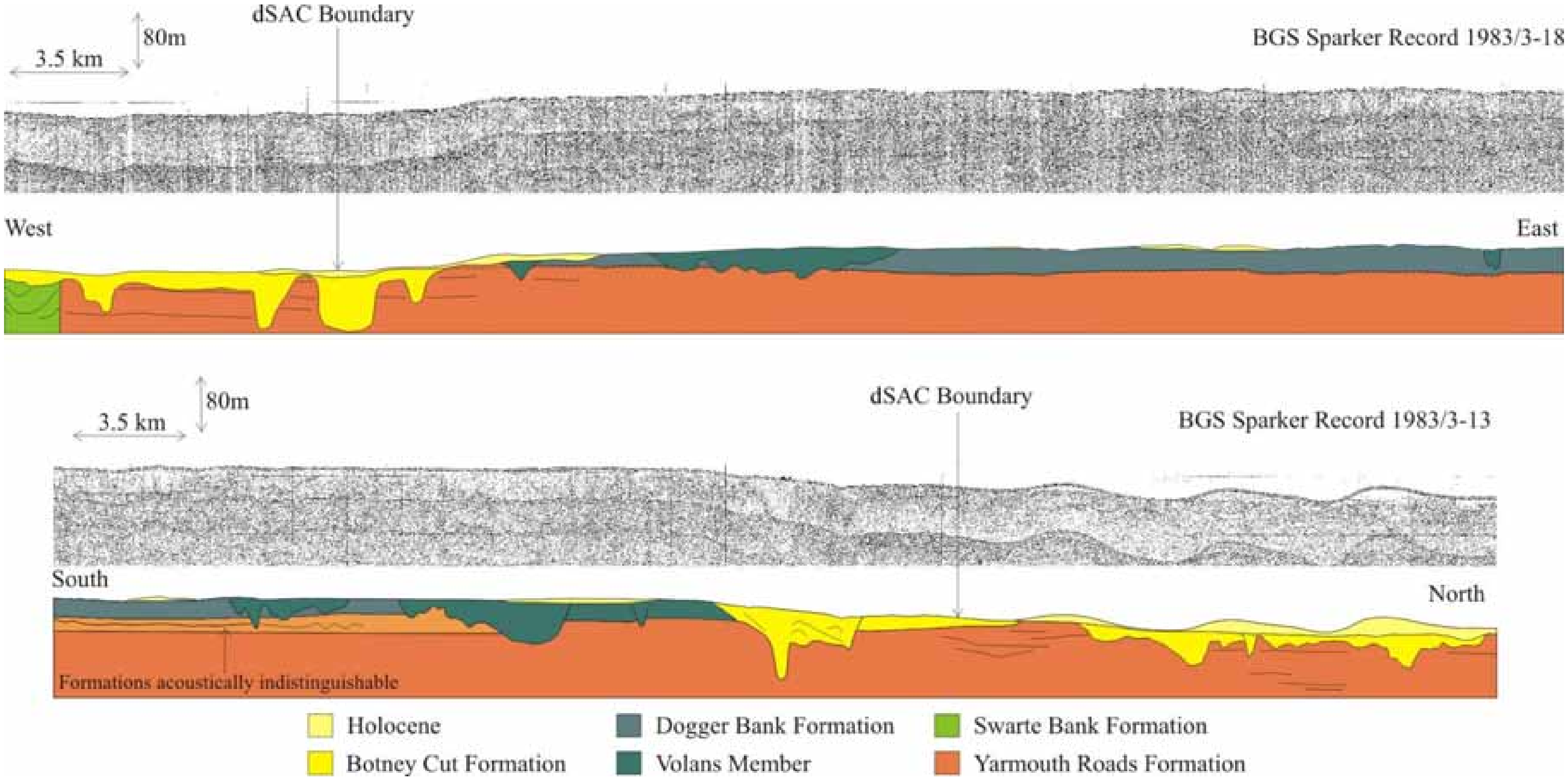

Figure 4.2. Example seismic lines with interpretation. The dashed line near the top of the Yarmouth Roads Formation indicates the Cleaver Bank and Egmond Ground Formations, which are rarely acoustically distinguishable from the overlying and underlying formations. For location of sections see Figure 4.1.

The Dogger Bank Formation is an acoustically distinguishable unit. This Late Weichselian proglacial deposit has a strong reflector at its base and although continuous horizontal reflectors are not common, there is an ordered appearance to the seismic package, which distinguishes it from the underlying Yarmouth Roads Formation and the incised Botney Cut Formation, which surrounds the Dogger Bank (Figure 4.2). The appearance of the Dogger Bank Formation on seismic records is related to the lithological properties of the formation, clay-rich diamictons with pebbles and occasional sands represent deposition in a pro-glacial lake.

The Dogger Bank Formation is 35–40 m in thickness in the shallowest section of the bank, thinning rapidly to the south where there is an abrupt change in slope (see Figures 4.3 and 4.4), which marks the edge of the bank. The Dogger Bank Formation becomes gradually thinner to the north, its limit marks the limit of ice during Weichselian times which surrounded Dogger Bank to the north and west. However, the northern extent of the Dogger Bank Formation is marked by a number of incised channels which form the Volans Member of the formation. Locally the Volans Member can be up to 60 m in thickness and is lithologically identical to the Dogger Bank Formation (Cameron *et al,* 1992).

Surrounding the Dogger Bank Formation to the north, south and west is the Botney Cut Formation. This formation forms a series of infilled palaeovalleys up to 200 m in depth incised into Weichselian and older deposits (Figure 4.2). These channels formed sub-glacially and are acoustically structureless which makes them easily identified as the channels cut in the horizontal reflectors of the Yarmouth Roads Formation. This formation is usually only distinguishable from the similarly incised Swarte Bank Formation via sample evidence. Therefore it is possible that some channels interpreted as belonging to the Botney Cut Formation may in fact comprise the Swarte Bank Formation.

The youngest sediments interpreted within the proposed Dogger Bank dSAC are those of Holocene age appearing as an acoustically transparent layer up to 16 m in thickness (Figure 4.2). The Holocene sediments were formed by the redistribution of sand deposited during glacial periods in the Pleistocene by tidal and storm currents. The Holocene deposits also comprise gravels, which are exposed at seabed in the shallowest areas of the Dogger Bank (see Section 4.3).

In summary, the Dogger Bank Formation and its Volans Member form the core of the Dogger Bank. The formation is not found anywhere else in the North Sea apart from the Dogger Bank. The Dogger Bank comprises Weichselian deposits that are overlain by Holocene sands and recent sand waves (Cameron *et al,* 1992). It commonly overlies the Cleaver Bank, Egmond Ground and Yarmouth Roads formations although it is not always acoustically distinguishable from these underlying deposits.

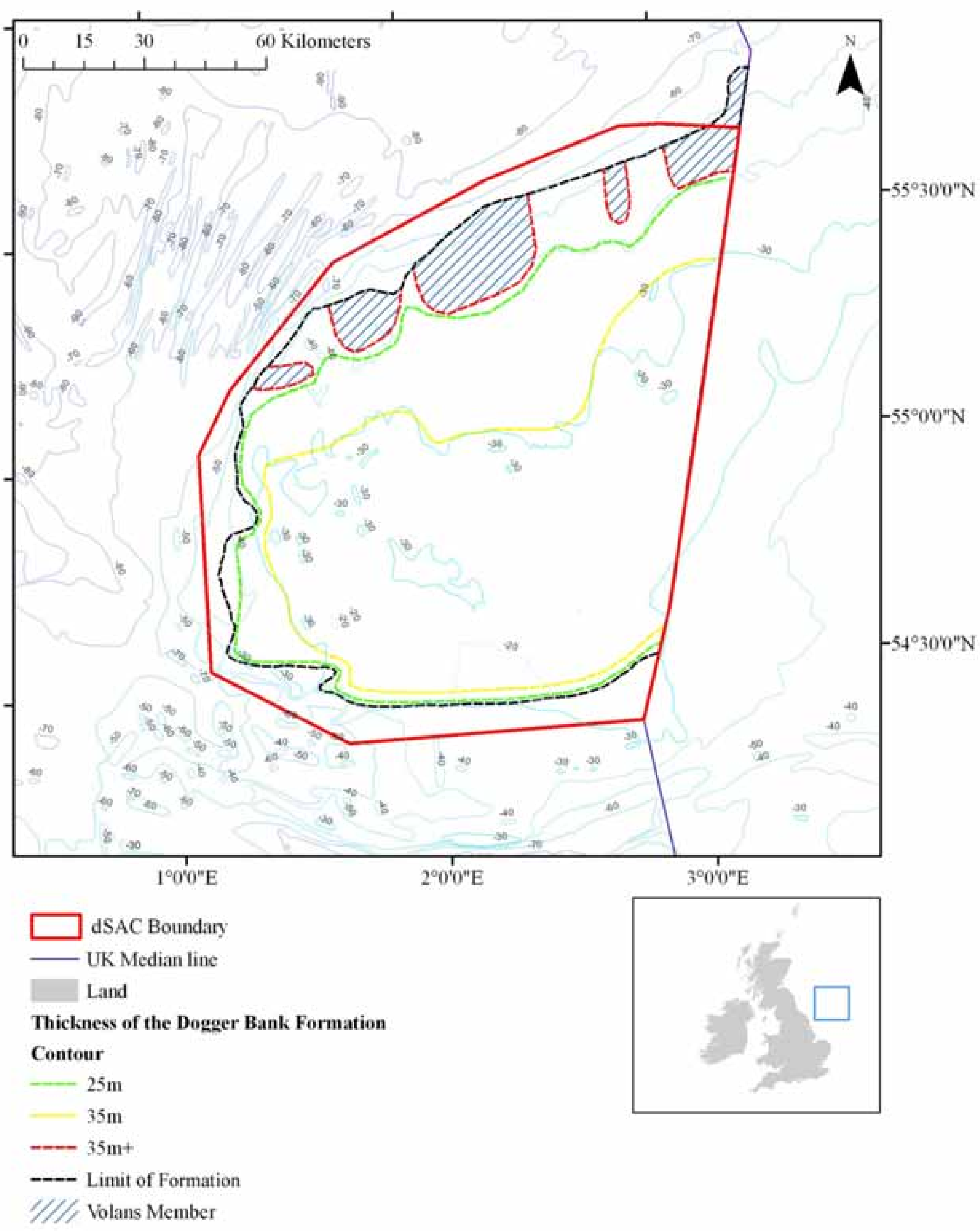

Figure 4.3. Extent and generalised thickness of the Dogger Bank Formation.

3.2 Bathymetry and slope

Water depths on the Dogger Bank range between 15 m and 70 m, with the shallowest areas situated in the south and southeast of the bank. Slopes are steepest in the south with values up to roughly 5° based on multibeam echosounder data (Figure 4.4). To the North, the Dogger Bank is gently sloping with maximum values on the order of 0.1°. The centre of the

Dogger Bank forms an essentially flat surface, which is slightly sloping towards the northwest. The Dogger Bank Formation largely controls the shape of the Dogger Bank, as the thickness of Holocene deposits is rather low (<5 m) over large parts of the bank. Only in the south are thicknesses in excess of 5 m encountered, contributing to the shallowness of this part of the bank and the relative steepness of its slopes.

Slope analysis was performed using previously available and newly collected bathymetric data to delineate the Dogger Bank. The slope boundary was considered to lie at the foot of slopes in excess of 0.1° in line with the procedure detailed by Klein (2006). This yielded a robust boundary except in the northwest, where slopes are consistently below 0.1°. A more detailed account of this procedure can be found in Appendix 1.

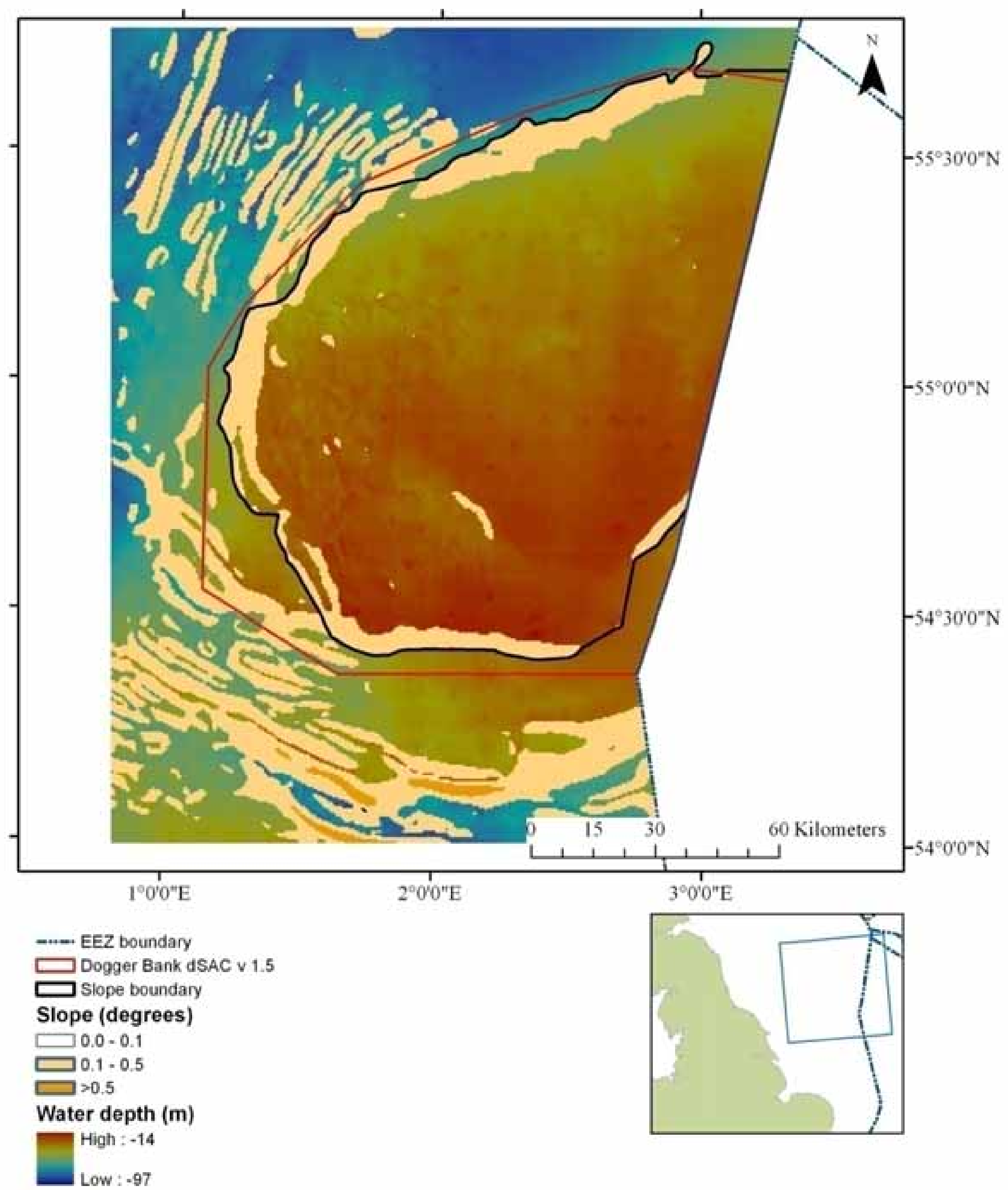

Figure 4.4. Results of the slope analysis and derived slope boundary.

3.3 Surface sediments

The seabed sediments of the Dogger Bank study area comprise a mobile veneer of terrigenous, and a smaller proportion of biogenic, sediments overlying Holocene and Pleistocene deposits. The terrigenous element of the seabed sediments on Dogger Bank is derived from underlying Pleistocene deposits, which are glacigenic in origin comprising clasts derived from the UK landmass (Cameron *et al,* 1992; Gatliff *et al,* 1994). The smaller component of biogenic gravel has been derived locally since the Dogger Bank became fully submerged around 7500 yrs ago. The seabed sediments are generally less than 1 m in thickness over the Dogger Bank, but attain significant thickness on the flanks of the bank passing down into the underlying deposits without much lithological variation. The Dogger Bank area is subjected to both tidal and storm-induced currents, with the ability to mobilise sediment up to gravel grade probably only taking place during storm events (Gatliff *et al,* 1994).

Gravelly sediment classified as gravel, sandy gravel, gravelly sand, gravelly muddy sand and muddy sandy gravel (Folk, 1954) covers approximately 20% of the area within the Dogger Bank proposed dSAC boundary (Figure 4.5). Gravelly sand forms most of this facies with locally developed patches of sandy gravel and gravel occurring in slight topographic depressions on the shallowest sections of the bank usually in water depths of less than 40 m. The gravel is dominantly composed of lithic clasts derived from the erosion of the underlying Dogger Bank Formation. Study of these clasts reveals sources in northern England and Scotland (Carr, 1999). A smaller proportion of locally formed biogenic gravel, mainly shell debris and tests, are also present. The biogenic component is Holocene in age forming in the last 7500 yrs since the Dogger Bank became fully submerged. Areas of gravelly sediment are characterised by gravel waves and coarse-grained sediment waves and are typically found on the Dogger Bank in areas with the shallowest water depths (Figure 4.6).

Sandy sediment, classified as slightly gravelly sand and sand (Folk, 1954), dominates the Dogger Bank covering approximately 80% of the seabed. This facies forms mobile sand streaks, which comprise a thin veneer actively being transported across the seabed, with mobile sand ripples and small sand waves forming where the seabed sediment is thicker. Typical ripple wavelengths are between 10 and 15 cm within the study area. Examination of the sidescan sonar and multibeam data indicate that areas of sandy sediment are not always characterised by sand ripples and waves; the mobile veneer of sand can appear devoid of significant bedforms (Figure 4.6). The boundary between featureless seabed and seabed displaying indicators of sediment transport roughly coincides with the location of the wave base (Figure 11 in Connor *et al,* 2006). Where only a veneer of sandy sediment is present the underlying Pleistocene deposits are intermittently exposed as the veneer moves over its surface. The exposed Pleistocene deposits, the Dogger Bank Formation, have been observed on camera sledge sites or recovered in Hamon Grab samples as clay-rich diamicton with frequent pebbles.

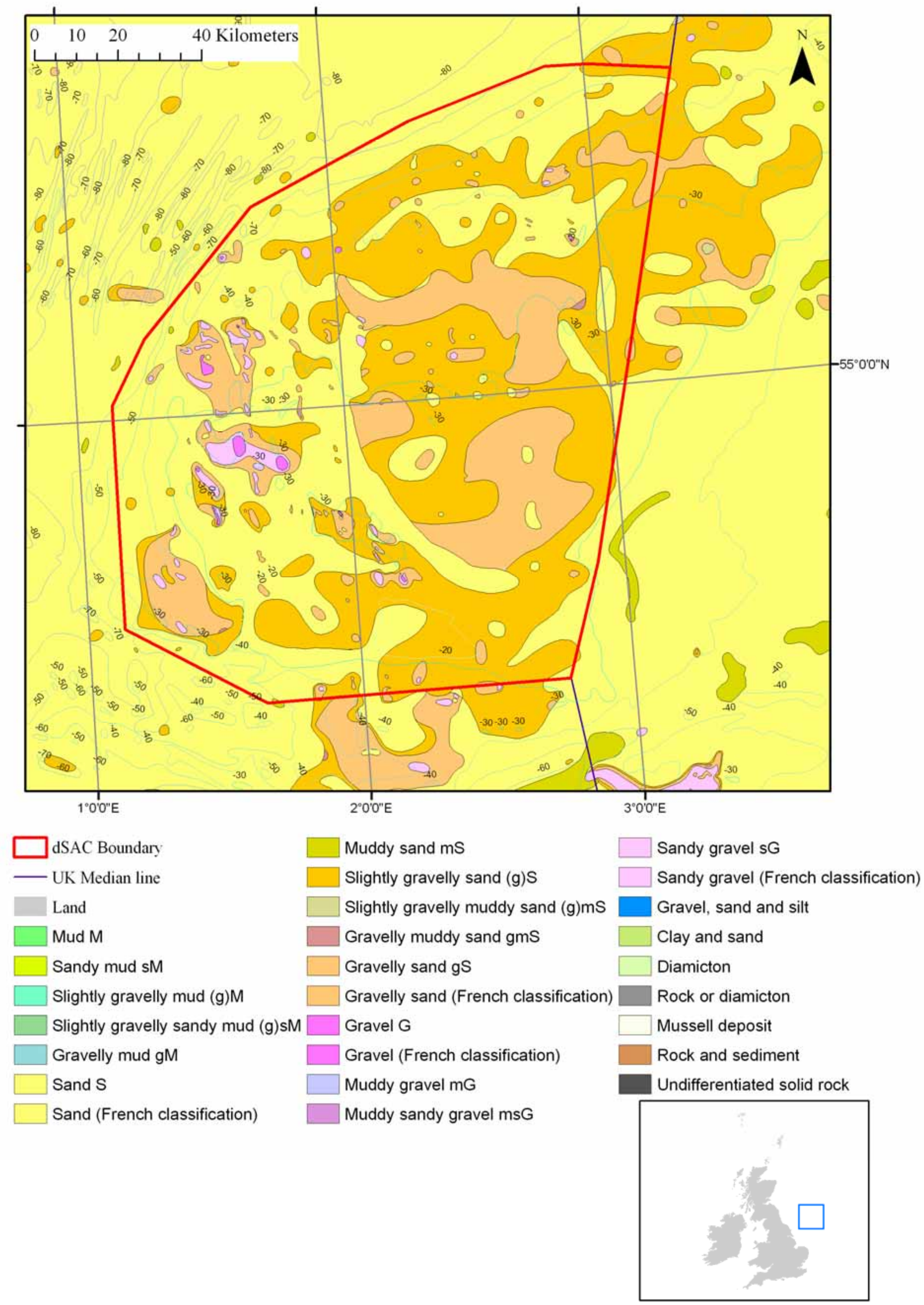

Figure 4.5. Revised seabed sediment distribution based on all PSA data available. The bathymetric contours are derived from BGS DigBath250k. (©BGS, licence no. 2009/037 DB)

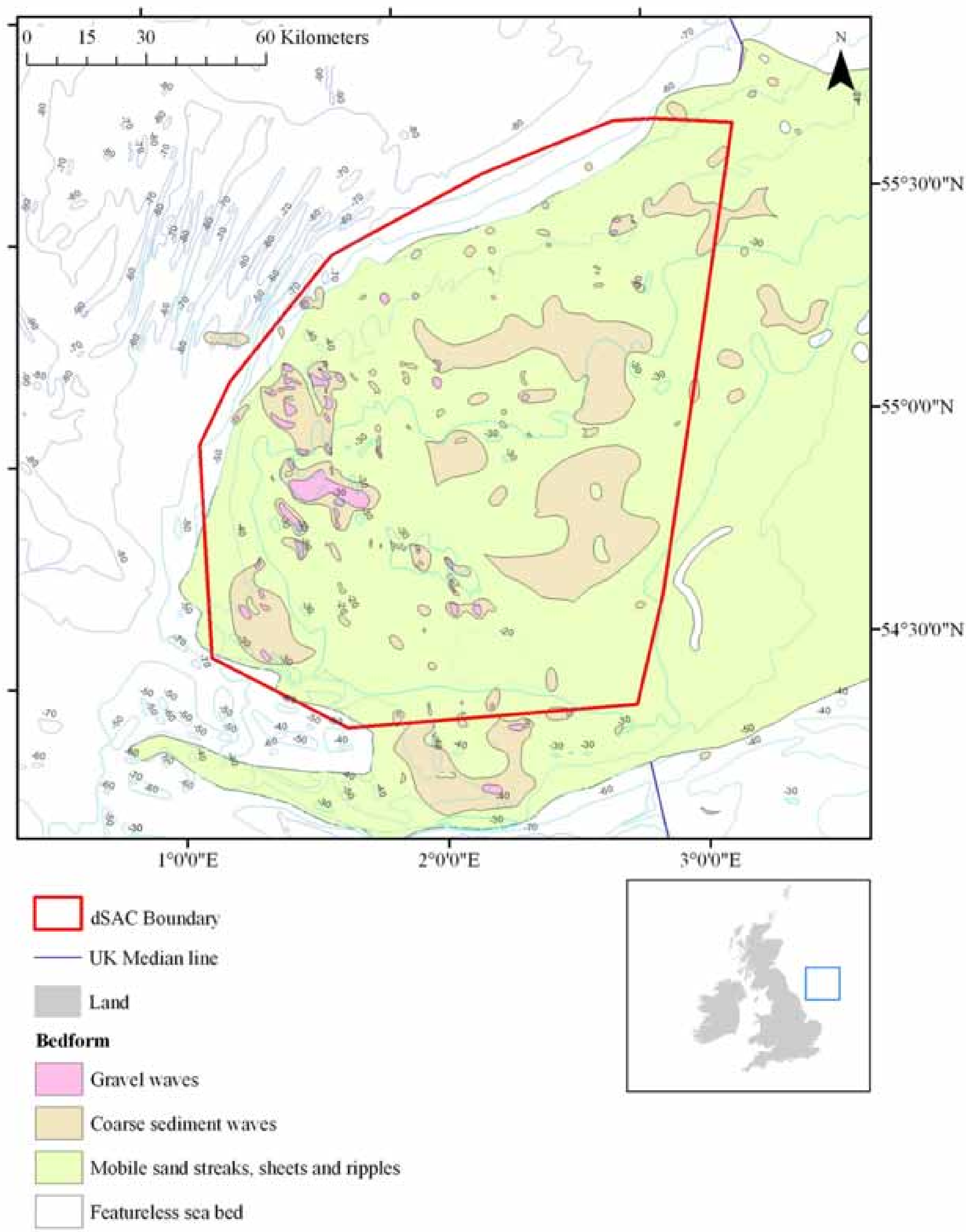

Figure 4.6. Interpreted distribution of bedforms within the Dogger Bank dSAC area.

There is a complicated relationship between the sandy and gravelly seabed sediments not previously revealed by the original distribution map (Figure 2.3). The sidescan sonar and multibeam data acquired during the course of this study indicate that the occurrence of gravelly sediment is patchy, usually associated with slight topographic depressions on the seabed. This is reflected in the new seabed sediment distribution map for the area, which shows many more smaller, isolated areas of coarse grained sediment separated from each other by sandier areas than previously thought (Figure 4.5). These small-scale, often elongated patches of gravel waves and coarse-grained sediment waves are ubiquitous on continental shelves worldwide (see Coco *et al*, 2007 for a review) and have been termed sorted bedforms (Murray and Thieler, 2004). Murray and Thieler (2004) suggested that storm wave motions interacting with large wave-ripples present on coarse-grained substrate generate near-bed turbulence that is greatly enhanced relative to that in fine sediment domains. This turbulence enhances entrainment and inhibits settling of fine material in an area dominated by coarse sediment. Thus, a feedback tending to produce accumulations of fine material separated by patches of coarse sediments is created. Murray and Thieler (2004) predicted spatial stability of sorted bedform patterns and Diesing *et al* (2006) showed that the sorted bedforms they investigated on the North Sea continental shelf did not significantly alter shape and location over a period of 26 years.

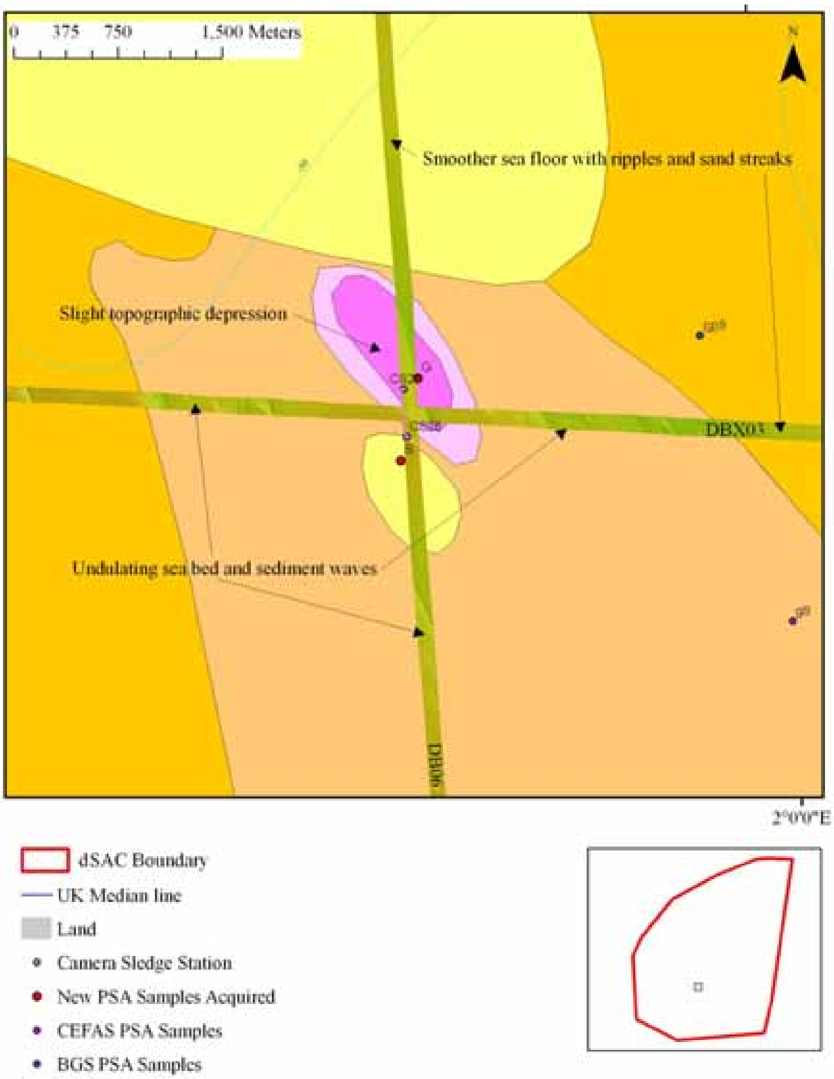

Figure 4.7. Example of the relationship between areas of gravelly sediment and areas of sandy sediment. PSA samples are indicated along with a camera sledge site and the interpreted distribution of seabed sediments (see Figure 4.5 for the seabed sediments legend). The bathymetric contours are derived from BGS DigBath250k. (©BGS, licence no. 2009/037 DB)

Figure 4.7 shows the relationship between gravelly and sandy sediment typical of that observed throughout the Dogger Bank dataset. The area of gravel is contained within a discreet topographic depression constituting a sorted bedform. The surrounding sandy gravel and gravelly sand area comprises topographically undulating seabed with sediment ripples visible on both the multibeam and sidescan sonar data. The camera sledge station CS28 verifies this observation. Combined with the change from sandy sediment into gravelly sand, the presence of sediment waves and ripples remains constant throughout station CS28. As the sediment becomes sand dominated it is interpreted from the data available that this coincides with a more uniform sea floor surface with no undulations. It is assumed that the areas of uniform sea floor comprise sand streaks and ripples, which have not been resolved by the multibeam and sidescan sonar data.

Muddy sediment, of which only muddy sand occurs in the vicinity of Dogger Bank, is almost entirely absent within the boundary and only sporadic occurrences of this grade of sediment occurs below the 50 m depth contour. The occurrence of muddy sand is limited to small patches to the east of the UK median line, the Outer Silver Pit and in the gradually increasing water depths to the north of Dogger Bank.

PSA data from the 51 samples gathered during this study have been employed to derive EUNIS level 3 classes as outlined in Connor *et al* (2006) and Long (2006). This yielded three different classes with ‘sand and muddy sand’ being most abundant (31 samples), while 17 samples were classed as ‘coarse sediment’ and the remainder (three samples) as ‘mixed sediment’. These classed stations were compared against visually assessed backscatter classes (high and low). Twenty-seven stations, classed as sand and muddy sand, were associated with low backscatter (as was expected) while one showed high backscatter and three did not have associated backscatter data available (Table 4.1). A less clear-cut correlation was however found for coarse sediment, which correlated with high backscatter (as expected) in 10 instances and low backscatter (unexpectedly) in seven occasions.

Table 4.1. EUNIS level 3 sediment classes, EntropyMax groups and visually assessed backscatter classes from sampling stations.

Station Code	EUNIS level 3 class	EntropyMax group	Backscatter class
G1	coarse sediment	fine sand	low
G2A	sand and muddy sand	coarse sediment	high
G2B	sand and muddy sand	fine sand	low
G3A	sand and muddy sand	fine sand	low
G3B	coarse sediment	coarse sediment	high
G4A	sand and muddy sand	fine sand	low
G4B	mixed sediment	coarse sediment	high
G5	mixed sediment	fine sand	low
G6	coarse sediment	fine sand	low
G8	coarse sediment	fine sand	low
G9	sand and muddy sand	fine sand	low
G10	sand and muddy sand	fine sand	low
G11A	coarse sediment	fine sand	low
G11B	sand and muddy sand	fine sand	low
G12	coarse sediment	fine sand	low
G15	sand and muddy sand	fine sand	low
G16	sand and muddy sand	fine sand	low
G17A	sand and muddy sand	fine sand	low
G17B	coarse sediment	coarse sediment	high
G18	sand and muddy sand	fine sand	low
G19A	coarse sediment	coarse sediment	high
G19B	sand and muddy sand	fine sand	low
G23	sand and muddy sand	fine sand	low
G24	sand and muddy sand	fine sand	low
G25	coarse sediment	coarse sediment	high
G26	sand and muddy sand	fine sand	low
G27A	sand and muddy sand	fine sand	low
G27B	coarse sediment	coarse sediment	high
G28A	coarse sediment	coarse sediment	high
G28B	sand and muddy sand	fine sand	low
G31A	coarse sediment	coarse sediment	low
G31B	coarse sediment	coarse sediment	high
G32	mixed sediment	coarse sediment	high
G33	sand and muddy sand	fine sand	low
G34	coarse sediment	coarse sediment	high
G35	sand and muddy sand	fine sand	-
G36	sand and muddy sand	fine sand	low
G37	coarse sediment	coarse sediment	high
G38A	sand and muddy sand	fine sand	low
G38B	coarse sediment	coarse sediment	high
G39	sand and muddy sand	fine sand	low
G40	sand and muddy sand	fine sand	low
G42	coarse sediment	fine sand	low
G43	sand and muddy sand	fine sand	low
G44	sand and muddy sand	fine sand	low
G45	sand and muddy sand	fine sand	-
G46	sand and muddy sand	fine sand	-
G47	sand and muddy sand	fine sand	low
G48	sand and muddy sand	fine sand	low
G50	sand and muddy sand	fine sand	low
G51	sand and muddy sand	fine sand	low

We therefore tried an additional approach to classify the seabed sediments using the software EntropyMax. This yielded an optimum classification with two classes, which were labelled ‘fine sand’ and ‘coarse sediment’ based on their sedimentological characteristics (Table 4.1 and Figure 4.8).

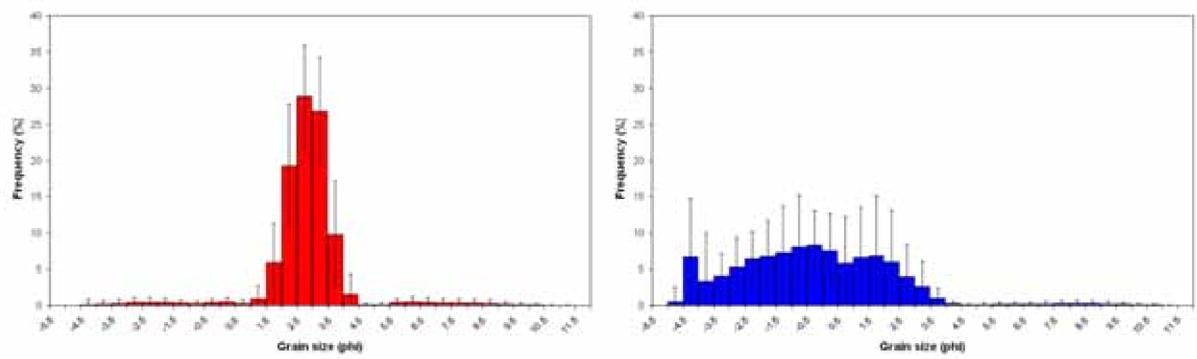

Figure 4.8. Average grain-size distributions and standard deviations (error bars) of fine sand (left) and coarse sediment (right) based on results from EntropyMax.

A comparison with visually assessed backscatter classes gave a near perfect match with fine sand linked to low backscatter and coarse sediment linked to high backscatter, the only exception being station G31A classed as coarse sediment but revealing low backscatter (Table 4.1). EntropyMax classes were subsequently plotted in a Folk triangle showing the four EUNIS classes (Figure 4.9). In general, there is a good correspondence between the two classifications, i.e. EntropyMax coarse sediments predominantly plot in the EUNIS coarse sediment field and EntropyMax fine sands tend to plot in the EUNIS sand and muddy sand field. However, six samples classed as EntropyMax fine sand plot in the EUNIS coarse sediment field and one EntropyMax coarse sediment plots in the EUNIS sand and muddy sand field. These are exactly the same stations, which did not match when comparing EUNIS classes against backscatter.

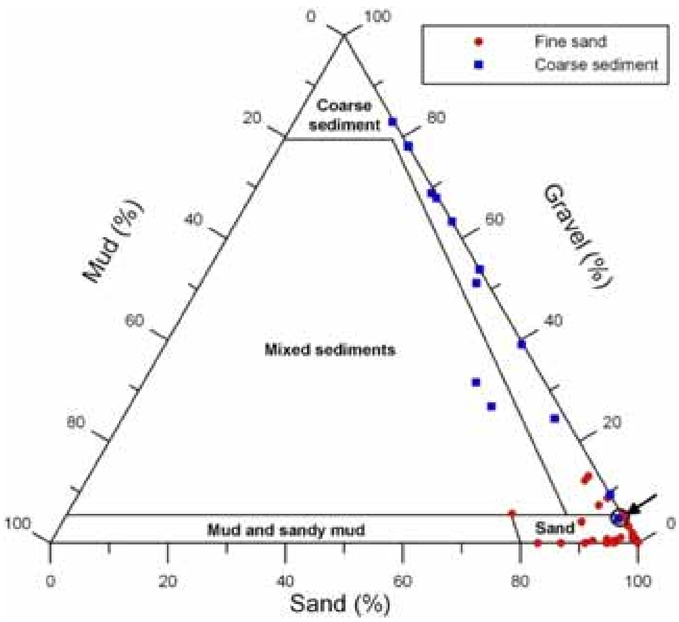

Figure 4.9. EntropyMax derived groups plotted in a Folk triangle showing EUNIS level 3 sediment classes. Arrow indicates samples shown in Figure 4.10.

Interestingly, there are some samples, which belong to different EntropyMax groups although their mud:sand:gravel-ratios are almost identical, thus plotting close to each other in the Folk triangle. However, this does not point to a weakness in the EntropyMax grouping; rather the opposite holds true. This is illustrated in Figure 4.10, which shows the grain-size distributions of two samples indicated by an arrow in Figure 4.9. Although the two samples have almost identical mud-, sand- and gravel contents (roughly 95% sand and 5% gravel), sample G2A displays a markedly different grain-size distribution with a coarser maximum around 0.5 ϕ (710 µm) compared to 2.5 ϕ (180 µm) for sample G6. Based on their mud:sand:gravel-ratios, the two samples fall into the same EUNIS class, but based on the shape of their grain-size distributions EntropyMax groups the samples into two different classes. It is apparent that the backscatter characteristics are also significantly different for the two stations, with high backscatter at station G2A and low backscatter at station G6. It follows from these results that classification into two different sediment groups (rather than lumping them together into one group) better reflects the nature of the seabed sediments in this area.

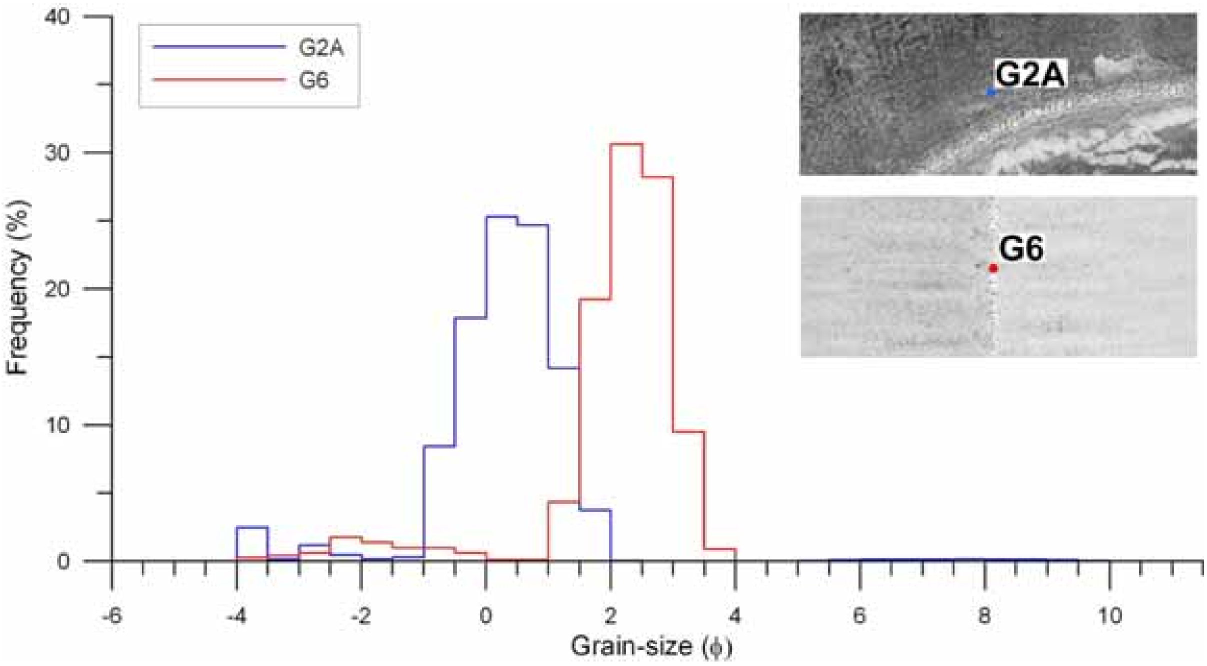

Figure 4.10. Grain-size distributions of two samples having nearly identical mud:sand:gravel-ratios, however displaying different distribution curves. Insets show sidescan backscatter at sampling sites. Size of the boxes is 260 m x 100 m.

We have chosen to use the EntropyMax methodology for further habitat categorisation employing the EUNIS classification for the following reasons:

(a) The EntropyMax groups better align with visually assessed backscatter data. This is of great importance as the actual mapping of habitats heavily relies on interpretation of backscatter imagery.
(b) There is a good correspondence between the two different classifications namely EntropyMax and EUNIS. Differences in categorisation are mostly found around the boundary between coarse sediment and sand.
(c) The definition of the boundary between coarse sediment and sand at 5% gravel is based on the assumption that it is ecologically significant rephrase for clarity.

However, the significance of this boundary has not yet been fully validated (*pers. comm.,* Neil Golding, JNCC).

3.4 Epifauna

The sediment records obtained from the video footage and stills images were visually assigned to one of the classes detailed in Table 4.2, which are based on the terminology used in Marine Recorder.

Table 4.2. List of the sediment categories used to characterise the sediment composition from estimates of percentage cover using video footage.

Sediment Category	Sediment Category
Coarse sand	Sandy pebble and gravel
Fine sand	Shelly sand
Gravel and Clay	Shelly sand and clay
Gravelly sand	Slightly gravelly sand
Gravelly sand and clay	Slightly pebbly sand
Medium sand	Slightly muddy sand
Muddy sand	Slightly shelly muddy sand
Pebble and sand	Very slightly shelly fine sand
Sandy gravel	Very slightly shelly medium sand
Sandy mud	Very slightly shelly muddy sand
Sandy pebble	

The species abundance data were explored subjectively at first, singling out species that were likely to be important for the classification of records into biotope types. It was apparent that some species were abundant and frequently recorded for their habitat type and perhaps of limited value for habitat differentiation because of that. For example, for soft sediment habitats, the sea potato *Echinocardium cordatum* and the masked crab *Corystes cassivelaunus* were very commonly recorded. Other species were less abundant or frequent, but probably significant for biotope differentiation, such as the anemone *Cerianthus lloydii,* the sea pen *Pennatula phosphorea* and the brittlestar *Ophiura ophiura*. Similarly, the soft coral *Alcyonium digitatum*, the bryozoan *Alcyonidium diaphanum* and Serpulid worms dominated the epifauna on pebbles whilst the brittlestar *Ophiothrix fragilis* and the bryzoan *Flustra foliacea* were less frequently recorded. The presence of the anemone *Bolocera tuediae*, is significant because it is a species that is more northern in its distribution (rare in the south) and the substrate it was found on at the Dogger Bank (sand) is unusual.

Many of the motile species were found on a variety of substrates and it is unlikely that they can be used to distinguish biotopes. The hermit crab *Pagurus* spp. and the echinoderm *Asterias rubens* were particularly ubiquitous. One exception is the sandeels that were found in quite high densities in medium fine sand (Table 4.3).

Table 4.3. Total abundance/frequency of occurrence of species recorded from the video/stills. Abundance was calculated by summing all records on a numeric abundance scale. The frequency is the number of records where the species were present out of a total of 64 samples.

Faunal group	Species	Total Abundance	Frequency (64 Records)
INFAUNA	*Echinocardium cordatum*	153	46
	Corystes cassivelaunus	79	31
	Ensis sp.	46	17
	Astropecten irregularis	44	22
	Lanice conchilega	38	19
	Cerianthus lloydii	16	7
	Pennatula phosphorea	10	4
	Aphrodita aculeata	10	8
	Ophiura ophiura	9	7
	Sabella sp. (tubes only)	8	4
	Polinices sp.	8	8
	Chaetopterus sp. (tubes only)	7	4
	Aporrhais pespelecani	4	4
	Cerastoderma edule	1	1
MOTILE	*Pagurus* sp.	147	60
	Asterias rubens	119	52
	Liocarcinus sp.	37	25
	Pleuronectes platessa	36	25
	Ammodytes sp.	42	19
	Pipefish	29	20
	Neptunea antique	14	8
	Luidia sarsi	8	6
	Cancer pagurus	3	3
	Calliactis parasitica	2	2
	Buccinum undatum	1	1
	Psammechinus miliaris	1	1
	Gibbula tumida	1	1
EPIFAUNA	*Alcyonium digitatum*	32	15
	Alcyonidium diaphanum	22	15
	Serpulids	21	10
	Ophiothrix fragilis	11	6
	Flustra foliacea	9	5
	Bolocera tuediae	6	4
	Urticina eques	6	4
	Encrusting orange bryozoan	5	2
	Sponge (branching)	3	2
	Encrusting corallines	2	1

The species composition was used in a semi-structured way to classify the samples by their most abundant species. More quantitative analyses were performed on the species records using the SIMPROF routine in PRIMER and this identified 13 clusters of which nine consisted of more than one sample. SIMPER analysis identified the dominant species primarily responsible for the similarity between the clusters (Table 4.4). *Pagurus* spp., *Echinocardium cordatum* and *Corystes cassivelaunus* were the predominant species in many of the groups. Some of the motile species appeared to distinguish the groups, but it is unclear how reliable they are for this purpose. Additionally, some samples appeared to be included in unexpected groups. It was considered that a comparison of the classes from the semi-structured, exploratory approach and the SIMPROF/SIMPER analysis might resolve some of the contradictions and result in a more robust classification.

Table 4.4. Epifaunal species, which account for most of the similarity within the clusters identified by SIMPER

Cluster Code	Mean Similarity (%)	Dominant Fauna	Cumulative Contribution to Similarity (%)
Group a	35.29	*Ammodytes* spp.	66.67
		Liocarcinus spp.	100
Group b	47	*Alcyonium digitatum*	25.56
		Pagurus spp.	45.93
		Asterias rubens	63.54
		Serpulids	78.99
		Ophiothrix fragilis	87.78
		Liocarcinus spp.	90.59
Group c	51.37	*Pagurus* spp.	59.99
		Asterias rubens	92.77
Group d	Too few stations		
Group e	50	*Corystes cassivelaunus*	42.86
		Echinocardium cordatum	71.43
		Pagurus spp.	85.71
		Pleuronectes platessa	100
Group f	Too few stations		
Group g	69.22	*Echinocardium cordatum*	46.65
		Pagurus spp.	84.21
		Asterias rubens	98.62
Group h	56.32	*Echinocardium cordatum*	27.34
		Corystes cassivelaunus	44.66
		Pagurus spp.	60.36
		Ensis sp.	68.93
		Asterias rubens	77.46
		Lanice conchilega	84.77
		Liocarcinus spp.	89.58
		Ammodytes sp.	93.14

Table 4.4 (continued)

Group i	54.8	*Echinocardium cordatum*	31.19
		Pagurus spp.	48.96
		Asterias rubens	59.14
		Pennatula phosphorea	68.49
		Liocarcinus spp.	77.41
		Epizoanthus papillosus	81.94
		Alcyonium digitatum	85.97
		Sabella sp. (tubes only)	89.85
		Neptunea antiqua	92.68
Group j	Too few stations		
Group k	Too few stations		
Group l	80.8	*Echinocardium cordatum*	22.95
		Asterias rubens	37.49
		Pagurus spp.	51.26
		Corystes cassivelaunus	65.03
		Epizoanthus papillosus	71.88
		Astropecten irregularis	78.71
		Pleuronectes platessa	85.54
		Pipefish	90.91
Group m	63.34	*Echinocardium cordatum*	17.84
		Epizoanthus papillosus	34.22
		Astropecten irregularis	49.7
		Asterias rubens	65.18
		Pagurus spp.	80.22
		Alcyonidium diaphanum	92.48

Table 4.5 lists the resulting classes and shows the correspondence (number of occurrences) between them and (a) depth and (b) sediment type. The original SIMPROF groups are included. Note that the minor SIMPROF groups have been amalgamated into other classes and that the largest group (h) has been divided into two classes. *Echinocardium cordatum* and *Corystes cassivelaunus* were found on medium and muddy sand across a wide range of depths and, although key species are probably not useful in differentiating between similar biotopes. *Lanice conchilega* and *Ensis* sp. (often together with *Echinocardium cordatum*) were more typical of the shallower sediments (<32 m). However, the general picture for the finer sediments is of variations on a limited range of species.

The possible exceptions were the deep (below 55 m) muddy sand and sandy mud communities with burrowing fauna (species uncertain) and *Pennatula phosphorea* that were found at the northern margin of the Dogger Bank. The stations have been plotted showing their assigned biota class (Figure 4.11). Some patterns emerge from this plot: (1) The majority of the shallow sandbank supported *Echinocardium cordatum* and either *Ensis* sp. (west Dogger Bank) or *Lanice concheliga* (east survey area); (2) Sparse motile communities were found on the margins of the shallow bank; (3) *Echinocardium cordatum* and *Corystes cassivelaunus* were found on the west and south flanks of Dogger Bank, and; (4) the slope on the northern flank supported *Echinocardium cordatum* and *Astropecten irregularis* and, in the deeper areas, *Echinocardium cordatum* and *Pennatula phosphorea*. These patterns not only accord with bathymetry but also the distribution of the sediments. The epifaunal communities were scattered around the outer margins of Dogger Bank and, since these habitats were targeted, this distribution may be the result of the stratified sampling design.

Table 4.5. Station groupings defined by epifaunal community characteristics with correspondence (number of occurrences between them along with depth and sediment type.

Biota Class	**SIMPROF group**	**Depth range (m)**			**Sediment**																					
		<-55	-55 to -35	>-35	Sandy pebble	Sandy pebble and gravel	Pebble and sand	Slightly pebbly sand	Sandy gravel	Gravelly sand	Slightly gravelly sand	Gravelly sand and clay	Gravel and clay	Shelly sand	Shelly sand and clay	Coarse sand	Very slightly shelly medium sand	Medium sand	Very slightly shelly fine sand	Fine sand	Slightly muddy sand	Slightly shelly muddy sand	Very slightly shelly muddy sand	Muddy sand	Sandy mud
Corystes/burrows	e		1																						1
Echinocardium/*Pennatula*	im	4																					1	3	
Echinocarduim/*Astropecten*	m(k)	2	2														1		1					2	
Echinocardium/*Corystes*	lh	2	2	3														1	1	1			1	3	
Echinocardium/*Ensis*	h		3	5															5	2	1				
Echinocardium/*Lanice*	h		1	7													2		2		2		2		
Echinocardium/sparse motile	g(dfj)	1	7	1													1	1	3	2			1	1	
Cerianthus/*Echinocardium*	eh		1	1									2	2	1	1			2						
Sparse motile	c(a)		4	7		1			1									1				1		1	
Sparse motile/Sandeel	c(a)		1	2					1									1		1					
Epifauna	b		1	4	1		1	1		1		1													
Epifauna/*Ophiothrix*	b			2			1				1														

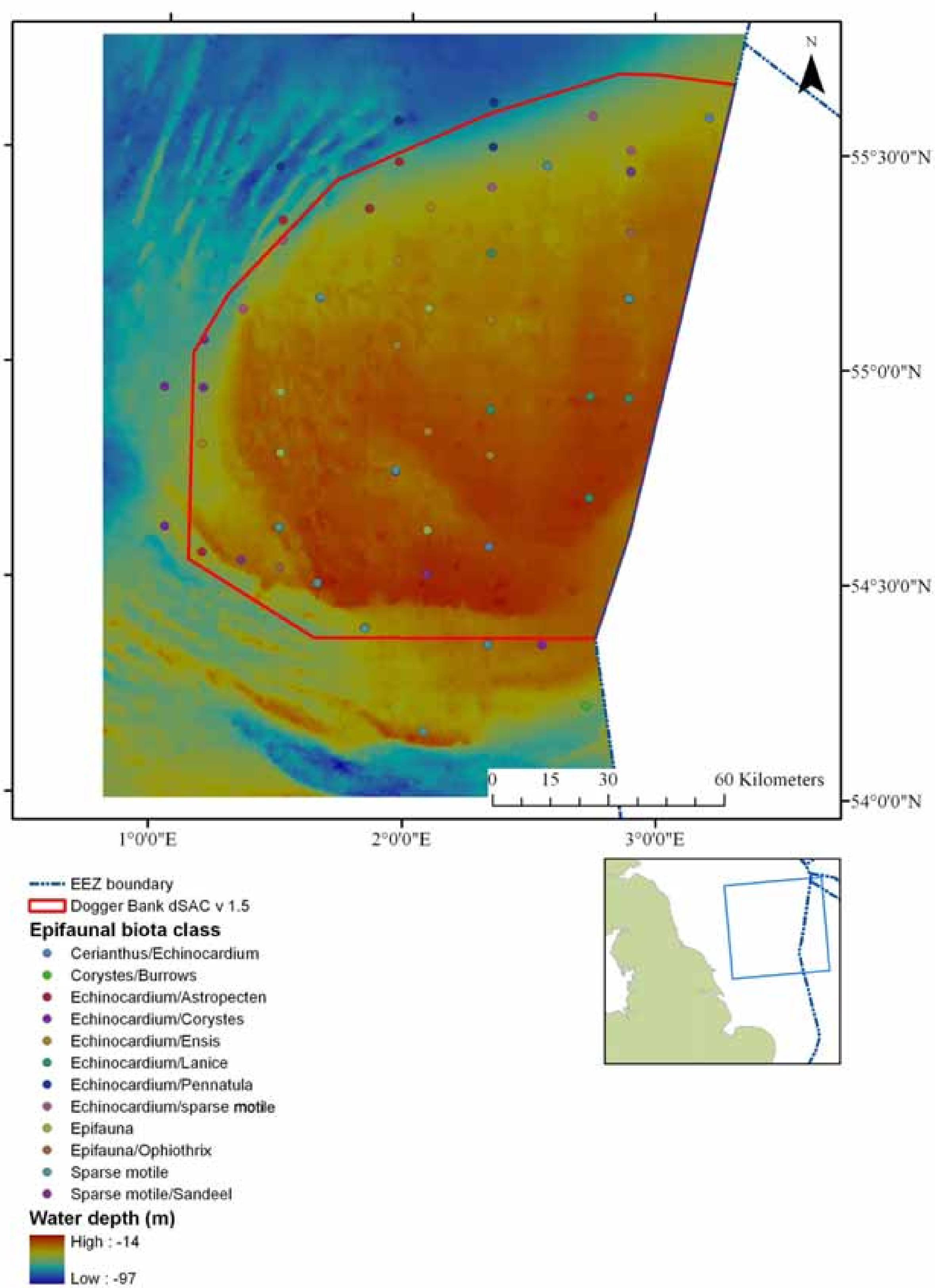

Figure 4.11. Epifaunal communities on the Dogger Bank.

3.5 Infauna

3.5.1 Multivariate analyses

The SIMPROF routine, applied to the infaunal species abundance data, identified 12 genuine clusters of which 8 consisted of more than one sample. SIMPER analysis identified a sub-set of species that were predominantly responsible for similarity within clusters (Table 4.6).

Table 4.6. Infaunal species, which account for most of the similarity within the clusters identified by SIMPROF.

Cluster Code	Mean Similarity (%)	Dominant Fauna	Cumulative Contribution to Similarity (%)
Group A	Too few stations		
Group B	Too few stations		
Group C	26.90	*Nemertea*	15.98
		Polycirrus sp.	27.28
		Pomatoceros lamarki	37.39
		Mysella bidentata	46.14
		Glycera alba	53.29
		Mediomastus fragilis	60.44
Group D	Too few stations		
Group E	32.19	*Notomastus* sp.	17.44
		Glycera lapidum	32.48
		Nemertea	43.59
		Protodorvillea kefersteini	54.17
		Pisione remota	58.23
		Amphiuridae	62.23
Group F	Too few stations		
Group G	27.31	*Galathowenia oculata*	25.82
		Thyasira flexuosa	45.24
		Goniada maculata	61.71
Group H	39.45	*Nephtys cirrosa*	64.39
Group I	32.95	*Echinocyamus pusillus*	18.11
		Chamelea striatula	34.87
		Nephtys cirrosa	49.64
		Scoloplos armiger	64.42
Group J	39.38	*Bathyporeia elegans*	24.29
		Magelona filiformis	39.38
		Scoloplos armiger	51.90
		Phoronis sp.	63.28
Group K	36.94	*Bathyporeia elegans*	15.10
		Magelona filiformis	28.85
		Bathyporeia guilliamsoniana	37.29
		Fabulina fabula	44.05
		Amphiuridae	48.96
		Nemertea	52.89
		Spiophanes bombyx	56.79
		Chaetozone christiei	60.64
Group L	22.16	*Spiophanes bombyx*	25.00
		Harpinia antennaria	50.00
		Lucinoma borealis	75.00

Stations assigned to the given infaunal groups were plotted in relation to the proposed dSAC boundary (Figure 4.13). The majority of stations within the slope boundary belong to the Group K. Species which account for most of the similarity within this group include the two amphipod species *Bathyporeia elegans* and *Bathyporeia guilliamsoniana* along with the polychaete *Magelona filiformis* and the burrowing bivalve *Fabulina fabula*, all of which have been identified as having a habitat preference for medium grained sediments with a relatively low mud content (Degraer *et al,* 2006). Furthermore, the species identified as being characteristic of stations assigned to Group K were also listed by Wieking and Kröncke (2001) as being characteristic of the 'Dogger Bank Community' that they identified using similar clustering techniques. Comparisons of infauna and PSA data identified that stations assigned to infaunal Group E were characterised by relatively coarse substrate (Figure 4.12) and this is reflected in certain of their characterising species (i.e. *Glycera lapidum*) which displays a preference for coarser sediments (Degraer *et al,* 2006). Stations assigned to Groups G, J and L are largely positioned along the deeper contours on the northern edge of the Bank (Figure 4.13). Sediments at these stations are typified by slightly higher mud content and this is reflected in the habitat preferences of certain of their characterising species (i.e. *Scoloplos armiger* and *Spiophanes bombyx*), which favour sediments with a higher mud content. Similarly, the study undertaken by Wieking and Kröncke (2001) identified a distinct 'Northeastern Community', which was typified by a similar subset of species to those identified here. Stations belonging to Group H are located in the southwestern region of the Bank in relatively shallow water. Species, which are typical of this group, are the polychaete *Nephtys cirrosa* and the amphipod *Bathyporeia elegans*; two species that are typically associated with medium to coarse grained sediments with a low mud content (Degraer *et al,* 2006).

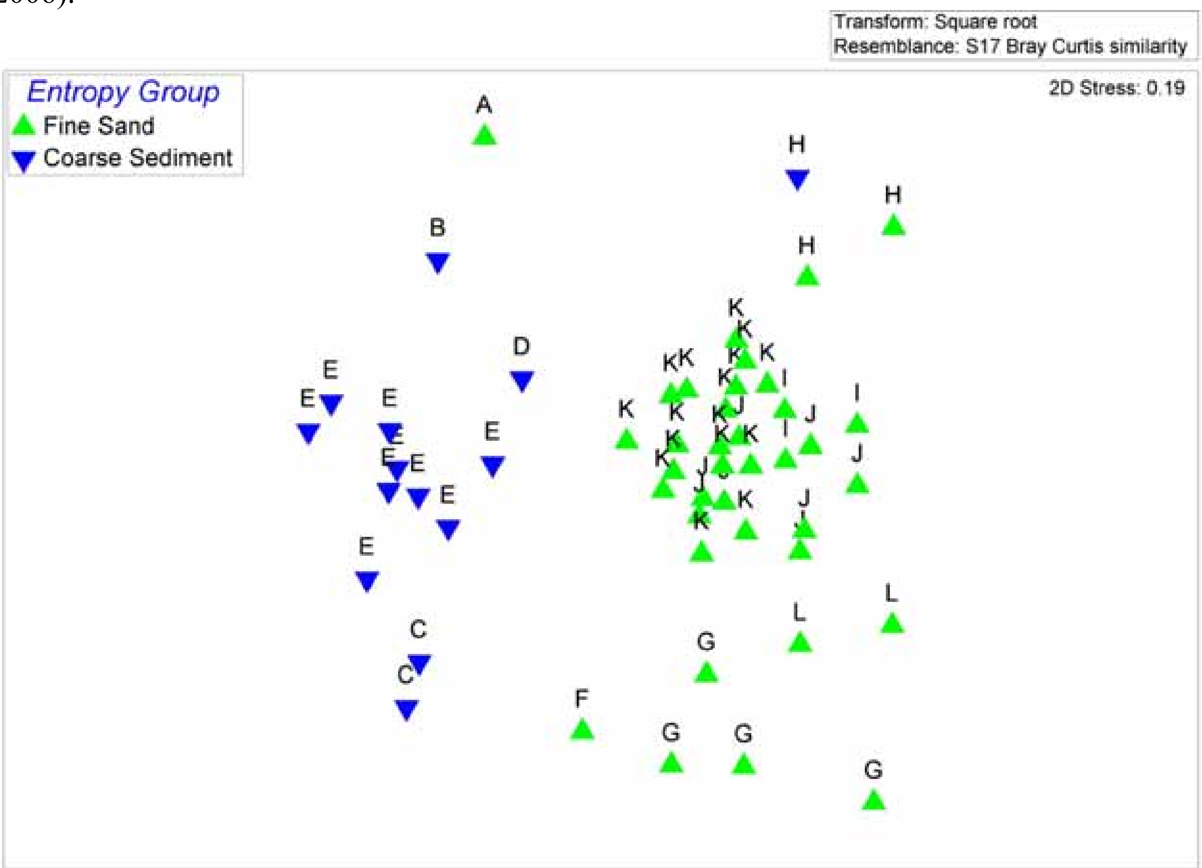

Figure 4.12. MDS plot tagged with Entropy groups.

Spatial distributions of infaunal communities across the Dogger Bank, and adjacent deeper areas, are largely determined by sediment characteristics and depth. As with the epifauna, spatial differences in infaunal community characteristics present within the sandy substrates (i.e. infaunal Groups F, G, H, I, J, K and L) are largely due to the relative abundances of a limited subset of species notably the polychaetes *Nephtys* sp., *Scoloplos armiger*, *Magelona filiformis* and *Spiophanes bombyx* and the amphipod *Bathyporeia* sp., and *Harpinia* sp. Additional species are responsible for distinguishing the deeper sandy stations from the sandy stations on the Bank. For example, stations belonging to Groups G and L, lying in the deeper water to the north of the bank, are characterised by comparatively higher numbers of certain bivalve species (e.g. *Lucinoma borealis* and *Thyasira flexuosa*). Stations assigned to Group J are largely situated in water of intermediate depth along the northern slope. Therefore, faunal communities that characterise this group are largely transitional between those present on the main bank area and those in deeper waters to the north. Detailed habitat descriptions, including the physical environment and the associated biological assemblage, are given in Appendix 4.

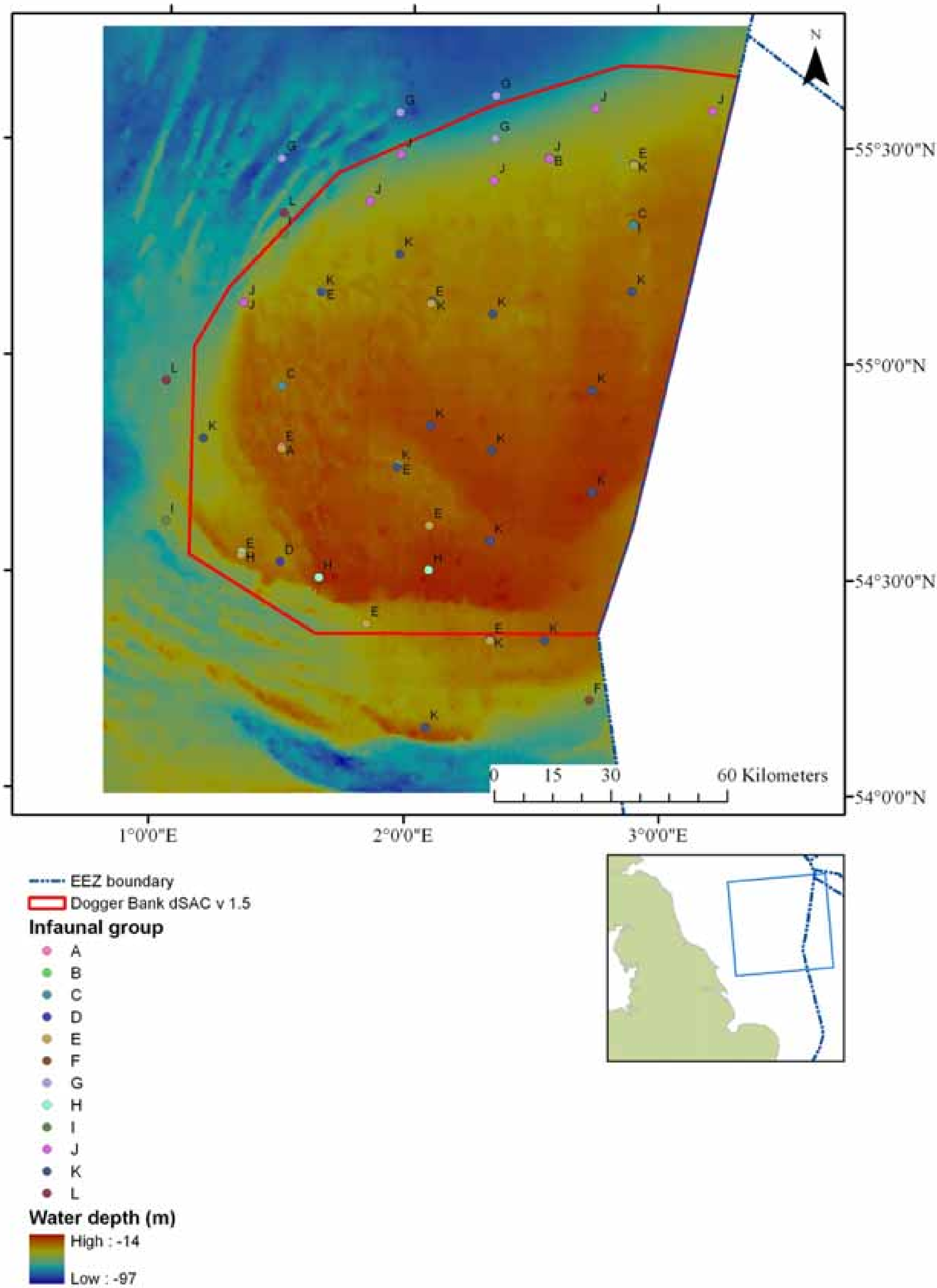

Figure 4.13. Infaunal communities on the Dogger Bank.

3.5.2 Univariate analyses

The univariate measures of Number of Species (S), Number of Individuals (N), Shannon-Wiener Diversity (H') and Ash Free Dry Weight (AFDW) were calculated for infaunal samples collected at each station. Values of the univariate measures were plotted for each station to examine any spatial patterns they exhibit (Figures 4.14 to 4.17).

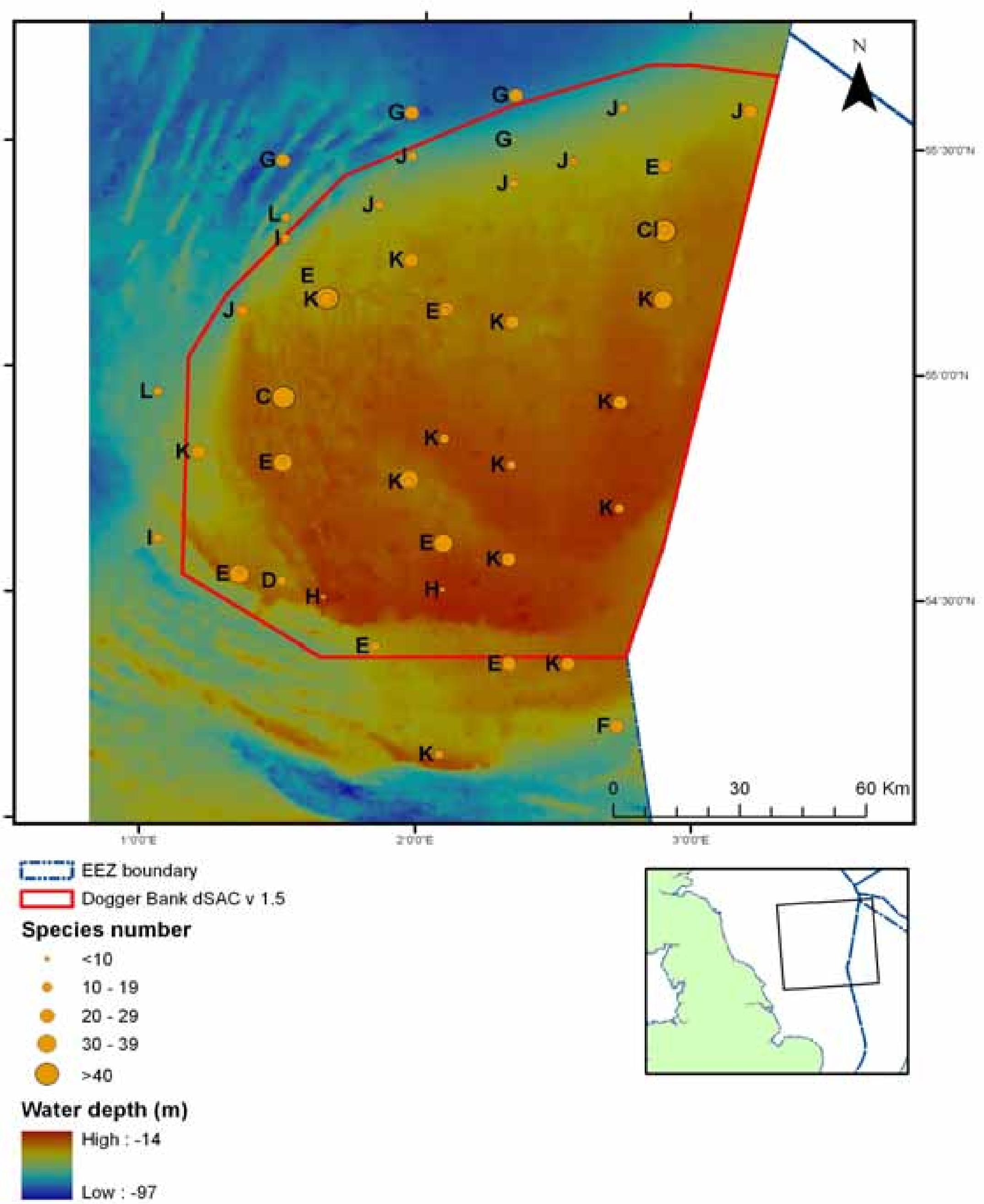

Figure 4.14. Number of Species (S) plotted by station. Letters indicate infaunal group.

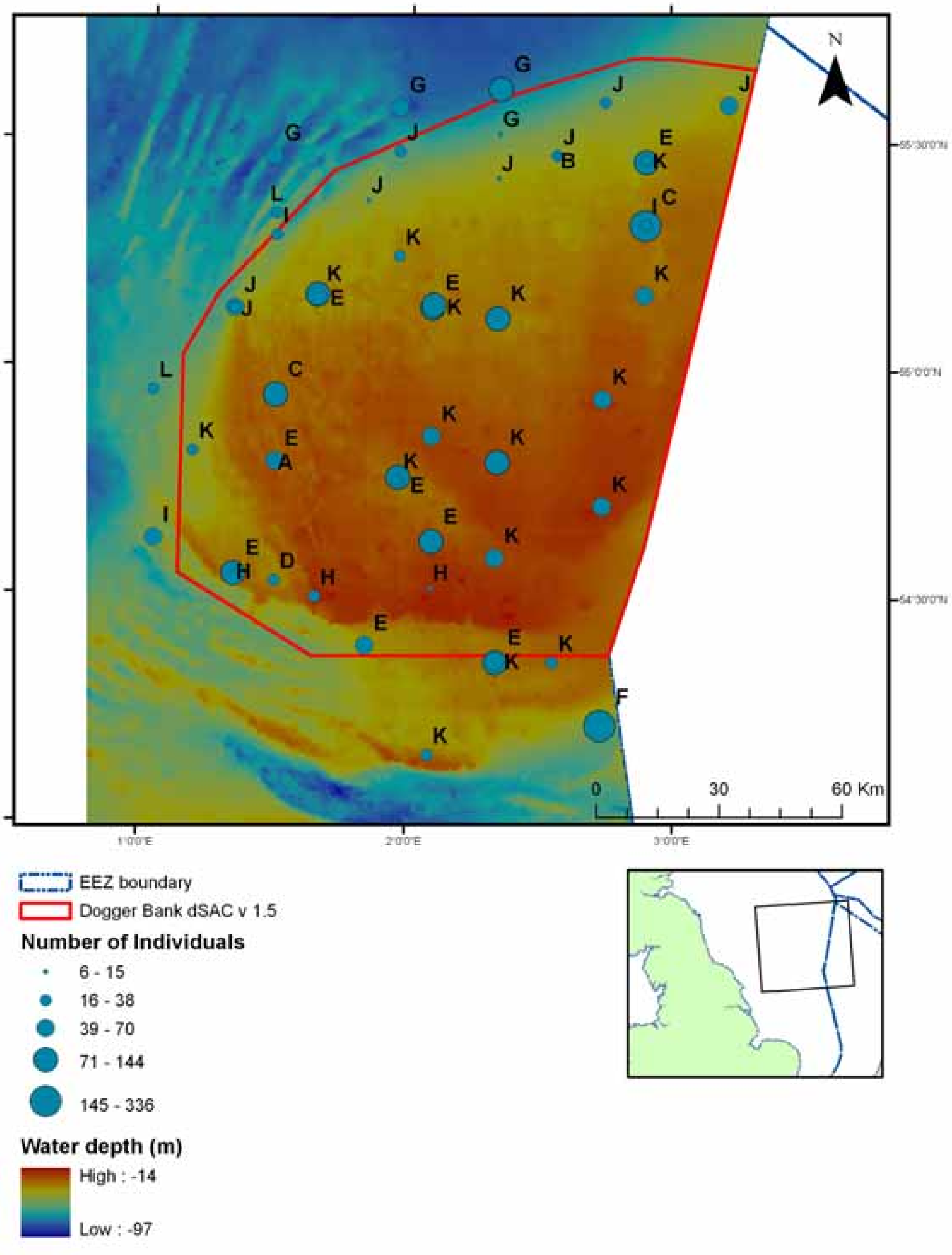

Figure 4.15. Number of Individuals (N) plotted by station. Letters indicate infaunal group.

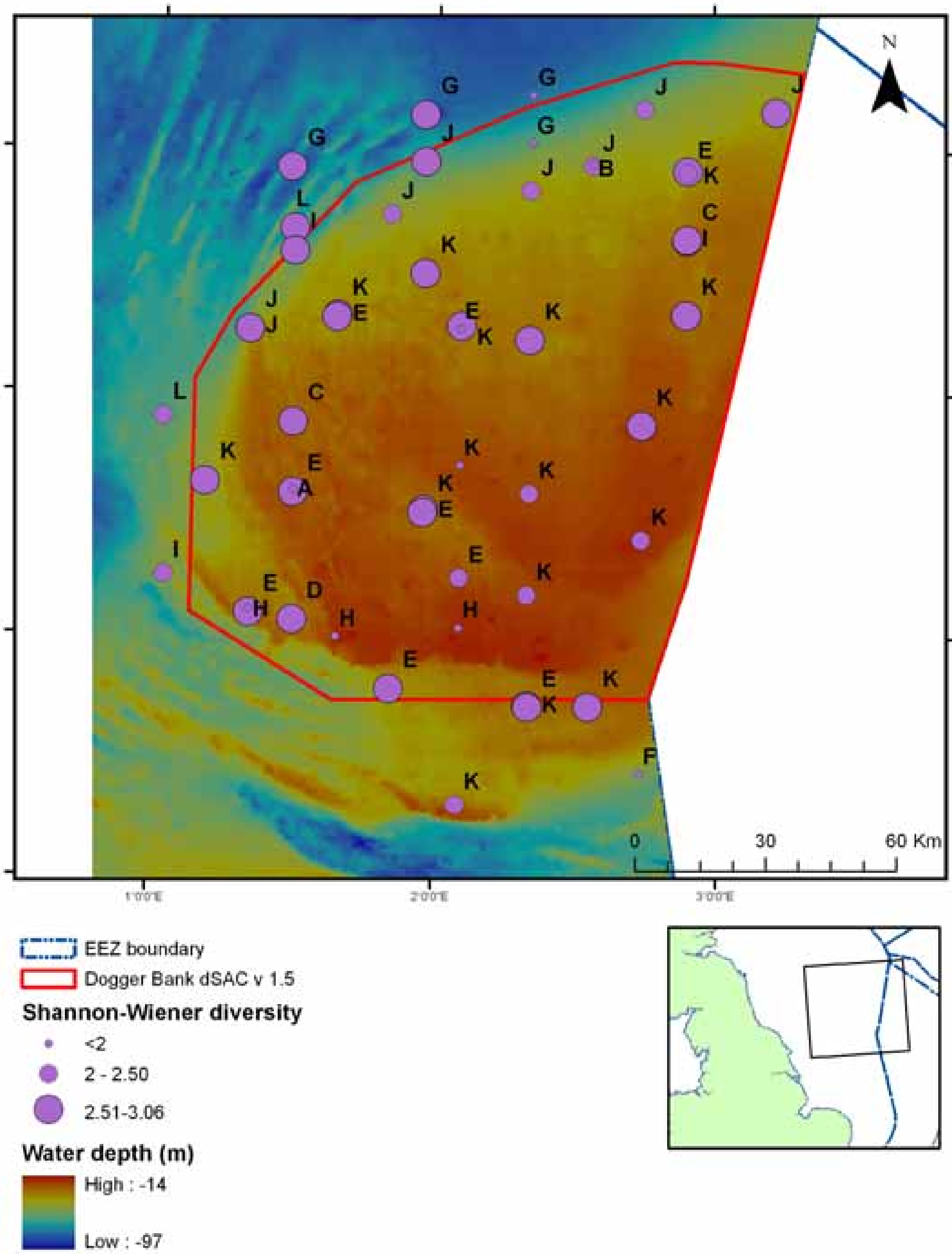

Figure 4.16. Shannon-Wiener diversity plotted by station. Letters indicate infaunal group.

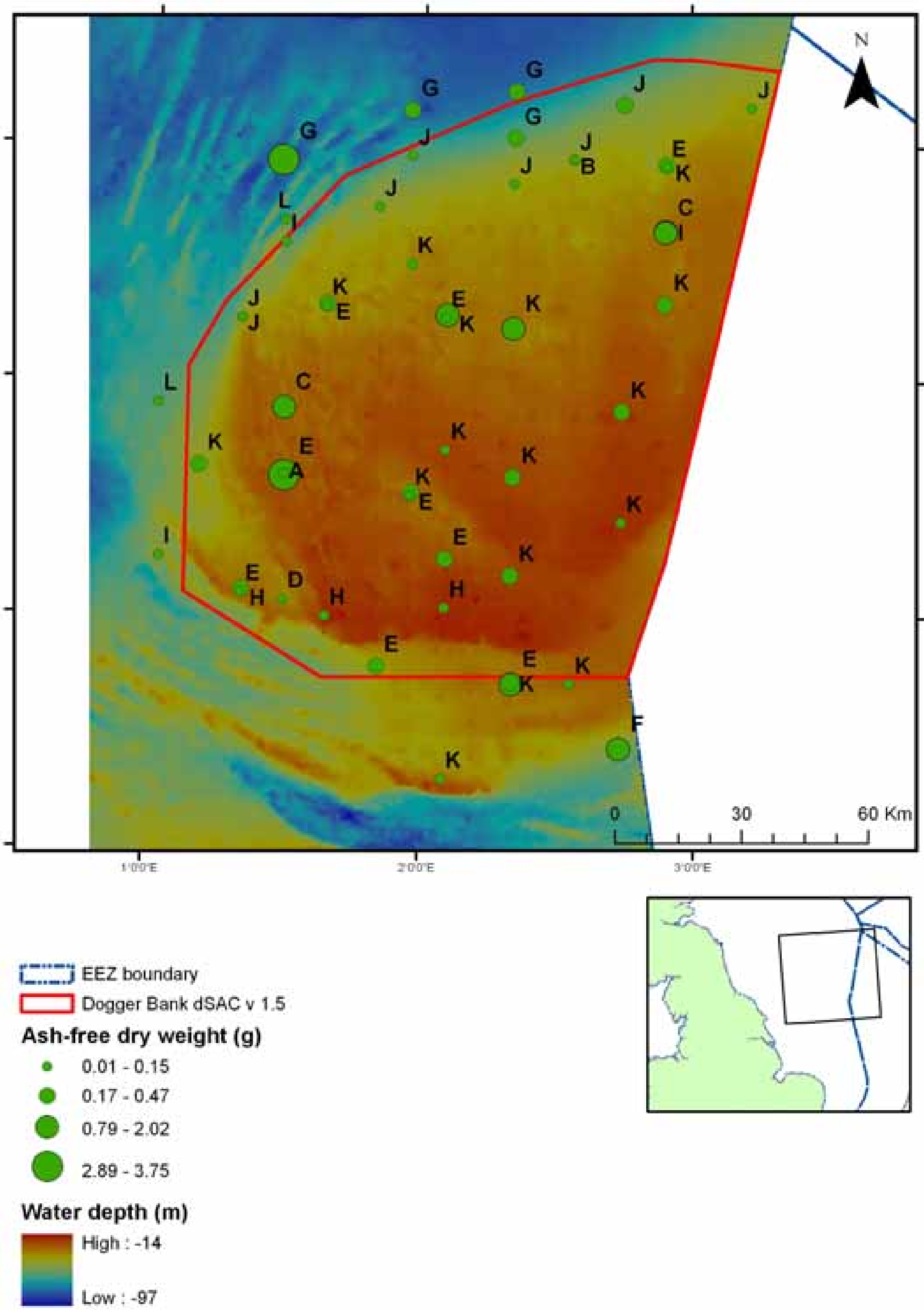

Figure 4.17. Total Ash-Free Dry Weight (AFDW) plotted by station. Letters indicate infaunal group.

There was little evidence of any discernable spatial trends in relation to the univariate measures calculated. Numbers of species, numbers of individuals and Shannon-Wiener Diversity were relatively consistent across all stations (Figures 4.14 to 4.16). The high values of AFDW (Figure 4.17) observed at certain stations could largely be attributed to the presence of single individuals belonging to relatively large species of crustacean (e.g. *Pagurus bernhardus*) or bivalves (e.g. *Dosinia* sp., *Thracia* sp., *Arctica islandica*).

3.6 Infaunal/Epifaunal links

Links between the spatial patterns in infaunal and epifaunal communities were identified (Table 4.7).

Table 4.7. Community groups based on links between infaunal and epifaunal community SIMPROF groups.

Infaunal SIMPROF Groups	Epifaunal SIMPROF Groups	Characteristic Infauna	Characteristic Epifauna	Stations
Sandy Sediment Bank Community				
(SIMPROF groups I, J, K, L)	(SIMPROF groups d, e, f, g, h, j, l, m)	*Nephtys cirrosa* *Magelona filiformis* *Scoloplos armiger* *Spiophanes bombyx* *Bathyporeia elegans* *Fabulina fabula* *Chamelea striatula* *Echinocyamus pusillus*	*Cerianthus lloydi* *Lanice conchilega* *Corystes cassivalaunus* *Ensis* sp. *Astropecten irregularis* *Echinocardium cordatum* Sparse motile	1, 4(A), 5, 6, 8, 9, 11(A&B), 12, 15, 16, 17(A), 18, 19(B), 23, 24, 26, 35, 38 (A), 40, 48, 50, 51
Shallow Sandy Sediment Bank Community				
(SIMPROF group H)	(SIMPROF groups a, c)	*Nephtys cirrosa*	*Ammodytes* sp.	31, 36
Coarse Sediment Bank Community				
(SIMPROF groups B, C, D, E, F)	(SIMPROF group a, b, c, e)	*Nemertea* *Polycirrus* sp. *Pomatoceros lamarki* *Notomastus* sp. *Glycera* spp.	*Ophiothrix fragilis* Sparse motile epifauna	2(A), 3(B), 4(B), 10, 17(B), 25, 27(B), 28(A), 32, 34, 37, 38(B)
Deep Community North of the Bank				
(SIMPROF group G)	(SIMPROF groups i and m)	*Galathowenia oculata* *Goniada maculata* *Thyasira flexuosa*	*Pennatula phosphorea* *Echinocardium cordatum*	43, 44, 45, 46

Links were investigated between the infaunal and epifaunal communities through an examination of the spatial correlations between the SIMPROF groups identified for both the infauna and epifauna. Spatial patterns relating to the SIMPROF groups were found to be largely consistent between the two faunal components and most stations could be assigned to one of the combined groupings (Table 4.7). In general, the stations located in the sandy sediments on the Dogger Bank, termed the 'Sandy Sediment Bank Community' could be characterised by typical sand-associated species described in Table 4.7. Within these sand dominated sediments on the Dogger Bank the shallower regions termed 'Shallow Sandy Sediment Bank Community' were delineated from the more extensive 'Sandy Sediment Bank Community' by the presence of sandeels. The faunal communities present in the coarse sediments on the Dogger Bank could also be distinguished from the more extensive sandy communities due to the presence of certain species more typically associated with such coarse sediments, namely the tube dwelling polychaeate *Pomatoceros lamarkii* and the brittlestar *Ophiothrix fragilis*. Finally, infaunal SIMPROF Group G correlated directly with epifaunal SIMPROF Groups i and m with stations comprising this group being situated in deeper water to the north of the Dogger Bank. Species identified as characteristic of this group included the polychaetes *Galathowenia oculata* and *Gonida maculata*, the bivalve mollusc *Thyasira flexuosa*, the seapen *Pennatula phororea* and the burrowing urchin *Echinocardium cordatum*.

3.7 Modelled biological zones

Biological zones or étages were originally defined by Glemarec (1973). The infralittoral zone is the zone dominated by photosynthetic organisms. Its lower limit is broadly correlated with the depth at which light reaching the seabed equals 1% of the surface value. Beyond this lies the circalittoral zone. Its lower limit can be approximated by the wave base. The zone between the wave base and the shelf break is termed the deep circalittoral.

Light attenuation data were derived from satellite scenes covering 1-31 August 2007. The derived depth of 1% light penetration was then interfaced with the bathymetry model of the Dogger Bank, yielding areas classed as photic and aphotic (Figure 4.18). Wave base data was obtained from the JNCC and is the same as used for the UKSeaMap (Connor *et al,* 2006: Figure 11). The resultant distribution of the biological zones is shown in Figure 4.20.

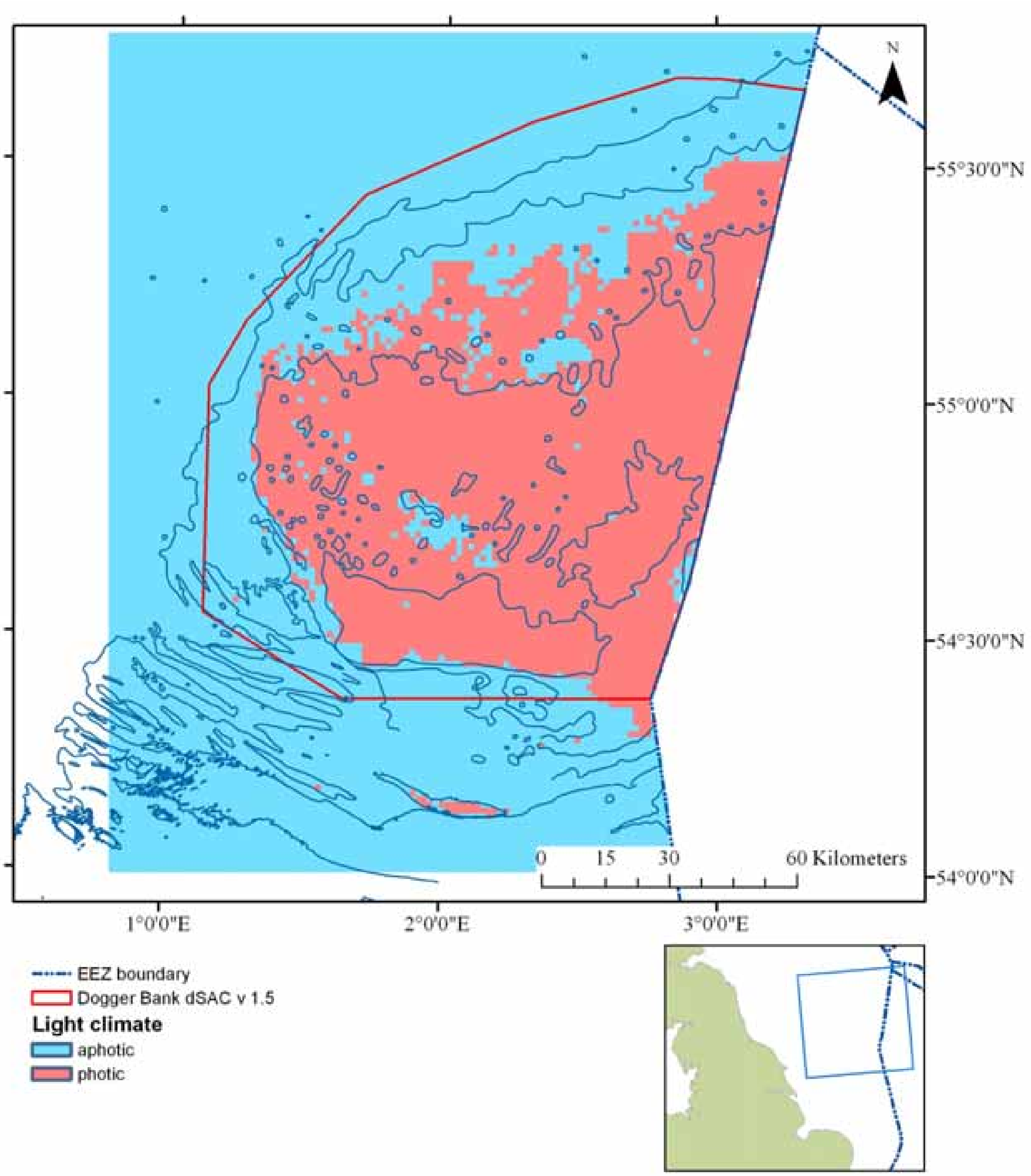

Figure 4.18. Photic and aphotic zones on the Dogger Bank.

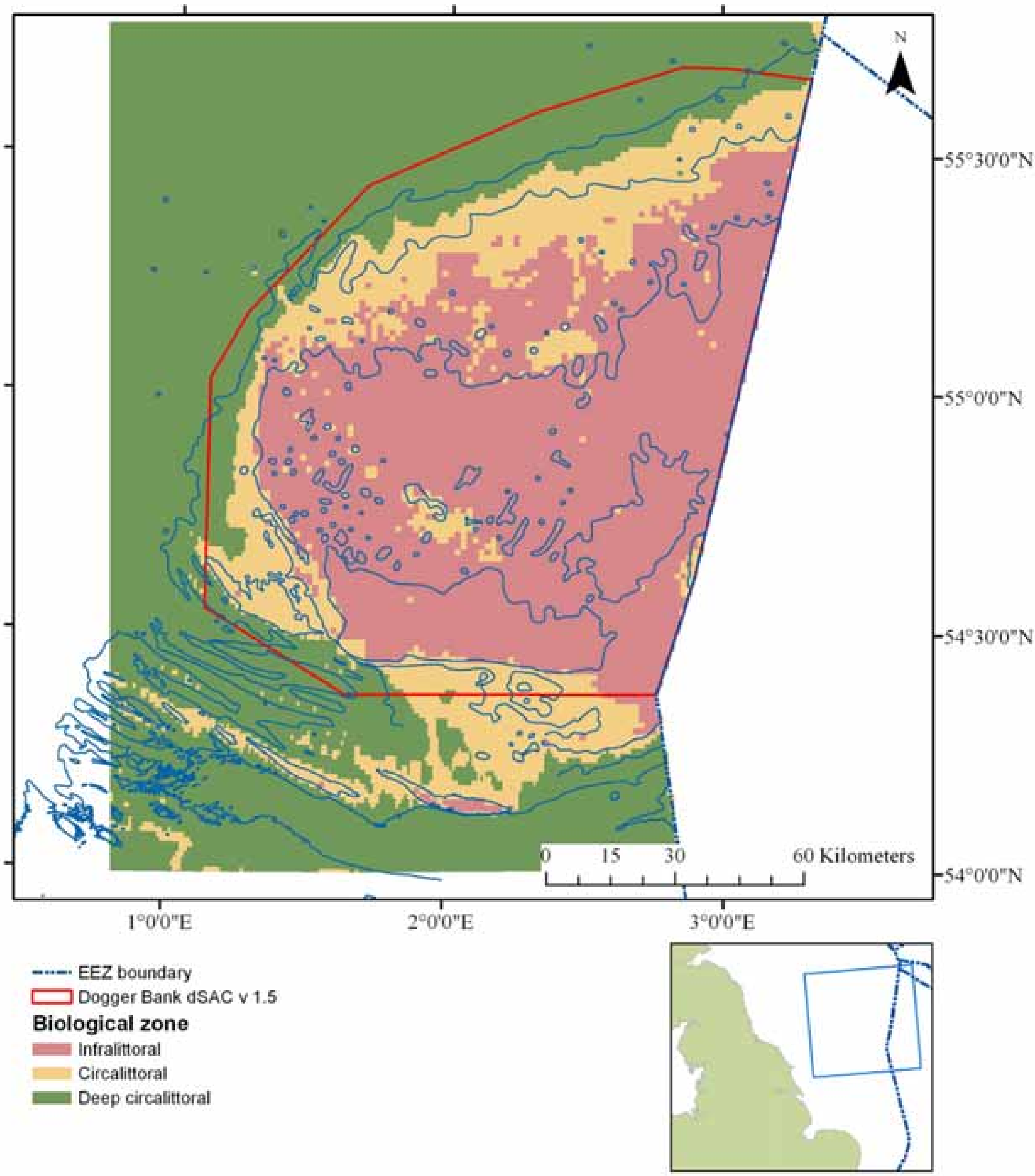

Figure 4.19. Modelled biological zones on the Dogger Bank.

3.8 EUNIS classifications

We classified the 51 grab stations based on physical parameters at level 4 of the EUNIS classification. The classification was based on sediment classes derived with EntropyMax (fine sand and coarse sediment), location in relation to the upper limit of featureless seabed (Figure 4.6) roughly equalling the wave base (above and below), location in relation to light climate (photic and aphotic; Figure 4.18) and mud content (above or below 5%, see Figure 7 in Appendix 1). In this way, six classes were discerned:

A5.13 Infralittoral coarse sediment – coarse sediment above the wave base and photic
A5.14 Circalittoral coarse sediment – coarse sediment above the wave base and aphotic

A5.23 Infralittoral fine sand – fine sand with less than 5% mud above the wave base and photic
A5.24 Infralittoral muddy sand – fine sand with more than 5% mud above the wave base and photic
A5.25 Circalittoral fine sand – fine sand with less than 5% mud above the wave base and aphotic
A5.27 Deep circalittoral sand – fine sand below the wave base

There is a clear distinction between sublittoral coarse sediment (A5.13 and A5.14) and sublittoral sands (A5.23, A5.24, A5.25 and A5.27) in the MDS plot (Figure 4.20). Further distinctions on EUNIS level 4 are, however, less clear. While infralittoral coarse sediment is exclusively linked to infaunal Group C as is circalittoral coarse sediment linked to infaunal Groups B and D, they both share the most frequent infaunal Group E. Similarly, infaunal Group K is linked to infralittoral fine sand and circalittoral fine sand. Deep circalittoral sand is exclusively connected to infaunal Groups F, G and L, but shares infaunal groups I and J with circalittoral fine sand. This pattern is explained by the rather subtle differences between infaunal groups and indicates a gradual change between biological zones rather than clear-cut boundaries. Biological zones can be derived based on physical parameters but they are less clearly reflected in the infaunal data.

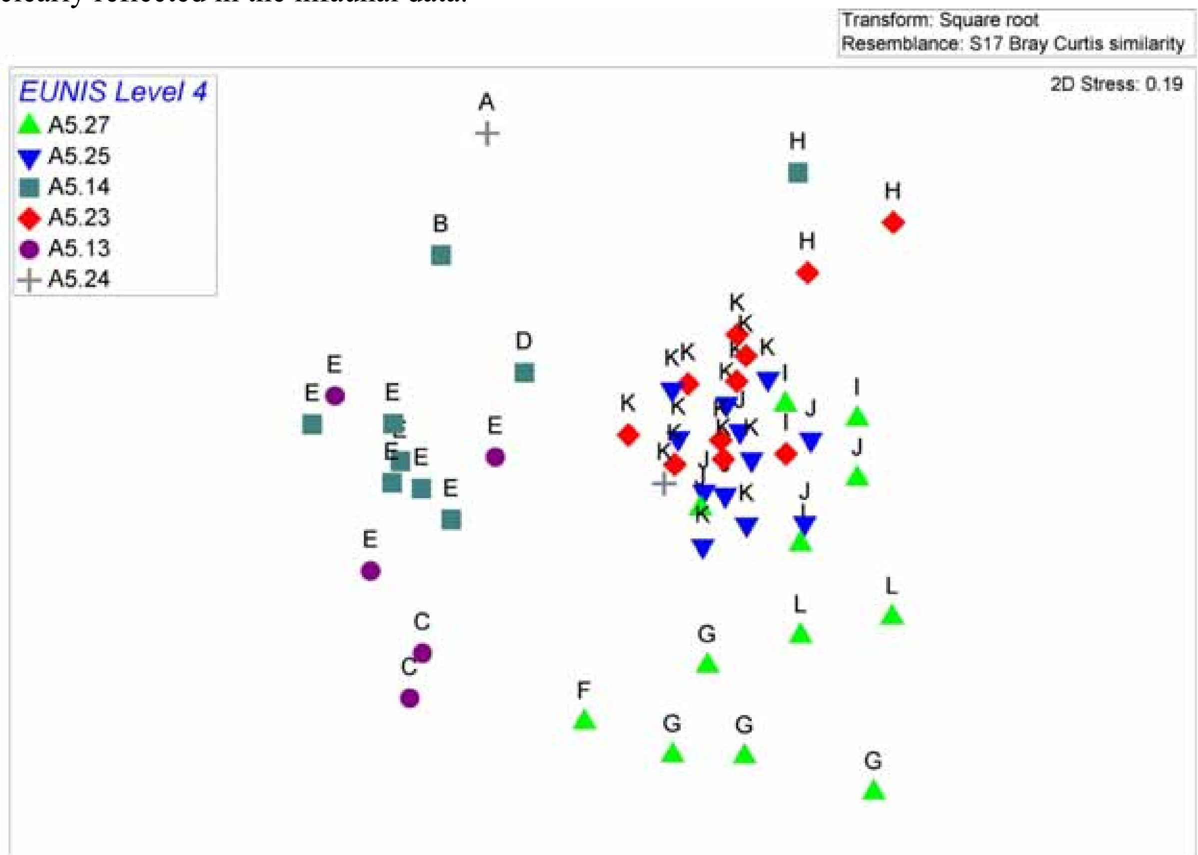

Figure 4.20. MDS plot tagged with EUNIS level 4 classes

We classified stations at EUNIS level 5 based on their infaunal and epifaunal communities. The results were mixed, with 22 stations matching the EUNIS level 4 assignments and 29 stations failing to match (Table 4.8).

Table 4.8. EUNIS levels 4 and 5 and UK Habitat Classifications version 04.05 (Connor *et al*, 2004) assigned to stations based on their physical and biological attributes. Shading indicates stations where EUNIS Level 4 classifications based on physical and biological attributes match.

Station	EUNIS Level 4/UK Habitat Classification Based on Physical Attributes	EUNIS Level 4/UK Habitat Classification Based on Faunal Community Characteristics	EUNIS Level 5/UK Habitat Classification Based on Faunal Community Characteristics
G1	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G2A	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G2B	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa.	A5.233/SS.SSa.IFiSa.NcirBat
G3A	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa.	A5.233/SS.SSa.IFiSa.NcirBat
G3B	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G4A	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G4B	A5.13/SS.SCS.ICS	A5.14/SS.SCS.CCS	A5.141/SS.SCS.CCS.PomB
G5	A5.24/SS.SSa.ImuSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G6	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G8	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G9	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G10	A5.27/SS.SSa.OSa	A5.27/SS.SSa.OSa	A5.272/SS.SSa.OSa.OfusAfil
G11A	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G11B	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G12	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G15	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G16	A5.25/SS.SSa.CFiSa	A5.25/SS.SSa.CFiSa	A5.252/SS.SSa.CFiSa.ApriBatPo
G17A	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G17B	A5.13/SS.SCS.ICS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G18	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G19A	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G19B	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G23	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G24	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G25	A5.13/SS.SCS.ICS	A5.14/SS.SCS.CCS	A5.141/SS.SCS.CCS.PomB
G26	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G27A	A5.24/SS.SSa.ImuSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G27B	A5.13/SS.SCS.ICS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G28A	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G28B	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G31A	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.144/SS.SCS.CCS.Nmix
G31B	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G32	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G33	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G34	A5.13/SS.SCS.ICS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G35	A5.23/SS.SSa.IFiSa	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G36	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G37	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
G38A	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat

G38B	A5.14/SS.SCS.CCS	A5.14/SS.SCS.CCS	A5.143/SS.SCS.CCS.Pkef
Station	**EUNIS Level 4/UK Habitat Classification Based on Physical Attributes**	**EUNIS Level 4/UK Habitat Classification Based on Faunal Community Characteristics**	**EUNIS Level 5/UK Habitat Classification Based on Faunal Community Characteristics**
G39	A5.25/SS.SSa.CFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G40	A5.23/SS.SSa.IFiSa	A5.23/SS.SSa.IFiSa	A5.233/SS.SSa.IFiSa.NcirBat
G42	A5.25/SS.SSa.CFiSa	A5.25/SS.SSa.CFiSa	A5.252/SS.SSa.CFiSa.ApriBatPo
G43	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G44	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G45	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G46	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G47	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G48	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G50	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr
G51	A5.27/SS.SSa.OSa	A5.26/SS.SSa.CMuSa	A5.262/SS.SSa.CMuSa.AbraAirr

While all coarse sediments were classed as circalittoral based on their faunal communities, fine sands fell into the infralittoral. Most strikingly, stations classed as circalittoral coarse sediment and infralittoral fine sand were often situated just a few hundred metres apart. No suitable level 5 classes were found within the level 4 deep circalittoral class. The best level 5 match for these stations fell within level 4 class circalittoral muddy sand.

We produced a level 4 EUNIS habitat map integrating the results mentioned above with the exception of the EUNIS level 5 class assignments based on infaunal data. As a starting point, the bedform distribution map was selected (Figure 4.6) and included additional information to derive EUNIS habitats. Featureless areas below the wave base were predominantly sandy with limited mud content below 20%. They were therefore translated into deep circalittoral sand. Areas displaying mobile sand streaks, sheets and ripples are situated above the wave base. Depending on the mud content with a cut-off at 5%, they were classed as fine sand or muddy sand. They were further subdivided into infralittoral and circalittoral based on their position in relation to modelled photic and aphotic seabed (Figure 4.18). Gravel wave areas translated into infralittoral coarse sediment, circalittoral coarse sediment or deep circalittoral coarse sediment, depending on their position in relation to the wave base and photic zone. The translation of areas displaying coarse sediment waves was however less straightforward. After an inspection of sidescan sonar data and Folk classes of sediment samples they were classed as coarse sediment, when backscatter was high and sediments were classed as gravel or sandy gravel and vice versa. This procedure yielded eight classes in total; the six as derived from grab data analysis and additionally deep circalittoral coarse sediment (A5.15) and circalittoral muddy sand (A5.26).

The resultant map (Figure 4.21) shows a clear dominance of infralittoral fine sand on Dogger Bank. These are rimmed by circalittoral fine sands. Patches of infralittoral coarse sediment and circalittoral coarse sediment are widespread, but are much smaller than previously anticipated. It should be noted that the distribution shown in Figure 4.21 is still a generalisation and only mapping the area with 100% coverage could unravel the true picture. Occurrence of infralittoral muddy sediment and circalittoral muddy sediment is limited and in most cases only defined by a single sample per patch. Towards greater water depths, i.e.

deeper than 45-55 m, deep circalittoral sands and deep circalittoral coarse sediments are found. Photographic examples of the EUNIS level 4 classifications identified using physical attributes on the Dogger Bank are given in Appendix 3.

The spatial distribution of the stations, labelled according to combined epifaunal/infaunal groupings, is shown in Figure 4.21. The majority of the stations are assigned to the 'sandy sediment bank community' and are largely confined to areas described by the EUNIS classifications as infralittoral and circalittoral fine sand. Stations that comprise the 'coarse sediment bank community' are more limited in number but broadly coincide with areas assigned to infralittoral and circalittoral coarse sediments. Stations assigned to the 'deep northern community' are positioned in the deep areas to the north of the Dogger Bank outside the proposed dSAC and are exclusively found in areas assigned to 'deep circalittoral sand'.

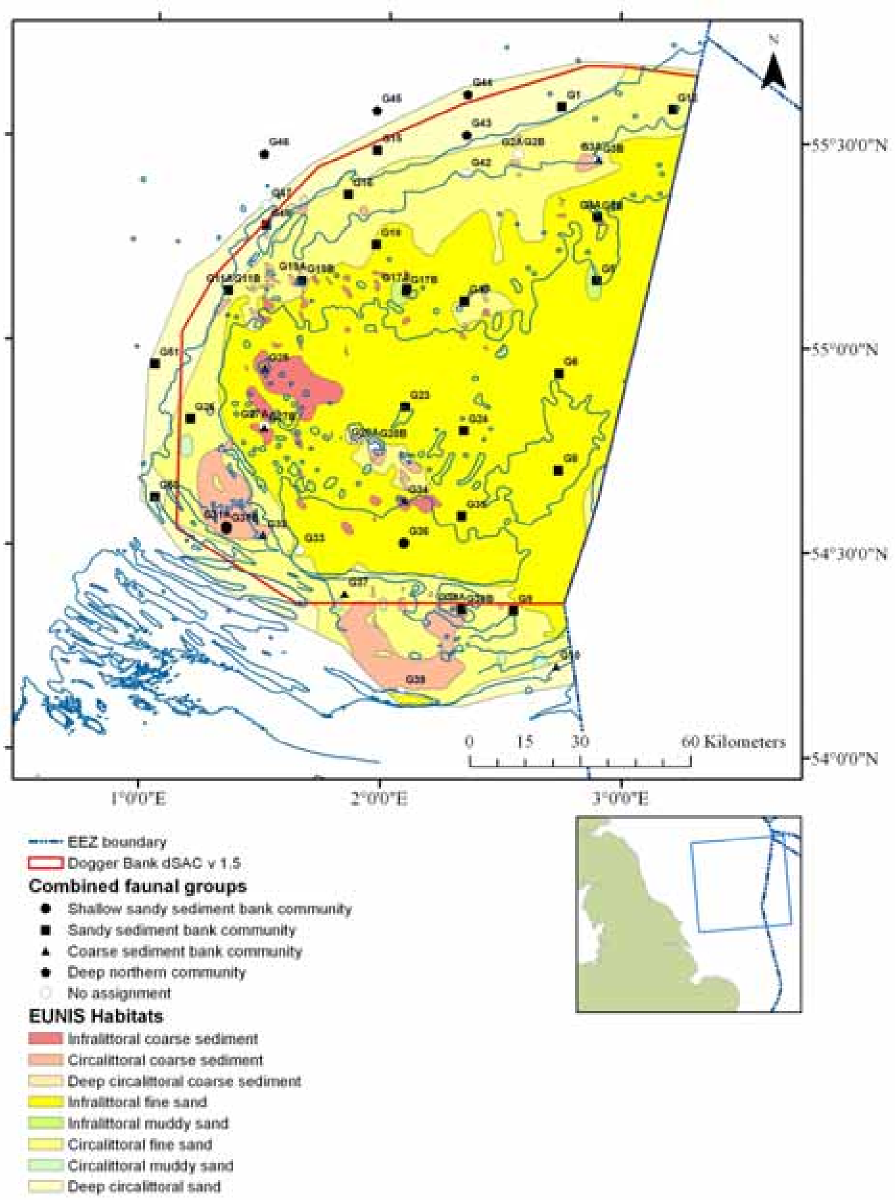

Figure 4.21. Mapped EUNIS level 4 habitats superimposed with combined faunal groups for each grab station (see chapter 4.6).

3.9 Annex I habitats

The extent and character of the Annex I sandbank habitat (1110-Sandbank) has been described in more detail in a separate report (see Appendix 1). Figure 4.22 shows the extent of the sandbank based on the slope analysis and the extent of the Dogger Bank Formation, both of which were critical in defining the spatial extent of the sandbank. All eight encountered EUNIS habitats, which are either sublittoral coarse sediments (A5.1) or sublittoral sands (A5.2) at level 3 of the classification, are characteristic for and in accordance with the definition of sandbanks (Commission of the European Community, 2007).

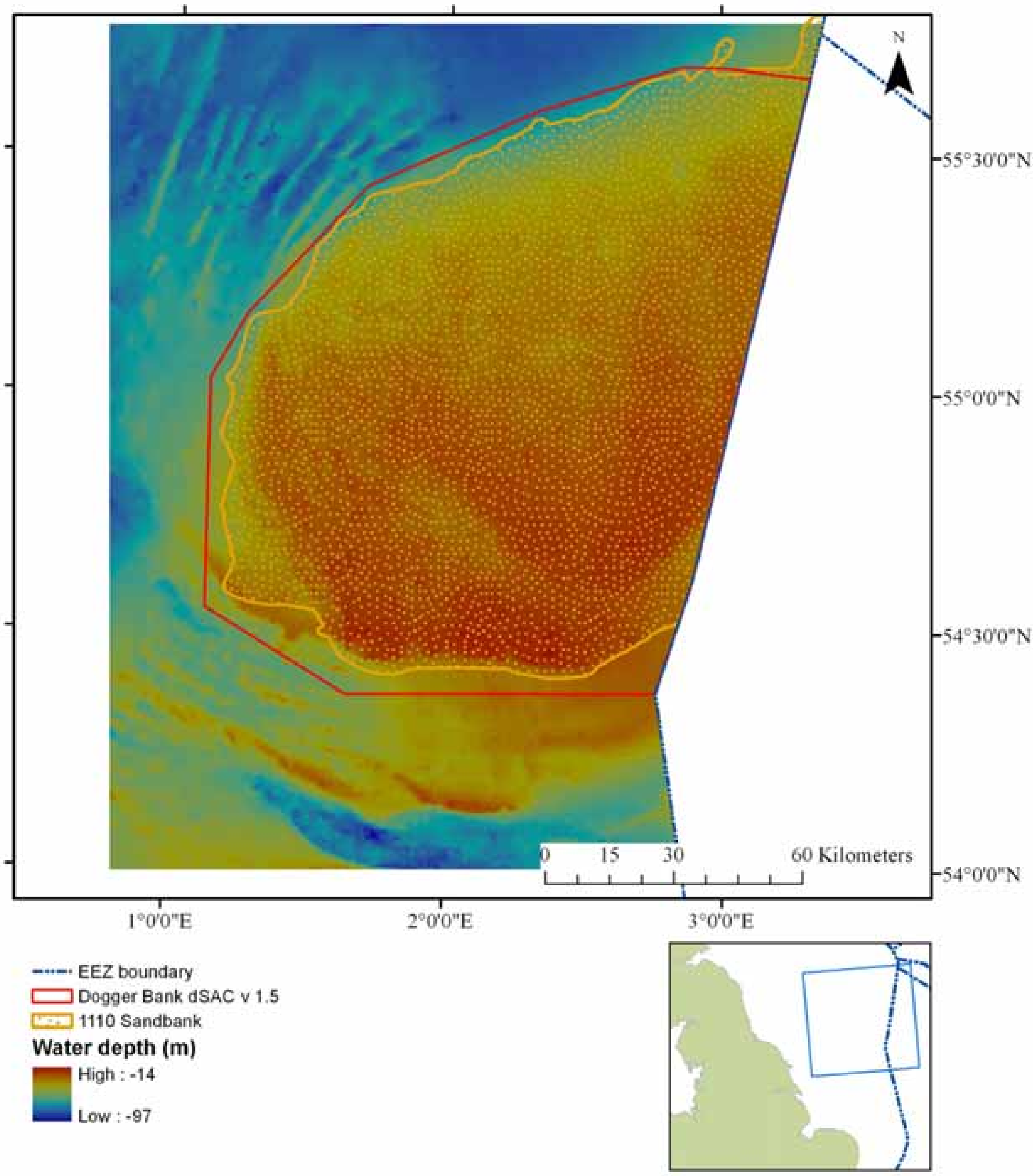

Figure 4.22. Extent of the Annex I sandbank habitat. No further Annex I habitats were identified.

In carrying out the survey of the Dogger Bank consideration was given to the identification of any areas that comprised other Annex I habitats, namely *Sabellaria* biogenic and stony reefs (1170-Reefs). Examination of both acoustic and ground-truthing data compiled during the survey did not indicate the presence of any *Sabellaria* reef within the area covered. However, it is possible that *Sabellaria* reef may be present in areas that were not investigated as part of this survey. The only way to confirm the presence or absence of *Sabellaria* reef within the proposed dSAC would be to carry out a more intensive survey with 100% coverage of the area at sufficiently high acoustic resolution. However, such a survey may be prohibitively costly and time consuming due to the extent of the area.

Some regions of the coarse sediments identified within the proposed dSAC were found to contain proportions of cobble. However, such areas identified during the survey contained insufficient densities of cobble for them to be considered an Annex I stony reef.

4 Discussion

4.1 Comparison of Dogger Bank habitats and ecology with other sandbanks in UK waters

4.1.1 Notable characteristics of Annex 1 Habitat 1110 ‘sandbanks which are slightly covered by sea water all the time’

In the European Commission’s 2007 Guidance (Commission of the European Community, 2007) the interpretation of sandbanks which are slightly covered by sea water all the time is described as ‘elevated, elongated, rounded or irregular topographic features, permanently submerged and predominantly surrounded by deeper water’. Representative flora of such habitats present in the North Atlantic and North Sea are given as ‘*Zostera* sp. and free living species of the *Corallinaceae* family’. However, it is further stated that ‘on many sandbanks macrophytes do not occur’. Similarly, typical fauna associated with submerged sandbanks of North Atlantic and North Sea are given as ‘invertebrate and demersal fish communities of sandy sublittoral (e.g. polychaete worms, crustacean, anthozoans, burrowing bivalves and echinoderms, *Ammodytes* spp., *Callionymus* spp., *Pomatoschistus* spp., *Echiichtys vivipera*, *Pleuronectes platessa* and *Limanda limanda*)’.

4.1.2 Distribution, ecology and status of potential sandbank sites in UK waters

SACs have been designated for their sandbanks in UK coastal and offshore waters (Appendix 5, Table 1); (www.jncc.gov.uk).

Table 5.1. Offshore sandbanks identified as pSACs and dSACs in UK waters.

Site	Notable features
North Norfolk Sandbanks and Saturn Reef pSAC.	Open shelf ridge sandbanks of intermediate coastal influence, in full salinity water. The site contains an extensive series of ten main roughly linear sandbanks and associated fragmented smaller banks formed as a result of tidal processes. The sandbanks are not vegetated, and support communities of invertebrates characteristic of southern North Sea sandbanks, ranging from those typical of highly-mobile fine sand sublittoral sediments, to communities on the outer banks which are more species rich, reflecting the lower sediment mobility. The site also supports aggregations of Sabellaria spinulosa and is a multi-feature site also graded for Annex I biogenic reefs.
Dogger Bank dSAC	The Dogger Bank is a sandy mound formed through glacial processes and submergence through sea-level rise. It is non-vegetated and subject to intermediate coastal influence in full salinity waters. Sediments range from fine sands containing shell fragments on top of the bank to muddy sands at greater depths supporting invertebrate communities characterised by polychaete worms and echinoderms. Sandeels are an important prey resource supporting a variety of species including fish, seabirds and cetacean.

The North Norfolk sandbank is a possible offshore SAC (pSAC[2]) whilst the Dogger Bank is currently recommended to government as a draft offshore SAC (dSAC[3]).

The Dogger Bank, situated in open sea approximately 150 km north west of the Humber Estuary, differs from the North Norfolk sandbanks and other existing and potential SACs (Appendix 5) in a number of ways. Firstly, as described earlier, the North Norfolk sandbanks are formed by tidal processes whilst the Dogger Bank was formed by glacial processes prior to being submerged through sea level rise. The formation processes of the Dogger Bank has resulted in it being the largest continuous expanse of shallow sandbank in UK waters with sediments ranging from relatively coarse and shelly sands to more muddy sands at increasing depths. Its open sea location exposes the Dogger Bank to relatively substantial levels of wave energy thus preventing the colonisation of its sediments by vegetation although the seabed of large parts of the Dogger Bank is photic (Figure 4.17).

The differences in terms of its formation process, location and sediment type result in the faunal communities of the Dogger Bank being quite different to those of the North Norfolk sandbanks. For example, the faunal communities of the North Norfolk sandbanks are largely typical of highly mobile fine sands and are largely dominated by a sparse array of species that are characteristic of such sediments including the polychaete *Nephtys cirrosa* and the isopod *Eurydice pulchra*. Typical epifaunal and fish species found on the North Norfolk sandbanks include the crustacean *Pagurus bernhardus*, *Liocarcinus depurator* and *Carcinus maenus,* the echinoderm *Asterias rubens* and the sandeels *Ammodytes* spp. Conversely, the faunal communities of the Dogger Bank are heterogeneous and this is largely due to the relatively heterogeneous nature of available habitats present within the bank. For example, whilst the shallower regions are typified by species largely associated with fine/medium sands with low mud content (i.e. *Nephtys cirrosa* and *Bathyporeia* sp.) there is a transition of community characteristics with depth with deeper, more silty regions being characterised by increasing numbers of the polychaetes *Scoloplos armiger*, *Spiophanes bombyx* and *Magelona filiformis*.

Substrates present on the Dogger Bank are also distinguished from those of the North Norfolk sandbanks by the presence of coarse sediments forming elongate patches on the order of tens to thousands of metres. These features are ubiquitous on storm-dominated continental shelves worldwide and have been termed sorted bedforms (Murray and Thieler, 2004). They are believed to form by a feedback-related sorting process and appear to be spatially stable (Diesing *et al,* 2006). Subsequently, the presence of such coarser sediments results in the presence of distinct communities due to the greater availability of micro-niches in these habitats. Certain species dominate including the polychaetes *Glycera lapidum* and *Notomastus* spp.

Whilst characteristic epifaunal species of the Dogger Bank are largely similar to those identified from the North Norfolk sandbanks (i.e. *Pagurus bernhardus*, *Asterias rubens*, *Liocarcinus* spp., *Buglossoides luteum*, *Pomatoschistus* spp.) high numbers of additional species, including the burrowing sea urchin *Echinocardium cordatum* and the crustacean *Corystes cassivelaunus*, were also present in certain regions of the Dogger Bank. Similarly, certain attached epifaunal species not routinely associated with the North Norfolk sandbanks were relatively abundant on the Dogger Bank (i.e. *Alcyonidium digitata* and *Alcyonidium*

[2] pSAC: are sites that have been formally advised to UK Government, but not yet submitted to the European Commission.
[3] dSAC: are sites that have been formally advised to UK Government as suitable for selection as SACs, but have not been formally approved by Government as sites for public consultation.

diaphanum) and again this could be attributed to the presence of regions of coarse sediments on the Dogger Bank.

4.2 Discussion of the Dogger Bank conservation considerations

4.2.1 Functional and ecological importance of the Dogger Bank dSAC

The Dogger Bank has been identified as a special ecological region in the central North Sea due to a variety of reasons (Krönke and Knust, 1995; Gubbay *et al,* 2002). It differs from other regions of the North Sea due to several factors including its hydrographic regime, sediment composition, phytoplankton production regime and faunal community characteristics (Krönke and Knust, 1995). The hydrography comprises a relatively complex regime of currents and eddies and is influenced by the anti-clockwise residual current system of the North Sea (Krönke and Knust, 1995). Modelling studies suggest that during the summer months the bank is influenced by water masses originating from the southern central North Sea and those travelling from the north with both meeting and mixing at the bank (Bo Pederson, 1993). As a result the Dogger Bank receives nutrients transported from English and European coasts and the English Channel via the southern water mass whilst the northern part is influenced by the nutrient and contaminant rich Atlantic bottom waters.

Whilst the surface sediments of the Dogger Bank are typified by sand, gravelly sediments are also present. Muddy sediments are almost entirely absent within the proposed Dogger Bank dSAC boundary and only sporadic occurrences of muddy sand occur below the 50 m depth contour and are limited to small patches to the east of the UK median line, the Outer Silver Pit and in the gradually increasing water depths to the north. High levels of lead and cadmium contamination are present in the <20 µm fraction of Dogger Bank sediments though the source and bioavailability of such contaminants, along with their potential progression along the food web, is not yet fully understood (Krönke and Knust, 1995; Langston *et al,* 1999).

High levels of phytoplankton production on the Dogger Bank have been found to occur all year round (Brockmann and Wegner, 1985, Brockmann *et al,* 1990) and as only part of the dense spring bloom is consumed in the water column a significant amount settles out onto the seafloor surface (Nielson and Richardson, 1989). This, in turn, appears to have a direct effect on the macrofaunal communities in that they exhibit little seasonality (Reiss and Kröncke, 2005). Macrofaunal communities of the Dogger Bank have been studied intensively over many years (Dyer *et al,* 1983, Kröncke , 1990, Kröncke and Rachor, 1992, Kröncke and Knust, 1995, Wieking and Kröncke, 2001, 2003, 2005, Reiss and Kröncke, 2005). A study carried out in 2001 indicated that samples collected there are characterised by a higher abundance, higher species number and higher biomass in comparison with samples collected on more southerly sandbanks (DTI, 2001). Recent studies suggest that the spatial distributions of macrofaunal communities present on the bank are the result of a number of factors but are principally controlled by the availability, quantity and quality of food in the benthic boundary layer and this in turn is largely controlled by frontal systems such as the Flamborough/Frisian frontal system (Wieking and Kröncke, 2003).

4.2.2 Potential anthropogenic impacts on the Dogger Bank

Whilst the Dogger Bank has been identified as a special ecological region in the central North Sea (Kröncke and Knust, 1995, Gubbay, 2002) it has historically and more recently been subjected to a variety of anthropogenic impacts including commercial fishing, oil and gas activities, cable and pipeline installations, shipping and prospecting for potential aggregate extraction.

The North Sea as a whole has historically been the focus of a variety of fishing activities for many centuries (Greenstreet *et al,* 1999, Jennings *et al,* 1999, Frid *et al,* 2000). Fishing activities in the North Sea, by both UK and international vessels, have historically targeted a variety of pelagic species (i.e. herring, sprat and sandeel), demersal roundfish species (i.e. cod, haddock and whiting), flatfish species (i.e. plaice and sole) and crustacea (*Nephrops norvegicus*) (Purdom and Garrod, 1990, Catchpole *et al,* 2007). Over the centuries the North Sea fisheries have undergone significant changes in terms of target species, fishing techniques and spatial and temporal distribution of fishing effort (Purdom and Garrod, 1990). Whilst trawling and seine netting account for the majority of the North Sea demersal fish catch (Jennings and Cotter, 1999) a marked decline in the use of seine net gear has been reported in recent literature with a shift towards increasing use of light otter and Nephrops trawls, demersal pair trawls and beam trawls (Greenstreet *et al,* 1999, Jennings and Cotter, 1999).

Fishing intensity across the North Sea is known to be spatially variable with many areas being fished relatively infrequently (Jennings *et al,* 1999). Furthermore, the severity of impacts on the seabed and its associated fauna has been shown to vary according to the type of fishing gear employed (Jennings *et al,* 1999, Frid *et al,* 2000). For example, impacts on seafloor habitats, and their ecosystem function, associated with bottom fishing gears (e.g. trawls and dredges) have been shown to be particularly pronounced in that such techniques remove a large proportion of the biomass of both target and non-target species (Jennings *et al,* 1999), mortality and damage to surface dwelling and shallowly-buried macrofauna (Tuck *et al,* 1998), alteration of physical habitat features and sediment properties (Auster *et al,* 1996, Churchill, 1989).

The Dogger Bank was considered to be one of the great fishing grounds in the 19^{th} and 20^{th} centuries and an assessment of the Dogger Bank fisheries since 1950 has reported that the importance of this area has largely increased for the English component of the cod, haddock, plaice and demersal fisheries as a whole (Purdom and Garrod, 1990). However, North Sea landings of the main roundfish species have declined considerably since a peak during the 1970s and 1980s when stocks were boosted by good year classes. Whilst the Dogger Bank has historically been subjected to relatively intensive fishing effort, Frid *et al* (2000) reported no significant impacts on benthic communities that could be attributed to fishing were apparent in this area between the early 1920s and late 1980s. However, it is hypothesised that fishing induced changes in benthic communities may have already occurred on the Dogger Bank prior to the 1920s (Frid *et al,* 2000).

Most recently the Dogger Bank has been the focus of an industrial fishery for sandeels (Figure 5.1) with between 26% and 62% of the entire North Sea sandeel catch being reported to have been taken from the Dogger Bank between 2000-2006. Whilst the physical impacts of the sandeel fishery on seafloor habitats are believed to be minimal, due to their use of relatively light otter trawls, some concern has been raised regarding the effects of the removal of sandeels on populations of their predators, i.e. seabirds, marine mammals and demersal fish (Temming *et al,* 2004, Pinnegar *et al,* 2006, Engelhard *et al,* 2008).

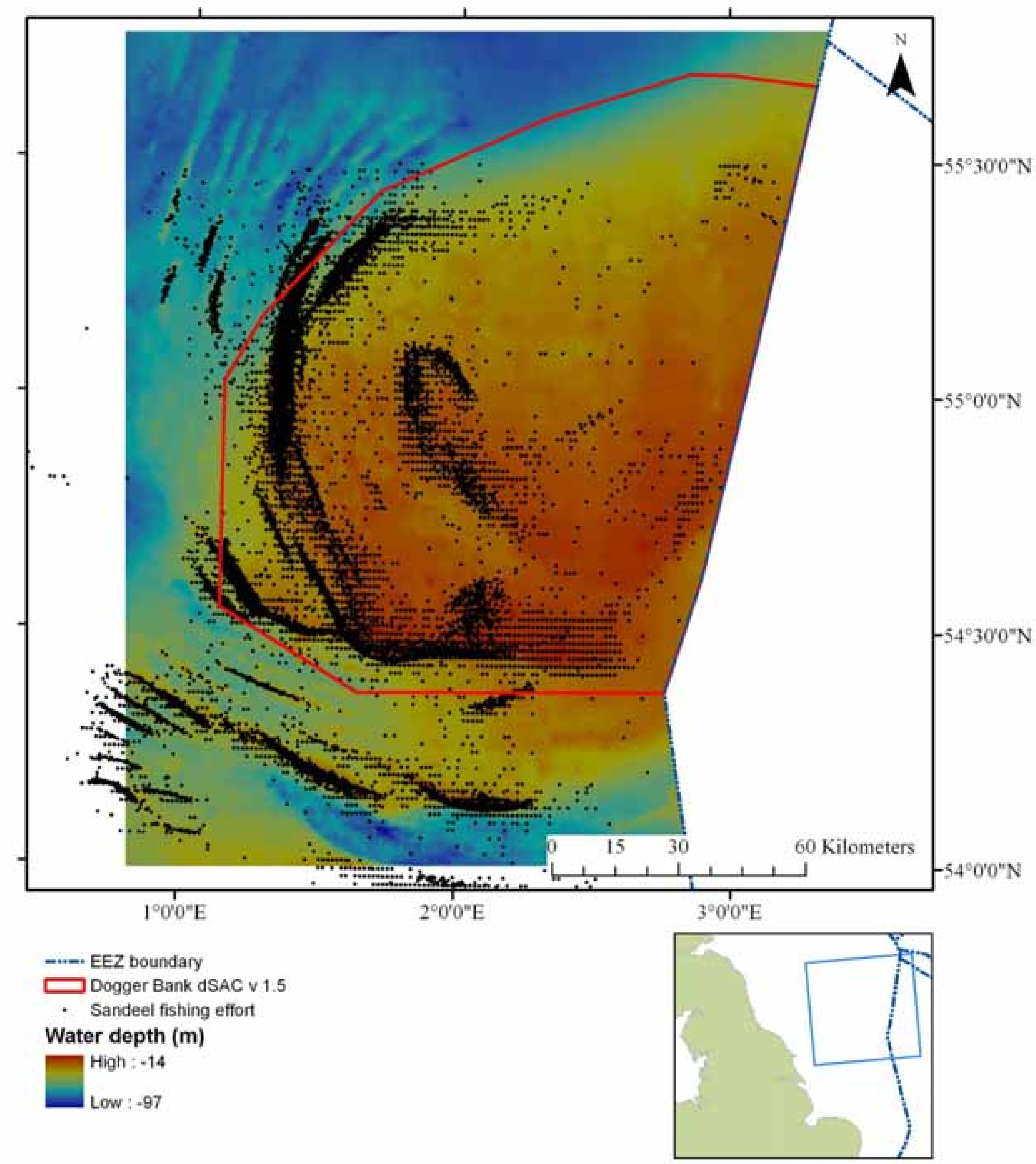

Figure 5.1. Distribution of sandeel fishing effort (Engelhard *et al,* 2008).

Some evidence of recent trawling was identified from the sidescan data collected during the Dogger Bank survey. Real-time observations of features observed in the sidescan record were recorded, along with their position, and these included the presence of trawl marks. The spatial distribution of such records is shown in Figure 5.2. Trawl marks centre in the eastern half of infralittoral fine sands dominating the top of the Bank. They are also found on deep circalittoral sand to the north of the bank and, less frequently, on circalittoral habitats to the south of the Bank.

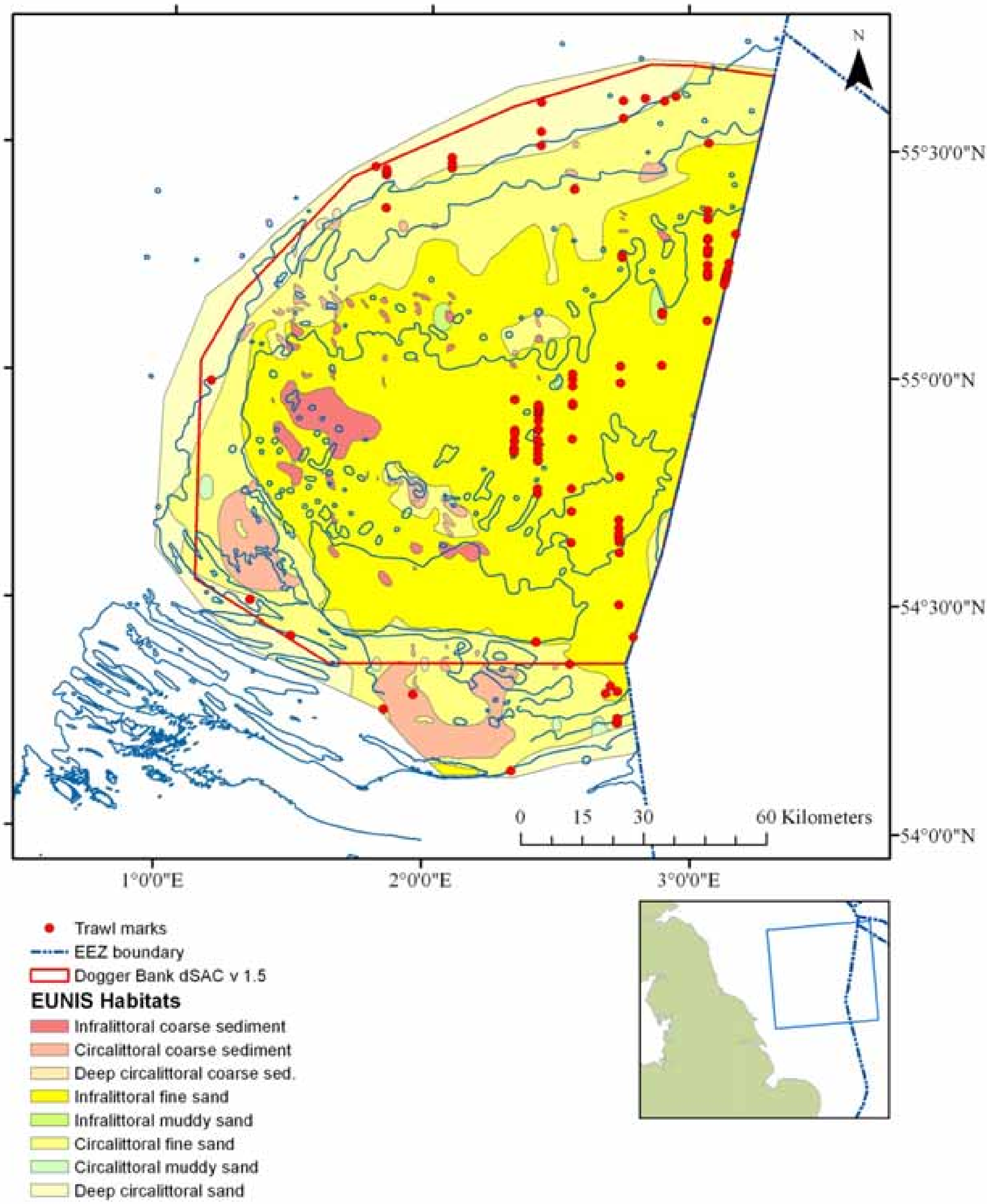

Figure 5.2. Location of trawl marks as identified with sidescan sonar in relation to mapped habitats.

Oil and gas related activities are also prevalent in the vicinity of the Dogger Bank with oil and gas pipelines known to extend across central and northern regions of the bank (Gubbay *et al*, 2002). Potential impacts arising as a result of such activities have been identified to include biological impacts from drilling waste and cuttings discharge up to a 5 km distance from the drilling site. Additionally, high levels of sediment mobilisation as a result of pipeline laying may also occur.

Whilst the central and northern areas of the North Sea do not receive as high a level of shipping activity as more southerly regions, levels of shipping traffic along with movements of fishing vessels are still considerable. Such levels of shipping activity have associated risks from oil spills and discharge of other pollutants, acoustic disturbance and alien species introductions via ballast water discharge (Gubbay *et al,* 2002).

4.3 Scientific justification underlying the proposed Dogger Bank draft SAC boundary

A detailed justification for the proposed dSAC boundary is given in the Boundary Justification Document attached as Appendix 1. In summary, the Dogger Bank is a morphologically distinguishable seabed feature with slopes in excess of 0.1° separating the sandbank from the ambient seafloor. At its summits it rises to water depths of less than 20 m. The morphology of the Dogger Bank is largely controlled by the extent of the Dogger Bank Formation, which forms its core. The formation is not found anywhere else in the North Sea. The dominant habitats are infralittoral fine sands and circalittoral fine sands with smaller, interspersed patches of infralittoral coarse sediment and circalittoral coarse sediment. Towards deeper waters (in excess of 45–55 m) these are replaced by deep circalittoral sand and deep circalittoral coarse sediment. Examination of associated spatial patterns in both epifaunal and infaunal communities across the Dogger Bank and adjacent areas found that the communities present are largely characteristic of those that are typically associated with subtidal sandbanks. Moreover, spatial patterns in both epifaunal and infaunal communities present appear to be primarily influenced by the observed variations in sediment characteristics and to a lesser extent water depth across the area (for further detail see sections 4.4 and 4.5).

The boundary for the Dogger Bank dSAC was delineated based on the derived slope boundary (Figure 4.4), which coincided extremely well with the distribution of sediment and fauna described above, and also coincided with the Dogger Bank Formation in the subsurface. An exception is made in the southeast of the Dogger Bank based on the fact that the Dogger Bank Formation extends beyond the slope boundary and because of the potential importance of this area as a sandeel nursery habitat (Cefas, 2007). Moreover, the dSAC boundary was kept as simple as possible to avoid an unnecessary number of nodes. Compared to the previous version of the dSAC boundary (EMU Ltd., 2008), the northern boundary is situated further to the north by up to 25 km. This is due to the revised boundary following a line up to the point where a slope of 0.1° or more is no longer encountered (needs re-phrasing for clarity). From thereon, a straight line towards the German north-western node was drawn (in line with Boedeker *et al,* 2006) until it met the UK-Dutch boundary. The total size of the proposed Dogger Bank draft SAC is 1,505,711 ha (15,057 km^2).

4.4 Suitability and cost-effectiveness of techniques utilised for seabed investigations of the Dogger Bank draft SAC

4.4.1 Acoustic techniques

Sidescan sonar and multibeam echosounder both deliver high-resolution and full-coverage images of the seabed across a certain swathe (see section 3.1.1). They are therefore capable of mapping the seabed in high detail. There are, however, differences between the two systems: sidescan sonar delivers the highest-resolution backscatter images of the seabed, and mainly due to the chirp system employed, covered a wider swathe at the water depths encountered in the study site. This holds especially true for the shallowest areas. Multibeam, on the other hand, has the advantage that is collects both bathymetry and backscatter simultaneously. Other than sidescan data, that provides geo-referenced images (geotiffs), the outputs can be treated numerically which gives more flexibility for data analysis. Multibeam systems also allow for higher survey speeds, thereby (partly) compensating for the lower swathe, when it comes to calculating the covered area per time. Whichever system is more cost-effective is therefore highly dependent on the area to be surveyed and water depths encountered. Another advantage of multibeam systems is the higher positioning accuracy, due to the fact that the offsets to the GPS antenna are static, while the layback of a towed sidescan sonar is variable.

Collection of high-resolution acoustic data is crucial to investigate, detect and map small-scale and patchy habitats like *Sabellaria* and cobble reefs. It is also indispensable for a better understanding of sediment distribution, bedforms and habitats, which could not be gained with other techniques such as singlebeam echosounder data or grab samples. For example, from the analysis of sidescan sonar and multibeam data, in conjunction with ground-truthing, it is clear that coarse sediment is limited to rather small-scale patches on the order of hundreds to thousands of metres in lengths and tens to hundreds of metres in widths. This is in striking contrast to the seabed maps previously produced, showing large areas of coarse sediment on the order of several tens of kilometres.

Good quality singlebeam echosounder data, with survey line spacing on the order of 100 m or below, is, however, sufficient for a morphological delineation of sandbanks based on critical slopes (slope analysis). Such datasets are routinely collected by the United Kingdom Hydrographic Office and the Maritime and Coastguard Agency (or on behalf of them) and made available via SeaZone as so-called Digital Survey Bathymetry (DSB). Although purchasing licences to use these datasets might be costly, it is still more cost-effective than conducting a new survey. Resolution of such singlebeam echosounder data is also normally sufficient to derive meaningful morphological units on a broad scale. However, DSB does not have attached backscatter data and therefore does not provide insights into the texture of the seabed.

4.4.2 Ground-truthing techniques

Ground-truthing techniques are indispensable in seabed and habitat mapping as acoustically-sensed results need to be transferred into sediment and habitat classes. PSA data of obtained sediment samples is crucial to derive sediment classes. The most widely used sediment classification is that of Folk (1954, 1980), yielding 15 different sediment classes based on the percentages of mud, sand and gravel content. The results can then be translated into four broader classes, which are better aligned with the EUNIS classification system (Connor *et al,* 2004; Long, 2006). However, such classifications do not necessarily closely correspond with acoustic backscatter strength as obtained with sidescan sonar or multibeam echosounder. In this case, there was a good correspondence between ‘sand and muddy sand’ and the expected low backscatter response. However, sites that were classed as ‘coarse sediment’ revealed an ambiguous backscatter response with both low and high backscatter classes. This indicates that the boundary between the two EUNIS classes at 5% gravel content is not reflected in the backscatter response, but this could not be expected anyway. Moreover, results indicate that sediments plotted in the same location of the Folk triangle can have markedly different grain-size distributions and hence backscatter responses.

Several studies have attempted to link backscatter and grain-size (Collier and Brown, 2005; Davis *et al,* 1996; Goff *et al,* 2000), but these have mainly focused on average characteristics such as mean grain-size. Although it is undeniable that there is a relationship, this is much more complicated than could be described by a simple linear regression and far from being understood. How this links up with ecologically significant parameters is even less clear. More research is clearly needed to adequately determine the linkages.

The application of additional ground-truthing techniques, utilising towed video, beam trawling and grabbing techniques, are essential in investigating associations between the habitats identified using acoustic techniques and the faunal communities associated with them. In achieving this it was particularly effective, both in terms of time and cost, to be able to process the acoustic data rapidly, throughout the survey, in order to better inform the positioning of subsequent ground-truthing stations. This project clearly benefited from the integration of scientific skills from a range of scientific disciplines. For example, having a wide range of expertise available throughout the survey aided rapid decision-making ensuring that adequate spatial coverage of all strata of interest (i.e. sediment types, depth ranges etc.) was achieved.

4.5 Recommendations for strategies and techniques employed for investigation of Annex 1 sandbanks

There are a number of criteria to address when studying sandbanks, namely (1) a robust delineation of the sandbank based on the criteria mentioned in Annex 1 of the Habitats Directive and (2) the production of a habitat map of the sandbank according to a widely recognised habitat classification system (e.g. EUNIS). To serve purpose 1 it is sufficient to gather decent quality singlebeam echosounder data of sufficient line spacing in order to derive a morphological delimitation of the bank structure. Further information is then needed to establish whether seabed sediments and associated fauna (and flora) are typical of a sandbank. Such an approach can often be performed as a desk study, given the relevant data (e.g. DSB, PSA data, faunal data) is available. This does, however, yield only a broad picture of the sandbank and small-scale habitats of conservation interest (e.g. cobble reefs, *Sabellaria* reefs) would certainly be missed.

To derive a more detailed picture of a sandbank, acoustic methods (sidescan sonar, multibeam echosounder) in conjunction with ground-truthing can deliver much of the necessary data. It is always advisable to obtain 100% coverage bathymetry and backscatter data, as only such an approach will yield a complete picture of the seabed. However, costs can be prohibitive, especially when the study site is large and shallow (which is often the case with sandbanks). Therefore other survey strategies (e.g. grid, corridors) need to be taken. There is no preference of one approach over the others. The chosen approach should always take into account the structure of the features to be mapped (if known) and the data available from previous studies (if any). Meaningful habitat maps can be produced even if the coverage is limited, but they should always be "read" with these limitations in mind.

Ground-truthing stations should be chosen based on the different acoustic classes encountered during the survey and taking into account different depths and a reasonable distribution of sampling points across the whole area. It would also be advisable to model biological zones upfront in order to equally cover different zones present in the study site.

5 Conclusions

5.1 Summary of habitats encountered on the Dogger Bank

Eight different habitats (EUNIS level 4) were encountered on the Dogger Bank:

- A5.13 Infralittoral coarse sediment
- A5.14 Circalittoral coarse sediment
- A5.15 Deep circalittoral coarse sediment
- A5.23 Infralittoral fine sand
- A5.24 Infralittoral muddy sand
- A5.25 Circalittoral fine sand
- A5.26 Circalittoral muddy sand
- A5.27 Deep circalittoral sand

The spatial distribution of the habitats is shown in Figure 4.20.

There is a clear distinction between infaunal groups supported by coarse sediment and those found in fine sand and muddy sand. This indicates that substrate type (grain size) has a major influence on the associated infauna. Biological zones are, however, less clearly reflected by the infaunal groups, displaying significant overlap. This clearly indicates that depth-related changes in infaunal groups are transitional rather than sharp.

5.2 Recommended draft SAC boundary

The boundary for the Dogger Bank dSAC has been largely drawn based on the derived slope boundary (Figure 4.4), which coincides well with the extension of the Dogger Bank Formation in the subsurface. An exception is made in the southeast of the Dogger Bank based on the fact that the Dogger Bank Formation extends beyond the slope boundary and because of the potential importance of this area as a sandeel nursery habitat (Cefas, 2007). The total size of the proposed Dogger Bank draft SAC is 1,505,711 ha (15,057 km^2). The revised recommended dSAC boundary incorporates the extent of the Annex I habitat described as ‘sandbanks, which are slightly covered by sea water all the time’.

5.3 Conservation interest of the proposed Dogger Bank draft SAC

The Dogger Bank has been identified as a special ecological region in the central North Sea as it differs from other regions of the North Sea due to several factors including its hydrographic regime, sediment composition, phytoplankton production regime and faunal community characteristics (Krönke and Knust, 1995). During the summer months the bank is influenced by water masses originating from the southern central North Sea and those travelling from the north with both meeting and mixing at the Dogger Bank (Bo Pederson, 1993). As a result the Dogger Bank receives nutrients transported from the English coast and the English Channel via the southern water mass whilst the northern part is influenced by the nutrient and contaminant rich Atlantic bottom waters. High levels of phytoplankton production on the Dogger Bank have been found to occur all year round (Brockmann and Wegner, 1985, Brockmann *et al,* 1990) and as only part of the dense spring bloom is consumed in the water column a significant amount settles out onto the seafloor surface

(Nielson and Richardson, 1989). This, in turn, appears to have a direct effect on the macrofaunal communities in that they exhibit little seasonality (Reiss and Kröncke, 2005). Macrofaunal communities are characterised by a higher abundance, higher species number and higher biomass in comparison with samples collected on more southerly sandbanks (DTI, 2001). Recent studies suggest that the spatial distributions of macrofaunal communities present on the bank are the result of a number of factors but are principally controlled by the availability, quantity and quality of food in the benthic boundary layer and this in turn is largely controlled by frontal systems such as the Flamborough/Frisian frontal system (Wieking and Kröncke, 2003).

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7 References

ABERDEEN UNIVERSITY MARINE STUDIES (AUMS) Ltd., 1989a. Block 44/12 single well pre and post environmental surveys 1989. Prepared for Marathon Oil UK Ltd., **Volume 1**.

ABERDEEN UNIVERSITY MARINE STUDIES (AUMS) Ltd., 1989b. Block 44/12 single well pre and post environmental surveys 1989. Prepared for Marathon Oil UK Ltd., **Volume 2**.

AUSTER, P.J., MALATESTA, R.J., LANGTON, R.W., WATLING, L., VALENTINE, P.C., DONALDSON, C.L.S., LANGTON, E.W., SHEPHEARD, A.N. & BABB, I.G., 1996. The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (northwest Atlantic): implications for conservation of fish populations. *Reviews in Fisheries Science*, **4**, 185-202.

BALSON, P.S. & JEFFERY, D.H. 1990. The glacial sequence of the southern North Sea: *In:* EHLERS, J., GIBBARD, P.L. & ROSE, J. (Eds.), *Glacial deposits in Great Britain and Ireland*. A.A.Balkema, pp. 245-253.

BOEDEKER, D., KRAUSE, J.C. & VON NORDHEIM, H. 2006. Interpretation, identification and ecological assessment of the NATURA 2000 habitats "sandbank" and "reef". *In:* VON NORDHEIM, H., BOEDEKER, D., KRAUSE, J.C. (Eds.), *Progress in Marine Conservation in Europe*. *Natura 2000 Sites in German Offshore Waters*. Springer, Berlin, Heidelberg, New York, pp. 47-64.

BLONDEL, P. & MURTON, B.J. 1997. *Handbook of seafloor sonar imagery*. Wiley-Praxis Series in Remote Sensing. John Wiley & Sons, Chicester, 314 pp.

BO PEDERSEN, F. 1993. The oceanographic and biological tidal cycle in shallow sea fronts in the North Sea and in the English Channel. *Estuarine Coastal and Shelf Science*, **38(3)**, 249-269.

BOYD, S.E., COGGAN, R.A., BIRCHENHOUGH, S.N.R., LIMPENNY, D.S., EASTWOOD, P.E., FOSTER-SMITH, R.L., PHILPOTT, S., MEADOWS, W.J., JAMES, J.W.C., VANSTAEN, K., SOUSSI, S. & ROGERS, S. 2006. The role of seabed mapping techniques in environmental monitoring and management. *Science Series Technical Report*, Cefas Lowestoft, **127**, 170 pp.

BROCKMANN, U. & WEGNER, G. 1985. Hydrography, nutrient and chlorophyll distribution in the North Sea in February 1984. *Archiv fur Fischereiwissenschaft*, **36**, 27-45.

BROCKMANN, U., LAANE, R.W.P.M. & POSTMA, H. 1990. Cycling of nutrient elements in the North Sea. *Netherlands Journal of Sea Research*, **26**, 239-264.

BROWN, C.J., COOPER, K.M., MEADOWS, W.J., LIMPENNY, D.S. & REES, H.L. 2002. Small-scale mapping of seabed assemblages in the eastern English Channel using sidescan sonar and remote sampling techniques. *Estuarine, Coastal and Shelf Science*, **54(2)**, 263-278.

BROWN, C.J., HEWER, A.J., MEADOWS, W.J., LIMPENNY, D.S., COOPER, K.M. & REES, H.L. 2004. Mapping seabed biotopes at Hastings Shingle Bank, eastern English Channel. Part 1. Assessment using sidescan sonar. *Journal of the Marine Biological Association of the United Kingdom*, **84(3)**, 481-488.

BUTLER, J., NEUMAN, M., PINKARD, D., KVITEK, R. & COCHRANE, G. 2006. The use of multibeam sonar mapping techniques to refine population estimates of the endangered white abalone (Haliotis sorenseni). *Fishery Bulletin*, **104(4)**, 521-532.

CALLAWAY, R., ALSVÅG, J., DE BOOIS, I., COTTER, J., FORD, A., HINZ, H., JENNINGS, S., KRÖNKE, I., LANCASTER, J., PIET, G., PRINCE, P. & EHRICH, S. 2002. Diversity and community structure of epibenthic invertebrates and fish in the North Sea. *ICES Journal of Marine Science*, **59**, 1199-1214.

CAMERON, T.D.J., CROSBY, A., BALSON P.S., JEFFERY, D.H., LOTT, G.K., BULAT, J. & HARRISON, D.J. 1992. *United Kingdom offshore regional report: the geology of the southern North Sea*. (London: HMSO for the British Geological Survey.)

CARR, S.J. 1999. The micromorphology of Last Glacial Maximum sediments in the Southern North Sea. *Catena*, **35**, 123-145.

CATCHPOLE, T.L., TIDD, A.N., KELL, L.T., REVILL, A.S. & DUNLIN, G. 2007. The potential for a new Nephrops trawl design to positively affect North Sea stocks of cod, haddock and whiting. *Fisheries Research*, **86**, 262-267.

CEFAS, 2004. Spatial and temporal distribution of predators and predator/prey interactions. *Cefas Contract Report* MF0317.

CEFAS, 2007. Multispecies fisheries management: a comprehensive impact assessment of the sandeel fishery along the English east coast. *Cefas Contract Report* MF0323/01.

CEFAS, 2008. Data Review and Slope Analysis Report. JNCC Contract Reference: F90-01-1221, 21pp**.**

CHURCHILL, J.H. 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. *Continental Shelf Research*, **9**, 841-864.

CLARKE, K.R. & GORLEY, R.N. 2006. PRIMER v6: user manual/tutorial. PRIMER-E: Plymouth.

COCO, G., MURRAY, A.B. & GREEN, M.O. 2007. Sorted bed forms as self-organized patterns: 1. Model development. *Journal of Geophysical Research*, **112**, F03015, doi:10.1029/2006JF000665.

COLLIER, J.S. & BROWN, C.J. 2005. Correlation of sidescan backscatter with grain size distribution of surficial seabed sediments. *Marine Geology*, **214(4)**, 431-449.

COMMISSION OF THE EUROPEAN COMMUNITY (CEC), 2007. *The interpretation manual of European Union Habitats*-EUR27[Online]. Brussels European Commission DG

Environment. Available from: http://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm

CONNOR, D.W., ALLEN, J.H., GOLDING, N., HOWELL, K.L., LIEBERKNECHT, L.M., NORTHERN, K.O. & REKER, J.B. 2004. The Marine Habitat Classification for Britain and Ireland Version 04.05. Joint Nature Conservation Committee, Peterborough.

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*. Joint Nature Conservation Committee, Peterborough.

DAAN, R. & MULDER, M. 2001. *The macrobenthic fauna in the Dutch sector of the North Sea in 2000 and a comparison with previous data*. Royal Netherlands Institute for Sea Research (NIOZ), Texel, The Netherlands.

DAAN, R. & MULDER, M. 2006. *The macrobenthic fauna in the Dutch sector of the North Sea in 2005 and a comparison with previous data*. Royal Netherlands Institute for Sea Research (NIOZ), Texel, The Netherlands.

DAVIS, K.S., SLOWEY, N.C., STENDER, I.H., FIEDLER, H., BRYANT, W.R. & FECHNER, G. 1996. Acoustic backscatter and sediment textural properties of inner shelf sands, northeastern Gulf of Mexico. *Geo-Marine Letters*, **16(3)**, 273-278.

DAVIS, R.A. & BALSON, P.S. 1992. Stratigraphy of a North Sea tidal sand ridge. *Journal of Sedimentary Petrology*, **62(1)**, 116-121.

DEGRAER, S., WITTOECK, J., APPELTANS, W., COOREMAN, K., DEPREZ, T., HILLEWART, H., HOSTENS, K., MEES, J., VANDEN BERGHE, E. & VINCX, M. 2006. *The macrobenthos of the Belgian part of the North Sea*. Biology Department, Ghent University.

DIESING, M., KUBICKI, A., WINTER, C., SCHWARZER, K. 2006. Decadal scale stability of sorted bedforms, German Bight, southeastern North Sea. *Continental Shelf Research*, **26(8)**, 902-916.

DTI, 2001. Strategic environmental assessment of the mature areas of the offshore North Sea. SEA2 Consultation Document 2001. Report to the Department of Trade and Industry.

DTI, 2005. Hunter Field Development Environmental Statement. Prepared for Caledonia Caister Limited by Rudell Blanchard. DTI Reference W/2559/2005.

EMU LTD. 2003. Marine aggregate extraction license Application Area 466 North West Rough: Environmental Statement. Prepared by Emu Limited on behalf of RMC Marine Limited. Ref. J/1/06/0316.

EMU LTD. 2007. Area 485 Southernmost Rough: Environmental Statement. Prepared by Emu Limited on behalf of CEMEX Marine UK Limited. Ref. J/1/06/0642/0575.

EMU LTD. 2008. Dogger Bank Offshore Draft SAC Seabed Investigations. Data Review & Slope Analysis Report: Recommendations for the revision of the dSAC boundary, JNCC Internal Report, 12 pp.

ENGELHARD, G.H., VAN DER KOOIJ, J., BELL, E.D., PINNEGAR, J.K., BLANCHARD, J.L., MACKINSON, S. & RIGHTON, D.A. 2008. Fishing mortality versus natural predation on diurnally migrating sandeels *Ammodytes marinus*. *Marine Ecology Progress Series*, **369**, 213-227.

FITCH, S., THOMSON, K. & GAFFNEY, V. 2005. Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research*, **64**, 185–196.

FOLK, R. L. 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *Journal of Geology*, **62**, 344-359.

FOLK, R.L. 1980. *Petrology of sedimentary rocks*. Hemphill Publishing Company, Austin, Texas, 184 pp.

FOX, C.J., TAYLOR, M., DICKEY-COLLAS, M., FOSUM, P., KRAUS, G., ROHLF, N., MUNK, P., VAN DAMME, C.J.G., BOLLE, L.J., MAXWELL, D.L. & WRIGHT, P.J. 2008. Mapping the spawning grounds of North Sea cod (*Gadus morhua*) by direct and indirect means. Proceedings of the Royal Society of London Series B, **275(1642)**, 1543-1548.

FRID, C.L.J., HARWOOD, K.G., HALL, S.J. & HALL, J.A. 2000. Long-term changes in the benthic communities on North Sea fishing grounds. *ICES Journal of Marine Science*, **57**, 1303-1309.

FRIEDLANDER, A.M., BOEHLERT, G.W., FIELD, M.E., MASON, J.E., GARDNER, J.V. & DARTNELL, P. 1999. Sidescan sonar mapping of benthic trawl marks on the shelf and slope off Eureka, California. *Fishery Bulletin*, **97(4)**, 768-801.

GATLIFF, R.W., RICHARDS, P.C., SMITH, K., GRAHAM, C.C., MCCORMAC, M., SMITH, N.J.P., LONG, D., CAMERON, T.D.J., EVANS, D., STEVENSON, A.G., BULAT, J. & RITCHIE, J. D. 1994. *United Kingdom offshore regional report: the geology of the central North Sea*. (London: HMSO for the British Geological Survey.)

GLEMAREC, M. 1973. The benthic communities of the European North Atlantic continental shelf. *Oceanogr. Mar. Biol. Ann. Rev*., **11**, 263-289.

GOFF, J.A., OLSON, H.C. & DUNCAN, C.S. 2000. Correlation of sidescan backscatter intensity with grain-size distribution of shelf sediments, New Jersey margin. *Geo-Marine Letters*, **20(1)**, 43-49.

GREENSTREET, S.P.R., SPENCE, F.B., SHANKS, A.M. & MCMILLAN, J.A. 1999. Fishing effects in northeast Atlantic shelf seas: patterns in fishing effort, diversity and community structure. II. Trends in fishing effort in the North Sea by UK registered vessels landing in Scotland. *Fisheries Research,* **40**, 107-124.

GUBBAY, S., BAKER, C.M. & BETT, B.J. 2002. The Darwin Mounds and the Dogger Bank: case studies of the management of two potential Special Areas of Conservation in the offshore environment. A report to WWF-UK.

HALL, A.J., WATKINS, J. & HAMMOND, P.S. 1998. Seasonal variation in the diet of harbour seals in the south-western North Sea. *Marine Ecology Progress Series*, **170**, 269-281.

HALL, A.J. & WALTON, M.J. 1999. The diet of grey seals using faecal and fatty acid analysis. *In*: J. Harwood Ed. *Effects of large-scale industrial fisheries on non-target species* (ELIFONTS). Final Report under contract 95/78 to DGXIV of the European Commission.

HAMMOND, P.S., HALL, A. J. & PRIME, J.H. 1994a. The diet of grey seals around Orkney and other island and mainland sites in north-eastern Scotland. *Journal of Applied Ecology*, **31**, 340-350.

HAMMOND, P.S., HALL, A.J. & PRIME, J.H. 1994b. The diet of grey seals in the Inner and Outer Hebrides. *Journal of Applied Ecology*, **31**, 737-748.

HEIP, C. & CRAEYMEERSCH, J.A. 1995. Benthic community structures in the North Sea. *Helgoländer Meeresuntersuchungen*, **49**, 313-328.

HUMBORSTAD, O., NOTTESTAD, L., LOKKEBORG, S. & RAPP, H.T. 2004. RoxAnn bottom classification system, sidecan sonar and video sledge: spatial resolution and their use in assessing trawling impacts. *ICES Journal of Marine Science*, **61(1)**, 53-63.

IACMST contribution to Charting Progress - an Integrated Assessment of the State of UK Seas (the 2nd of five Reports).

JAMES, J.W.C. 2007. Sidescan sonar. *In*: R. Coggan *et al* (Eds.). *Review of Standards and Protocols for Seabed Habitat Mapping*. MESH, pp. 45-52.

JANSEN, J.H.F. 1976. Late Pleistocene and Holocene history of the Northern North Sea, based on acoustic reflection records. *Netherlands Journal of Sea Research*, **10**, 1-43.

JEFFREY, D. & LONG, D. 1989. Early Pleistocene sedimentation and geographic change in the UK sector of the North Sea (abstract). *Terra Abstracts*, **1**, 425

JELGERSMA, S., OELE, E. &WIGGERS, A.J. 1979. Depositional history and coastal development in the Netherlands and the adjacent North Sea since the Eemian. Acta Universitatis Upsaliensis. *Symposia Quigentesimum Celebrantis*, **Vol. 2**. Uppsala, pp. 115–142.

JENNINGS, S. & COTTER, A.J.R. 1999. Fishing effects in northeast Atlantic shelf seas: patterns in fishing effort, diversity and community structure. I. Introduction. *Fisheries Research*, **40**, 103-106.

JENNINGS, S., LANCASTER, J., WOOLMER, A. & COTTER, J. 1999. Distribution, diversity and abundance of epibenthic fauna in the North Sea. *Journal of the Marine Biological Association* UK, **79**, 385-399.

JOHNSTON, C.M., TURNBULL, C.G. & TASKER, M.L. 2002. Natura 2000 in UK Offshore Waters: Advice to support the implementation of the EC Habitats and Birds Directives in UK offshore waters, *JNCC Report* No 325, 162 pp.

JOON, B., LABAN, C. & VAN DER MEER, J.J.M. 1990. The Saalian glaciation in the Dutch part of the North Sea. *Geologie en Mijnbouw*, **69**, 151-158.

KLEIN, A. 2006. Identification of submarine banks in the North Sea and the Baltic Sea with the aid of TIN modelling. *In*: VON NORDHEIM, H., BOEDEKER, D. & KRAUSE, J.C. (Eds.). *Progress in Marine Conservation in Europe. Natura 2000 Sites in German Offshore Waters*. Springer, Berlin, Heidelberg, New York, pp. 97-110.

KOSTYLEV, V.E., TODD, B.J., FADER, G.B.J., COURTNEY, R.C., CAMERON, G.D.M. & PICKRILL, R.A. 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. *Marine Ecology Progress Series*, **219**, 121-137.

KOSTYLEV, V.E., COURTNEY, R.C., ROBERT, G. & TODD, B.J. 2003. Stock evaluation of giant scallop (*Placopecten magellanicus*) using high-resolution acoustics for seabed mapping. *Fisheries Research*, **60**, 479-492.

KRÖNKE, I. 1990. Macrofauna standing stock of the Dogger Bank. A comparison: II. 1951-52 versus 1985-87. Are changes in the community of the north-eastern part of the Dogger Bank due to environmental change? *Netherlands Journal of Sea Research*, **25(1/2)**, 189-198.

KRÖNKE, I. & RACHOR, E. 1992. Macrofauna investigations along a transect from the inner German Bight towards the Dogger Bank. *Marine Ecology Progress Series*, **91**, 269-276.

KRÖNKE, I. & KNUST, R. 1995. The Dogger bank: a special ecological region in the central North Sea. *Helgoländer Meeresuntersuchungen*, **49**, 335-353.

KRÖNKE, I., STOECK, T., WIEKING, G. & PALOJÄRVI, A. 2004. Relationship between structural and functional aspects of microbial and macrofaunal communities in different areas of the North Sea. *Marine Ecology Progress Series*, **282**, 13-31.

LANGSTON, W.J., BURT, G.R. & POPE, N.D. 1999. Bioavailability of metals in sediments of the Dogger Bank (Central North Sea): a mesocosm study. *Estuarine Coastal and Shelf Science*, **48**, 519-540.

LONG, D. 2006. Seabed sediment classification. MESH, 7pp.

LURTON, X. 2002. An introduction to underwater acoustics. Principles and applications. Springer, London, 347 pp.

MATTIOPOULOS, J., MCCONNAL, B., DUCK, C. & FEDAK, M. 2004. Using satellite telemetry and aerial counts to estimate space use by grey seals around the British Isles. *Journal of Applied Ecology*, **41**, 476-491.

MATTIOPOULOS, J., 2007. Preliminary methods for designing marine SACs for UK pinnipeds on the basis of space use. Special Committee On Seals 2007 Briefing Paper No. 07/08.

METOC PLC. 2004. Environmental Statement for the Cavendish Area development. *Metoc Report* No. 1274. RWE Dea document No. RD-CAV-SRT001.

MURRAY, A.B. & THIELER, E.R. 2004. A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and "rippled scour depressions". *Continental Shelf Research*, **24**, 295-315.

NIELSEN, T.G. & RICHARDSON, K. 1989. Food chain structure of the North Sea plankton communities: seasonal variations of the role of the microbial loop. *Marine Ecology Progress Series*, **56**, 75-87.

NIELSON, T.G., LOKKEGAARD, B., RICHARDSON, K., BO PEDERSON, F. & HANSEL, L. 1993. Structure of plankton communities in the Dogger Bank area (North Sea) during a stratified situation. *Marine Ecology Progress Series*, **95**, 115-131.

ORPIN, A.R. & KOSTYLEV, V.E. 2006. Towards a statistically valid method of textural sea floor characterization of benthic habitats. *Marine Geology*, **225(1-4)**, 209-222.

PICKRILL, R.A. & TODD, B.J. 2003. The multiple roles of acoustic mapping in integrated ocean management, Canadian Atlantic continental margin. *Ocean and Coastal Management*, **46(6-7)**, 601-614.

PINNEGAR, J.K., VAN DER KOOIJ, J., ENGELHARD, G.H., BLANCHARD, J.L., WARR, K.J. & RIGHTON, D. 2006. Small-scale variability in fish diet and whether or not this reflects local patterns in prey availability. ICES CM 2006/F:06.

PRAEG, D. & LONG, D. 1997. Buried Sub- and Proglacial Channels: 3D-Seismic Geomorphology. *In*: DAVIES, T.A., BELL, T., COOPER, A.K., JOSENHANS, H., POLYAK, L., SOLHEIM, A., STOKER, M.S. & STRAVERS, J.A. (eds) *Glaciated Continental Margins: an atlas of acoustic images*. Chapman & Hall, London. 66-67.

PURDOM, C.E. & GARROD, D.J. 1990. Fisheries on the Dogger Bank. ICES CM 4-12 October 1990. ICES Copenhagen, 5 pp.

REISS, H. & KRÖNKE, I. 2005. Seasonal variability of infaunal community structures in three areas of the North Sea under different environmental conditions. *Estuarine, Coastal and Shelf Science*, **65**, 253-274.

ROBERTS, J.M., BROWN, C.J., LONG, D. & BATES, C.R. 2005. Acoustic mapping using a multibeam echosounder reveals cold-water coral reefs and surrounding habitats. *Coral Reefs*, **24**, 654-669.

RYAN, D.A., BROOKE, B.P., COLLINS, L.B., KENDRICK, G.A., BAXTER, K.J., BICKERS, A.N., SIWABESSY, P.J.W. & PATTIARATCHY, C.B. 2007. The influence of geomorphology and sedimentary processes on shallow-water benthic habitat distribution: Esperance Bay, Western Australia. *Estuarine, Coastal and Shelf Science*, **72**, 379-386.

SCOS, 2007. Scientific advice on matters relating to the management of seal populations.

SEABEAM INSTRUMENTS, 2000. Multibeam Sonar - Theory of Operation. L-3 Communications, East Walpole, USA.

SHAND, C.W. & PRIESTLY, R. 1999. A towed sledge for benthic surveys. Scottish Fish Information Pamphlet No 22.

SHANNON, C.E. 1948. A Mathematical Theory of Communication. *The Bell System Technical Journal*, **27**: 379–423 and 623–656.

STOKER, M S., BALSON, P S., LONG, D. & TAPPIN, D R. In press. An overview of the lithostratigraphic framework for the Quaternary deposits on the United Kingdom continental shelf. *British Geological Survey Research Report*, 80 pp.

SZUMAN, M., BRENDT, C., JACOBS, C. & BEST, A. 2006. Seabed characterisation through a range of high-resolution acoustic systems - a case study offshore Oman. *Marine Geophysical Researches*, **27**, 167-180.

TEMMING, A., GÖTZ, S., MERGARDT, N. & EHRICH, S. 2004. Predation of whiting and haddock on sandeel: aggregative response, competition and diel periodicity. *Journal of Fish Biology*, **64**, 1351-1372.

TODD, B.J. 2005. Morphology and composition of submarine barchan dunes on the Scotion Shelf, Canadian Atlantic margin. *Geomorphology*, **67**, 487-500.

TUCK, I.D., HALL, S.J., ROBERTSON, M.R., ARMSTRONG, E. & BASFORD, D.J. 1998. Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea loch. *Marine Ecology Progress Series*, **162**, 227-242.

VAN DER KOOIJ, J., SCOTT, B.E. & MACKINSON, S. 2008. The effects of environmental factors on daytime sandeel distribution and abundance on the Dogger Bank. *Journal of Sea Research*, **60**, 201-209.

WIEKING, G. & KRÖNKE, I. 2001. Decadal changes in macrofauna communities on the Dogger Bank caused by large-scale climate variability. *Senckenbergiana maritima*, **31(2)**, 125-141.

WIEKING, G. & KRÖNKE, I. 2003. Macrofaunal communities of the Dogger Bank (central North Sea) in the late 1990s: spatial distribution, species composition and trophic structure. *Helgoland Marine Research*, **57**, 34-46.

WIEKING, G. & KRÖNKE, I. 2005. Is benthic trophic structure affected by food quality? The Dogger Bank example. *Marine Biology*, **146**, 387-400.

WHITE, J., JEGAT, V., VAN LANCKER, V., DELEU, S. & VANSTAEN, K. 2007. Multibeam Echo Sounders. *In*: R. Coggan *et al* (Eds.), *Review of Standards and Protocols for Seabed Habitat Mapping*. MESH, pp. 53-72.

WOOLFE, K.J. & MICHIBAYASHI, K. 1995. "BASIC" entropy grouping of laser-derived grain-size data: An example from the Great Barrier Reef. *Computers & Geosciences*, **21(4)**, 447-462.

WORSFOLD, T., HALL, D. & ASHELBY, C. 2005. Unicomarine procedural guidelines and quality control systems. Version 4.6.

Appendix 1. Data Review and Slope Analysis Report

1.1 Summary

An updated draft boundary for the Dogger Bank Special Area of Conservation (SAC) on the UK continental shelf is proposed. The definition of the boundary is based on multiple data layers including subsurface geology, slope, surficial sedimentology, epifauna, infauna and sandeel distribution data. The total size of the proposed Dogger Bank draft SAC is 1,505,711 ha (15,057 km^2).

1.2 Introduction

This document summarises the steps undertaken and the results obtained to derive a boundary for the Dogger Bank draft Special Area of Conservation (SAC) in accordance with the relevant definitions for sandbanks (European Commission, 2007; Johnston *et al,* 2002). Due to the fact that the definition of a sandbank according to European Commission (2007) is based on its morphology, surface sediments and associated biota, we have analysed different information layers and mapped their spatial extent. These include slope analysis of the Dogger Bank based on the methodology developed by Klein (2006), Particle Size Analysis (PSA) of surface sediments and mapping of textural groups (Folk, 1954; 1980) as well as mud content, and analysis of epifaunal and infaunal communities along with sandeel distribution patterns (Cefas, 2007; Engelhard *et al, in press*; van der Kooij *et al, in press*). In addition, we have also incorporated information on the subsurface geology, as the morphology of the Dogger Bank is largely controlled by the extent of the Dogger Bank Formation, a tabular depositional unit up to 42 m thick that was deposited in a proglacial environment at the end of the last ice age (Cameron *et al,* 1992).

1.3 Methods

1.3.1 Subsurface geology

The original outline of the Dogger Bank Formation is derived from BGS published 1:250,000 Quaternary geology map series (map sheets California, Swallow Hole, Silver Well and Dogger). It very clearly has an error, a mismatch along 55°N between the California and Swallow Hole map sheets. Around 55°20'N 1°30'E and 55°40'N 3°E the limit extends well beyond the draft SAC boundary (EMU Ltd., 2008). Examination of the latter area shows detailed mapping and it reflects the current seabed topography. It is therefore assumed to be correct. However in the former area it extends into an area of large relict sand ridges. The northern limit of the Dogger Bank Formation differs from the southern limit in that the latter is typically a steep and sudden end to an acoustic unit with faint sub-horizontal internal reflectors and a strong sub-horizontal basal reflector. On the northern side the basal reflector is also present but the internal structure is less obvious. It is frequently cut by channels infilled with a unit that is taken to be an uppermost part of the Dogger Bank Formation known as the Volans member. This is interpreted as an ice marginal feature, presumably formed during the initial retreat after the final ice advance over-riding the Dogger Bank Formation. The infill is lithologically the same as the Dogger Bank Formation and probably derived from it. These channels lead into the Botney Cut Formation to the north. They make mapping the northern extent of the Dogger Bank Formation difficult. BGS examined all the digital scans of sub-bottom profiles available from this area and consider that in several places what has been mapped are the Holocene sand ridges stacked against the Dogger Bank - often overlying a thin (basal) Dogger Bank Formation (Figure 1). Therefore the extent of the thick upstanding Dogger Bank Formation forming the Dogger Bank is slightly reduced. BGS have also examined the geological core descriptions to check that the proposed revised limit does not conflict with sample evidence. A revised Dogger Bank Formation outline has been drawn (see results and Figure 4).

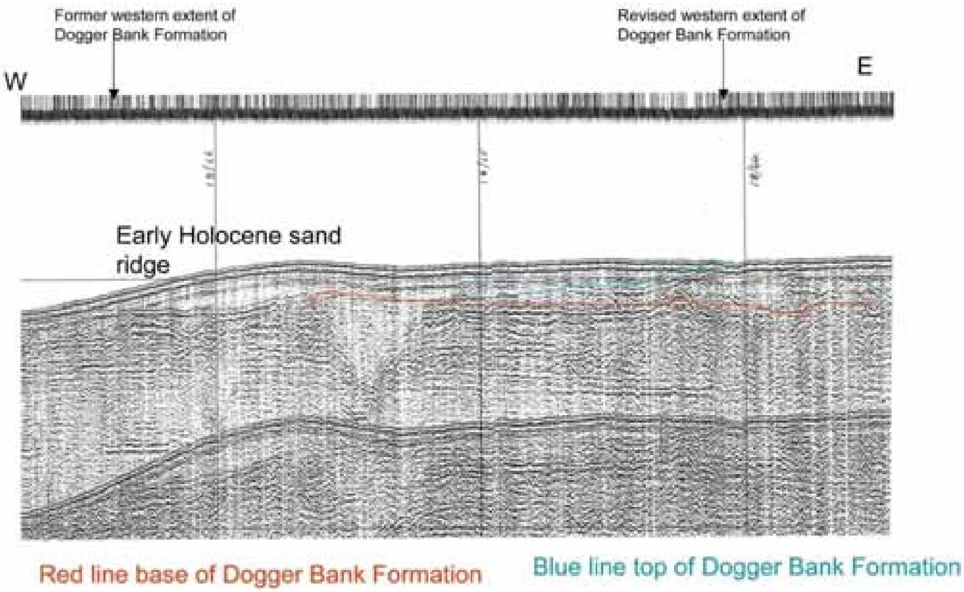

Figure 1. Example sub-bottom profile of the north-western end of the Dogger Bank Formation. Original interpretations encompassed early Holocene sand ridges stacked against the Dogger Bank Formation. These have been excluded in the revised outline of the Dogger Bank Formation, resulting in a shift of the boundary on the order of ten kilometres.

1.3.2 Bathymetry and slope

Three sources of bathymetry data were available from the UK part of the Dogger Bank and surrounding areas (Table 1):

Table 1. Sources of bathymetry data

Source	Type	Age	Spatial resolution
BGS	Depth observations from geophysical surveys	Predominantly 1960-1980	Good resolution along track; widely spaced survey lines over entire area
SeaZone	Single beam echosounder soundings	Unknown.One of survey blocks known to be collected in 1986	Good spatial coverage; limited to small area to southwest of Dogger Bank
Cefas	Multibeam echosounder soundings	3-19 April 2008	Very high resolution for swathe along survey lines; widely spaced lines over entire Dogger Bank

The SeaZone data provides a higher spatial resolution in a small area, compared to the widely spaced survey lines by BGS and Cefas providing depths along the survey lines only. The difference in spatial resolution was expected to result in differences between the datasets during analysis. It was therefore decided not to include the SeaZone data in the development of the small-scale bathymetry model of the Dogger Bank.

The BGS data was mainly derived from geophysical records during the continental shelf mapping programmes between 1960 and 1980. Seismic records were used to extract water depth along survey lines, generally every 100 to 300 m. Since the data was not collected for hydrographic purposes, no tidal corrections were applied to the data. This is not expected to cause major problems, as the tidal range on the Dogger Bank is generally less than 2 m. The lack of tidal corrections did not cause any issues in the generation of surface models and did not have an impact on resulting slope models.

The Cefas data was collected using a modern multibeam echosounder system, allowing production of bathymetric surfaces with a resolution of 1 m. As such a high resolution is not required for a broad-scale morphology analysis, the very high resolution Cefas data was re-sampled to a resolution of 20 m. The high-resolution multibeam lines were however inspected to confirm the slopes derived from the broad-scale model (see below). The depth soundings were reduced to Mean Sea Level, as this would be closer to the uncorrected BGS data than Chart Datum.

The combined BGS and Cefas data was used to create a bathymetry model for the Dogger Bank. The Golden Software Surfer v8 package was used to undertake initial data processing. The data was interpolated using the "Triangulation with Linear Interpolation" method with a grid spacing of 500 m. This interpolation method preserves the values of the original data (Figure 2) compared to other methods such as “Inverse distance weighting”, and will therefore also produce accurate slope calculations from the data. Slope calculations were undertaken in Golden Software Surfer v8.

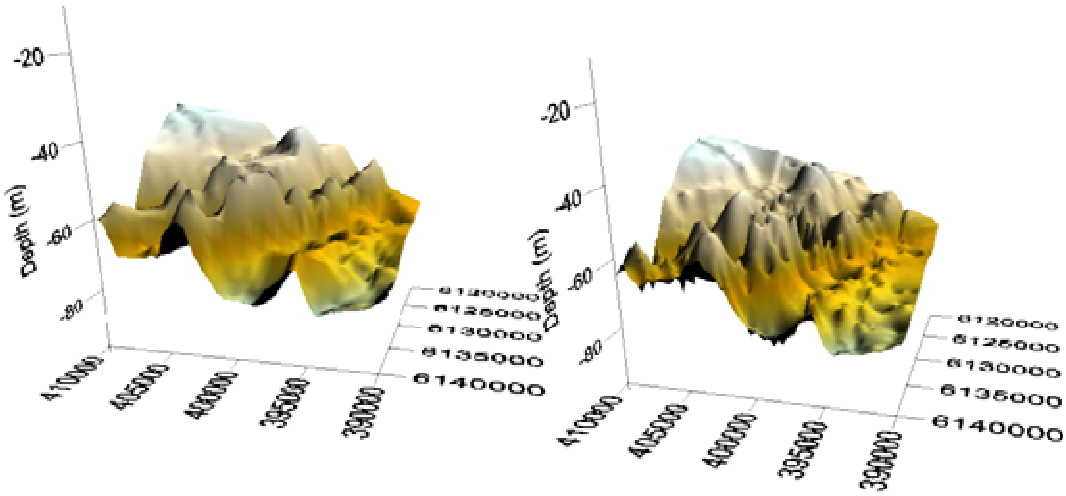

Figure 2. (left) Bathymetry surface using "Triangulation with linear interpolation" method; (right) Bathymetry surface using an "Inverse distance weighting" method, note the features created as a result of the interpolation method.

The "Profile Curvature" method was evaluated in an attempt to delineate the extent of the Dogger Bank as a geomorphological feature. This method determines the downhill or uphill rate of change in slope. The highest change in slope can generally be found at the bottom and top of a sloping surface and the technique can differentiate between these convex and concave profiles. The "Profile Curvature" calculation is therefore able to identify the foot of the slope around the Dogger Bank. Due to the interest in large-scale features rather than the smaller morphological features, the bathymetry dataset was filtered using 7 by 7 grid cells (3500 m by 3500 m) moving average filter. The generalised bathymetry surface model was used for "Profile Curvature" calculations (Figure 3).

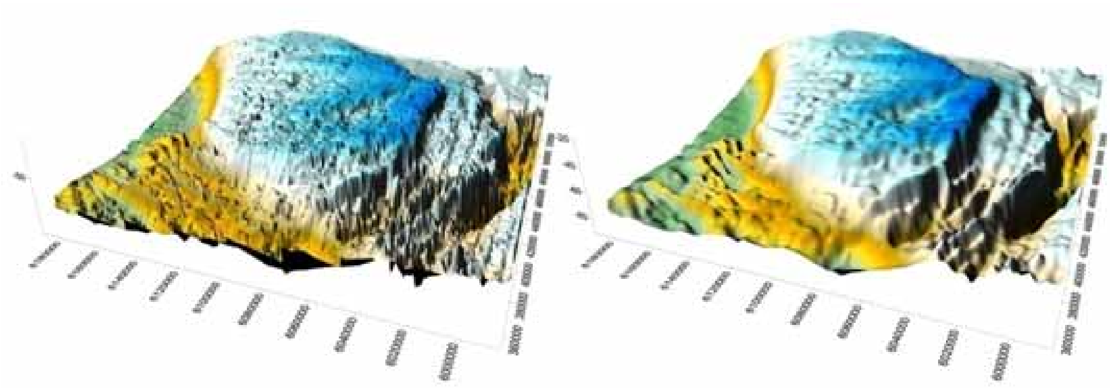

Figure 3. (left) Original TIN model of the Dogger Bank bathymetry; (right) Dogger Bank bathymetry after filtering.

The resulting grids were converted to ASCII CSV format and imported in ArcGIS 9.2. The point data set was then converted to a raster at the same resolution as originally created in Surfer. Single-beam bathymetric data of the Dutch part of the Dogger Bank was made available to us and was processed in the same way (though no profile curvature was calculated). Although this data is not strictly necessary for the task of delineating the UK part of the Dogger Bank, it nevertheless is very helpful to understand the wider picture.

1.3.3 Surface sediments

A total of 895 PSA samples were included. These were derived from (i) the BGS database from within a 25 km buffer around the working draft SAC boundary as proposed by EMU (637 samples), (ii) the Cefas database yielding one dataset covering the entire Dogger Bank (207 samples) and (iii) 51 samples collected during cruise CEnd 07/08 (Cefas, 2008). Folk textural groups were plotted based on mud, sand and gravel content (weight-%). Additionally, mud content was interpolated with the Natural Neighbour method and plotted in ArcGIS 9.2.

1.3.4 Epifauna

Video footage, and stills, generated from the video tows was examined following methods outlined in the NMBAQC Guidance Document (National Marine Biological Analytical Quality Control Scheme, 2008). For the purpose of informing decisions pertaining to the boundary definition abundance of faunal groups were examined using the SACFOR scale and stations were grouped according to the relative dominance of species present.

1.3.5 Infauna

Multivariate analyses of infaunal species abundance data were carried out using Primer v6 (Clarke and Gorley 2006). Hierarchical cluster analysis, using the Bray-Curtis similarity measure applied to root transformed species abundance data, was used to examine groupings of stations with similar species assemblages. The 'similarity profile' (SIMPROF) permutation test was also employed to look for statistically significant evidence of genuine clusters. The community groupings identified using SIMPROF were further explored by applying the similarity percentages program (SIMPER) to determine the contribution of individual species to the average similarity within the clusters.

1.3.6 Sandeel distribution patterns

The findings of Cefas contract M0323 'Multispecies fisheries management: a comprehensive impact assessment of the sandeel fishery along the English east coast' were utilised to inform decisions pertaining to the proposed Dogger Bank SAC boundary position in relation to the distribution of potentially important sandeel habitats. The main objectives of investigations carried out under the contract was to produce a spatially explicit, multispecies model that can be used to explore how alternative sandeel fishery management options for the Dogger Bank may impact on sandeels and their predators. However, data collated during field investigations carried out under previous Defra funded contracts MF0315, MF0317 and MF0318 were utilised to provide insights into the environmental conditions that influence sandeel distribution patterns.

1.4 Results

1.4.1 Subsurface geology

Figure 4 shows the extent of the Dogger Bank Formation on the UK continental shelf as outlined in the BGS Quaternary geology map series (purple) and the revised boundary (blue) after correcting for errors found when inspecting available sub-bottom profiles.

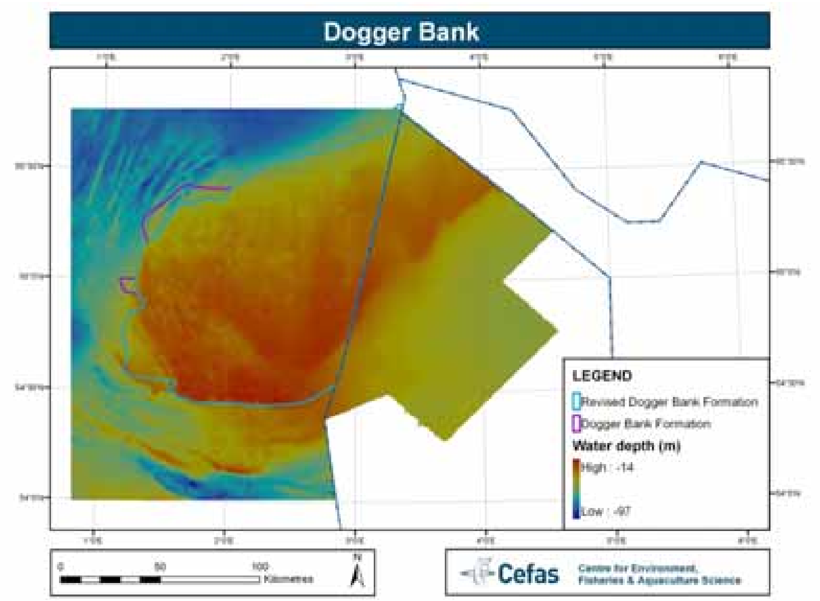

Figure 4. Extent of the Dogger Bank Formation based on BGS Quaternary geology map sheets (purple) and revised outline after inspecting sub-bottom profiles (blue).

1.4.2 Slope analysis

Klein (2006) provides a practical definition of marine banks as follows:

- Submarine banks are permanently submerged.

- They can be distinguished as independent elevations of the seabed.
- Their boundaries are generally marked by slopes of more than 0.5°. However, if the density of data is low, slopes of up to 0.1° can also be included.
- Boundaries are generally drawn at the transition from the slopes of the bank into surrounding plains.
- In more level areas they are marked by the straight line between the ends of slopes as defined above.
- The line marking the slope area should be at least three times longer than the straight line.
- The banks that the model accounts for must be bigger than 1 km^2.

We consider the data density underlying our bathymetry model as low. Therefore a critical slope of 0.1° is appropriate to delineate the bank structure. The results of the slope analysis are depicted in Figure 5 showing areas sloping between 0.1° and 0.5° coloured in amber and slopes above 0.5° coloured in red. It is especially reassuring that our slope analysis results match very well with those independently derived from the bathymetry model of the Dutch continental shelf. Additionally, north-to-south running multibeam lines were inspected to scrutinise the results derived from the broad-scale bathymetry model. It became apparent that slopes along the southern edge of the Dogger Bank are apparently steeper (up to roughly 5°) than shown in the broad-scale model. On the other hand, the rather subtle slopes of 0.1° at the northern edge of the Dogger Bank were largely confirmed.

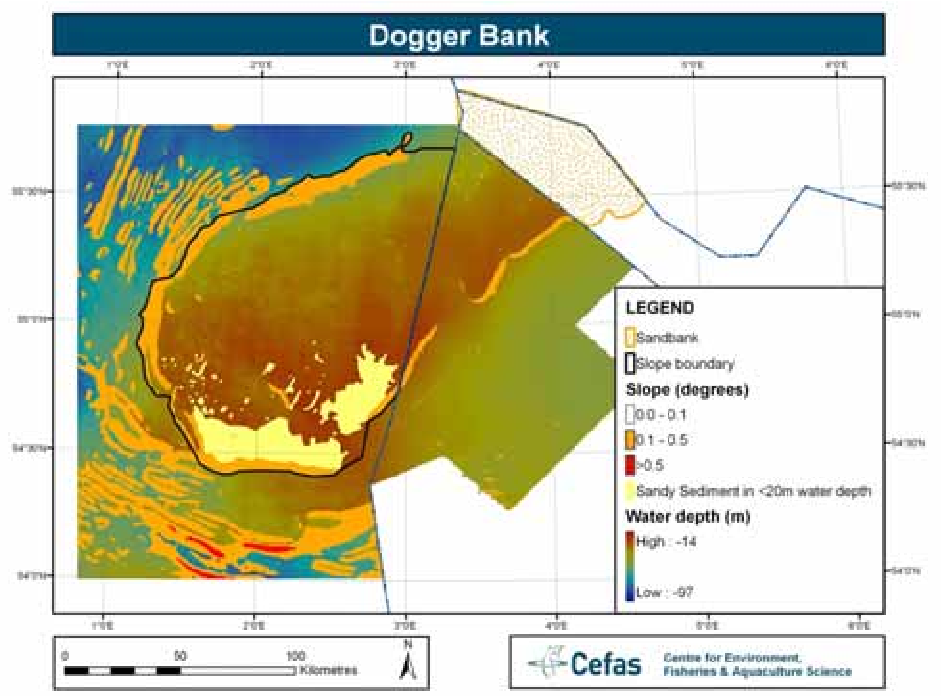

Figure 5. Results of the slope analysis and derived slope boundary.

Following the guidelines above it was possible to define the outline of the Dogger Bank based on its slope. However, it was necessary to extend the definition for banks:

- In the northwest, early Holocene sand ridges are stacked against the Dogger Bank. As these do not belong to the Dogger Bank, they were excluded, which forced us to draw the boundary across sloping areas in a straight line.

- In the southwest, the slopes are bifurcating, forcing us to make judgements which slope to follow. We decided to draw the boundary along the base of the slope that is closest to the summit of the bank and leads into a flat surrounding area of significant size.
- In the northeast corner, the seabed is essentially flat with slopes below 0.1°. In such a case, a straight line should be drawn connecting slopes above 0.1° (see above). However, there is no information available where the closest slope above 0.1° is located (possibly on the Danish continental shelf). Therefore, an arbitrary straight line running from west to east was drawn, but should not be taken as definitive. This highlights the problems introduced when nationally delineating a seabed feature that straddles international boundaries.

The outline derived in this way shows a remarkable correspondence with the revised boundary of the Dogger Bank Formation (Figure 10), underpinning the notion that the Dogger Bank Formation largely controls the morphology of the Dogger Bank (Cameron *et al,* 1992).

1.4.3 Surface sediments

Most samples are in line with the definition of a sandbank given in Johnston *et al* (2002), i.e. they fall into the textural groups sand, slightly gravelly sand, gravelly sand, slightly gravelly muddy sand and muddy sand (Figure 6). Coarser sediments (gravel, sandy gravel and muddy sandy gravel) are also found on the Dogger Bank. These form relatively small-scale patches of coarse sediment as obvious in the sidescan sonar data. Such coarse sediment patches are ubiquitous on continental shelves worldwide and are known as sorted bedforms (e.g. Diesing *et al,* 2006; Murray and Thieler, 2004).

As Folk textural groups had low discriminatory power in differentiating the sandbank from the surrounding seafloor, mud content (weight-%) of samples was interpolated and plotted (Figure 7). There is a pattern emerging in that areas with higher mud content above 5 weight-% are rimming the bank structure. This is especially true along the south-eastern boundary of the bank on the Dutch and German continental shelf. However, low mud content <5 weight-% is also found in areas which lie outside the bank as defined based on slope analysis; especially in the south and west of the bank.

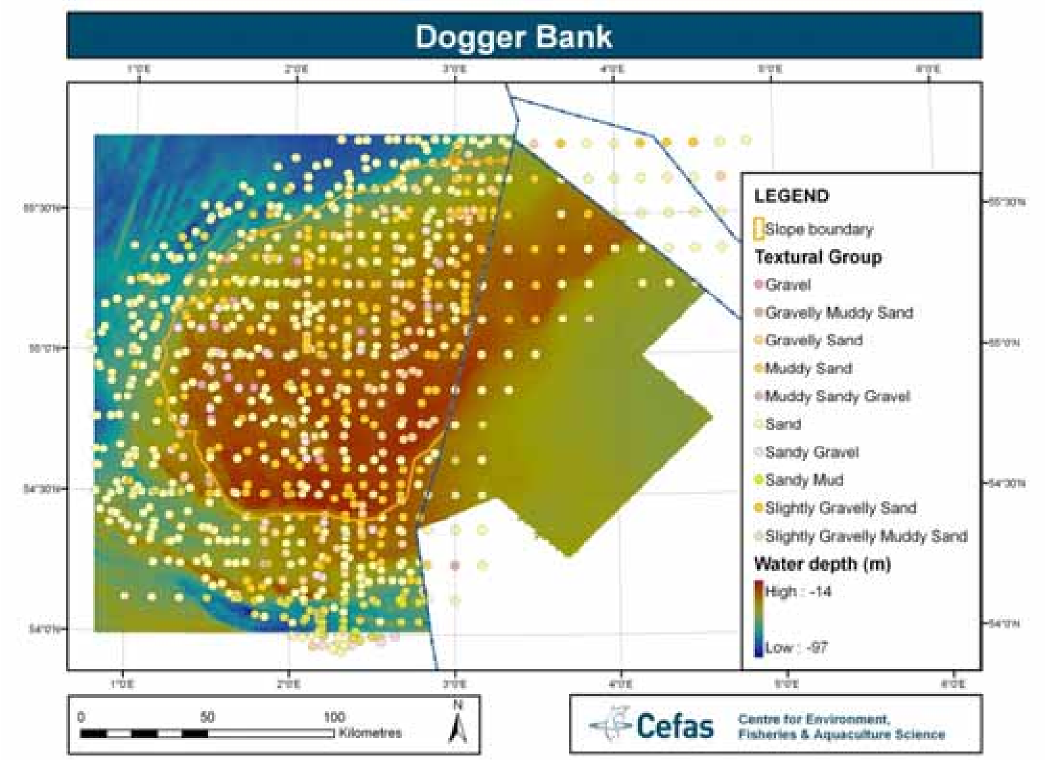

Figure 6. Textural groups according to Folk (1954).

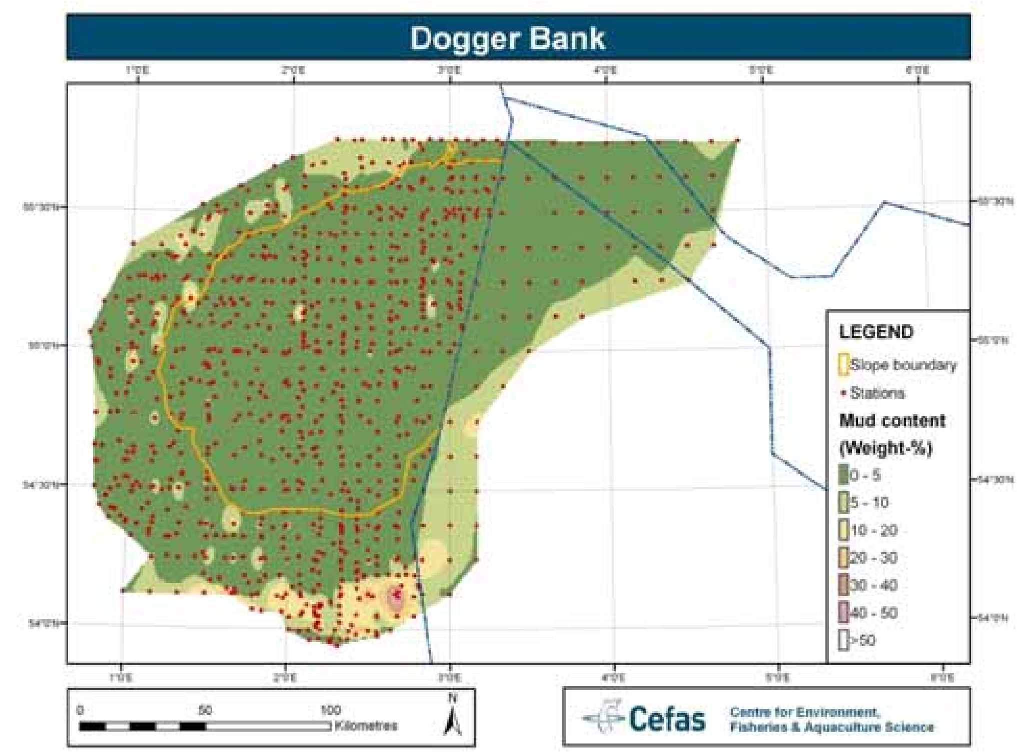

Figure 7. Interpolated mud content.

1.4.4 Epifauna

Video stations were assigned to one of 18 groups based on the relative dominance of fauna present (Table 2).

Table 2. Dominant fauna that characterise the groups assigned to epifaunal communities identified from video tows.

Group Number	Dominant Fauna
1	*Echinocardium*
2	*Corystes*/Epifauna
3	Sparse Motile
4	*Echinocardium/*Sandeel
5	*Echinocardium/Lanice/Corystes*
6	Epifauna/*Ophiothrix*
7	*Corystes*/Burrows
8	*Cerianthus/Echinocardium*
9	*Echinocardium/Ensis*
10	*Echinocardium/Astropecten*
11	Epifauna
12	*Echinocardium/Corystes*
13	Faunal Turf
14	Sandeel
15	*Echinocardium/Lanice*
16	*Echinocardium/Pennatula*
17	Sparse Epifauna
18	*Echinocardium*/Burrows

Stations assigned to the given epifaunal groups were plotted in relation to the outline derived from slope analysis (Figure 8).

The majority of the stations situated within the slope boundary were characterised by faunal assemblages that were largely dominated by *Echinocardium* sp. Additional dominant fauna present at stations situated within the slope boundary included the crab *Corystes cassivelaunus*, the polychaete *Lanice conchilega*, the burrowing bivalve *Ensis* sp. and the sandeel *Ammodytes* sp. At the deeper water stations, situated to the north of the slope boundary, faunal communities are still characterised by relatively high abundances of *Echinocardium* sp. However, these stations are distinguished from those located in the relatively shallower waters within the slope boundary by the presence of the seapen *Pennatula* sp. (group 16 in Figure 8).

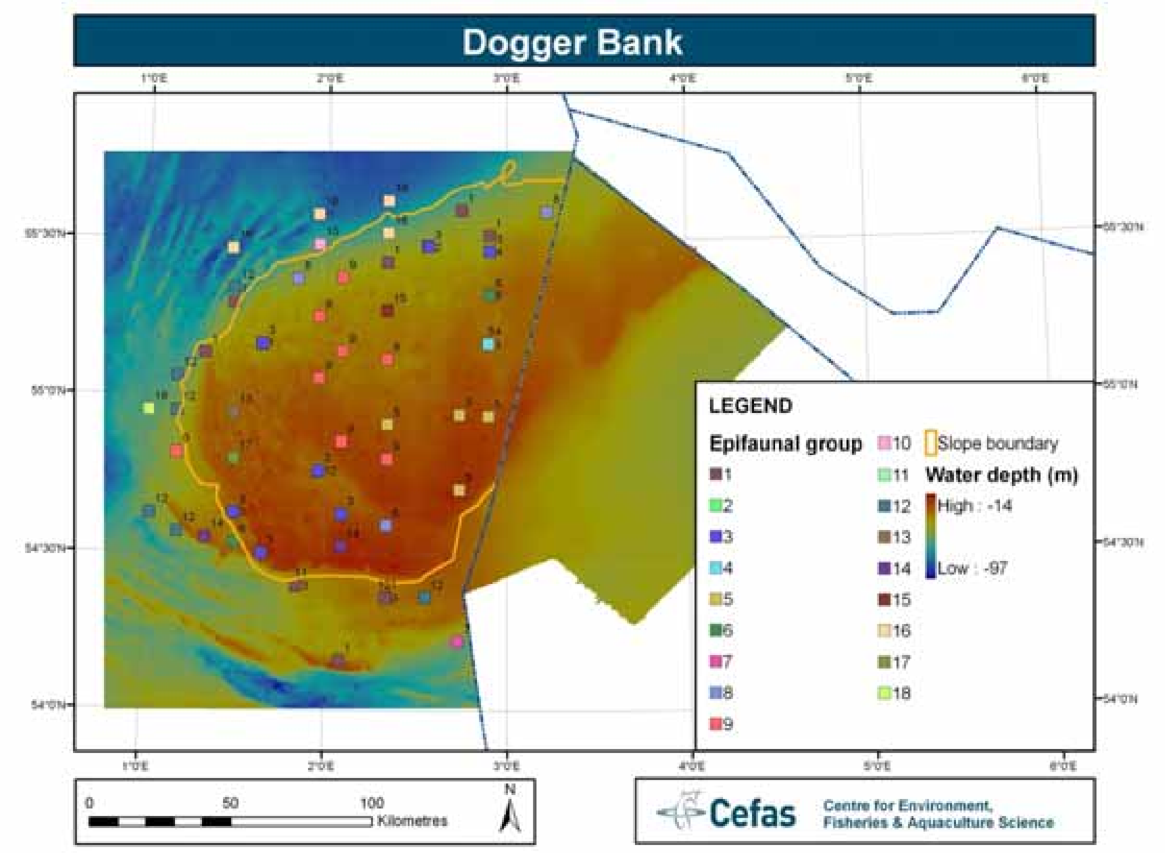

Figure 8. Epifaunal communities on the Dogger Bank.

1.4.5 Infauna

The SIMPROF routine, applied to the infaunal species abundance data, identified 12 genuine clusters. SIMPER analysis identified a sub-set of species that were predominantly responsible for similarity within clusters (Table 3).

Stations assigned to the given infaunal groups were plotted in relation to the slope boundary (Figure 9). The majority of stations within the slope boundary belong to the group K. Species which account for most of the similarity within this group include the two amphipod species *Bathyporeia elegans* and *Bathyporeia guilliamsoniana* along with the polychaete *Magelona filiformis* and the burrowing bivalve *Fabulina fabula*, all of which have been identified as having a habitat preference for medium grained sediments with a relatively low mud content (Degraer *et al,* 2006). Furthermore, the species identified as being characteristic of stations assigned to group K were also listed by Wieking and Kröncke (2001) as being characteristic of the 'Bank Community' that they identified using similar clustering techniques. Particle size analysis of sediments collected from stations assigned to group E identified these stations as having a relatively high gravel content and this is reflected in certain of their characterising fauna (i.e. *Glycera lapidum*) which displays a preference for coarser sediments (Degraer *et al,* 2006). Group E stations are located in coarse sediment patches (sorted bedforms, see below). Stations assigned to groups G, J and L are largely positioned along the deeper contours on the northern edge of the bank. Sediments at these stations are typified by relatively higher mud content and this is reflected in the habitat preferences of certain of their characterising species (i.e. *Scoloplos armiger* and *Spiophanes bombyx*), which favour sediments with a higher mud content. Similarly, the study undertaken by Wieking and Kröncke (2001) identified a distinct 'Northeastern Community', which was typified by a similar subset of species to those identified here.

Table 3. Infaunal species, which account for most of the similarity within the clusters identified by SIMPROF

Cluster Code	**Mean Similarity (%)**	**Dominant Fauna**	**Cumulative Contribution to Similarity (%)**
A	Too few stations		
B	Too few stations		
C	26.90	*Nemertea*	15.98
		Polycirrus sp.	27.28
		Pomatoceros lamarki	37.39
		Mysella bidentata	46.14
		Glycera alba	53.29
		Mediomastus fragilis	60.44
D	Too few stations		
E	32.19	*Notomastus sp.*	17.44
		Glycera lapidum	32.48
		Nemertea	43.59
		Protodorvillea kefersteini	54.17
		Pisione remota	58.23
		Amphiuridae	62.23
F	Too few stations		
G	27.31	*Galathowenia oculata*	25.82
		Thyasira flexuosa	45.24
		Goniada maculata	61.71

Table 3 continued

H	39.45	*Nephtys cirrosa*	64.39
I	32.95	*Echinocyamus pusillus* *Chamelea striatula* *Nephtys cirrosa* *Scoloplos armiger*	18.11 34.87 49.64 64.42
J	39.38	*Bathyporeia elegans* *Magelona filiformis* *Scoloplos armiger* *Phoronis sp.*	24.29 39.38 51.90 63.28
K	36.94	*Bathyporeia elegans* *Magelona filiformis* *Bathyporeia guilliamsoniana* *Fabulina fabula* *Amphiuridae* *Nemertea* *Spiophanes bombyx* *Chaetozone christiei*	15.10 28.85 37.29 44.05 48.96 52.89 56.79 60.64
L	22.16	*Spiophanes bombyx* *Harpinia antennaria* *Lucinoma borealis*	25.00 50.00 75.00

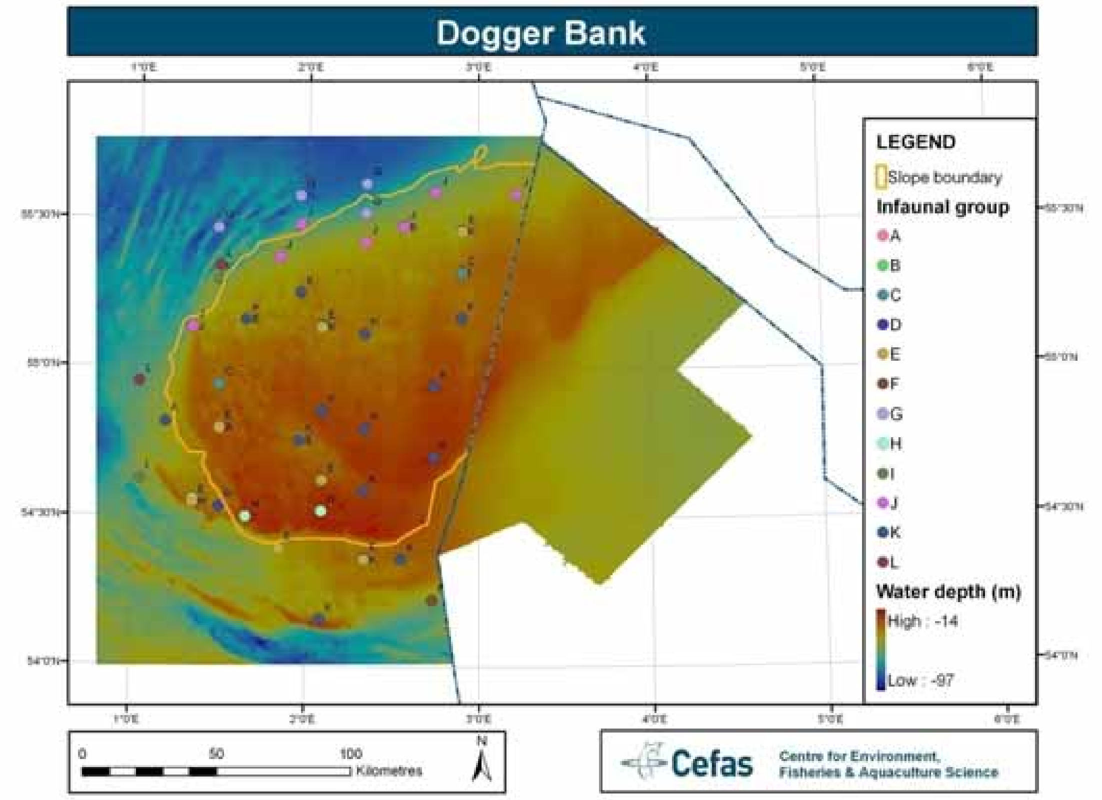

Figure 9. Infaunal communities on the Dogger Bank.

1.4.6 Sandeel distribution patterns

Data acquired during field surveys, carried out between spring 2004 and autumn 2006, to support objectives of a separate contract 'Multispecies fisheries management: a comprehensive impact assessment of the sandeel fishery along the English east coast' were examined to inform decisions pertaining to the placement of the proposed Dogger Bank SAC in relation to potentially important sandeel habitats (Cefas, 2007). The surveys investigated sandeel distribution patterns in two experimental grids. Grid 1 lies in a heavily fished area within the proposed Dogger Bank SAC boundary whilst Grid 2 lies to the west of the Dogger Bank in a lightly fished area (Figure 10). Results indicated that densities of sandeels were greatest during all years within Grid 1 and this was particularly evident during spring 2006 (Figure 10). Moreover, examination of the size composition of sandeels in the two grids indicated that during spring the presence of juvenile sandeels was largely restricted to Grid 1 and it was hypothesised that this may indicate that this area is representative of an important sandeel nursery habitat. It is further suggested that such relatively confined 'core areas' may be of crucial importance for successful recruitment in sandeels (Cefas, 2007).

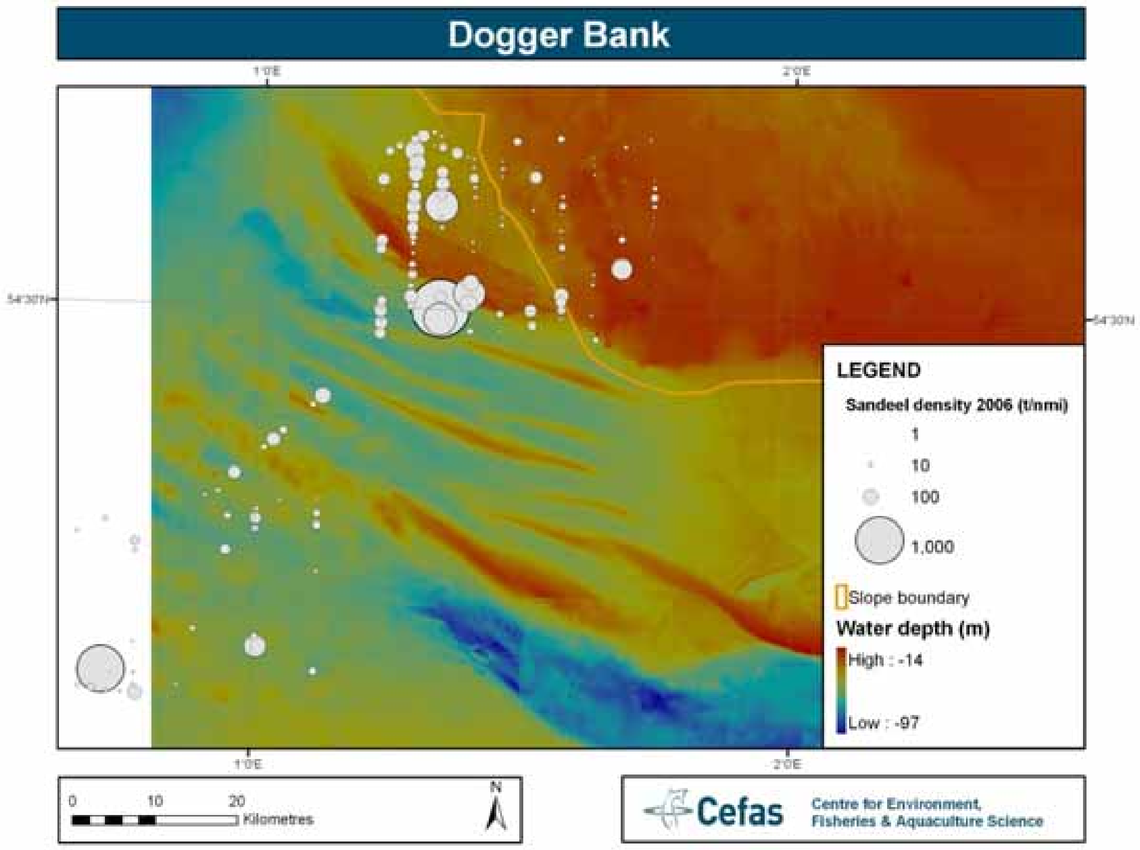

Figure 10. Spatial distribution of sandeels in the water column for 2006. Area size of grey symbols proportional to densities (tons per 1 nautical mile equidistant sampling unit equally scaled between years and areas).

1.5 Definition of the draft SAC boundary

The updated boundary for the Dogger Bank draft SAC has been largely drawn based on the derived slope boundary (Figure 11), which coincides well with the extension of the Dogger Bank Formation in the subsurface. An exception is made in the southeast of the Dogger Bank based on the fact that the Dogger Bank Formation extends beyond the slope boundary and because of the importance of this area as a sandeel nursery habitat. The bank area is largely covered with sediments that are typical for a sandbank. The gentle slope along the northern boundary – especially when compared to the rather abrupt boundary in the south – is also reflected in the gradual change of infaunal and, to a certain extent, epifaunal communities.

The Dogger Bank draft SAC boundary was drawn closely along the slope and Dogger Bank Formation boundaries, yet keeping it simple to avoid an unnecessary amount of nodes. An exception was made along the southern boundary, which was drawn in a way that it meets the southern Dutch node at the UK-Dutch boundary. As a consequence, the boundary lies slightly further to the south, as it would have been proposed otherwise. However, compared to the previous version of the draft SAC boundary (EMU Ltd., 2008), it is situated further to the north by up to 25 km. In the north the draft SAC boundary follows the slope boundary up to the point where a slope of 0.1° or more is no longer encountered (Figure 5). From thereon, a straight line aiming at the German north-western node was drawn until the UK-Dutch boundary. Here, the proposed draft SAC boundary does not meet the Dutch node. The total size of the proposed Dogger Bank draft SAC is 1,505,711 ha (15,057 km^2).

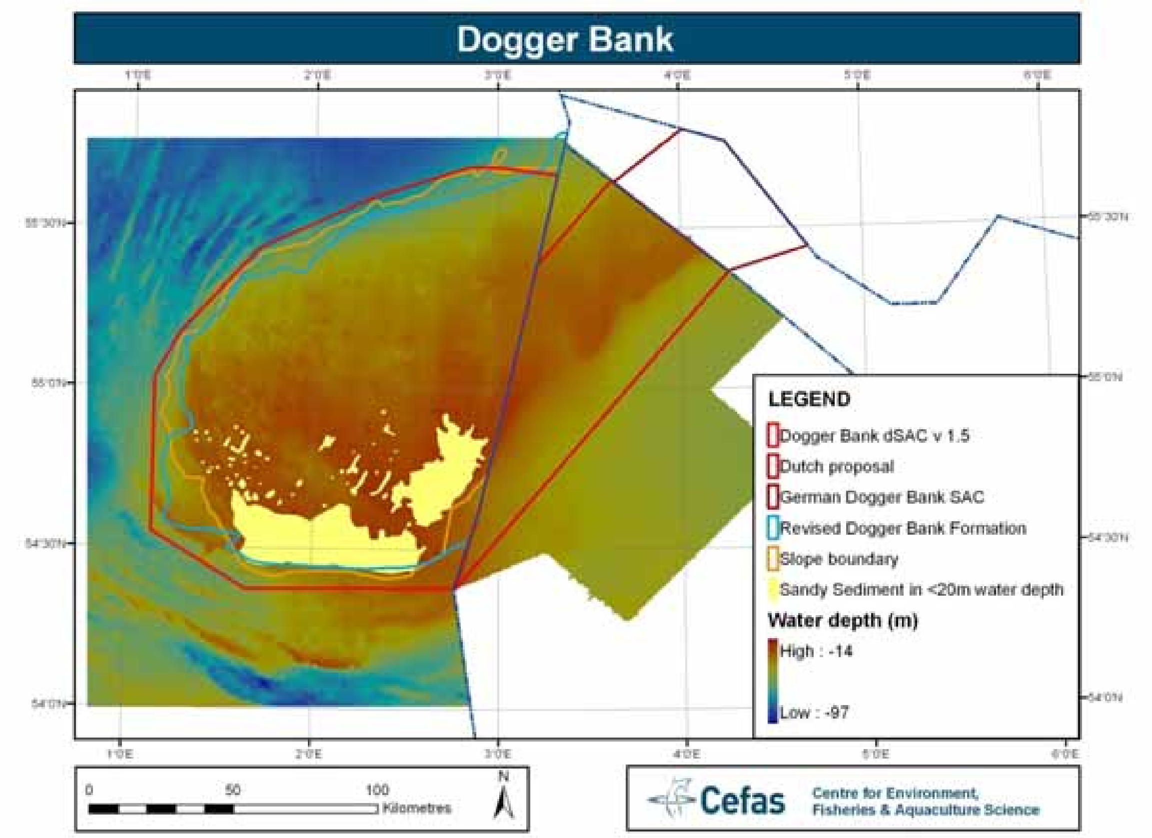

Figure 11. Outline of the proposed Dogger Bank draft SAC

1.6 References

CAMERON, T., CROSBY, A., BALSON, P., JEFFERY, D., LOTT, G., BULAT, J. & HARRISON, D. 1992. *The Geology of the Southern North Sea*. HMSO for the British Geological Survey, 152 pp.

CEFAS, 2007. Multispecies Fisheries Management: A Comprehensive Impact Assessment of the Sand eel Fishery Along the English East Coast. *CEFAS Contract Report* MF0323/01.

CEFAS, 2008. Understanding the marine environment - seabed habitat investigations of the Dogger Bank offshore draft SAC. *Cruise Report* CEND 07/08, 133 pp.

CLARKE, K.R. & GORLEY, R.N. 2006. PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth.

DEGRAER, S., WITTOECK, J., APPELTANS, W., COOREMAN, K., DEPREZ, T., HILLEWAERT, H., HOSTENS, K., MEES, J., VANDEN BERGHE, E. & VINCX , M. 2006. *The macrobenthos atlas of the Belgian part of the North Sea*, 164 pp.

DIESING, M., KUBICKI, A., WINTER, C., SCHWARZER, K. 2006. Decadal scale stability of sorted bedforms, German Bight, southeastern North Sea. *Continental Shelf Research* **26**, 902-916.

EMU LIMITED. 2008. Dogger Bank Offshore Draft SAC Seabed Investigations. Data Review & Slope Analysis Report: Recommendations for the revision of the dSAC boundary, 12 pp.

ENGELHARD, G.H., VAN DER KOOIJ, J., BELL, E.D., PINNEGAR, J.K., BLANCHARD, J.L., MACKINSON, S. & RIGHTON, D.A. In press. Fishing mortality versus natural predation on diurnally migrating sandeels Ammodytes marinus. *Marine Ecology Progress Series*.

EUROPEAN COMMISSION. 2007. Appendix 1. Marine Habitat types definitions. Update of “Interpretation Manual of European Union Habitats", 18 pp.

FOLK, R.L. 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *Journal of Geology* **62**, 344-359.

FOLK, R.L. 1980. *Petrology of sedimentary rocks*. Hemphill Publishing Company, Austin, Texas, 184 pp.

JOHNSTON, C.M., TURNBULL, C.G., TASKER, M.L. 2002. Natura 2000 in UK Offshore Waters: Advice to support the implementation of the EC Habitats and Birds Directives in UK offshore waters, *JNCC Report* No. 325.

KLEIN, A. 2006. Identification of submarine banks in the North Sea and the Baltic Sea with the aid of TIN modelling. *In*: VON NORDHEIM, H., BOEDEKER, D. & KRAUSE, J.C. (Eds.) *Progress in Marine Conservation in Europe*. Natura 2000 Sites in German Offshore Waters. Springer, Berlin, Heidelberg, New York, pp. 97-110.

MURRAY, A.B. & THIELER, E.R. 2004. A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and "rippled scour depressions". *Continental Shelf Research* **24**, 295-315.

NATIONAL MARINE BIOLOGICAL ANALYTICAL QUALITY CONTROL SCHEME, 2008. Development of Video Ring Test - Guidance Document, 4 pp.

VAN DER KOOIJ, J., SCOTT, B.E. & MACKINSON, S. In press. The effects of environmental factors on daytime sandeel distribution and abundance on the Dogger Bank. *Journal of Sea Research*.

WIEKING, G. & KRÖNCKE, I. 2001. Decadal changes in macrofauna communities on the Dogger Bank caused by large-scale climate variability. *Senckenbergiana Maritima* **31**, 125-141.

Appendix 2. Geological Context

2.1 Solid Geology

The stratigraphy and lithology of the solid geology within the report area can be summarised as follows:

Table 1. Stratigraphy and lithology of the solid geology within the report area.

<table>
<tr><th>Solid geology lithology</th><th colspan="2">Age</th></tr>
<tr><td>Siliclastic Argillaceous Rocks undifferentiated</td><td>Neogene and Palaeogene undivided</td><td>Tertiary</td></tr>
<tr><td>Chalk</td><td>Upper</td><td rowspan="2">Cretaceous</td></tr>
<tr><td>Mudstone and Limestone Calcareous</td><td>Lower</td></tr>
<tr><td rowspan="4">Mudstone and Limestone undifferentiated, interbedded and Limestone and Sandstone</td><td>Undivided</td><td rowspan="4">Jurassic</td></tr>
<tr><td>Upper</td></tr>
<tr><td>Middle</td></tr>
<tr><td>Lower</td></tr>
<tr><td>Mudstone, Halite, Sandstones and Argillaceous-stones undifferentiated</td><td colspan="2">Triassic</td></tr>
<tr><td>Undifferentiated rocks</td><td colspan="2">Permian to Triassic</td></tr>
<tr><td>Zechstein Group, Mud stone and Gypsum anhydrite</td><td colspan="2">Permian</td></tr>
<tr><td>Igneous Intrusion and siliclastic Argillaceous sand stone and limestone</td><td colspan="2">Carboniferous</td></tr>
</table>

The oldest rocks outcropping along the north east coast of England are late Carboniferous rocks comprising a sequence of fluviodeltaic and redbed lithotypes, which were gently folded during the Variscan Orogeny. These rocks are also buried 2500–4000 m beneath Permian, Mesozoic and Cenozoic sediments below Dogger Bank. They, together with Devonian sediments, are the basement rocks recovered by drilling from the Dogger Bank area. During Permian and Triassic times the majority of the Southern North Sea was part of a subsiding basin that extended from Eastern England, through Germany, to Poland.

For the period of the Early Permian the basement of Carboniferous and Devonian rocks were exposed to continental conditions where fluvial and aeolian sediments were deposited within a desert environment in a basin called the Anglo Dutch Basin that was enclosed between the London Brabant Massif and the Mid North Sea High (Figure 1). In the Late Permian a series of brief marine transgressions produced a complex sequence of evaporite deposits that can be locally more than 1000 m thick. These evaporites are at the origin of the diapirs and salt pillows found in much of the North Sea developed by halokinesis since Middle Triassic. These salt diapirs are present beneath the southwest part of the survey area and play an important role in the search for hydrocarbons.

During Triassic times a sequence of reddish brown mudstone with secondary sandstones and evaporites were deposited in a series of playa-lake, fluvial floodplains and shallow marine environments. Full marine conditions were restored at the end of the Triassic period and they have continued irregularly until the present day.

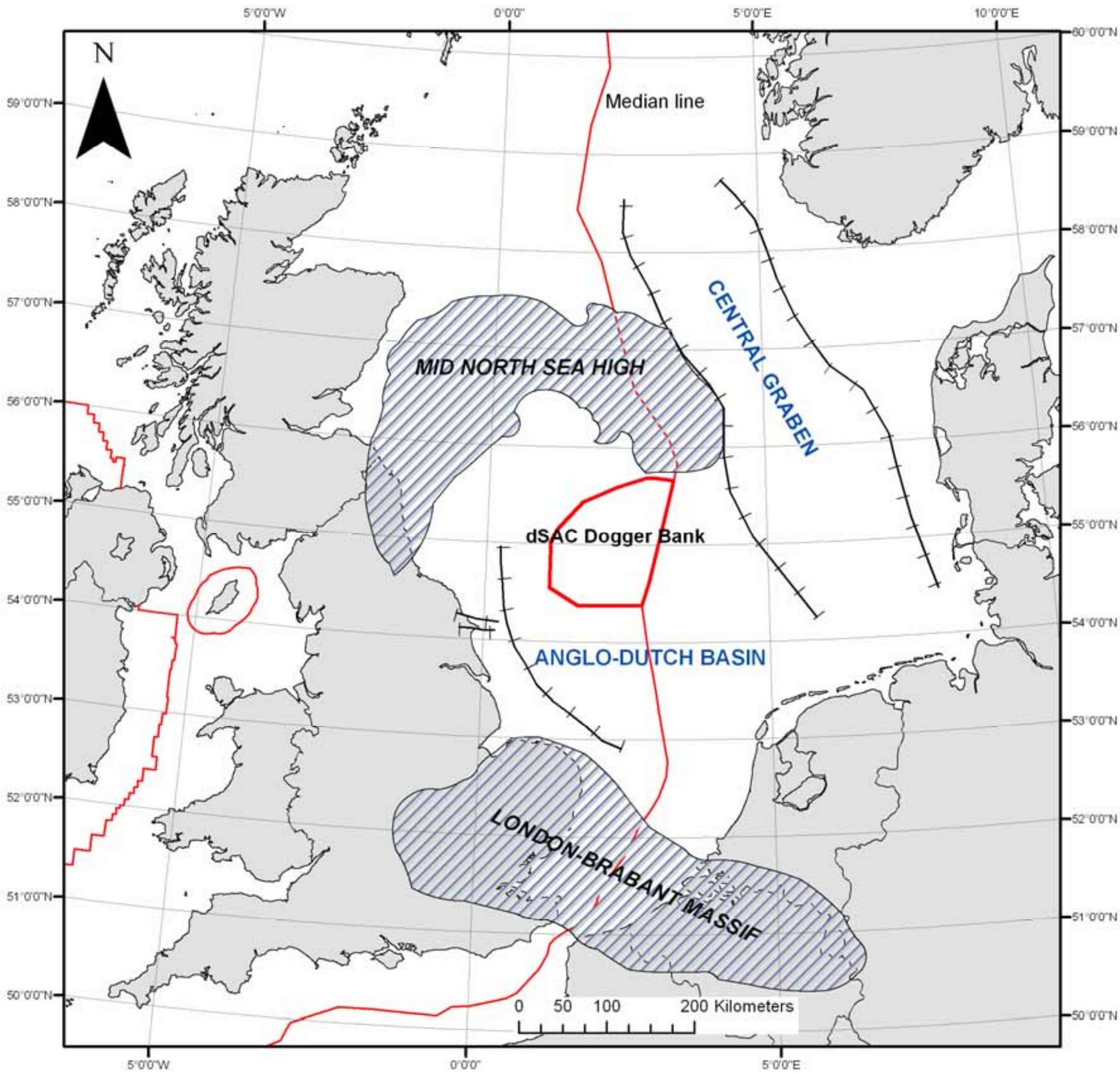

Figure 1. Schematic regional structural settings in the report area (modified from Cameron *et al,* 1992)

The western part of the Anglo Dutch Basin was a depocentre during the Jurassic times with more than 1000 m of marine mudstones with subsidiary limestone and sandstones deposited. However much of these sediments were eroded at the end of the Jurassic Period following a post Jurassic inversion restricting their distribution to the very western part of the Dogger Bank. At the end of the Jurassic times, the general uplift was replaced by general subsidence within the major grabens present in the area. Marine sedimentation combined with a low rate of subsidence restarted in the early Cretaceous times with increased sediment accumulation in faulted areas with an overall accumulation of 1000 m of marine argillaceous sediments.

During the late Cretaceous period a global rise in sea level allowed the deposition of pelagic carbonate sediments across the majority of the North Sea. The London Brabant Massif was submerged for the first time since the Palaeozoic, and the Chalk group series condensed over its top. The Sole Pit Trough and the Cleaver Bank High were again depocentres during this period and allowed the deposition of more than 1000 m of Upper Cretaceous sediments.

At the end of the Cretaceous period a phase of basin inversion affected many basins across the North Sea area, including the Sole Pit Trough and the Cleveland Basin, this tectonic activity has been interpreted as resulting of a phase of regional compression that reactivated basement faults (Cameron *et al,* 1992). The widespread uplift and the consequent marine regression from the British Isles and the surrounding continental shelf caused the creation of an unconformity that separates the Chalk Group from the overlaying Palaeogene sediments.

During the Tertiary and the Quaternary Era regional subsidence continued in the area characterized by a broad synclinal deposition with maximum subsidence and deposition to the north east of the Dogger Bank study area. Chalk deposition continued into the earliest Palaeogene (Danian) but with deepening waters was succeeded by deposition of clastic sediments. The Palaeogene sequence consists of 800 m of dominantly argillaceous marine sediments with thin limestones and sandstones but also includes volcanic tuff beds towards the base. It seems probable that these tuffs were derived from either volcanoes in the developing Rockall-Greenland rift zone or a volcano in the Skagerrak region.

During Oligocene and Miocene times the Alpine compression as the African plate pushed into the European plate, had its effects also in this area and many of the basement faults were reactivated, the Sole Pit Trough and other basins such as the Weald Basin were inverted. This tectonic activity also triggered a major new phase of halokinesis, and most of the salt swell pillows and diapirs were initiated during mid Tertiary times. Overall this led to uplift of Britain and the western edge of the North Sea causing erosion of Palaeogene and older sediments in the western part of the Dogger Bank area and limiting Oligocene and Neogene sediments to the north-eastern parts of the study area. This exposed older rocks along the western edge of the North Sea.

In the Late Neogene, Pliocene sediments are conformably succeeded by early Pleistocene sediments deposited in a marine continental shelf environment with deltaic sedimentation extending into the area from the south-east. The boundary between the Pliocene and the Pleistocene is uncertain so only approximate estimates of sediment thickness are possible. The Quaternary sediments may be more than 800 m thick and include deposits related to glacial processes.

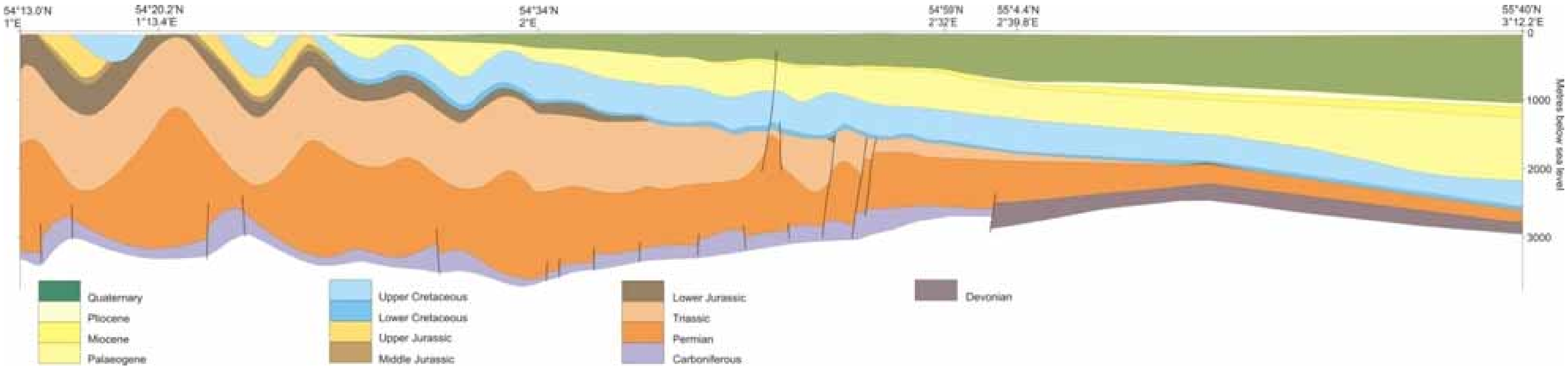

Figure 2. Cross section southwest to northeast across Dogger Bank showing the bedrock geology

2.2 Quaternary geology

The Quaternary Era represents a period of considerable global climatic instability, with repeated cycles of climate change. The base of the Quaternary is considered to be 1.8 Ma ago although already from 2.5 Ma a major change in the fauna of north west Europe is evident and may be considered the first signal of this major cooling event in Europe. Within the Dogger Bank area iceberg scars and palaeontological evidence for the presence of sea-ice has been found in the Dutch sector dating back to about 2.2 Ma (Kuhlmann *et al,* 2008).

Please see Table 2.1 in the main body of the text for the offshore stratigraphy of the Quaternary based on seismostartigraphic evidences. The Divisions and Elements are discussed in more detail below and represented in Figure 3.

2.3 Pleistocene

2.3.1 Southern North Sea Deltaic Group

Element A

Element A is in turn subdivided into seven seismostratigraphic different units, the definition of these units is made by correlating seismic data and borehole information. All the lithofacies and acoustic facies, defined as subunit of Element A, delineate a succession of sediment that goes from “pro delta”, to “delta front” to “delta top” depositional environments. They are constituted by sigmoid sedimentary bodies laying against each other and indicating a progradation of the deltas towards north–northwest. A vertical section trough these formations would indicate a variation of the lithology from silty clays intercalated with fine bioturbated sands (Pro Delta formation), sandier deposits with shelly bioturbated subtidal sands and mud (Front Delta Formation), and finally an intertidal fine sand dominated unit representing the Top Delta Formation.

The seven sub-units of Element A are, from the bottom:

Westkapelle Ground Formation

This formation is the basal and oldest formation of element A, it can be extended back to the very late Pliocene. It crops out in the shallow waters of the north east coast of East Anglia. The facies has been sampled in British Geological Survey (BGS) boreholes and it consists of “silty clays with fine glauconitic bioturbated sands passing upward into mud-free sands” (Cameron *et al,* 1992). This formation is equivalent in its upper part to the Red Crag Formation along the coast of East Anglia.

Smith’s Knoll Formation / Ijmuiden Ground Formation

Additional supply of sediments from Britain produced the overlying Smith’s Knoll Formation. The formation, restricted to a narrow zone east of the Westkapelle Ground Formation, is 20-30m thick, further offshore the seismic character of this formation is dissolved in the Ijmuiden Ground Formation, and they are considered laterally equivalent. Samples of its facies by BGS boreholes consist of “muddy fined grained glauconitic locally micaceous sand with minor intercalation of silty clay of pebbly and shelly sand” (Cameron *et al,* 1992).

While the Westkapelle Ground and Smith's Knoll formations received their sediments supply from a source situated in the British side of the delta system, the Ijmuiden Ground Formation received sediment from the European mainland and the delta in the Netherlands. This formation overwhelmed the previous ones and its delta front facies contributed to build a lenticular body 190 m thick with westward sigmoid structures.

Winterton Shoal Formation and Markham's Hole Formation

The Winterton Shoal Formation is the formation where the two deltas, the eastern and the western delta, came together and advanced northwards. The northward direction of the prograding facies is well showed in the Markham's Hole Formation, which has been sampled by BGS boreholes and has more than 105 m thickness of delta front sediments. The top 12 m of the formation are slightly coarser and probably belong to delta top acoustic facies. During the time of the deposition of this Pleistocenic marine formation, the coast line of East Anglia was probably situated about 80 km further east than the present day coast line.

Outer Silver Pit Formation and Aurora Formation

The deposition of these two formations signalled the northwest advance of the delta. The Outer Silver Pit Formation is 100 m thick and the Aurora Formation is 75 m thick, only the Outer Silver Pit has been sampled and it records "fine grained slightly pebbly and weakly calcareous sand" of a delta top acoustic facies (Cameron *et al,* 1992).

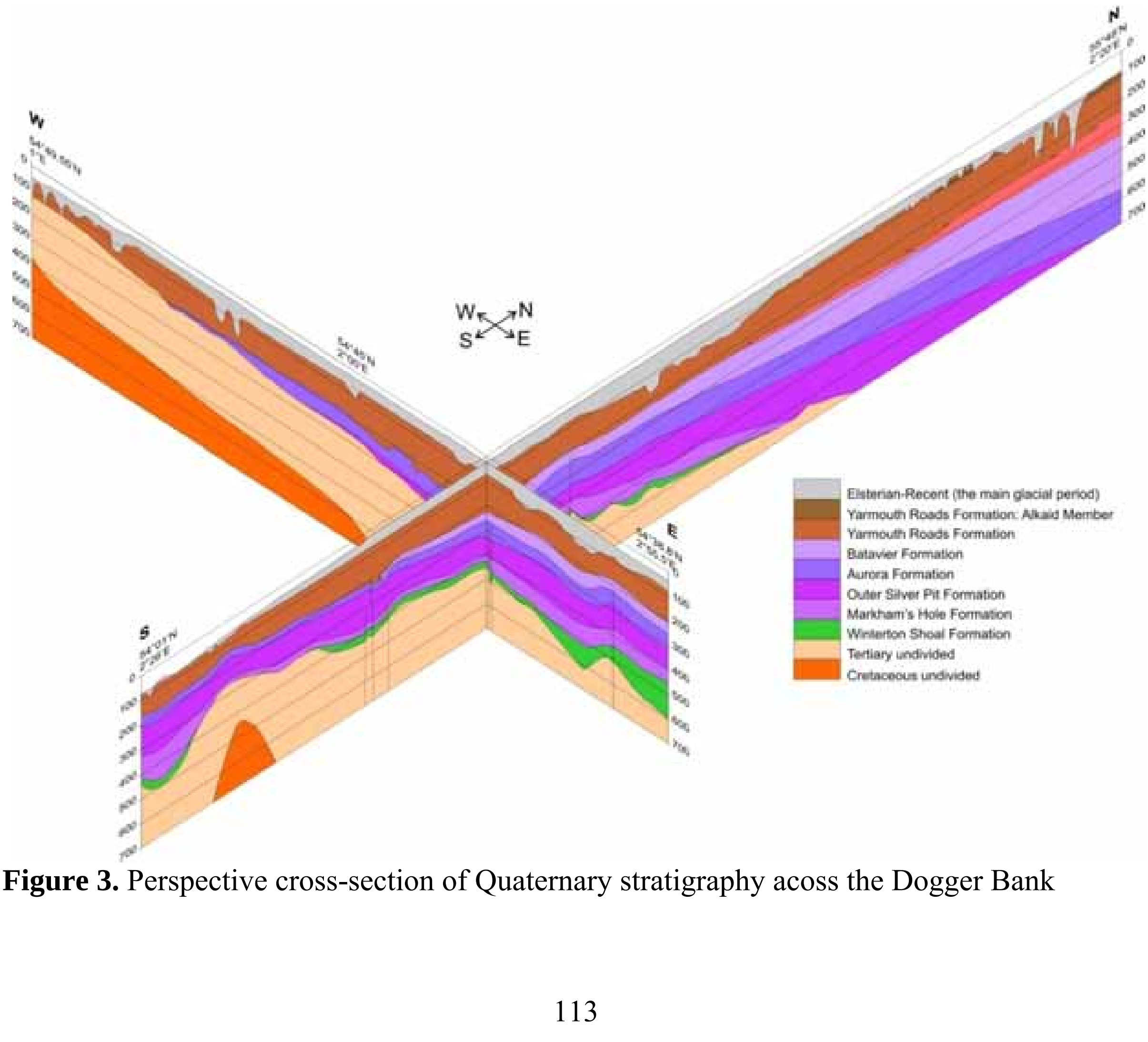

Figure 3. Perspective cross-section of Quaternary stratigraphy acoss the Dogger Bank

2.3.2 Dunwich Group

Element B

The Dunwich Group, separated from the Southern North Sea Deltaic Group by a strong reflector that probably represents the transition from fully marine conditions to a sequence that represents a low energy shallow water environment, is a unit with a chaotic acoustic signature with sporadic sub-horizontal reflectors (Cameron *et al,* 1992). It comprises the Yarmouth Roads Formation that can reach 160 m of thickness, numerous boreholes have been explored in this formation and they reported a sediment "constituted prominently by decalcified sands, with scattered pebbles (including chalk) abundant plant debris peat and wood clasts" (Cameron *et al*, 1992). This type of sediment is characteristic of a delta top environment with different depositional local origins.

In the area south of Dogger Bank the Yarmouth Road Formation can be subdivided into three different acoustic groups comprising lagoonal clays at the bottom and two upper members with fine sand and plant remains. These members of the formation show a transition to more terrestrial conditions and also contain beach deposits (BGS Silver Well Quaternary Geology sheet). The formation has been deposited in a delta top environment when the UK shoreline was probably in the vicinity of 55° N, during early Pleistocene times. The delta plain was extensive and has been called Ur-Frisia (Jeffery and Long, 1989).

2.3.3 The Californian Glacigenic Group

The Californian Glacigenic Group consists of a number of formations that often comprise fragmented, variable lithologies reflecting transgressive and regressive episodes within a series of glacial episodes. The non deltaic division has been deposited under a varied range of climatic conditions, for example two Elements C and H are erosive events that incised "tunnel valleys" into the lower Pleistocene succession and they are related to the Elsterian and the Weichselian glaciations respectively. Not all elements are present within the Dogger Bank study area but are geographically close reflecting the oscillation of the glacial/interglacial/glacial cycles.

Element C

Element C is formed exclusively by the Swarte Bank Formation and it represents the first record of the presence of the ice into the Southern North Sea Basin. The Swarte Bank Formation comprised three different members that have been sampled in BGS boreholes, the lowermost member comprises grey diamicton with coarse glaciofluvial sand overlain by a very well layered glacio-lacustrine mud; the uppermost member is characterised by an association of micro fauna typical of very shallow and cold waters.

The Formation infills a series of valleys that are considered to be formed by glacial melt waters under pressure of the glacier. The valleys are called "tunnel valleys", often anatomising with an irregular thalweg. Their geometry is controlled by the hardness of the underlying formations and they can be up to 12 km wide and 450 m deep (Praeg and Long, 1997), cutting down into the underlying deltaic deposits.

The Swarte Bank Formation correlates well with the Anglian Chalky-Jurassic Tills onshore (Cameron *et al,* 1992). The southern limit of the tunnel valleys therefore represents the southern limit of the ice at that time.

Element D

Element D comprises two formations: the Sand Hole and the Egmond Ground formations. They are both marine formations that were deposited during the interglacial Holstenian stage after the collapse of the Elsterian Ice sheet.

The Sand Hole Formation is up to 20 m thick and is confined to an area around the Silver Pit; BGS boreholes recovered laminated clays with a diverse assemblage of interglacial shallow marine foraminifera, in a localised marine environment during a warm phase of the Holstenian Stage. Subsequently open marine conditions were established and the Egmond Ground Formation was deposited, it consists of gravely sand, interbedded with silt and clay.

Element E

Element E consists of two formations, the Tea Kettle Hole and Cleaver Bank formations. They were deposited during the Saalian Stage and they represent deterioration in climatic conditions with restoration of glacially dominated sedimentation. The Cleaver Bank is a thin formation with laminated dark grey clays with scattered angular granules of chert or chalk. The formation is interpreted as a marine-periglacial deposit.

The Tea Kettle Hole formation is only present intermittently in the UK sector and mainly comprises an aeolian periglacial deposit. It becomes thicker and more persistent in the Dutch sector where it merges with sub-glacial deposits (Joon *et al,* 1990).

These deposits support the model that glacial ice did not reach the study area during Saalian times with glacial conditions being considerably less extensive both onshore and offshore the UK than in either Elsterian or Weichselian times (Sumbler, 1983; Balson and Jeffery, 1991).

Element F

Element F was deposited during the interglacial Eemian stage when a transgressive event followed by a new regression deposited the Eem and Brown Bank formations. These two formations and the older Cleaver Bank Formation are absent in the area north of Dogger Bank. This is probably due to the erosion of these deposits during the subsequent Weichselian glaciation. Evidence suggests the formation was deposited in a brackish lagoon that was at the time supplied by sediment from the south-west.

Element G

Element G comprises two laterally equivalent formations: the Bolders Bank Formation and the Dogger Bank Formation. They were deposited during the Weichselian stage and they record the development, expansion and initial decline of the ice sheet.

Numerous BGS boreholes have been sampled in the Bolders Bank Formation and they record a "reddish to greyish diamicton with massive structure and in places show some arenaceous layering and some deformational structure" (Cameron *et al,* 1992). The formation contains also pebbles with different lithologies mainly chalk, this coarse sediment is derived from the erosion of the sedimentary rocks in Eastern England. Clasts originating from northern England and Scotland have also been found (Carr, 1999). Together this indicates that the Bolders Bank Formation was deposited by a British ice sheet. The Bolders Bank formation is not very thick and is preserved in the area west of Dogger Bank. The morphology of the deposit indicates a subglacial and supraglacial origin.

In BGS seismic records the base of this unit is defined by a high amplitude, gently undulating reflector. This reflector continues under the Dogger Bank and here is surmounted by 42 m of the Dogger Bank Formation, a tabular deposit with regular internal reflectors. The acoustic signature of this deposit suggests a proglacial lacustrine environment of deposition. The lithology consists of a clay-rich diamicton with scarce pebbles and well developed lamination and stratification. Detailed microfabric analysis indicates that the sediments were subsequently overridden by ice, compacting them (Carr, 1999). The Dogger Bank Formation forms the core of the topographic high known as the Dogger Bank that has been covered by Holocene sand mainly reworked from the underlying and surrounding glacial deposits.

Element H

Element H represents the deposit generated by the final stage of the Weichselian glaciation comprising the Botney Cut Formation and the Sunderland Formation. The Botney Cut Formation occurs in a series of scaphiform valleys 100 m deep and less the 8 km wide originated in the same way as the larger valleys formed during the Elsterian glaciation (Element C). Their reduced dimension is probably due to the presence of thinner ice. BGS boreholes indicate that this formation comprises reddish brown diamicton with an upper member composed of soft laminated glaciolacustrine to glaciomarine mud (Cameron *et al,* 1992). The Sunderland Formation constitutes water-laid muds deposited by the westward retreating glacier during the late Weichselian stage. It may be up to 25 m thick in places and comprises soft reddish brown proglacial mud.

During the early Holocene rising sea level coincident with isostatic rise of the UK landmass occurred and the glaciomarine deposition and the erosion of the scaphiform valleys gave way to the deposition of intertidal mud, silt and peats.

Appendix 3. Example photographic stills for EUNIS level 4 classifications identified using physical data described in section 4.7

Figure 1. Infralittoral coarse sediment (EUNIS A5.13, UK Habitat Classification code SS.SCS.ICS)

Figure 2. Circalittoral coarse sediment (EUNIS A5.14, UK Habitat Classification code SS.SCS.CCS)

Figure 3. Infralittoral fine sand (EUNIS A5.23, UK Habitat Classification code SS.SSa.IFiSa)

Figure 4. Infralittoral muddy sand (EUNIS A5.24, UK Habitat Classification code SS.SSa.IMuSa)

Figure 5. Circalittoral fine sand (EUNIS A5.25, UK Habitat Classification code SS.SSa.CFiSa)

Figure 6. Deep circalittoral sand (EUNIS A5.27, UK Habitat Classification code SS.SSa.Osa)

Appendix 4. Detailed description of seabed habitats, including physical environment and associated biological assemblage, for each sample station

Station	EUNIS Level 4/UK Habitat Classification Based on Physical Attributes	Sediment description from Hamon grab sample	Infaunal SIMPROF group
G1	A5.27/SS.SSa.OSa	Fine sand with shell	J
G2A	A5.14/SS.SCS.CCS	Medium grained sand with shell frags and clay	B
G2B	A5.25/SS.SSa.CFiSa	Fine, slightly muddy sand with occasional shell frags	J
G3A	A5.25/SS.SSa.CFiSa	Fine sand	K
G3B	A5.14/SS.SCS.CCS	Pebble: flint/river gravel, well sorted, little sand, clay present. Pebbly gravel	E
G4A	A5.23/SS.SSa.IFiSa	Very fine muddy sand	I
G4B	A5.13/SS.SCS.ICS	Muddy gravelly sand with cobbles and clay	C
G5	A5.24/SS.SSa.ImuSa	Dark grey clay with shell frags. Veneer of sand at sea bed	K
G6	A5.23/SS.SSa.IFiSa	Muddy fine sand with shell	K
G8	A5.23/SS.SSa.IFiSa	Medium shelly sand	K
G9	A5.25/SS.SSa.CFiSa	Fine sand with small amount of shell frags	K
G10	A5.27/SS.SSa.OSa	Very muddy very fine sand	F
G11A	A5.25/SS.SSa.CFiSa	Fine sand with shell	J
G11B	A5.27/SS.SSa.OSa	Fine shelly sand	J
G12	A5.25/SS.SSa.CFiSa	Very shelly, fine sand with small lumps of clay	J
G15	A5.27/SS.SSa.OSa	Fine sand	J
G16	A5.25/SS.SSa.CFiSa	Fine muddy sand	J
G17A	A5.23/SS.SSa.IFiSa	Fine muddy sand	K
G17B	A5.13/SS.SCS.ICS	Gravel comprising varying lithologies, some shell frags	E
G18	A5.23/SS.SSa.IFiSa	Fine sand with small clay lumps (approx 5cm x 5cm)	K
G19A	A5.14/SS.SCS.CCS	Sandy gravel	E
G19B	A5.25/SS.SSa.CFiSa	Slightly muddy fine sand	K
G23	A5.23/SS.SSa.IFiSa	Clean, fine sand.	K
G24	A5.23/SS.SSa.IFiSa		K
G25	A5.13/SS.SCS.ICS	Muddy sandy gravel	C
G26	A5.25/SS.SSa.CFiSa	Muddy sand	K
G27A	A5.24/SS.SSa.ImuSa	Clay with a veneer of sand	A
G27B	A5.13/SS.SCS.ICS	Sandy gravel	E
G28A	A5.14/SS.SCS.CCS	Gravel	E
G28B	A5.25/SS.SSa.CFiSa	Fine sand (little shell)	K

G31A	A5.14/SS.SCS.CCS	Slightly gravelly clean coarse sand	H
G31B	A5.14/SS.SCS.CCS	Slightly sandy gravel and cobbles	E
G32	A5.14/SS.SCS.CCS	Gravel on clay	D
G33	A5.23/SS.SSa.IFiSa	Clean, fine sand	H
G34	A5.13/SS.SCS.ICS	Muddy gravelly shelly sand with cobbles	E
G35	A5.23/SS.SSa.IFiSa	Fine sand with shell and occasional lithic frags.	E
G36	A5.23/SS.SSa.IFiSa	Clean sand, bit of shell	K
G37	A5.14/SS.SCS.CCS	Very shelly coarse sand and gravel.	H
G38A	A5.25/SS.SSa.CFiSa	Muddy sand	K
G38B	A5.14/SS.SCS.CCS	Muddy gravel	E
G39	A5.25/SS.SSa.CFiSa	Slightly muddy fine sand, less shell than before.	K
G40	A5.23/SS.SSa.IFiSa	Slightly muddy fine sand.	K
G42	A5.25/SS.SSa.CFiSa	Muddy fine sand with shell.	J
G43	A5.27/SS.SSa.OSa	Sandy mud	G
G44	A5.27/SS.SSa.OSa	Sandy mud	G
G45	A5.27/SS.SSa.OSa	Muddy sand	G
G46	A5.27/SS.SSa.OSa	Muddy sand	G
G47	A5.27/SS.SSa.OSa	Muddy very fine sand.	L
G48	A5.27/SS.SSa.OSa	Very fine, muddy sand.	I
G50	A5.27/SS.SSa.OSa	Slightly muddy sand	I
G51	A5.27/SS.SSa.OSa	Muddy sand	L

Appendix 5. Sandbanks identified in UK waters (January 2009)

Site	**Notable features**
Dornoch Firth and Morrich More SAC	Sandbank is graded C at this site.
Firth of Tay and Eden Estuary SAC	Sandbank is graded C at this site.
Moray Firth SAC	Sandbank is graded C at this site.
The Wash and North Norfolk Coast SAC	Coastal sublittoral sandbanks, representative of this habitat type on the sheltered east coast of England. Headland associated, estuary mouth sandbanks and sandy mounds are all found at this site. The sandbanks vary in composition from coarse gravelly to muddy sand, and some support eelgrass beds. Salinity is variable/reduced and coastal influence is strong. Benthic communities on sandflats in the deeper, central part of the Wash are particularly diverse including brittlestar beds and epifauna associated with the polychaete *Lanice conchilega*. The banks also provide nursery grounds for young commercial fish species. The common seal *Phoca vitulina* is also present within the site and is another primary reason for designation (Grade B).
North Norfolk Sandbanks and Saturn Reef pSAC.	Open shelf ridge sandbanks of intermediate coastal influence, in full salinity water. The site contains an extensive series of ten main roughly linear sandbanks and associated fragmented smaller banks formed as a result of tidal processes. The sandbanks are not vegetated, and support communities of invertebrates characteristic of southern North Sea sandbanks, ranging from those typical of highly-mobile fine sand sublittoral sediments, to communities on the outer banks which are more species rich, reflecting the lower sediment mobility. The site also supports aggregations of *Sabellaria spinulosa* and is a multifeature site also graded for Annex I biogenic reefs.
Dogger Bank dSAC	The Dogger Bank is a sandy mound formed through glacial processes and submergence through sea-level rise. It is non-vegetated and subject to intermediate coastal influence in full salinity waters. Sediments range from fine sands containing shell fragments on top of the bank to muddy sands at greater depths supporting invertebrate communities characterised by polychaete worms and echinoderms. Sand eels are an important prey resource supporting a variety of species including fish, seabirds and cetacean.
Essex Estuaries SAC	Sandbank is graded C at this site.

Humber Estuary cSAC	Sandbank is graded C at this site.
Solent Maritime SAC	Sandbank is graded C at this site.
Plymouth Sound and Estuaries SAC	Plymouth Sound and Estuaries has been selected for its extensive areas of sublittoral sandbanks, which consist of a range of sandy sediments within the inlet and on the open coast. These sediments include tide-swept sandy banks in estuarine habitats, sandy muds north of the Breakwater, muddy sands in Jennycliff Bay, fine sands with eelgrass *Zostera marina* and a rich associated flora and fauna in the Yealm entrance, as well as tide-swept sandy sediments with associated hard substrates colonised by distinctive communities of algae and invertebrates. The estuary mouth sandbanks sit in variable and reduced salinity waters and are subject to strong coastal influence.
Fal and Helford SAC	This is a sheltered site with a low tidal range and a wide range of substrates resulting in biologically one of the richest examples of sandbanks in the UK. Sublittoral sandbanks are present throughout much of the ria system and Falmouth Bay. There are particularly rich sublittoral sand invertebrate communities with eelgrass *Zostera marina* beds near the mouth of both the Fal and Helford and in some channels of the rias, such as the Percuil River and Passage Cove. Of particular importance are the maerl (*Phymatolithon calcareum* and *Lithothamnion corallioides*) beds that occur in the lower Fal on St Mawes Bank, and the extensive areas of maerl gravel which extend throughout the Carrick Roads and Falmouth Bay. These are the largest beds in south-west Britain and harbour a rich variety of both epifaunal and infaunal species.
Isles of Scilly Complex SAC	The Scilly archipelago, off the south-west tip of England, encompasses extensive sublittoral sandy sediments, which, between the islands, are contiguous with the intertidal sandflats. They are important in the UK for the extent and diversity of their associated communities. In particular, their isolation and the presence of oceanic water contribute to the special nature of the site, which is characterised by shallow sandy sediments with low silt content and by the fully marine salinity. There are rich communities present on the tide-swept sandbanks in the narrow channels between the islands and in the deeper, more stable, wave-sheltered sediments. The fauna of these sediments includes tanaid crustaceans, a diversity of polychaete worms, and various echinoderms.

Carmarthen Bay and Estuaries/ Bae Caerfyrddin ac Aberoedd SAC	Carmarthen Bay and Estuaries on the south coast of Wales includes the sandbank of Helwick Bank, a linear shallow subtidal sandbank that is unusual in Wales in being highly exposed to wave and tidal action. The animal communities found in and on the bank reflect these conditions, being tolerant of high levels of disturbance. Other primary reasons for site designation at this location were the presence of Annex I estuaries, mudflats and sandflats not covered by seawater at low tide, large shallow inlets and bays, Salicornia and other annuals colonising mud and sand and Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*) and the Annex II twaite shad *Alosa fallax*.
Lundy SAC	Sandbank is graded C at this site.
Severn Estuary cSAC	Sandbank is graded C at this site.
Y Fenai a Bae Conwy/ Menai Strait and Conwy Bay SAC	Menai Strait and Conwy Bay between mainland Wales and Anglesey includes the Four Fathom Banks complex, which is a relatively rare type of subtidal sandbank in Wales, in that it is comparatively large, and is fairly sheltered from wave action but situated in an area of open coast. The sandbanks vary from stable muddy sands in areas that experience weak tidal streams to relatively clean well-sorted and rippled sand in the outer area of the bank where tidal streams are stronger. In very shallow waters, particularly in the inner shore areas, relatively species-rich sandy communities are dominated by polychaetes such as *Spio filicornis*. In some years when numbers of bivalves are high, internationally important flocks of common scoter *Melanitta nigra* have been observed to congregate in the area of the Four Fathom Banks complex to feed. Another area of sandbanks (collectively referred to as the Menai Strait Banks) includes the subtidal sediments adjacent to large complexes of intertidal sandflat close to the northern and southern entrances to the Menai Strait. To the north this includes Dutchman's Bank and Penmaen Swatch, while to the south this includes subtidal sediments between Felinheli and Abermenai Point.
Pen Llyn a`r Sarnau/ Lleyn Peninsula and the Sarnau SAC	Pen Llyn a'r Sarnau on the north-west coast of Wales includes the sandbanks of Devil's Ridge, Bastram Shoal, the Tripods and an area to the south of Tremadog Bay. These include examples of fully marine salinity, tide-swept sandbanks and relatively sheltered sandbanks. On Devil's Ridge, Bastram Shoal and the Tripods strong tides mean that the sand, shell and gravel sediments are constantly shifting, and as a result the sandbanks support animals that can tolerate these high levels of disturbance.

Solway Firth SAC	The Solway is representative of sublittoral sandbanks on the coast of north-west England/south-west Scotland. The sandbanks comprise mainly gravelly and clean sands, owing in part to the very dynamic nature of the estuary. The inner estuary contains constantly changing channels, and a predominance of sand is characteristic of such high-energy systems. There is a transition to less extreme conditions in the outer estuary. The dominant species of the infaunal communities comprise different annelid worms, crustaceans, molluscs and echinoderms, depending on the nature of the substrate. For example, the bivalve molluscs *Fabulina fabula* and *Spisula subtruncata* occur at the edge of sandbanks in fine and medium sand respectively. These communities are richer in the less extreme conditions of the outer estuary.
Cardigan Bay/ Bae Ceredigion SAC	Sandbank is graded C at this site.
Pembrokeshire Marine/ Sir Benfro Forol SAC	Sandbank is graded C at this site.
Morecambe Bay SAC	Sandbank is graded C at this site.
Murlough SAC	Sandbank is graded C at this site.
Luce Bay and Sands SAC	Sandbank is graded C at this site.
Sanday SAC	Sandbank is graded C at this site.

Sound of Arisaig SAC	The Sound of Arisaig is representative of sublittoral sandbanks on the west coast of Scotland. It is sheltered, with low turbidity, and has an unusually high diversity of sublittoral sediment habitats within a relatively small area. These range from very soft mud and muddy sands in Loch Ailort and the deeper parts of its entrance to coarse, clean shell-sand in the more exposed parts of the site. This site is particularly significant in that it supports some of the most extensive beds of maerl in the UK. These maerl beds have very rich associated communities that include several rare and scarce species, such as the alga *Gloiosiphonia capillaris* and the hydroid *Halecium plumosum*. Eelgrass *Zostera marina* is found on shallow sand in outer Loch Ailort. In the more sheltered conditions in inner Loch Ailort muddy sand occurs, supporting large populations of the echiuran worm *Amalosoma eddystonense*, a nationally scarce species. The Sound of Arisaig supports species with predominantly southern distributions, such as the sipunculan worm *Sipunculus nudus*, and those with predominantly northern distributions, such as the starfish *Luidia sarsi*. The site is an important part of the transition from southern to northern communities that occurs along the coast of the UK.
Rathlin Island SAC	Sandbank is graded C at this site.
Loch nam Madadh SAC	Sandbank is graded C at this site.