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A multi-scale investigation into seafloor topography of the northern Mid-Atlantic Ridge based on geographic information system analysis

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ABSTRACT

The Mid Atlantic Ridge (MAR) has been identified as an important component of the lower bathyal (800 – 3500 m depth) benthic biogeographic province in the North Atlantic Ocean. We performed a multi-scale characterization of seafloor topography of the MAR. In the basin-scale analysis, we have used the 30″ General Bathymetric Chart of the Oceans (GEBCO) grid to estimate the area of different components of lower bathyal habitat in the main North Atlantic basin and to produce a corresponding depth–area relationship. The regional-scale investigation is based on swath bathymetry surveys which show the flanks to MAR to comprise a series of sediment-draped flat plains (37.65% of area) with intervening gentle slopes ranging from 5° to 30° (56.70% of area) and slopes steeper than 30° (5.65% of area). The steep slopes have significant areas of hard substrate (70%) comprising bare cliff faces and rock outcrops. Within the local-scale approach, detailed surveys of such steep areas were done by multi-beam sonar and cameras mounted on a Remotely Operated Vehicle (ROV). In several locations, the terrace-like seafloor topography has also been identified. Overall, it has been shown that the MAR lower bathyal is 95% covered with soft sediment.

1. Introduction

The general form of the world's ocean basins and the presence of a mid-ocean ridge in the Atlantic Ocean have been known for over 100 years (Murray and Hjort, 1912). Despite progressively more detailed information on the structure of the ridge (Tolstoy, 1951; Heezen and Tharp, 1957; Purdy et al., 1990), only recently has quantitative information on the areas of different habitats become available. A major step forward was the availability of global satellite altimeter-derived bathymetry (Smith and Sandwell, 1997) with 2′ grid resolution. This has subsequently been enhanced by combining with other data sets to create global grids at 1′ (GEBCO released in 2003) and 30″ resolution (GEBCO released in 2009). Using the 1′ grid, Costello et al. (2010) estimated the areas of seabed in all world's oceans identifying mid-ocean ridges, seamounts and slopes. Yesson et al. (2011a, 2011b) used the 30″ SRTM30 grid data to catalog 33,452 seamounts and 138,412 knolls worldwide. In a parallel series of developments, use of Global Navigation Satellite Systems (GNSS) and dynamic position-keeping enables ships to be stationed at precise locations on the high seas. This, together with multi-beam sonar and Remotely Operated Vehicles (ROVs) equipped with cameras and high-resolution sonars, has greatly advanced studies of complex seabed topography as exemplified by a study on cold water coral reefs within deep canyons (Huvenne et al., 2011).

UNESCO (2009) identified the lower bathyal zone at depths of 800 – 3500 m as an important biogeographic province in the North Atlantic Ocean including the Mid-Atlantic Ridge (MAR) from the Reykjanes Ridge to approximately the equator, together with the eastern and western continental margins. Watling et al. (2013) extended this analysis further to define the area of lower bathyal in the North Atlantic as 18.75×10^6 km^2 divided between two provinces, the North Atlantic Boreal zone (BY2) to the north and the North Atlantic bathyal (BY4) to the south. However, these measurements include the Mediterranean and Carribean Seas and the extent of the ocean margins, seamounts and the MAR was not defined.

The objective of the work presented in this paper is to provide a multi-scale characterization of the seafloor topography of the northern Mid-Atlantic Ridge, more specifically its extended

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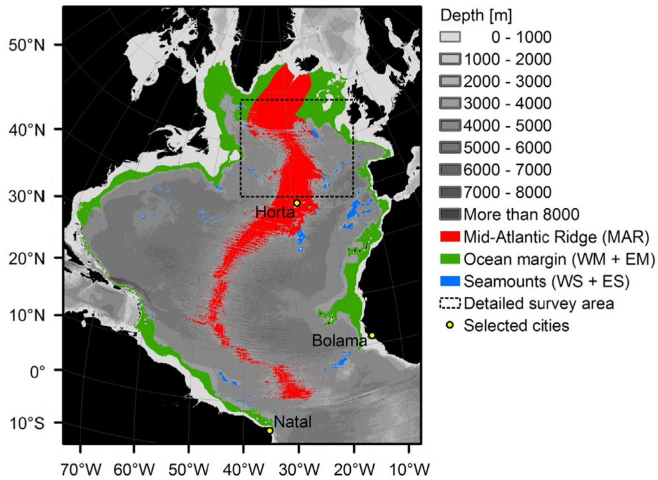

Fig. 1. Bathymetry map of the North Atlantic Ocean, based on the GEBCO 30″ grid, showing the extent of lower bathyal (depth 800–3500 m) area on the Mid-Atlantic Ridge, the ocean margins and seamounts. The area in red corresponds to the Extended Mid Atlantic Ridge Lower Bathyal Province (EMARLBP). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bathyal zone. Availability of bathymetric data intrinsically splits the characterization into basin-, regional- and local-scale approaches. In the basin-scale scrutiny, we use the 30″ grid data to estimate the area of different components of lower bathyal habitat in the main North Atlantic basin and to calculate the associated depth–area curve. The regional-scale approach; however, is based on multi-beam bathymetry surveys, carried out using sonars mounted on research vessels. Herein, the regional-scale bathymetric data are used to identify sites for biological sampling (Priede et al., 2013b, 2013c) and to evaluate details of slopes and topography that cannot be resolved by the global data set. Finally, within the local-scale experiment, we use ROV surveys (multi-beam bathymetry and high-definition photographs) to identify substrate type and presence of benthic fauna. The overall aim is to determine the contribution of the MAR to lower bathyal habitat in the North Atlantic Ocean.

The novelty of the work presented in this paper is associated with the progress in geospatial technologies. Having access to modern subsea technologies outlined above, we can employ tools offered by Geographic Information Systems (GIS) to provide new, more detailed insight into seafloor topography. Sonars mounted on ships or ROVs offer high-resolution digital elevation models, the unprecedented resolution of which allows researchers to study even small underwater landforms and the associated habitats.

2. Materials and methods

Methods presented in this section are based on areas of seafloor derived from several different bathymetric data sets. All areas are computed in two dimensions and hence they depart from true surface areas of inclined terrain.

2.1. Basin-scale analysis (resolution 30″ × 30″)

For the purposes of the analysis, the North Atlantic Basin was defined as the area of the Atlantic Ocean north of a straight line between Bolama in Guinea-Bissau (11°35'N 15°28'W) and Natal in Brazil (05°47′S 35°12'W), and bounded by shallows around the ocean margin and ridges in the north (Fig. 1). Bathymetry data for this area with a latitudinal and longitudinal spatial resolution of 30″ × 30″ were accessed from GEBCO, General Bathymetric Chart of the Oceans (Hall, 2006). The gridded data set "GEBCO_08.nc" was read using the GEBCO Grid Demonstrator Software Interface v2.12 and exported to an ESRI ASCII raster format for transfer to an ArcGIS environment (ESRI official webpage: http://www.esri.com/, access date: 15 February 2010). The global bathymetric grids are amalagamations of data from two sources: satellite altimetry (low spatial resolution) and acoustic survey (high spatial resolution), and the resolution considerably impacts investigations into detailed topography of the seafloor (Yesson et al., 2011a).

The present study focused on the lower bathyal zone defined as seafloor with depths from 800 to 3500 m following the UNEP GOODS Bioregional Classification (UNESCO, 2009). The bathyal zone was obtained by reclassifying the GEBCO bathymetry with ArcGIS (ArcMap 9.3 and ArcMap 9.3.1 by ESRI under the ArcInfo license) into 100-m depth intervals, i.e. 0 – 100 m, 100 – 200 m and so on, where depth boundaries were determined by adding a very small fractional number. For practical reasons, the reclassified raster data were converted to vector data, and the lower bathyal zone was extracted using the selection tool, i.e. vector features meeting the depth criterion 800 – 3500 m were retrieved and polygons corresponding to 100-m depth increments, i.e. 800 – 900 m, 900 – 1000 m,…, 3400 – 3500 m (the same depth boundaries applied), were obtained (this vector layer was denoted as B). This map was subsequently divided into three distinctive lower bathyal zone layers comprising: ocean margin, seamounts and the MAR itself.

We define the MAR lower bathyal habitat to include all seafloor at depths from 800 to 3500 m within 400 km either side of the axis of the ridge. This definition includes bathyal zones of seamounts and knolls on the flanks of the MAR, but the bases of which may be outside the 3500 m contour bounding the MAR. In the region of the Reykjanes Ridge where depths either side of the MAR are less than 3500 m, we use the 400 km distance to delineate the boundary between the MAR and adjacent northern margin of the Atlantic Ocean. We term this the "Extended Mid Atlantic Ridge Lower Bathyal Province" (EMARLBP). Estimation of the area of this province was attained in three steps. First, a median line defining the main axis along the ridge was plotted. After transforming the spatial data to the Equidistant Cylindrical projection (standard parallel 60°N), a 400-km wide buffer zone either side of the MAR axis was generated. Second, knowing that the remaining fragments of the reclassified bathyal zone vector map outside the MAR intrinsically consist of either the ocean margin part or seamounts, these two elements were subjectively classified with reference to standard atlases (Couper, 1983). The following features were classified as seamount lower bathyal zone elements: Ceara Rise, Sierra Leone Rise, New England Seamounts, Corner Seamounts, Great Meteor Seamount, Cruiser Seamount, Madeira Rise, Horseshoe Seamounts, Azores Biscay Rise, Milne Seamounts, Charcot Seamounts, East Thulean Rise (partially). Third, the remaining features of the reclassified bathyal zone layer, those outside the EMARLBP and the seamount lower bathyal zones, were assumed to form the ocean margin bathyal zone. The selected seamounts therefore only include seamounts independent of the MAR and the ocean margin, and they do not correspond to the full catalog of seamounts in the North Atlantic as identified by Yesson et al. (2011b) using the SRTM30 bathymetry data set.

In order to accurately calculate areas, the resulting vector features were transformed to the Lambert Azimuthal Equal Area projection centered at 35°N and 35°W. Then, a new field in a database was added and areas of individual polygons were calculated. To calculate the sea-floor area at specific depths the model algorithm was developed under Python with ArcGIS geoprocessing. In order to evaluate the MAR contribution to the overall area of the bathyal zone, we calculated the fraction of the bathyal habitat in the MAR with respect to the total bathyal habitat in the North Atlantic, and this ratio was denoted as I_{MAR}.

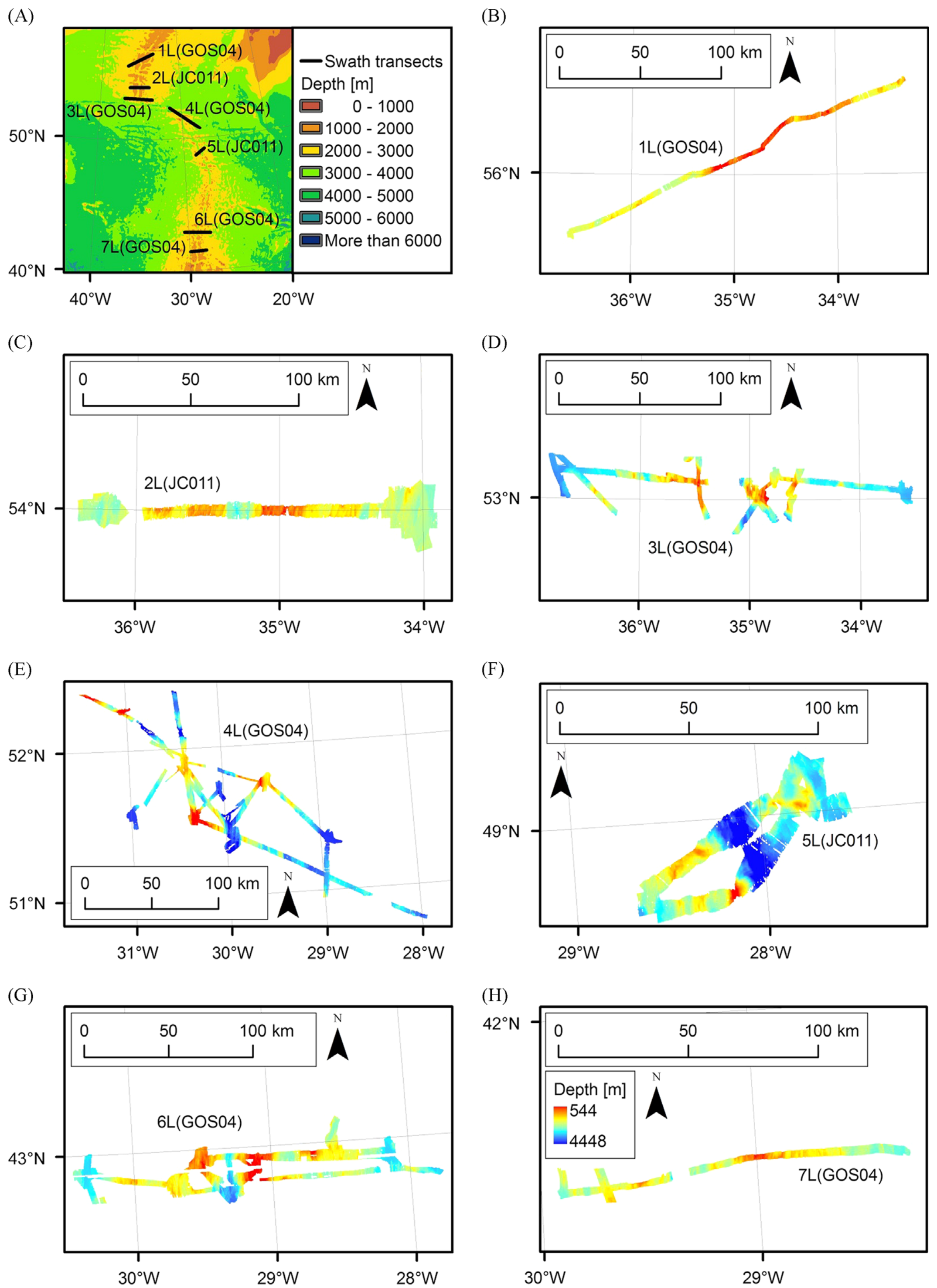

Fig. 2. Regional-scale seafloor bathymetry data obtained from vessel-mounted swath bathymetry by the RV *G.O. Sars* (Cruise GOS04) and RRS *James Cook* (cruise JC011): (A) location of transects, (B) transect no. 1L(GOS04), (C) transect no. 2L(JC011), (D) transect no. 3L(GOS04), (E) transect no. 4L(GOS04), (F) transect no. 5L(JC011), (G), transect no. 6L(GOS04), (H) transect no. 7L(GOS04). Colors indicate depth (m) as on the key in panel H. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Regional-scale analysis (resolution 75 m)

The regional-scale analysis, using intermediate bathymetry resolution (grid size between GEBCO- and ROV-based bathymetry), serves a purpose of identifying terrace-like structures on flanks of the MAR.

Multi-beam swath bathymetry data were collected across the MAR between 41°N and 57°N (Fig. 2A) during cruise 2004110 of the RV *G.O. Sars* in 2004 (Wenneck et al., 2008) and cruise JC011 of the RRS *James Cook* in 2007 (Priede et al., 2013c) using Simrad (Kongsberg) EM300 and EM120 sonars, respectively. The RV *G.O. Sars* undertook extensive surveys during transit between sampling stations over a wide latitudinal range. The RRS *James Cook* focused on two transects across the MAR, a southern ECOMAR transect at around 49°N and a northern ECOMAR transect at 54°N (Priede et al., 2013c). On both vessels, data were monitored in real-time on board using the OLEX software (Olex

AS, Trondheim, Norway) to display the results and navigate the vessel in the relation to bottom topography. Segments of the surveys where the weather was rough and the ships' motion excessive (pitching or rolling) were rejected from the subsequent analysis on shore.

Since raw data from the Simrad system are not stored in the ASCII format, they are not directly readable under standard GIS environments thus intermediate processing was necessary. The data from the RRS *James Cook* were read using the MB-System software (MB-System official webpage: http://www.ldeo.columbia.edu/res/pi/MB-System/, access date: 28 January 2010) which is specifically designed to handle various sonar formats (Schmidt et al., 2006). In our analyses, we used MB-System 5.1.1beta23 under Linux Poseidon 3.1. The raw data from JC011 cruise was in MBIO Data Format ID no. 56, and was transformed to MBIO Data Format ID no. 57 using a script in Perl as recommended by Schmidt et al. (2006). The sonar data captured during JC011 cruise was split into discrete spatially localized segments, each of which was processed separately. Each segment may comprise many type-57 files, so before combining them, they were individually scrutinized and noisy sections with excessive ship motion were eliminated. After this initial cleaning of the data, an additional procedure was applied to remove the remaining outliers at the edges of each swath. Similar procedures were applied to the RV *G.O. Sars* data set.

The clean bathymetry data, stored as relatively small and easily manageable charts, were gridded under the MB-System with an arbitrarily chosen grid size of 75 m and finally exported to ESRI ASCII format. Eight regional mosaic rasters were generated under ArcGIS (Fig. 2).

Habitat classification was done using slope criteria. Slope layers were calculated by transforming from the Equidistant Cylindrical Plate Carrée projection to the Lambert Azimuthal Equal Area projection centered at 35°N and 35°W to enable area computation with horizontal and vertical coordinates expressed in meters. The choice of the projection followed the previous selection for the basin-scale analysis. Note that in the regional-scale analysis the equal-area criterion is also important as areas of the classified slope layer are calculated. Following Burrough and McDonell (1998), the slope was calculated by fitting a plane to values of a local matrix (3×3 grid around a central cell), and applying the average maximum technique. The slope raster map was reclassified, and the 3-color mosaic was produced to represent sea-floor in three slope categories: (1) less than 5°, (2) between 5° and 30°, (3) more than 30°. These three categories were chosen as representing three distinctive potential habitats that had to be sampled in different ways. The flat areas ($<5°$) were made up of thick sediment with no rocky obstructions and could be sampled by trawl and coring equipment (Priede et al., 2013c). The intermediate slopes ($5-30°$) were predominantly sediment-covered, but presence of rock either just below the surface or outcropping above the sediment precluded the use of trawls and corers. The steep slopes ($>30°$) were areas of complex topography that could only be sampled using the maneuverability of a remotely operated vehicle and had significant areas of bare rock supporting a distinctive hard-substrate sessile fauna.

2.3. Local-scale analysis (resolution <5 m)

Selected areas on the flanks of the MAR were inspected in detail using the ROV *Isis* on cruise JC048 of the RSS *James Cook* in 2010 (Priede and Bagley, 2010; Priede et al., 2013c). Surveys focused on areas at ca. 2500 m depth close to each of the ECOMAR superstations at the ends of the JC011 transects, the southern transect, SE superstation 49°02.60'N 27°43.48′W, SW superstation 48°46.80′N 28°38.43′W, and the northern transect, NW superstation 53°59.33′N 36°07.39′W and NE superstation 54°00.05′N 34°10.61′W. Charts prepared from the JC011 swath bathymetry data were used to navigate the ROV.

Sonar surveys were carried out using the Kongsberg Mesotech MS2000 128 beam multi-beam swath transducer mounted in downward-looking orientation on the ROV *Isis*. Doppler-corrected USBL (Ultra Short Base Line) positioning was used to track the ROV and with the aid of an altimeter the ROV was maintained at ca. 20 m above the seafloor. Survey lines were run at a speed of 0.2 $\mathrm{m\,s^{-1}}$ giving a swath width of about 40 m and spatial resolution <1 m. Three survey lines were done, one at the NW station on 5 June 2010 (dive 161), one at the NE station on 10 June 2010 (dive 165), and one at the SW station on 21 June 2010 (dive 173). These were directed perpendicular to local, approximately north–south oriented, terraced structure of MAR flanks to investigate details of steep slopes areas identified in the ship-borne swath surveys. Data were logged on board the RSS *James Cook* using the TECHnical and Scientific sensors Acquisition System (TECHSAS), viewed using SUMATRA (Software for real-time mission monitoring based on ArcGIS 10) and post-processed on shore using CARAIBES seafloor mapping software (IFREMER, 2013).

Video surveys were done from an altitude of 2 m using a downward-looking HD (High Definition) color camera mounted on the ROV *Isis* tool tray (Priede and Bagley, 2010). Forty eight randomly located 500 m long transects were completed, 12 at each of the ECOMAR superstations comprising 4 in each of three categories of slope: flat areas (0–2° slope), slopes (8–12° slope) and cliffs ($>30°$ slope). In each transect, the ROV was run in a straight line, on a set bearing, at a constant speed of 0.13 $\mathrm{m\,s^{-1}}$. The transect width was 2 m (maximum variation ± 0.1 m) viewing 1000 $\mathrm{m^2}$ of seafloor in each transect. In steep areas (e.g. cliffs), where downward viewing was not possible, the orientation of the camera was switched to horizontal and ROV maneuvering technique modified accordingly. Two parallel lasers beams 100 mm apart provided a scale within the field of view. To evaluate percentage cover of soft sediment a simple line transect measurement was done as the videos were replayed and the sediment type traversed by one laser spot was scored at a resolution of ca. 1 cm. Distance covered on different substrates was converted to area percentage directly. Images of interest were extracted from the HD video.

Combining ROV-mounted sonar bathymetry with ROV-taken photographs allows us to verify the hypothesis that flat areas and moderately inclined slopes are composed of soft sediment, and that they are parts of the terraced-like morphology of the seafloor.

3. Results

3.1. Basin-scale analysis of GEBCO bathymetry

Lower bathyal seafloor habitat in the North Atlantic Ocean (Fig. 1) was divided in three elements: the extended MAR province including associated seamounts, ocean margins including associated seamounts (western and eastern) and non-contiguous seamounts (western and eastern). The total area of lower bathyal depths in the North Atlantic Ocean is 8,109,116 $\mathrm{km^2}$ of which 50% is on the continental margins and 46% on the MAR (Priede et al., 2013a). The results of Priede et al. (2013a) are based on the same definition of MAR, hence it corresponds to our EMARLBP. Fig. 3 shows the relationship between depth (elevation) contributions of the different elements to area of seafloor within the lower bathyal zone based on data from Table 1. The eastern and western contributions of seamounts and ocean margins are approximately equal to one another, indicating topographic symmetry across the ocean.

The curves for the ocean margins and seamounts in Fig. 3A show almost no change of the area with depth from 800 m to 2100 m indicating relatively constant average slope of the seafloor

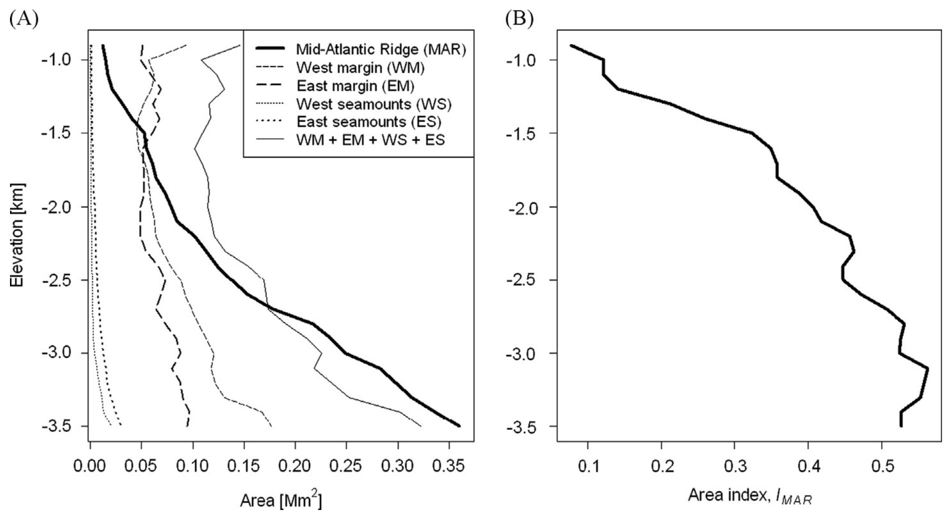

Fig. 3. The relationship between depth and area of lower bathyal seafloor in the North Atlantic Ocean: (A) areas of the MAR, ocean margins and non-contiguous seamounts ($Mm^2 = 10^{12}$ m^2), (B) fraction of lower bathyal accounted for by the MAR.

Table 1
Areas of parts of lower bathyal seafloor in the North Atlantic Ocean, with division into 100 depth bins. EMARLBP is the Extended Mid Atlantic Ridge Lower Bathyal Province.

Elevation min. (m)	Elevation max. (m)	EMARLBP area (km²)	West margin area (km²)	East margin area (km²)	West seamounts area (km²)	East seamounts area (km²)
−900	−800	12127	92857	51328	304	1442
−1000	−900	15038	57053	49129	318	1476
−1100	−1000	16918	61967	58819	395	1680
−1200	−1100	21593	59949	68807	416	1827
−1300	−1200	31133	52192	60959	512	1973
−1400	−1300	40908	46879	67398	580	2180
−1500	−1400	52364	45560	60637	640	2530
−1600	−1500	54642	47037	51230	734	2909
−1700	−1600	60348	53091	51604	802	3114
−1800	−1700	63877	57118	52911	934	3440
−1900	−1800	72451	57677	52931	1005	3892
−2000	−1900	78599	59816	48766	1164	4820
−2100	−2000	84495	62480	49053	1299	4985
−2200	−2100	101389	64227	49128	1522	5793
−2300	−2200	113205	70386	53719	1606	5975
−2400	−2300	123754	78156	66656	1768	6494
−2500	−2400	137712	88012	73047	2027	6961
−2600	−2500	153316	92480	68738	2187	8096
−2700	−2600	178828	98956	63695	2365	9245
−2800	−2700	217503	104940	73384	2688	10292
−2900	−2800	235013	113016	83694	3310	11377
−3000	−2900	248695	119725	88340	4466	12967
−3100	−3000	282212	117575	79566	6382	15433
−3200	−3100	297855	121422	88303	8751	17059
−3300	−3200	313654	130553	90443	11154	20657
−3400	−3300	336755	168376	96480	12781	25108
−3500	−3400	360019	176485	94497	20892	30742

over this depth range. By contrast, on the MAR the area increases with depth. At depths <1000 m the MAR only contributes about 10% of lower bathyal area (Fig. 3B), since much of the MAR crest does not reach within 1000 m of the sea surface. At depths >2700 m, the MAR contributes over 50% of the North Atlantic lower bathyal seafloor area.

3.2. *Regional-scale analysis of swath bathymetry*

The swath bathymetry surveys by the RV *G.O. Sars* and RSS *James Cook* covered a depth range 544–4448 m (Fig. 2). Analysis of percentage of the three different slope categories for the entire area surveyed by the two research vessels between 800 and 3500 m indicates that the MAR is dominated by flat plains and gentle slopes. Steep topography ($>30^{\circ}$), at the spatial resolution of 75 m, occupies a small proportion of the total area (Table 2). At both the northern and southern ECOMAR transects perpendicular to the ridge axis (Fig. 4) typical mid-ocean ridge structure is evident with a mid-axial valley and parallel ridge crests on either side. At the ECOMAR northern transect (Figs. 2C and 4A) the axial valley is 2816 m deep and 13.8 km wide between the 2000 m depth contours (Figs. 2C and 4A). The summits of the ridge crests are 1440 m and 1295 m in west and east, respectively. The NE and NW ECOMAR superstations at 2500 m depth are 127 km apart. At the ECOMAR southern transect (Figs. 2F, and 4B) the axial valley descends to a depth of over 3800 m. On either side ridge crests rise to 1578 m in the west and 2149 m in the east. The two ECOMAR stations SW and SE, where moorings were placed at 2500 m depth, are 73 km apart. A detour was made in the swath survey to inspect the summit of a seamount (Fig. 4B). A minimum sounding of

733 m was recorded at 48°N 43.2′N 28°09.7′W corresponding closely to the seamount number 37,378 cataloged by Yesson et al. (2011b).

Inspection of the records showed distinctive flat plains with intervening undulating topography and steep slopes (Fig. 5). This was interpreted as a series of sediment-covered terraces on the flanks of the MAR with steep slopes facing towards the axis of the MAR (Fig. 6). The lines of the terraces are broadly parallel to the axis of the MAR.

3.3. Local-scale analysis based on ROV Isis data

At three of the ECOMAR superstations, namely NW, NE and SW, the ROV *Isis* high resolution swath bathymetry system was used to survey details of steep terrace slopes that could not be accurately resolved with the 75 m spatial resolution from the ship-borne systems. Fig. 7 shows an east-facing slope at the NW superstation near the point indicated as "Terrace summit 2210 m" in Fig. 6. The elevation difference between the flat plain at the base of the slope and summit of the terrace is ca. 400 m with an average slope of 47°. Parts of the slope are near-vertical cliffs (Fig. 7B and C), impossible to resolve with a downward-looking multi-beam sonar. Fig. 8 shows an east-facing terrace at the SW station with an elevation difference of 165 m and average slope of 28°. Rough topography within that overall slope value creates numerous readings of slopes up to 70° (Fig. 8C). On the other side of the MAR, at the NE station, Fig. 9 shows a terrace with a west-facing slope, elevation difference of ca. 250 m and average slope of 32°. Within the complex structure, slopes of over 75° were detected (Fig. 9C).

Video inspection showed that the areas identified as flat plains in the ship-derived swath bathymetry were indeed smooth flat sediment-covered plains with lebenspüren and bioturbation in the form of tracks and burrows, showing evidence of extensive activity by benthic infauna and epifauna (Fig. 10 F, H) (Bell et al., 2013). The stratified random line transects showed that these areas with slope $<5\%$ were 100% sediment-covered, with no rocky outcrops (Table 2). Areas with $8-12°$ slopes differed little from flat areas (Fig. 10 E, G) showing a similar appearance but with occasional rocky outcrops amounting to 1.6% of area. Such an outcropping rock is shown in Fig. 10A, with attached stalked crinoids (*Anachalypsicrinus nefertiti*) and sponges (Craig et al., 2011). At the southern stations the sediment on both flat and gentle slopes was often covered with pteropod shells giving a coarser texture to the substrate (Fig. 10 A, G). The shells showed signs of winnowing by the bottom currents producing a banded appearance on the sea-floor in some areas, with ridges of deposited shells alternating with bare sediment with a distance of $0.5-1.5$ m between the lines of shells. On the steep slopes fine sediment adhered to any surface with a slope of less than ca. 45°. Thus, on lumpy-textured rock faces there was often a high percentage of sediment cover even on near-vertical outcrops (Fig. 10C). At the NE site (Fig. 10 D)

Table 2
Slopes and sediment cover on the MAR. The areas of different slopes were estimated from swath bathymetry surveys and the sediment cover from subsamples inspected by ROV video (see text).

Slope category		% of total	Sediment cover	
			% of category	% of total MAR
Flat	0°–5°	37.65	100.0	37.65
Gentle	5°–30°	56.70	98.4	55.79
Steep	> 30°	5.65	33.1	1.87
Total	100.00		95.31	

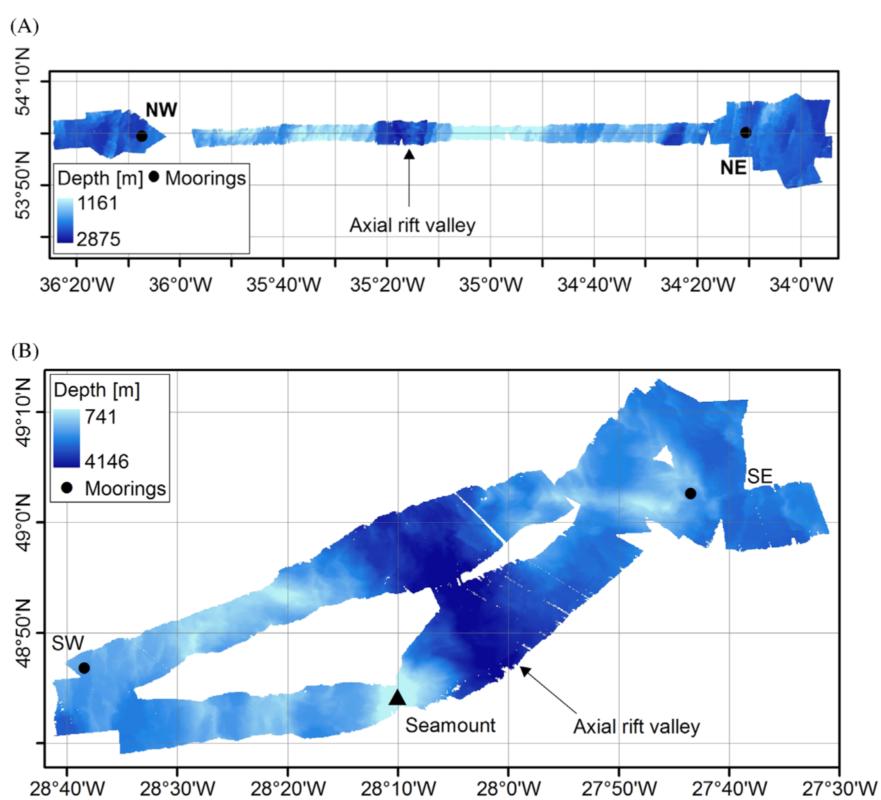

Fig. 4. Swath bathymetry transects across the MAR between the ECOMAR superstations surveyed during RRS *James Cook* (cruise JC011): (A) Northern transect between the NW and NE superstations denoted as 2L(JC011) in Fig. 4C, (B) Southern transect between the SW and SE super-stations denoted as 5L(JC011) in Fig. 4F. The seamount corresponds to number 37,378 in the catalog of Yesson et al. (2011b). Mooring locations are marked by circles.

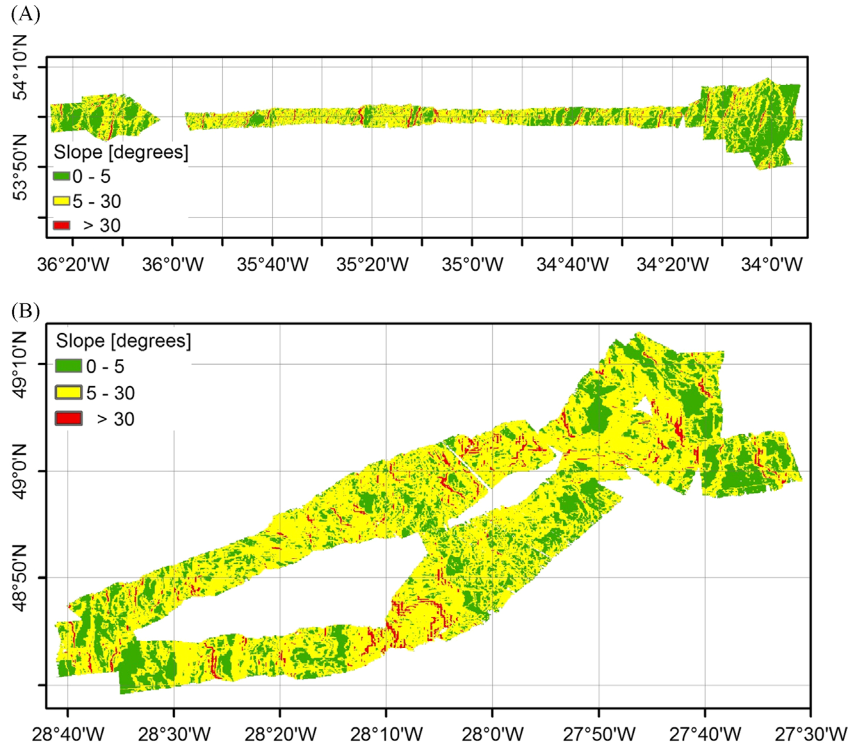

Fig. 5. Swath bathymetry transects across the MAR between the ECOMAR superstations surveyed during RRS *James Cook* (cruise JC011) showing slopes in three categories: $0-5^{\circ}$, $5-30^{\circ}$ and $>30^{\circ}$ for (A) the Northern transect between the NW and NE superstations, (B) the Southern transect between the SW and SE superstations.

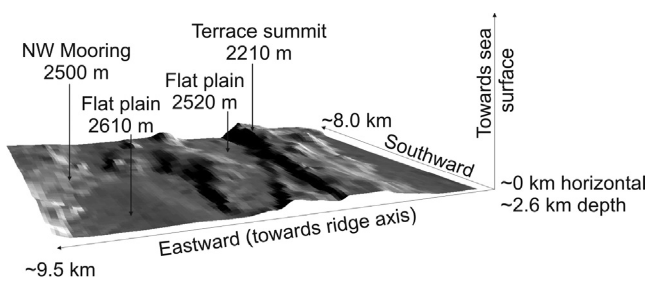

Fig. 6. Three dimensional display of RRS *James Cook* (cruise JC011) ship-borne swath bathymetry of the seafloor in the vicinity of the NW ECOMAR superstation (53°59.33'N 36°07.39'W)—NW mooring. Note the steep slopes face the MAR axis and the features marked with their depths. The vertical scale and horizontal scales are the same.

there were some areas of smooth basaltic rock faces, which were almost totally devoid of sediment. At the bases of the terrace slopes, a talus of loose soft sediment was often observed (Fig. 10B), which was unstable and subject to small avalanches when approached by the ROV. Mobile benthic fauna such as holothurians could gain no traction on such slopes and were observed to roll down, if displaced. In general, even on the steep slopes there was significant sediment cover (Table 2).

4. Discussion

The Extended Mid Atlantic Ridge Lower Bathyal Province (EMARLBP) (Fig. 1) represents the largest area of lower bathyal habitat in the North Atlantic Ocean in contrast to the narrow strips around ocean margins and isolated seamounts. Generally, biodiversity of megafauna and fishes in the deep-sea reaches a peak at mid-bathyal depths between 1000 and 2500 m, with fewer species at deeper and shallower depths (Rex and Etter, 2010; Priede et al., 2010). The MAR increases the lower bathyal living space in the North Atlantic Ocean and likely has a positive effect on biodiversity through the species-area effect (Schopf, 1980). It should be noted that the EMARLBP definition used in this study includes seamounts based on the lower flanks of the MAR so our area estimate is larger than would be derived from strict adherence to the 3500 m contour around the MAR (Watling et al., 2013). We believe this is ecologically realistic since lower bathyal fauna are likely to move freely between the ridge itself and seamounts on the flanks of the MAR.

Most of the MAR is at deeper parts of bathyal depth range >2000 m (Fig. 3), and these depths are widely separated on opposite flanks of the MAR. Such a fragmentation of the habitat will probably further enhance biodiversity beyond the simple species-area effect. The two sides of the MAR however are interconnected through fracture zones providing pathways for interchange between east and west. The MAR is an area of complex topography and high heterogeneity likely to enhance biodiversity, as observed on the continental margins (Levin et al., 2010).

Using the SRTM30 bathymetry, Yesson et al. (2011a, 2011b) identified over 4000 seamounts in the North Atlantic Ocean in Food and Agriculture Organization of the United Nations (FAO) areas 21, 27, 31 and 34 (there is a small discrepancy between the definition of the North Atlantic area in our study and these FAO areas). Seamounts form an important component of the MAR, for example in the Azores area where Morato et al. (2008) detected 3.3 seamount peaks per 1000 km^2 which in total accounted for 37% of the Exclusive Economic Zone (EEZ) area.

In our study, we consider seamounts on the flanks of the MAR as an integral component of the Extended Mid Atlantic Ridge Lower Bathyal Province. As spatial resolution of global bathymetry has improved, so the number of features identified has increased, including small seamount-like features (Morato et al., 2008) and knolls (Yesson et al., 2011a, 2011b). There is no doubt that large seamount summits >1000 m above the surrounding sea-floor,

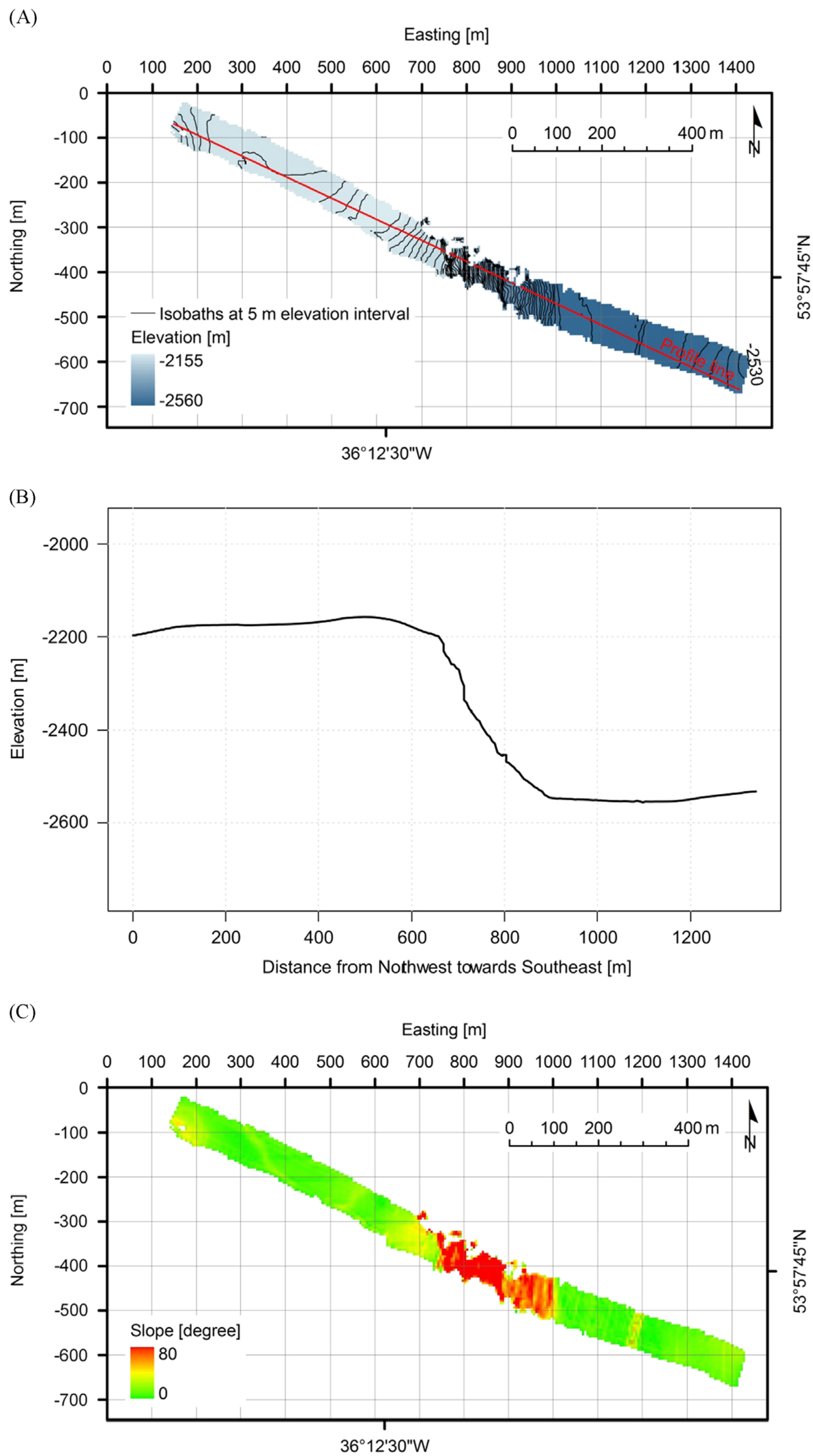

Fig. 7. High resolution swath bathymetry from an ROV *Isis* transect across steep slopes of a terrace at the NW ECOMAR superstation: (A) chart of depths with contours at 5 m intervals, (B) plot of depths along the line transect indicated in A, (C) chart of distribution of slopes (deg).

especially those with summits <1500 m below the surface, have a special importance as biodiversity hotspots where fishes congregate (Morato et al., 2010) and provide targets for commercial fisheries (Clark, 1999; Clark and Rowden, 2009). However, in most respects the fauna of seamounts is similar that occurring on nearby open slopes (Rowden et al., 2010), so we believe that our approach of measuring depth distributions, areas, slopes and bottom type is a valid counterpart to detecting and counting peaks in understanding deep-sea benthic biodiversity. The non-contiguous seamounts between the MAR and continental margins may be particularly important as stepping stones for dispersal of species across the Atlantic Ocean.

In our swath bathymetry surveys we identified one seamount (Fig. 4B) with a summit of 733 m at 48°N 43.2′N 28°09.7′W near

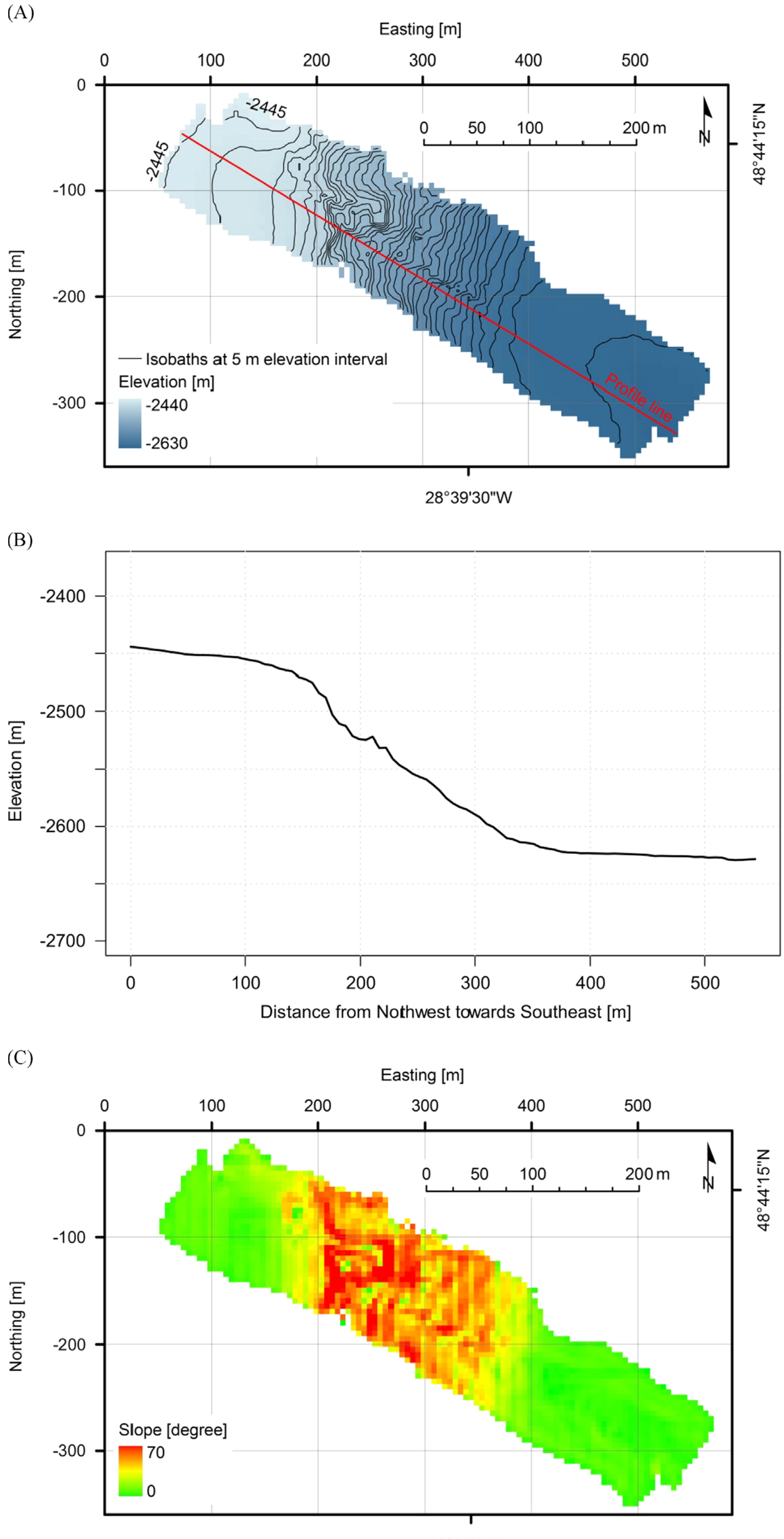

Fig. 8. High resolution swath bathymetry from an ROV *Isis* transect across steep slopes of a terrace at the SW ECOMAR superstation: (A) chart of depths with contours at 5 m intervals, (B) plot of depths along the line transect indicated in A, (C) chart of distribution of slopes (deg).

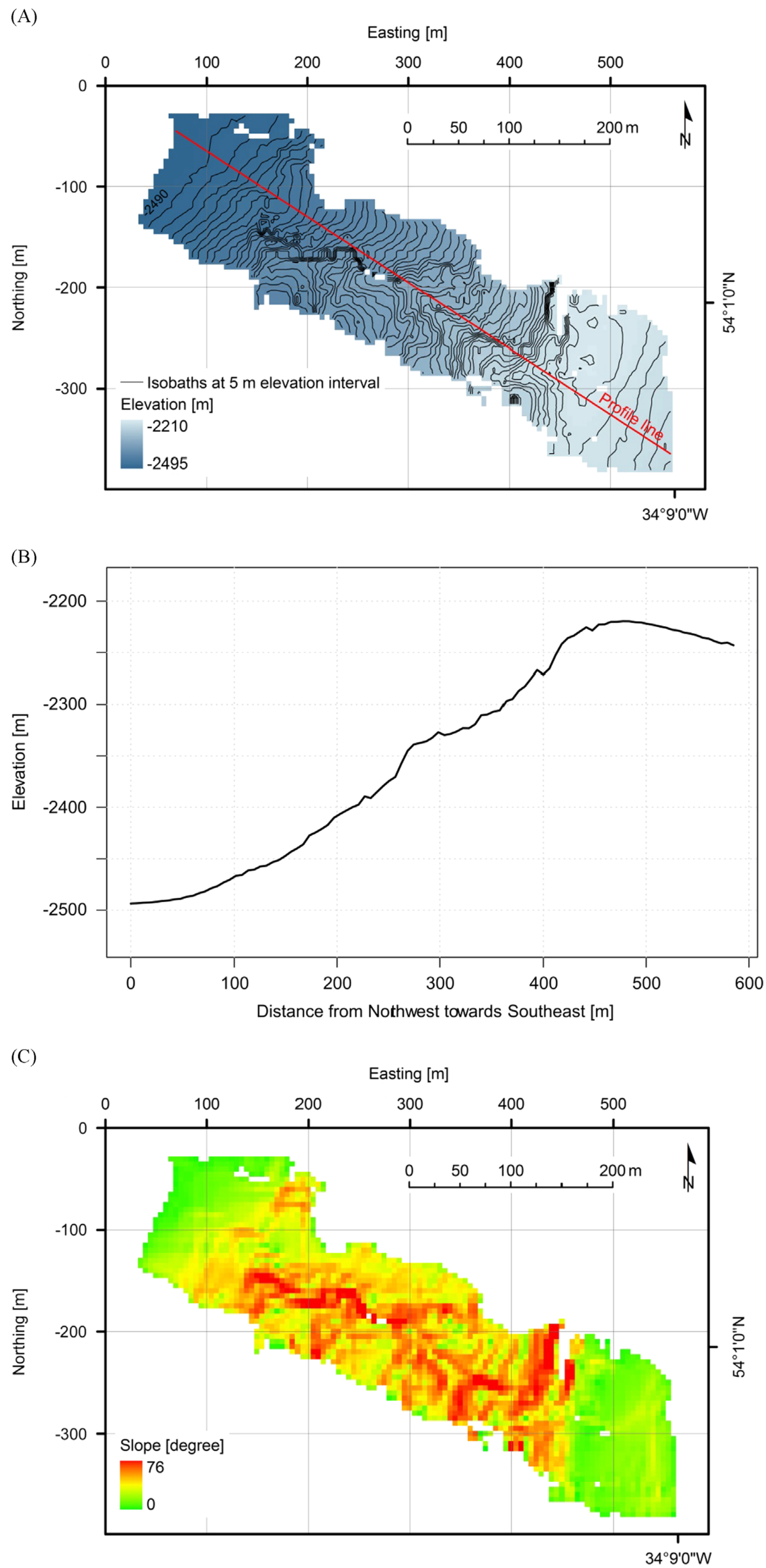

Fig. 9. High resolution swath bathymetry from an ROV *Isis* transect across steep slopes of a terrace at the NE ECOMAR superstation: (A) chart of depths with contours at 5 m intervals, (B) plot of depths along the line transect indicated in A, (C) chart of distribution of slopes (deg).

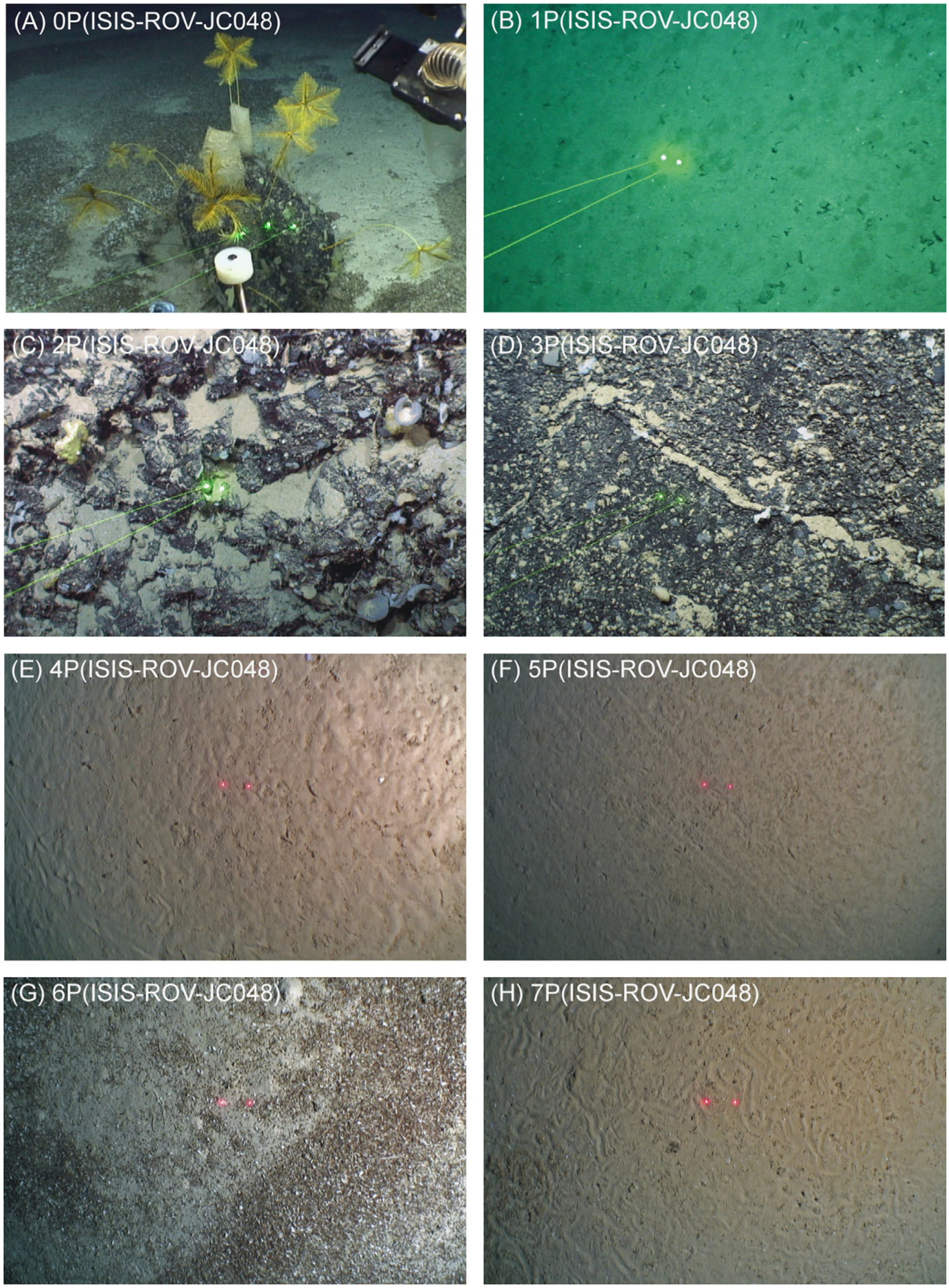

Fig. 10. Images of sea-floor on the MAR taken by ROV *Isis* cameras during RRS *James Cook* cruise JC048: (A) rock outcrop surrounded by sediment on a nominal 10° slope at the SE ECOMAR superstation (note contrasting areas of pale fine sediment and areas of coarse superficial deposit of pteropod shells; forward-facing camera looking obliquely downwards), (B) soft sediment talus covering 30° slope at the NE superstation (forward-facing camera looking obliquely downwards), (C) rock outcrops with sponges attached on a steep slope at the NE superstation (note sediment cover on horizontal ledges; camera looking horizontally at a steep cliff face), (D) rock surface at the NE superstation (camera looking horizontally at a vertical cliff face), (E) soft sediment covering an 8–12° slope at the NE superstation, (F) soft sediment covering a flat area at the NE superstation, (G) soft sediment covering an 8–12° slope at the SE superstation (note the contrast between fine sediment and coarser shell deposits), (H) soft sediment covering a flat area at the SE superstation. The camera is looking vertically downwards below the ROV except where indicated. Paired parallel laser beams 10 cm apart provide a reference scale. Note extensive bioturbation or lebenspüren.

the ECOMAR southern transect. This seamount forms part of the western crest of the MAR with a continuous slope on the east flank down to a depth of 3980 m in the center axial rift valley at a distance of 11.74 km, and an average slope of 15.5°. To the west the topography undulates downwards across a series of terraces towards the SW ECOMAR superstation. This seamount appears to correspond to number 37,378 in Yesson et al. (2011b) which gives a summit of 760 m depth at 48°43.8′N 28°09.72′W; 1.1 km to the north of the putative summit we propose. Given that Yesson et al. (2011a, 2011b) used the 30″ SRTM30 bathymetry (resolution 900 m in latitude and 612 m in longitude), the discrepancy between the two locations is not significant. The summit is part of an extended ridge crest oriented approximately north–south, further exploration by swath bathymetry is necessary to properly define this seamount. An ROV *Isis* dive inspected the summit and collections were made of glass sponges (Tabachnick and Menshenina, 2013).

Mid-ocean ridges are associated with the presence of large areas of rocky substrate. However, we find on that a large percentage of the area is sediment-covered. This has a profound effect on the organisms living there. Morris et al. (2012) investigated a segment of the MAR at latitude 45°30′N at 2500 – 3500 m depth and found 10 times more corals on rocky areas compared with sedimented areas. On the flat plains such as those shown in Fig. 6 the sediment was sufficiently thick that it could be sampled by multi-corer (Shields and Blanco-Perez 2013) and soft sediment infauna and epifauna are predominant (Priede et al., 2013c). From early seismic profiler studies Ewing et al. (1964) concluded that the average thickness of sediment on the MAR is 100 – 200 m except in the immediate vicinity of the ridge crest where it is almost zero. However, Rex and Etter (2010) point out that the layer of benthic animal life in deep-sea sediments is extraordinarily thin with 90% of the macrofauna and meiofauna biomass occurring in the top few centimetres of sediment. Therefore, even thin coverings of sediment such as we observe on steep slopes are sufficient to harbor a full complement of soft sediment fauna replacing the hard substrate fauna that prevails on rocky surfaces.

The flat areas (0 – 5° slope), which appear like lakes between the terraces of the ridge in 3D displays of swath bathymetry (e.g. OLEX or Fig. 6), were confirmed by video transects to be 100% sediment—covered with underlying rocky features entirely buried by the sediment accumulation. Extensive biological activity in the form of burrows and surface traces was evident. Such areas become smaller toward the axis of the ridge (Fig. 5). For the MAR south of the Azores, Tolstoy (1951) describes extensive areas of flat terraces at 3000–4500 m depth with sediments accumulations over 300 m thick.

On the gentle slopes (5 – 30°) it is remarkable how prevalent sediment cover is. It is only where there are distinctive elevated outcrops which are presumably swept clear of sediment by currents or the slope is too steep to retain sediment that bare hard substrate occurs. Such sites are presumably optimal for sessile fauna such as corals and sponges that are dependent on food carried by prevailing currents (Mortensen et al., 2008). Steep slopes (> 30°) devoid of sediment tend to occur as linear features on the faces of terrace slopes (Figs. 5–9) or around the seamount summit. These occupy a small percentage of total area (Table 2), either as continuous bare near-vertical rock faces or as complex topography.

A fundamental problem in deep-sea ecology is that, owing to scattering of light by water, only very small areas can be visually inspected by manned or unmanned submersibles to identify what fauna are present. Investigators have therefore turned to predictive habitat model to determine potential species distributions using information on preferred depths, slopes, substrates, temperatures and other factors using GIS models to extrapolate beyond the directly verified areas of species occurrence. Davies and Guinotte (2011) notably used global 30″ bathymetry to model distributions of reef framework forming deep cold-water corals. A similar approach could be used with our data, for example it is evident that most species of coral can only occur on steep terrain where there is a high probability of hard substrates. Wilson et al. (2007) used swath bathymetry data to predict occurrence of squat lobsters. The information from the present analysis for the MAR has been combined with known relationships between benthic biomass and depth (Wei et al., 2010) to estimate the total biomass on the entire MAR area, shown in Fig. 1 (Priede et al., 2013a). Watling et al. (2013) point out that their North Atlantic bathyal province, which includes the eastern and western Atlantic Ocean, the MAR and the Mediterranean Sea, may well be subdivided following further analysis. Our subdivisions form part of that continuing process but different provinces may be recognized according to the questions being asked.

To conclude, the study provided a multi-scale characterization of the MAR, and the analyses were performed using Geographic Information Systems. Within the basin-scale approach, based on relatively coarse GEBCO bathymetry, we calculated areas of different components of the Extended Mid Atlantic Ridge Lower Bathyal Province. Our exercise employed the depth–area relationship, and all estimations of areas should be interpreted in the light of the fact that given our definition of the above-mentioned province a larger extent of MAR is taken into account. The regional and local-scale analyses, with multi-beam bathymetry acquired from ship or ROV mounted sonars, offered new high-resolution seafloor topography maps. These spatial data, classified according to slope criteria, serve the purpose of identifying sites for biological sampling. Such high-resolution digital elevation models and the corresponding slope layers were interpreted along with the ROV-taken photographs of sea-floor. The combination of the two allowed us to link topography with substrate type and the presence of benthic fauna.

Acknowledgments

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