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Widespread rocky reef occurrence in the central English Channel and the implications for predictive habitat mapping

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ABSTRACT

Reefs are one of the marine habitats listed in Annex I of the European Union's Habitats Directive, which aims to establish a coherent European ecological network of Special Areas of Conservation. EU Member States are required to prepare and propose a national list of sites for evaluation under the scheme, but currently the occurrence of reefs in the United Kingdom's nearshore and offshore areas is not well documented. Here we report on our search for rocky reefs in the central English Channel, which unexpectedly revealed an extensive reef system covering an area of 1100 km^2. Prior to our work, it was generally perceived that the seabed in this area comprised mostly gravel, with a few isolated rock outcrops.

Our approach to determining the location, extent and character of these reefs incorporated broad, medium and fine-scale analyses over a 3200 km^2 area of seabed, using single- and multi-beam acoustic data, ground-truthed by underwater video and stills imagery. A benthic terrain model was developed in ArcGIS to map topographic features at the broad and medium scales. Biotope assignments were made at the fine scale through detailed analysis of video footage obtained from 30 sampling stations. The study area has a complex geological history and lies at the centre of a major bedload-parting zone. Together, these strongly influence the seabed character and the distribution of biotopes. An integrated assessment of the physical and biological features was used to map the study area to level 4 of the EUNIS habitat classification system.

Similar physical conditions exist in other areas of the UK continental shelf, raising the prospect of predicting where other rocky reef systems might occur. In the absence of a co-ordinated national seabed survey programme, such predictions, coupled with interpretation of existing single-beam bathymetry data, can help prioritise areas where limited survey resources could be most effectively deployed.

1. Introduction

Rocky reefs are important ecological features, noted for their high biodiversity (Taylor, 1998). They include both bedrock outcrops and boulder or cobble fields where the consolidated substrate presents what is essentially a hard, rock surface at the seabed. The solidity of rock and the fractal complexity of its surface provide an abundance of stable, niche habitats exploited by a wide diversity of species, leading to the modern perception that rocky reefs habitats have high biodiversity (Kostylev et al., 2005). The ecological value of sublittoral rock reefs has only been truly recognised within the past 50 years, when the advent of SCUBA equipment and underwater imaging systems allowed these places to be routinely observed (Hiscock, 1998). This, in turn, has also led to a greater appreciation of their vulnerability to a range of external pressures resulting directly or indirectly from human activities (Kaiser et al., 2002; Perrings, 2002; Hiscock and Breckels, 2007; Przeslawski et al., 2008).

The perceived value and vulnerability of reefs is such that they are increasingly becoming the subject of conservation measures worldwide. In Europe, the Habitats Directive obliges Member States of the European Union to protect species and habitats through a coherent network of so-called Special Areas of Conservation (SAC). Annex I of the Directive lists the habitats in need of special conservation measures, one of which is reefs, which are defined as follows (European Commission, 2007): "Reefs can be either biogenic concretions or of geogenic origin. They are hard compact substrata on solid and soft bottoms, which arise from the sea floor in the sublittoral and littoral zone". Hard solid substrata are taken to include rocks, boulders (>256 mm in diameter) and cobbles (64–256 mm in diameter).

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The Habitats Directive has now been transposed into UK law. However, the efficacy of such legislation ultimately relies on a certain adequacy and reliability in knowledge of the location, extent and nature of important habitats to inform the appropriate selection of representative examples for conservation and monitoring. Unfortunately, such knowledge is limited for the UK and most of Europe, where there has not yet been a modern, systematic, fit-for-purpose survey of the entire seabed.

Although we now have advanced technologies in place to map the seabed with high resolution and accuracy, namely multi-beam echosounder (MBES) and sidescan sonar (Anderson et al., 2008), costs for mapping large swathes of the continental shelf are often considered to be prohibitive. As a consequence, our knowledge of shelf morphology and sediment distribution is far from complete.

To map a large area (approximately 3200 km^2) of continental shelf south of the Isle of Wight in the English Channel within reasonable time and costs, we have adopted a three-tiered approach incorporating broad, medium and fine-scale analysis. Single-beam echosounder data for the entire area was analysed using state-of-the-art terrain modelling techniques to produce a broadscale topographic map. This was complemented by a similar analysis applied to a smaller nested area where higher resolution MBES coverage was available. Fine-scale analysis of seabed features was made through interpretation of seabed video and photographic images, and an integrated analysis of all the materials was used to derive a seabed habitat map. When combined with knowledge of the physical processes occurring in the study area, this approach provides a framework for predicting the occurrence of rocky reefs in other areas, allowing more effective prioritisation of areas to be searched and a more cost-effective deployment of limited survey resources.

2. Setting

The English Channel is a funnel-shaped, ENE-WSW trending, relatively shallow shelf sea situated between France and England. This study is concerned with the central part of the English Channel roughly between 0° 30′ W and 2° 0′ W, and focuses on the sector of the UK's Exclusive Economic Zone (EEZ) beyond the12 nautical mile limit.

Physiographically, the most extensive element in the English Channel is a gently dipping planation surface of Neogene age, which slopes directly away from the coast. It is dissected by a network of palaeovalleys of Pleistocene age, most of which have been infilled with sediment. However, the so-called Northern Palaeovalley, situated in the study site, remains largely unfilled (Hamblin et al., 1992). This is thought to be the product of at least two megaflood events (Gupta et al., 2007) arising from the breaching of a rock dam at the Dover Strait releasing the contents of a meltwater lake situated in the southern North Sea during glacial times (Smith, 1985; Gupta et al., 2007).

The study site is a low-depositional environment; therefore it exhibits a discontinuous cover of coarse-grained lag deposits generally less than 0.5 m thick, within which there are 'windows' of exposed rock at the seabed. Significant areas of sediment-free rock occur coincident with outcrops of hard strata within the Jurassic and Lower Cretaceous (BGS, 1989). Tertiary (Palaeogene) strata can also produce hard positive features in the English Channel, but are more abundant to the east of our study site (James et al., 2007). Different types of bedrock can be distinguished based on their textures of bathymetry (Collier et al., 2006). Bedrock at the seabed comprises an almost complete succession from the Middle to Upper Jurassic Oxford Clay Formation to the Eocene Wittering Formation (Fig. 1). The bedrock is exclusively sedimentary, but shows a great variety including sandstone, mudstone, shale, limestone and marl, among others.

The Channel is a tide-dominated environment but is also influenced by long swell waves approaching from the open Atlantic Ocean. The greatest current speed occurs to the south of the Isle of Wight, where on spring tides it reaches 2.5 m/s at the sea surface. To the east and west of this area, the maximum current speed decreases, with a lowest values of 2.0 m/s at the western edge of the research site and only 1.3 m/s at the eastern boundary (Department for Business, Enterprise & Regulatory Reform, 2008). At the seabed, current speeds in excess of 1 m/s have been measured along a transect between the Isle of Wight and Cotentin peninsula, France (Velegrakis et al., 1997). Under such conditions, grains up to pebble size are mobile. The study site lies within a bedload-parting zone (Johnson et al., 1982; Hamblin et al., 1992), resulting in a net transport away from the central area to both east and west.

Annual mean significant wave heights range between 1.5 and 2.2 m in the offshore areas of the central English Channel (Department for Business, Enterprise & Regulatory Reform, 2008). Significant disturbance of the seabed (i.e. more than 5% of the time during a year) is largely limited to the coastal zone in waters less than 30 m (Grochowski and Collins, 1994). However, annual maximum significant wave heights can be much higher. Under such conditions, waves are able to disturb the seabed in all but the deepest parts of the research site, i.e. >60 m depth (Connor et al., 2006: Fig. 11).

3. Methods

3.1. Single-beam echosounder

As a full-coverage multi-beam echosounder survey of the entire study area was considered to be prohibitively expensive, we obtained available Digital Survey Bathymetry (DSB) data from SeaZone Solutions Ltd. These data were originally collected for navigational charting purposes by the United Kingdom Hydrographic Office from single-beam acoustic surveys conducted between 1978 and 2003. Individual soundings had been converted to depths by applying measured sound-velocity profiles in water and reduced to Lowest Astronomical Tide (LAT). The DSB data was supplied by SeaZone Solutions Ltd. as 'XYZ' ASCII-files giving Longitude, Latitude (both WGS 84) and water depth (metres below Chart Datum). Coverage is shown in Fig. 2, where the image has been derived by interpolation of the DSB data presented at a 75 m pixel resolution with shaded relief.

3.2. Multi-beam echosounder (MBES)

Multi-beam data were collected using a dual-head Kongsberg EM 3000D echosounder fitted to the retractable keel on the *RV* Cefas Endeavour. The survey track is illustrated in Fig. 1; a line spacing of approximately 6 times the water depth was used in areas where full coverage of the seabed was achieved. Data acquisition was through Kongsberg's SIS software, with the raw data being recorded in the proprietary "ALL" file format. Sound velocity profiles were taken at regular intervals or as necessary using a SAIV SD204 instrument, and applied in the acquisition software. Quality control measures were implemented during the acquisition and processing of MBES data, including a full calibration of the system. Tidal corrections were applied to the raw data using tidal curves calculated for a series of adjacent tidal 'zones' across the survey area. This provided a fully cleansed and seamless bathymetry data set. Data processing was undertaken using CARIS Hips and IVS3D Fledermaus. The data were acquired over an area of approximately 300 km^2 and are presented at 2 m pixel resolution.

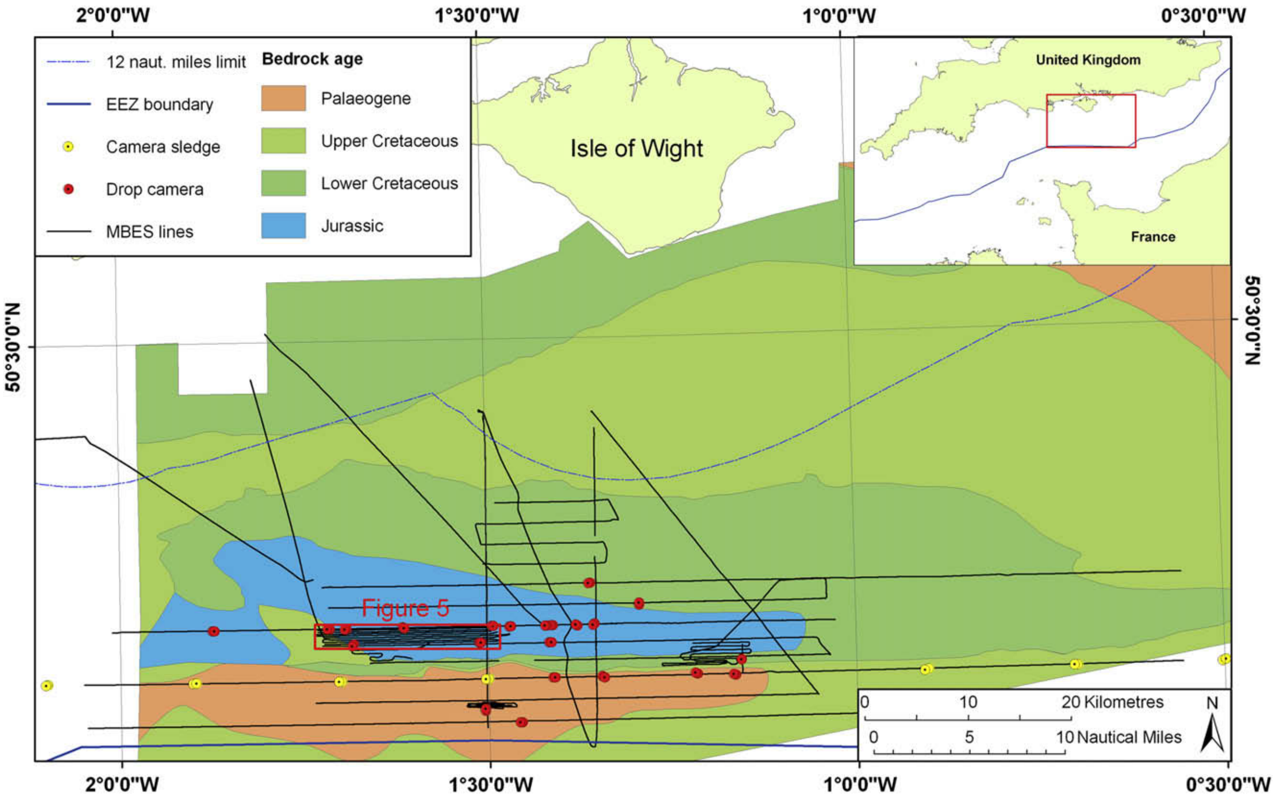

Fig. 1. Location of the study site in the English Channel (inset, indicated by red box) south of the Isle of Wight. Locations of MBES lines and ground-truth stations are indicated. Red box shows location and extent of full-coverage MBES survey discussed in this paper. Bedrock geology adapted from Collier et al. (2006) and Hamblin et al. (1992).

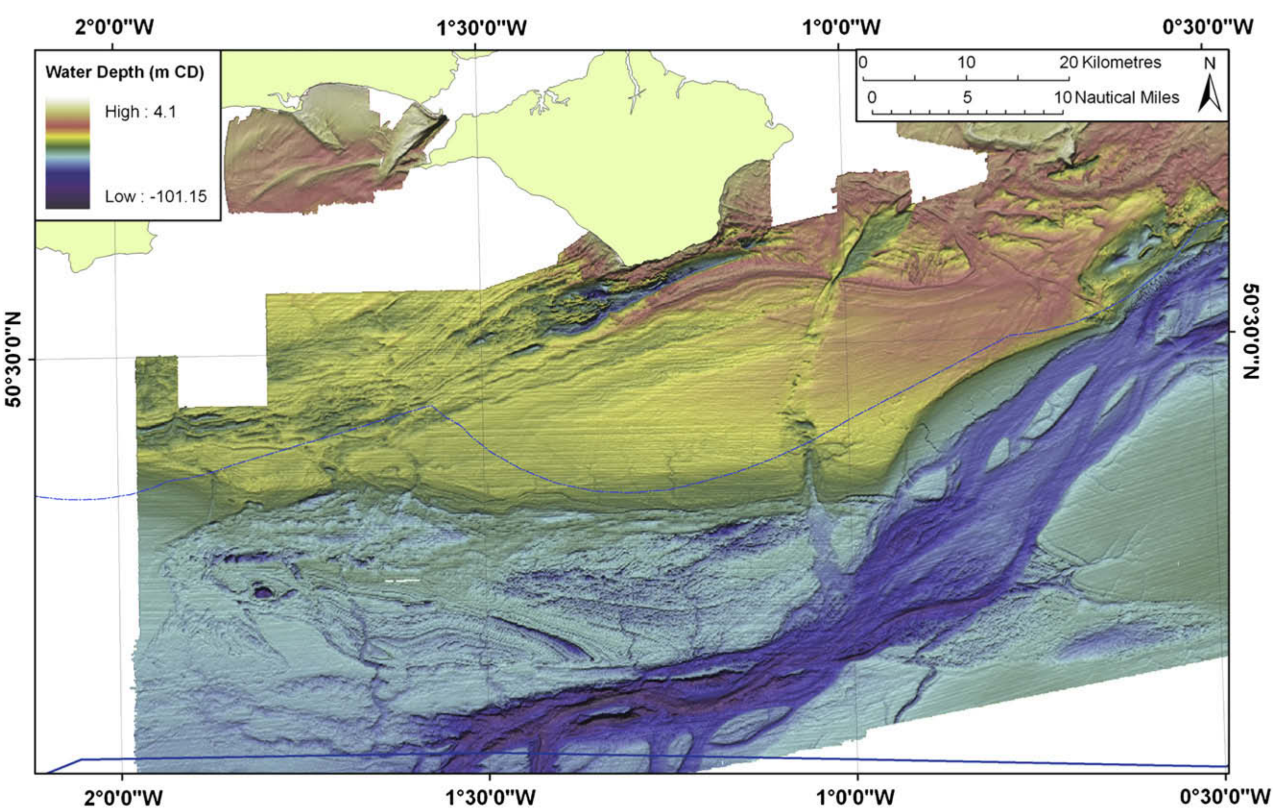

Fig. 2. Single-beam DSB data set used in the broad-scale analysis of this study. Water depths are shown in relation to Chart Datum (CD). Artificial illumination is from the north-west. ©British Crown & SeaZone, 2007. Lic. No. 042007.005. Not to be used for navigation.

3.3. Benthic Terrain Modeler

The Benthic Terrain Modeler (BTM) is an ArcGIS Spatial Analyst extension that was originally developed to classify benthic terrain around American Samoa based on multi-beam data (Lundblad et al., 2006). In this study, we applied the BTM methodology to both the multi-beam and single-beam data sets. The BTM application relies on the concept of bathymetric position index (BPI), a measure of the elevation of a point on the seabed relative to its surroundings. Positive BPI values denote points, features or regions that are higher than the surrounding area, i.e. crests. Conversely, negative values characterise depressions, while values near zero show either flat areas (where the slope is near zero) or areas of constant slope (where the slope is significantly greater than zero). A grid of such BPI values within a locale, or 'neighbourhood' allows a model of the benthic terrain to be created.

By default, the critical angle discriminating slopes from flats is set to 5° (Lundblad et al., 2006), which equates to a 17.5 cm rise over a distance of 2 m. This is appropriate for high-density data sets, such as multi-beam, where there is one data point for every few square metres of seabed. However, in the gridded bathymetry that we derived from the DSB data set, data density was much lower, with one point for every 75 m by 75 m of seabed, so detecting the same magnitude of rise required adjustment to this critical angle. Following trials (Table 1) an angle of 0.5° was selected, which equates to a rise of 65 cm over a distance of 75 m.

The size of the 'neighbourhood' used during the BPI determination can be selected by adjusting a variable 'scale factor' during the set up of the procedure. Benthic Terrain Modeler makes use of two neighbourhoods, a large one for the broad-scale BPI, which highlights the major topographic features, and a small one for the fine-scale BPI, which highlights the smaller benthic terrain features. Several scale factors were tested (Table 1) in order to achieve the best BPI zone and structure classifications. For the single-beam data we selected a scale factor of 6 for the broad-scale BPI (i.e. a neighbourhood with radius $6 \times 75\ \text{m} = 450\ \text{m}$) and 3 for the fine-scale BPI (a radius of $3 \times 75\ \text{m} = 225\ \text{m}$). For the multi-beam data, the values selected were 250 for the broad-scale BPI (500 m radius neighbourhood) and 30 for the fine-scale BPI (60 m radius neighbourhood).

As per the BTM procedure, the fine and broad-scale BPI's were standardised prior to classifying the outputs into terrain forms, based on the existing 'benthic zone' and 'benthic structure' classification dictionaries provided with the application. We made only minor modification to these, using a critical angle of 0.5° when applied to the single-beam analysis (as explained above), and merging the 'shelf' and 'broad flats' classes in the benthic structures dictionary, as the former is defined as 'flat terrain shallower than 22 m' and not appropriate to the environment of our study area.

3.4. Video analysis

Video observations were made at ground-truth sampling stations selected to cover a representative range of seabed features and acoustic signatures identified in the multi-beam acoustic survey (Fig. 1). On flat grounds, the camera was mounted on a sledge and towed along the seabed. On rough grounds, it was mounted in a drop-frame and hovered approximately 1 m above the seabed. Deployments were for a nominal time of 20 min, at approximately 0.2–0.4 m/s and covered roughly 300 m of ground. Positions were recorded continuously on differential GPS and the dynamic positioning capability of the vessel used to steer along pre-determined transects. Video was recorded continuously, with still images taken at 1-minute intervals (or thereabouts). Full details of the system and protocols for camera sledge and drop camera are given in James et al. (2007) and Coggan et al. (2008).

In the laboratory, the video for each station was analysed following a protocol developed over several years of similar work. This entails dividing the video record up into segments representing different ground types encountered along the transect, then making a detailed analysis of each segment, recording the physical characteristics of the substrate and the variety and abundance of life forms and/or recognisable taxa observed. Relative abundance was scored using the SACFOR scale (Anonymous, 1996) and taxon identification aided by viewing still images from each respective video segment. Once the analysis was complete, the observer used expert judgement to assign each segment of the video to one of the biotopes listed in the EUNIS habitat classification (see http://eunis.eea.europa.eu/habitats.jsp). The EUNIS classification system is hierarchical, with the progressive layer dealing with different habitat features or characteristics. In the littoral and sublittoral realm, the basic framework for the classification is based on substrate (rock and sediment) and biological zone (littoral, infralittoral, circalittoral). Rock is then further subdivided based on the energy input from waves and currents (high, moderate and low energy), while sediments are broadly grouped based on grain-size (coarse sediment, sand, mud and mixed sediment). Further details of the methodology can be found in Connor et al. (2004).

Table 1
Details of trials run to determine critical angle and scaling factors for the broad-scale (DSB data set) and medium-scale (MBEs data set) analyses. Chosen values are indicated by bold print.

	Single-beam data set (DSB)				multi-beam data set (MBES)				
Grid dimension	75 m × 75 m				2 m × 2 m				
Critical angle	0.25	**0.5**	1	5	1	2	3	4	**5**
Fine-scale BPI scaling factor		**3**			10	20	**30**		
Broad-scale BPI scaling factor	**6**	9	12		50	70	126	**250**	

4. Results and interpretation

Owing to the nature of the available data sets, i.e. 'full-coverage', low-resolution DSB data, high-resolution MBES data with limited coverage of the research site and very detailed but localised seabed imagery, we decided to break down the interpretive process into several steps according to scale. Results were then integrated with auxiliary environmental data to derive a habitat map based on the EUNIS classification.

4.1. Broad-scale analysis (DSB data)

Input bathymetry data used for terrain analysis is shown in Fig. 2. The continental shelf is gently sloping towards the south with an average gradient of roughly 1:1000 (0.057°). The Northern Palaeovalley dissects the seabed as a roughly 100 km long structure running from northeast to southwest. Notably, the extent of the palaeovalley floor (blue colours in Fig. 2) is approximately delimited by the 60 m isobath. A network of inner channels that divert from each other and rejoin again can be recognised from the bathymetric data.

Classification of the DSB data with the Benthic Terrain Modeler yields four benthic zones (Fig. 3). An elongated east–west trending area centred in the study site shows high variability in benthic zones displaying crests, slopes, flats and depressions. There is a preference for an east–west orientation of benthic zones. Individual crests can be followed for several tens of kilometres. This area is surrounded by flat and almost featureless seabed. The course of the Northern Palaeovalley is clearly picked up by continuous slopes and, to a lesser extent, crests that bound broad, flat floors in

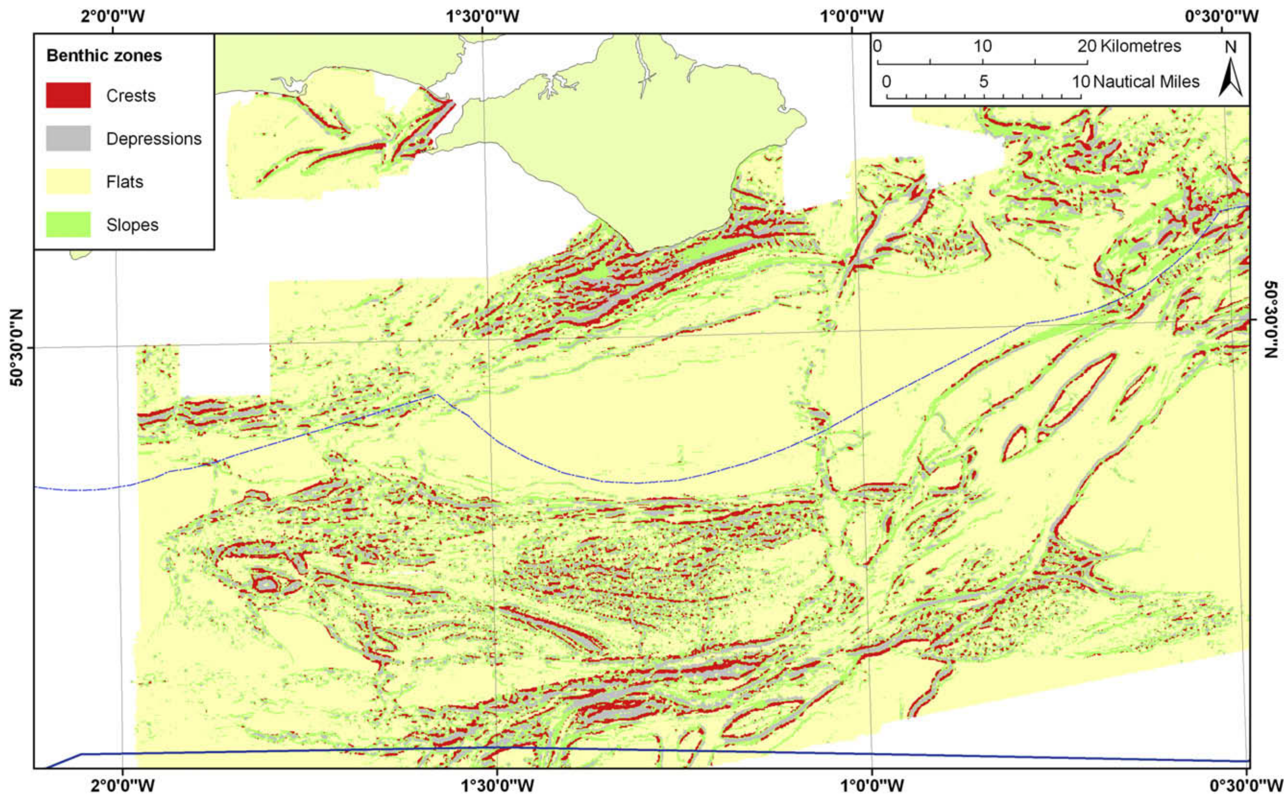

Fig. 3. Benthic zones derived from single-beam DSB data set with Benthic Terrain Modeler.

the north of the valley. To the south, the floor of the palaeovalley gets increasingly rugged with roughly east-to-west trending depressions in the south.

Based on these results and knowledge of bedrock geology (Fig. 1), we mapped eight different classes of seabed character (Fig. 4). The km-long and continuous slopes, crests and depressions in the centre of the site are interpreted as series of bedrock ridges of Jurassic and Lower Cretaceous age. In particular, the Jurassic bedrocks display series of well-defined ridges and depressions due to the cyclic nature of the strata (predominantly interbedded mudstones, shales and thin limestones of the Kimmeridge Clay Formation). Lower Cretaceous bedrock outcrop (predominantly sandstones, shales, mudstones and siltstones of the Wealden Group) appears to be somewhat more irregular. Bedrock ridges of Palaeogene age (predominantly sands, clays and mudstones of the London Clay Formation) were encountered in the south of the study site.

Large portions of the seabed are flat and smooth and largely coincide with the occurrence of massively bedded Upper Cretaceous chalk. According to information obtained from seabed sampling (BGS, 1989), the chalk bedrock is covered by gravel and sandy gravel forming a thin layer of coarse-grained lag deposit.

Large areas of the palaeovalley are classed as palaeovalley floor including the inner channels mentioned earlier. The floor appears to be largely covered with gravel and sandy gravel according to seabed samples from BGS (1989). The floor is bordered by a rim, which normally forms a narrow ribbon but reaches a width of more than 4 km in the north of the palaeovalley, where it dissects chalk bedrock and forms a bench-like structure (Fig. 4). Streamlined islands or mesas (Gupta et al., 2007) are located in the north and south of the palaeovalley, but not in the centre part, where it is cut into Lower Cretaceous bedrock. Several tributaries, only the larger of which where mapped, feed into the palaeovalley.

4.2. Medium-scale analysis (MBES data)

A smaller area measuring 32 km^2 and situated within the Jurassic bedrock ridges was mapped with high-resolution MBES, yielding a bathymetric data set gridded to 2 m by 2 m bin size (Fig. 5). Water depths range from 47 m to 65 m (Fig. 5 top). The Benthic Terrain Modeler identified eleven different benthic structures; however seven of them are negligible with occurrences below 1% of area (Fig. 5 middle). Most widespread are broad flats, which cover roughly 80% of classified seabed area. An exclusively flat area is located in the west and is bounded by a northwest-to-southeast trending narrow crest line. We interpret this area as a thin gravel lag overlaying Upper Cretaceous chalk, being similar in its smoothness and flatness to ground-truth sites where such gravel lag was observed. Open slopes and narrow crests tend to be largely parallel to each other. They roughly trend in an east–west direction and indicate ridges of upper Jurassic (Corallian and Kimmeridge Clay) bedrock. The cyclic nature of the upper Jurassic lithology is reflected in series of bedrock ridges, intervened by flats or troughs. Due to different resistance to erosion, hard substrata such as limestone stand proud and form ridges while soft substrata (e.g. mudstone) are eroded and form troughs. The ridges display bends due to folding and displacements due to faulting.

Meandering broad depressions with open bottom, roughly trending north-to-south, indicate the presence of palaeovalley tributaries.

Based on these benthic structures and the presence of subaqueous dunes visible in the multi-beam bathymetry data, we identified five different types of seabed character (Fig. 5 bottom). The bedrock ridges, flat, smooth seabed and palaeovalley tributaries are complemented by two other classes, namely flat bedrock partly covered by mobile sediment (subaqueous dunes) and small-scale gullies.

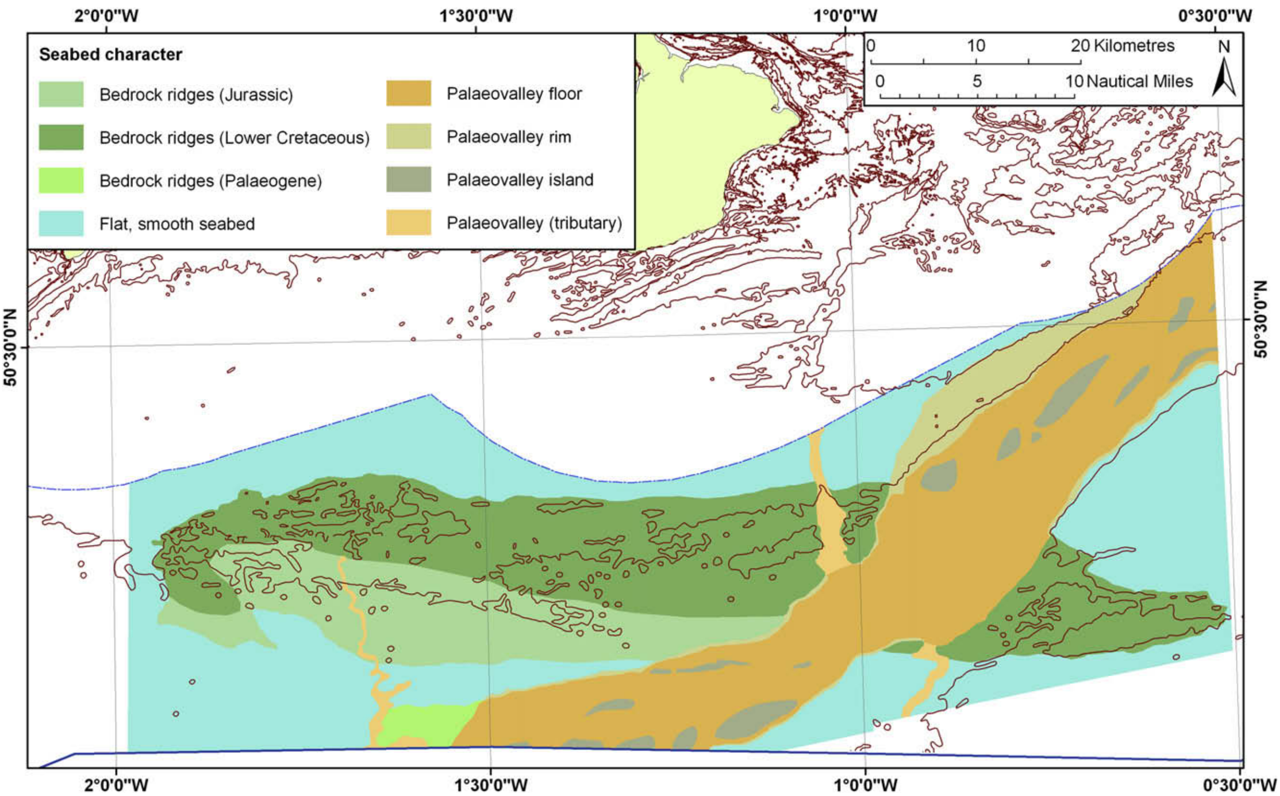

Fig. 4. Map of seabed character derived from benthic zones (Fig. 3) and bedrock geology (Fig. 1).

This interpretation of the medium-scale MBES data is largely consistent with that of the broader-scale DSB data. However, it became apparent that areas classified as bedrock ridges in the DSB interpretation could include the class of flat bedrock covered by thin sediment that was only discriminated from the higher resolution MBES data.

4.3. Fine-scale analysis (underwater video)

Thirty stations were sampled with video (Fig. 1). Eight of these had been selected a-priori as part of a larger east–west transect for a parallel study designed to sample sediments using grabs, trawls and towed camera sledge. Hence, none contained 'rock' habitats. The remaining 22 stations were selected post-priori as part of the reef survey, using a drop-camera system to ground-truth features of interest revealed by the multi-beam sonar. All except one of these stations contained rock habitat supporting a substantial coverage of fauna and so are consistent with the definitions of rocky reef according to the Habitats Directive (see Introduction).

Bedrock was typically well exposed over the majority of the video record, frequently in a series of ridges up to approximately 4 m high with some sediment in the troughs between ridges. This pattern was evidently the surface expression of bedding planes with a low dip angle, such that a series of small 'escarpments' was covered during the video tow. There was therefore frequently an alternating pattern of two or three biotopes as the camera passed from the sediment filled trough, up the steeper irregular scarp face and down the (less steep) planar, dip slope. The exposed rock surfaces were typically entirely covered in fauna, except in the lower reaches adjacent to mobile sediments where the rock was subject to significant scour. Scarp and dip slopes tended to support slightly different biotopes, the scarp slopes featuring taxa frequently associated with faster moving water, such as the hydroid *Tubularia indivisa*, while the dip slopes were typically characterised by the bryozoan *Flustra foliacea* and encrusting communities comprising sponges, hydroids and bryozoa. Scour tolerant communities, typified by anemones *Urticina felina* and *Sagartia spp*. occurred near the interfaces between sediment and exposed rock. Taxa normally associated with rock or hard surfaces were commonly found among some of the sediments, which evidently laid thinly over underlying rock and were formed into ripples or dunes.

At deeper stations, sponges became more prevalent, thin encrusting forms giving way to cushion and erect forms, such as *Polymastia boletiformis* and ultimately the massive forms such as *Pachmatisma johnstonia*. The more fragile bryozoan *Pentapora foliacea* (also known as 'Ross Coral') was also frequently recorded. Boulder fields and steep rock faces associated with the palaeovalley supported similar fauna. Variability among biotopes appeared to be related entirely to the topographic and hydrodynamic characteristics of the local environment and was not noted to be linked to changes in basal rock type.

The floor of the palaeovalley was typically of cobble and pebble substrate and, supported a sponge and faunal 'turf', which indicated a degree of stability in the seabed. Evidently, this 'turf' itself helped to further stabilise the sediment, promoting even more luxuriant growth, turning the seabed into a bio-geo-concretion. While superficially this concretion might be regarded as a 'rock' habitat, we elected to classify it as a sediment habitat, as particles smaller than cobbles were present. Boulder and cobble substrates occurring at the base of steep rock outcrops found at the edge of the palaeovalley were classified as rock habitats. Outside the palaeovalley, in the smaller tributaries, the substrate tended to be finer (more pebble than cobble) and less stable, and supported a much reduced fauna characterised by hard-shelled life forms such as barnacles and the tube-worm *Pomatoceros*, which are resistant to abrasion by

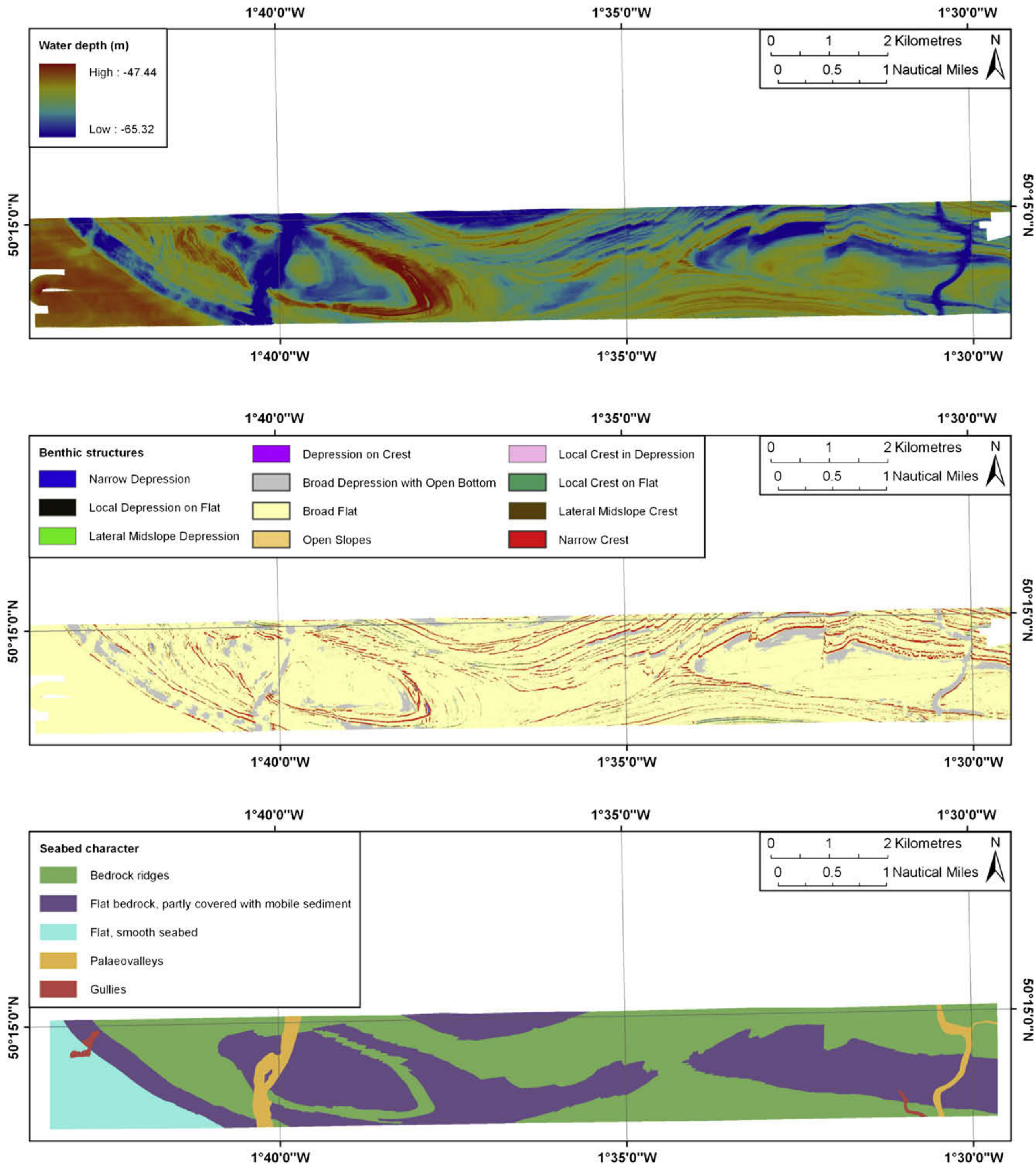

Fig. 5. MBES data set used in the medium-scale analysis (top) and resultant benthic structures derived with Benthic Terrain Modeler (middle). Seabed character (bottom) was derived from benthic structures and additional information (occurrence of subaqueous dunes etc.).

sand carried as bedload and resilient to physical damage caused by turn-over of the substrate. 'Streams' of finer, well-sorted gravel, entirely devoid of fauna were observed running along the palaeovalley and tributaries, having the appearance of streambeds.

A few stations had significant amounts of mobile sand smothering sections of the outcropping rock and occasionally forming dunes, some up to 4 m high, which could over spill the steep scarp slopes. No fauna were found to be associated with such dunes.

There was a notable absence of some species and taxa commonly associated with rocky habitats in the western channel, such as the urchin *Echinus esculentus*, the holothurian *Holothuria forskali*, the sea fan *Eunicella verrucosa*, and the cup coral *Caryophyllia smithii*. Large crabs (*Cancer*, *Liocarcinus*, *Necora*) were rare, but smaller stone crabs (e.g. *Ebalia*) relatively common. No biogenic reefs were encountered (e.g. *Sabellaria*, *Modiolus*). No alga was recorded; even the encrusting forms like *Lithothamnion* were absent.

The distribution of selected rock biotopes expressed in EUNIS classes is mapped in Fig. 6a to c, while that for the sediment biotopes is mapped in Fig. 6d.

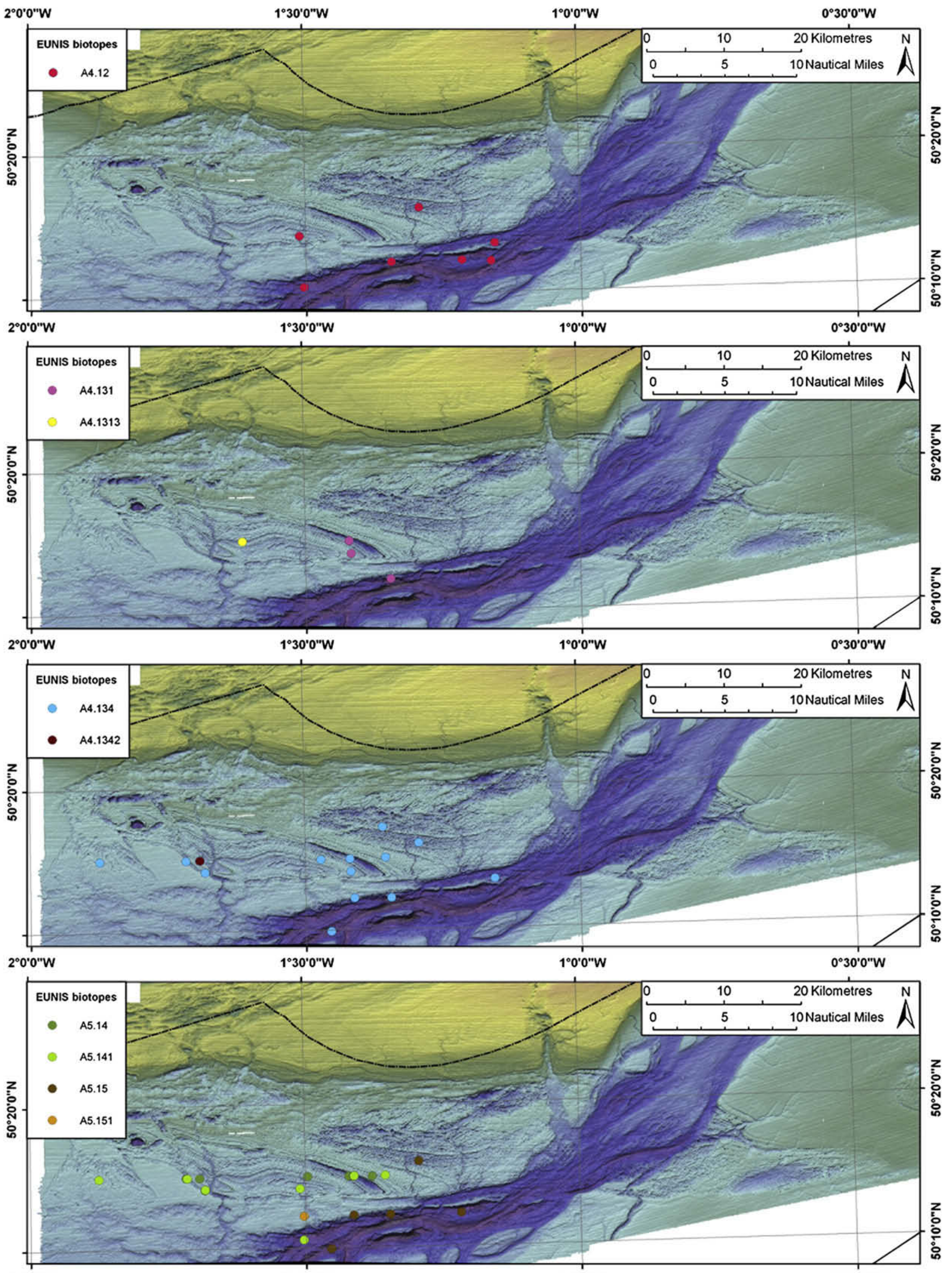

Fig. 6. Distribution of EUNIS biotopes based on video analysis showing: Top panel – sponge communities on deep circalittoral rock (A4.12), Centre panels – mixed faunal turf communities on circalittoral rock (A4.13) and Bottom panel – circalittoral coarse sediment (A5.14) and deep circalittoral coarse sediment (A5.15). Water depths are as shown in Fig. 1. Bathymetry ©British Crown & SeaZone, 2007. Lic. No. 042007.005. Not to be used for navigation.

4.4. Integration of results

Results were integrated to derive a habitat map based on the EUNIS classification (Fig. 7). With water depths ranging between 25 m and 100 m, the study site is exclusively aphotic (Connor et al., 2006: Fig. 9); hence it is placed in the circalittoral and deep circalittoral biological zones. Surface tidal currents are in excess of 1.5 m/s which classifies them as strong (Connor et al., 2004). The mapped area of bedrock ridges therefore translates into high-energy circalittoral rock (EUNIS class A4.1), which is consistent with the video interpretations (Fig. 6a–c). There is evidence from a limited number of video stations (not shown in Fig. 6) that moderate energy circalittoral rock (A4.2) is present in locally sheltered locations. Due to the local nature and limited occurrence this habitat has, however, not been mapped. The total area mapped as high-energy circalittoral rock amounts to 1100 km^2, approximately three times the size of the Isle of Wight.

Sediments are predominantly coarse (gravel and sandy gravel). The remainder of the seabed is therefore classed as sublittoral coarse sediment (A5.1) with the opportunistic fauna associated with more mobile areas being characteristic of biotopes listed under 'circalittoral coarse sediments' (A5.14), while the sponges and faunal turfs of the more stable, consolidated sediments are aligned with biotopes listed under 'deep circalittoral coarse sediments' (A5.15) The transition between these two classes is most closely associated with a move from the rim to the floor of the palaeovalley (Fig. 6d). As this typically occurs in $\approx$60 m water depth this has been taken as the modelled boundary between the two habitat classes, and is consistent with the local wave base (Connor et al., 2006: Fig. 11). There is evidence from the video footage that the steep walls of the palaeovalley exhibit rock. These areas are, however, too small to be mapped at the scale adopted.

5. Discussion

Our results are in contradiction to expectations, in that most maps depict the study site as being covered with coarse sediment rather than showing the presence of extensive bedrock (e.g. Pratje, 1950; Vaslet et al., 1978; Larsonneur et al., 1982; BGS, 1989). This discrepancy is the result of the different methodologies adopted. Previous studies have relied heavily on the collection of surface sediment samples whereas we were able to discriminate rocky reef using acoustic techniques and through the targeting of ground-truthing. In previous investigations, rock was only mapped if no sample was retrieved, leading to an underestimate of the extent of bedrock in the area. This holds also true for the most recent seabed sediment map of the study site (BGS, 1989), although in the accompanying text it is stated that the sediment cover is thin and discontinuous and that significant areas of rock outcrop occur within areas characterised by Jurassic and Lower Cretaceous strata. Our study undoubtedly benefited from the integration of a number of techniques and data-sources. The choice of techniques adopted in any study will clearly influence the fraction of the seabed that is sampled and will also determine the capacity to discriminate seabed habitats such as rocky reefs. Such choices also have a bearing on the nature of the final habitat map and will have implications for both derived habitat classification schemes and any management decisions relating to the conservation or use of the area. The use of good-quality single-beam echosounder data combined with modern terrain analysis techniques dramatically increased our knowledge and understanding of the area. Collection of full-coverage MBES data providing both bathymetry and backscatter remains the ultimate goal to support the sustainable management of offshore resources (Pickrill and Todd, 2003). However, as such a task needs a concerted effort and significant

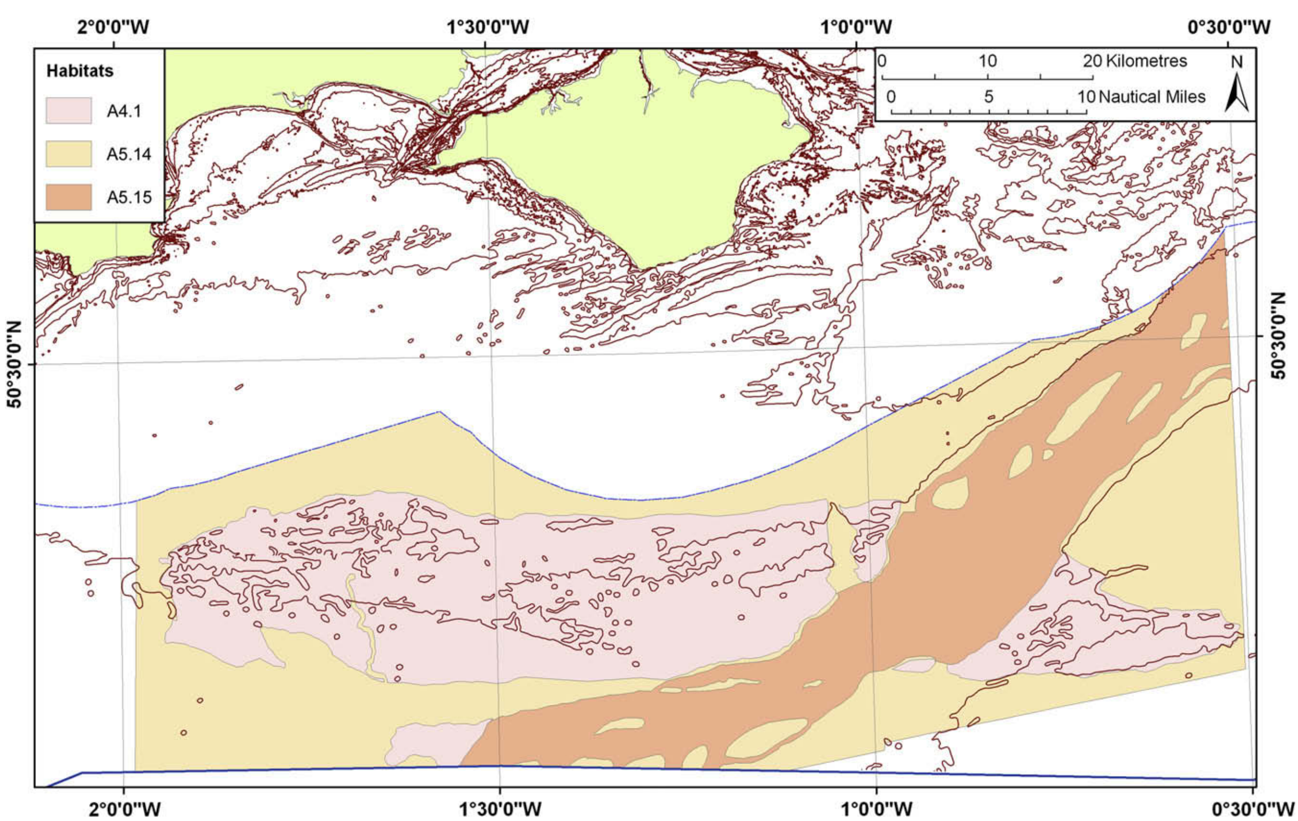

Fig. 7. Resultant map of EUNIS habitats showing the distribution of high-energy circalittoral rock (A4.1), circalittoral coarse sediments (A5.14) and deep circalittoral coarse sediments (A5.15).

resources, making best use of available DSB data, which is primarily gathered for hydrographic purposes, is of key importance to better understand and manage the marine environment.

Our results demonstrate a clear correlation between bedrock geology (Fig. 1) and physical habitat (Fig. 4). Areas, where bedrock ridges are widespread, largely coincide with the distribution of Jurassic and Lower Cretaceous rocks. This is due to the fact that Upper Jurassic and Lower Cretaceous bedrock comprises a varied and partly cyclic lithology, displaying a differential resistance to erosion (Hamblin et al., 1992; Collier et al., 2006). As the strata was slightly folded and tilted, it developed into series of ridges and intervening sediment-filled troughs through differential erosion. Variety in the nature and the form of the substrate is important for biodiversity. The rocky areas provide a range of habitats for both epifauna and infauna, and characteristically presented a diverse mosaic of biotopes. At the fine scale, the complexity of the rock forms themselves presents both a greater surficial area for colonisation and a greater variety of niche habitats than would a flat rock surface. Johnson et al. (2003) observed that topographically complex surfaces may contain more species due to increased habitat diversity or as a result of increased area per se. Consequently, both area and complexity of habitat are important explanatory variables of biodiversity (Kostylev et al., 2005).

Conversely, where the underlying rock is of Upper Cretaceous chalk, the seabed is predominantly smooth and flat, with a thin covering of lag-gravel. This is a consequence of the lithology of Upper Cretaceous chalk being soft and uniform (Hamblin et al., 1992; Collier et al., 2006) and the fact that bedding is very close to horizontal (1°–2° according to BGS, 1995). Rock scarps, although present close by (e.g. to the east and west of the Isle of Wight), are largely absent in the study site and the physical habitat can be described as rather uniform consisting of mixed or coarse sediment; hence, only sediment biotopes are found here.

The only area that shows no apparent correlation with bedrock lithology is the Northern Palaeovalley, but this can be expected of a large-scale erosive feature. In fact, Gupta et al. (2007) note that the valley crosscuts a variety of bedrock lithologies, indicating that lithology does not significantly control the valley morphology. The palaeovalley is typically floored with coarse substrates comprising pebbles and cobbles, classified as deep circalittoral coarse sediment (Fig. 6d). The depth of the valley floor, below the wave base, confers stability on the substrate such that it becomes densely overgrown by sponges and faunal turf to an extent that it resembles a rock habitat. In contrast, the circalittoral coarse sediments found predominantly north of the palaeovalley, in shallower water (Fig. 6d) comprise finer clasts up to pebble size. These are both more susceptible to, and more exposed to remobilisation, and consequently they have a far reduced epifaunal complement, and may even be azoic in places.

There is only limited evidence regarding the mobilisation of seabed sediments in the study site. Based on current measurements, Velegrakis et al. (1997) estimated that grains up to pebble size can be mobilised in this area by tidal action. This could explain why coarse sediments outside the palaeovalley (up to pebble size) are mobilised at least occasionally, while those on the floor of the valley (pebbles and cobbles) are essentially stable. The low mobility of the coarse sediments flooring the palaeovalley facilitates the colonisation towards a climax community (Holme and Wilson, 1985), with the presence of encrusting sponges appearing to accelerate and enhance this stability, in a feedback process.

The outcomes of this study show there is a potential for applying our methodological approach to the task of predicting the occurrence of rocky reefs. We have demonstrated that there is a clear correspondence between bedrock geology, the resulting seabed morphology and the nature of the benthic habitats. Knowledge of the distribution, disposition and lithology of the bedrock will therefore be important in predicting the distribution of rocky reef habitats.

We explain the occurrence of bedrock at the seafloor south of the Isle of Wight by a combination of several factors. These include the presence of a non-depositional environment where strong currents and bedload-parting keep the seabed essentially free of sediment and low sediment availability, mainly due to the fact that the English Channel was only marginally influenced by Pleistocene glaciations (Hamblin et al., 1992). Similar factors apply to the Bristol Channel and, consequently, Warwick and Uncles (1980) found a good correlation between tidal shear stress and seabed type, where the occurrence of bedrock was linked to high tidal stress. Comparing the locations of bedload-parting zones (e.g. Johnson et al., 1982) to the mapped seabed sediments around the UK coast (BGS, 1987a,b) shows that several of the zones exhibit exposures of either bedrock (Bristol Channel and Pentland Firth) or Pleistocene strata (St. Georges Channel) at the seabed, while others are characterised by lag-gravel. Presumably, the latter ones are characterised by higher sediment availability and/or lower bedload transport capacity in relation to grain-size of the ambient seabed sediments. Bedrock has also been mapped in places located away from bedload-parting, especially along the coasts of southwest England and Wales (Fig. 4.4 in Johnson et al., 1982) and off the Outer Hebrides (BGS, 1987b). Here, the seabed is most likely kept sediment-free by the stirring motion of long swells arriving from the open Atlantic.

It appears that there is a strong likelihood of locating potential areas of rocky reef given sufficient information on tidal and wave stress, Holocene sediment thickness, distribution of Pleistocene deposits and bedrock lithology. Rocky reefs can be expected in areas of non-deposition (Holocene sediment thickness equals zero) that were not or only marginally affected by glaciations and exhibit a bedrock geology that is suitable for producing hard positive features at the seabed (e.g. varied lithology, tilted strata etc.). Besides this, other, less predictable factors, which cannot be accounted for in this study, might be of importance, e.g. rock emplacement, mass movement and coastal erosion.

Cabioch (1968) identified the importance of tidal influences on biodiversity patterns in the English Channel, mediated through effects on substratum type, particulate transport and water mixing, a finding matched by Warwick and Uncles (1980) from a synoptic survey of the hydrodynamically energetic Bristol Channel. Their findings were comparable with that of Rees et al. (1999) who examined the benthic biodiversity around the UK coast, and with the aid of correlation analyses demonstrated a link between the degree of physical disturbance of sediments and broad trends in the numbers and densities of taxa. On the basis of such evidence, Hall (1994) concluded that it is the hydrodynamic regime that largely determines the sedimentary characteristics of an area and which is ultimately responsible for determining broadscale community patterns. However, links between current stress, seabed type and benthic communities do not appear to have been tested on a shelf-wide basis to predict likely areas of rocky reef. Most of the data sets for such a task are readily available and can be easily exploited with the help of geographic information systems. Available or newly gathered single-beam bathymetry data of sufficient quality could then, in turn, further refine the areas of highest likelihood to be surveyed with MBES to map the occurrence of rocky reefs. In this way, effort to map areas of the coastal and offshore seabed could be directed in a cost-effective manner. The challenge would then turn to using the knowledge derived from the analysis of resulting data sets to promote the sustainable use of the marine environment.

6. Conclusions

We have mapped habitats in the central English Channel south of the Isle of Wight at different scales and resolutions with a variety of techniques. Results were then integrated into a EUNIS habitat map (Fig. 7). Based on our results we draw the following conclusions:

1. Available good-quality single-beam bathymetry data collected for hydrographic purposes can be useful and cost-effective to map habitats at scales needed for management. Integrated with ground-truth data, it is by far superior to existing seabed sediment maps, especially when mapping rocky reefs.
2. South of the Isle of Wight, the physical benthic habitat is mainly governed by bedrock geology: Areas where Jurassic and Lower Cretaceous rocks are present exhibit a series of rock ridges and sediment-filled troughs due to the varied and partly cyclic nature of the strata. A variety of rock and sediment biotopes are present here. Conversely, areas with Upper Cretaceous chalk in the subsurface are flat and uniformly covered with a thin layer of coarse sediment. The encountered biotopes are exclusively sedimentary and more limited in their variety.
3. The floor of the Northern Palaeovalley is predominantly covered with coarse sediment. This is largely immobile and functions to some extent as a 'rock' habitat.
4. The variety and distribution of the observed biotopes is closely linked to local physical and hydrodynamic conditions, and appear independent of limited change in basal bedrock type. Where cobbles substrates are stable, they support similar fauna to that found on exposed bedrock, and can be regarded as 'rock' rather than 'sediment' habitats.
5. The occurrence of bedrock at the seabed south of the Isle of Wight is due to the fact that the area is non-depositional as strong currents and bedload-parting inhibit sedimentation and sediment availability is limited as the area was only marginally affected by Pleistocene glaciations.
6. On a shelf-wide scale, the likely occurrence of bedrock could be predicted based on tidal and wave sheer stress, Holocene sediment thickness, distribution of Pleistocene sediments and bedrock lithology.

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References

Anderson, J.T., Van Holliday, D., Kloser, R., Reid, D.G., Simard, Y., 2008. Acoustic seabed classification: current practice and future directions. ICES Journal of Marine Science 65, 1004–1011.

Anonymous, 1996. Appendix 9 'Abundance Scales'. In: Hiscock, K. (Ed.), Marine Nature Conservation Review: Rationale and Methods. Joint Nature Conservation Committee, Peterborough, p. 142.

Cabioch, L., 1968. Contribution à la connaissance des peuplements benthiques de la Manche occidentale. Cahier de Biologie Marine 9, 493–720.

Coggan, R., Mitchell, A., White, J., Golding, N., 2008. Recommended operating guidelines (ROG) for underwater video and photographic imaging techniques, 32 pp. Available from: http://www.searchmesh.net/PDF/GMHM3_Video_ROG.pdf.

Collier, J.S., Gupta, S., Potter, G., Palmer-Felgate, A., 2006. Using bathymetry to identify basin inversion structures on the English Channel shelf. Geology 34, 1001–1004.

Connor, D.W., Allen, J.H., Golding, N., Howell, K.L., Lieberknecht, L.M., Northen, K.O., Reker, J.B., 2004. The Marine Habitat Classification for Britain and Ireland Version 04.05: Introduction. Joint Nature Conservation Committee, Peterborough. Available from: www.jncc.gov.uk/MarineHabitatClassification. 49 pp.

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. Available from: http://www.jncc.gov.uk/page-3918. 104 pp.

Department for Business, Enterprise & Regulatory Reform, 2008. Atlas of UK marine renewable energy resources: Atlas pages. Available from: http://www.renewables-atlas.info.

European Commission, 2007. Interpretation Manual of European Union Habitats – EUR 27 Available from: http://ec.europa.eu/environment/nature/legislation/habitatsdirective/docs/2007_07_im.pdf. 142 pp.

Grochowski, N.T.L., Collins, M.B., 1994. Wave activity on the sea-bed of the English Channel. Journal of the Marine Biological Association of the United Kingdom 74, 739–742.

Gupta, S., Collier, J.S., Palmer-Felgate, A., Potter, G., 2007. Catastrophic flooding origin of shelf valley systems in the English Channel. Nature 448, 342–345.

Hall, S.J., 1994. Physical disturbance and marine benthic communities: life in unconsolidated sediments. Oceanography and Marine Biology: an Annual Review 32, 179–239.

Hamblin, R., Crosby, A., Balson, P., Jones, S., Chadwick, R., Penn, I., Arthur, M., 1992. United Kingdom Offshore Regional Report: The Geology of the English Channel. HMSO for the British Geological Survey, London, 106 pp.

Hiscock, K., 1998. Introduction and Atlantic–European perspective. In: Hiscock, K. (Ed.), Marine Nature Conservation Review. Benthic Marine Ecosystems of Great Britain and the North-east Atlantic. Joint Nature Conservation Committee, Peterborough, pp. 3–70.

Hiscock, K., Breckels, M., 2007. Marine Biodiversity Hotspots in the UK: their identification and protection, WWF-UK, Godalming. Available from: http://assets.wwf.org.uk/downloads/marinehotspots.pdf. 116 pp.

Holme, N.A., Wilson, J.B., 1985. Faunas associated with longitudinal furrows and sand ribbons in a tide-swept area in the English Channel. Journal of the Marine Biological Association of the United Kingdom 65, 1051–1072.

James, J.W.C., Coggan, R.A., Blyth-Skyme, V.J., Morando, A., Birchenough, S.N.R., Bee, E., Limpenny, D.S., Verling, E., Vanstaen, K., Pearce, B., Johnston, C.M., Rocks, K.F., Philpott, S.L., Rees, H.L., 2007. The eastern English Channel marine habitat map. Science Series Technical Report, Cefas Lowestoft 139, 191 pp. Available from: http://www.cefas.co.uk/publications/techrep/tech139.pdf.

Johnson, M.A., Kenyon, N.H., Belderson, R.H., Stride, A.H., 1982. Sand transport. In: Stride, A.H. (Ed.), Offshore Tidal Sands. Chapman and Hall, London and New York, pp. 58–94.

Johnson, M.P., Frost, N.J., Mosley, M.W., Roberts, M.F., Hawkins, S.J., 2003. The area-independent effects of habitat complexity on biodiversity vary between regions. Ecology Letters 6, 126–132.

Kaiser, M.J., Collie, J.S., Hall, S.J., Jennings, S., Poiner, I.R., 2002. Modification of marine habitats by trawling activities: prognosis and solutions. Fish and Fisheries 3, 114–136.

Kostylev, V.E., Erlandsson, J., Ming, M.Y., Williams, G.A., 2005. The relative importance of habitat complexity and surface area in assessing biodiversity: fractal application on rocky shores. Ecological Complexity 2, 272–286.

Larsonneur, C., Bouysse, P., Auffret, J.P., 1982. The superficial sediments of the English Channel and its western approaches. Sedimentology 29, 851–864.

Lundblad, E.R., Wright, D.J., Miller, J., Larkin, E.M., Rinehart, R., Naar, D.F., Donahue, B.T., Anderson, S.M., Battista, T., 2006. A Benthic terrain classification scheme for American Samoa. Marine Geodesy 29, 89–111.

Perrings, C., 2002. Biological invasions in aquatic systems: the economic problem. Bulletin of Marine Science 70, 541–552.

Pickrill, R.A., Todd, B.J., 2003. The multiple roles of acoustic mapping in integrated ocean management, Canadian Atlantic continental margin. Ocean & Coastal Management 46, 601–614.

Pratje, O., 1950. Die Bodenbedeckung des Englischen Kanals und die maximalen Gezeitenstromgeschwindigkeiten. Deutsche Hydrographische Zeitschrift 3, 201–205.

Przeslawski, R., Ahyong, S., Byrne, M., Woerheide, G., Hutchings, P., 2008. Beyond corals and fish: the effects of climate change on noncoral benthic invertebrates of tropical reefs. Global Change Biology 14, 2773–2795.

Rees, H.L., Pendle, M.A., Waldock, R., Limpenny, D.S., Boyd, S.E., 1999. A comparison of benthic biodiversity in the North Sea, English Channel, and Celtic Seas. ICES Journal of Marine Science 56, 228–246.

Smith, A.J., 1985. A catastrophic origin for the palaeovalley system of the eastern English Channel. Marine Geology 64, 65–75.

Taylor, R.B., 1998. Density, biomass and productivity of animals in four subtidal rocky reef habitats: the importance of small mobile invertebrates. Marine Ecology Progress Series 172, 37–51.

Velegrakis, A.F., Gao, S., Lafite, R., Dupont, J.P., Huault, M.F., Nash, L.A., Collins, M.B., 1997. Resuspension and advection processes affecting suspended particulate matter concentrations in the central English Channel. Journal of Sea Research 38, 17–34.

Warwick, R.M., Uncles, R.J., 1980. Distribution of benthic macrofauna associations in the Bristol Channel in relation to tidal stress. Marine Ecology Progress Series 3, 97–103.

Maps

BGS, 1987a. South Sheet. 1:1 000 000, Sea Bed Sediments Around the UK. British Geological Survey, Edinburgh, Scotland.
BGS, 1987b. North Sheet. 1:1 000 000, Sea Bed Sediments Around the UK. British Geological Survey, Edinburgh, Scotland.
BGS, 1989. Wight. 1:250 000, Sea Bed Sediments and Quaternary Geology. British Geological Survey, Edinburgh, Scotland.
BGS, 1995. Wight. 1:250 000, Solid Geology. British Geological Survey, Edinburgh, Scotland.
Vaslet, D., Larsonneur, C., Auffret, J.P., 1978. Surficial Sediments of the English Channel (Map and Booklet). Bureau de Recherches Geologiques et Minieres, Orleans, France.