ORIGINAL PAPER

Andreas Beyer · Bishwajit Chakraborty
Hans Werner Schenke

Seafloor classification of the mound and channel provinces of the Porcupine Seabight: an application of the multibeam angular backscatter data

Abstract In this study multibeam angular backscatter data acquired in the eastern slope of the Porcupine Seabight are analysed. Processing of the angular backscatter data using the 'NRGCOR' software was made for 29 locations comprising different geological provinces like: carbonate mounds, buried mounds, seafloor channels, and inter-channel areas. A detailed methodology is developed to produce a map of angle-invariant (normalized) backscatter data by correcting the local angular backscatter values. The present paper involves detailed processing steps and related technical aspects of the normalization approach. The presented angle-invariant backscatter map possesses 12 dB dynamic range in terms of grey scale. A clear distinction is seen between the mound dominated northern area (Belgica province) and the Gollum channel seafloor at the southern end of the site. Qualitative analyses of the calculated mean backscatter values i.e., grey scale levels, utilizing angle-invariant backscatter data generally indicate backscatter values are highest (lighter grey scale) in the mound areas followed by buried mounds. The backscatter values are lowest in the inter-channel areas (lowest grey scale level). Moderate backscatter values (medium grey level) are observed from the Gollum and Kings channel data, and significant variability within the channel seafloor provinces. The segmentation of the channel seafloor provinces are made based on the computed grey scale levels for further analyses based on the angular backscatter strength. Three major parameters are utilized to classify four different seafloor provinces of the Porcupine Seabight by employing a semi-empirical method to analyse multibeam angular backscatter data. The predicted backscatter response which has been computed at 20° is the highest for the mound areas. The coefficient of variation (CV) of the mean backscatter response is also the highest for the mound areas. Interestingly, the slope value of the buried mound areas are found to be the highest. However, the channel seafloor of moderate backscatter response presents the lowest slope and CV values. A critical examination of the inter-channel areas indicates less variability within the estimated three parameters.

A. Beyer (✉) · H. W. Schenke
Alfred Wegener Institute for Polar and Marine Research,
P.O. Box 120161, 27515 Bremerhaven, Gemany
E-mail: abeyer@awi-bremerhaven.de

B. Chakraborty
National Institute of Oceanography, Dona Paula, Goa, 403 004 India

Introduction

Large scale oceanographic explorations are presently continuing around the Porcupine Seabight area, which is located towards the south-west of Ireland. This area is an embayment of the North Atlantic continental margins. Its importance due to the dominant hydrocarbon resources is well documented [1], and on-going experiments are important due to the involvement of higher-order variability (in terms of physical and geological settings) around this area [2]. This area shows northward flowing slope currents following the North Atlantic continental slope contours. Geologically, it is a sedimentary environment controlled by drift deposits, and highly complex channel and levee systems. The Porcupine Seabight area possesses dominant carbonate mounds ([3, 4]) and channel systems related structures, and understanding of the seafloor morphological aspects was initiated by applying long and short-range side scan sonar data, extensive sediment sampling, and single channel seismic profiles ([5, 6] and references therein and [7]).

Recent initiatives of the European Union's GEOMOUND programme provided detailed high-resolution multibeam bathymetric survey results from the Porcupine Seabight area during the RV Polarstern expedition ANT *XVII*/4 [8]. Analyses of bathymetric data reveal interesting features at the eastern slope of the Porcupine Seabight starting from numerous mounds and associated buried mounds which are part of the Belgica mound province at the northern end of the area followed by the east-west trending Kings channel and Gollum channel systems (bathymetric map in [8]).

Apart from acquiring seafloor topographic data, seabed characterization can also be implemented using angular backscatter data. The multibeam backscatter data were acquired simultaneously with the bathymetric data (Hydrosweep DS-2). Qualitative side scan sonar based backscatter data analyses and quantitative texture analyses of the surrounding areas close to the presently studied locations are available ([7, 9, 10]), but no quantitative multibeam angular backscatter analyses have so far been made from the Porcupine Seabight.

In order to study various seafloor systems, a semi-empirical approach for the angular backscatter data of the GLORIA side scan sonar was implemented by [11]. Such a classification technique for the seafloor sections involves the shape, variance, and magnitude of the angular response of the measured multibeam angular backscatter strength and is applied in this study. However, a careful selection of seafloor segments is necessary to provide the entire angle range of backscatter data within the segments. If the seafloor properties vary within a very small area, the full angular coverage may not be available for analyses due to the swath coverage. Furthermore, the scattering of the backscatter values needs to be reduced using binning to calculate representative angular backscatter parameters.

In this paper, section two deals with the processing of the angular multibeam Hydrosweep DS-2 backscatter data. It also involves the normalization technique of the angular backscatter strengths, which provides a segmented seafloor based on the sediment lithology of the varying mounds and channel seafloor from the Porcupine Seabight. A mention about the survey sites is included in section three along with a presentation of the angle-invariant backscatter results from the mounds and the channel seafloor. A semi-empirical method is applied to the multibeam dataset to employ seafloor classification in section four.

Multibeam backscatter data processing

The multibeam echo-sounding system Hydrosweep DS-2 operates at 15.5 kHz [12]. It uses a beam-forming technique to generate 59 pre-formed beams (PFBs) covering beam angles from $-45°$ to $+45°$. The received signals are pre-amplified and corrected for real-time transmission loss with a Time Varied Gain. These 59 beams are sampled and converted into echo root mean square voltages using a window of -6 dB around the central peak amplitude. In order to compute seafloor acoustic backscatter strength, an off-line data processing algorithm known as 'NRGCOR' is employed [13]. Necessary system settings are stored and available for backscatter processing (for example source level, pulse length). The computed gain-corrected electrical signal values are converted into acoustic echo levels by employing receiving voltage response. The next step of the 'NRGCOR' algorithm is a geometric correction using the beam-wise bathymetric data for the computation of the seafloor slope (along track and across track slope) and true angles of incidence on the seafloor. The third important step is a computation of the seafloor area insonified by each beam. The computed backscatter strength is used for the present study with binning at $1°$ incidence angle interval.

The angular backscatter strength is a function of seafloor characteristics. Sediment type (combination of for example grain size, porosity, density) and surface structure affect the backscattering. Furthermore, backscattering occures not only at the seabed surface but also in the sediment body. The penetration into the seabed depends on sediment type and frequency. However, there is no data from the Porcupine Seabight available to the authors but we expect not more than 1–2 m penetration for the sonar frequency used [14]. Angular backscatter shape variations are dominant due to the closeness of the beams to the normal incidence direction. For smooth seafloor sediments, this function varies steeply compared to a rough seafloor surface. However, to generate a backscatter map similar to the bathymetry for seafloor interpretation, such systematic effect needs to be removed [15]. The angle-invariant backscatter data provide sufficient basis for first-order seafloor classification based on the sediment lithology [16]. In order to remove the angular dependency from the presently studied area of the Porcupine Seabight, a scheme is proposed in this paper.

The original processed backscatter output file of the 'NRGCOR' comprises the backscatter strength values (with respect to the incidence angles and beam numbers) and position data. At the very beginning, stored backscatter strength values with respect to the $1°$ binned incidence angles are averaged utilizing the entire 'NRGCOR'-processed dataset (Fig. 1a). Then, this averaged angular backscatter function is utilized to normalize each set of the angular backscatter strength with respect to a reference incidence angle. Since fluctuations of the backscatter data are dominant close to the normal incidence direction we have chosen the $10°$ angle as a reference angle. The results of such a process allow the removal of the angular effect in the sense that the mean angular fall of the backscatter strength is removed from the data (Fig. 1b).

However, fluctuations parallel to the ship tracks and local variations are still seen in the normalized data. The effects of seafloor type on the backscatter are expected to be normalized in the angular backscatter strength values. Therefore, the systematic effect which is consis-

Fig. 1 Changing of the angle-invariant backscatter map by applying the mean angular backscatter function and beam pattern determined during the processing. **a** Shows the mean angular backscatter function of the area. This function has been removed from the data shown in (b). Beam-pattern effects visible in (b) (track line parallel artefacts) are removed from the data in (c) and (d) which show significant improvement between the incidence angles 10–20°. **b** and **d** Show a combination of five parallel track lines of the same area
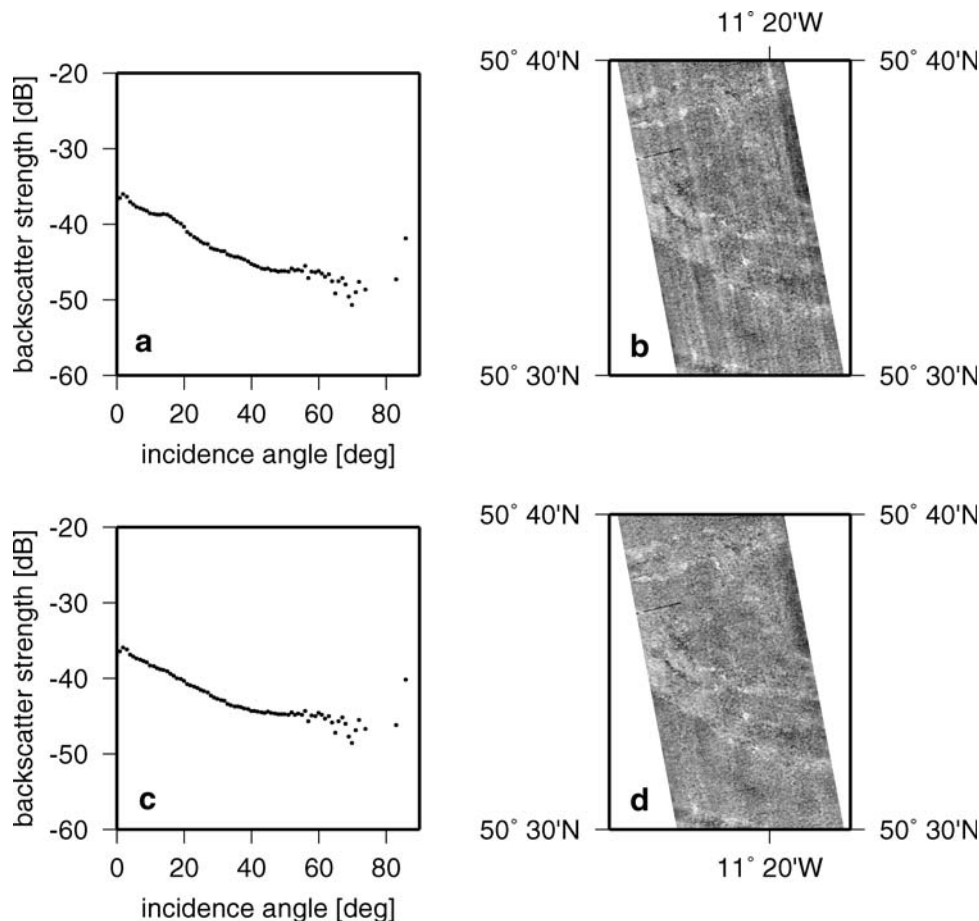
tently appearing in the normalized data (parallel lines around the track lines) (Fig. 1b) is realized to be related to the beam-pattern effect. This systematic effect due to the beam-patterns (function of beam number) is recovered from the normalized angle-invariant backscatter data on ping by ping basis as an average backscatter value with respect to the beam number. An improvement of the 10–20° angular part of the mean angular backscatter strength of Fig. 1a is seen in Fig. 1c where the averaging of the angular backscatter data is carried out after incorporating corrections due to the beam pattern effect. The effects due to the beam-patterns are found to be removed considerably at the end of the initial process (Fig. 1d). In a similar manner, further iterations prove to be effective in normalizing the entire Porcupine Seabight area data set. We have employed, in total, three iterations to remove the beam-pattern effect along with the normalizations, which have considerably improved the present set of data. However, more iterations can be made for the improvement of the image quality, but an increase in the height of the angular backscatter function towards the higher incidence angles is realized when iterations are increased. This is due to the correlation of the incidence angle and beam number within the areas chosen for averaging.

Such a technique provides grey scales compatible with the seafloor sediment lithology of the area which can form a useful basis of homogeneous seafloor segments. Interestingly, the achieved homogeneously segmented data can be utilized for seafloor characterization. Once iterations are completed, a grid has been calculated out of the point distribution of the backscatter data. The grid size of 50 m and data points within a radius of 75 m around each grid point were used to calculate the grid cell value. These settings correspond to the largest footprint size of the beams and averaging is performed. On the whole, the multibeam backscatter processed data, free from mean angular backscatter shape parameters from the Porcupine Seabight area, is presented in Figs. 2a, b. A grey scale dynamic range of 12 dB (−42 dB to −30 dB) is observed within the angle-invariant backscatter image, which comprises mound and channel systems. The grey level contrast variations among different feature types are distinctly clear for the Porcupine Seabight backscatter data.

Porcupine Seabight—study area description and angle-invariant backscatter data

The Porcupine Seabight extends approximately from 49°N to 52°N in latitudes and from 14°W to 11°W in longitudes. For the present study, we have processed
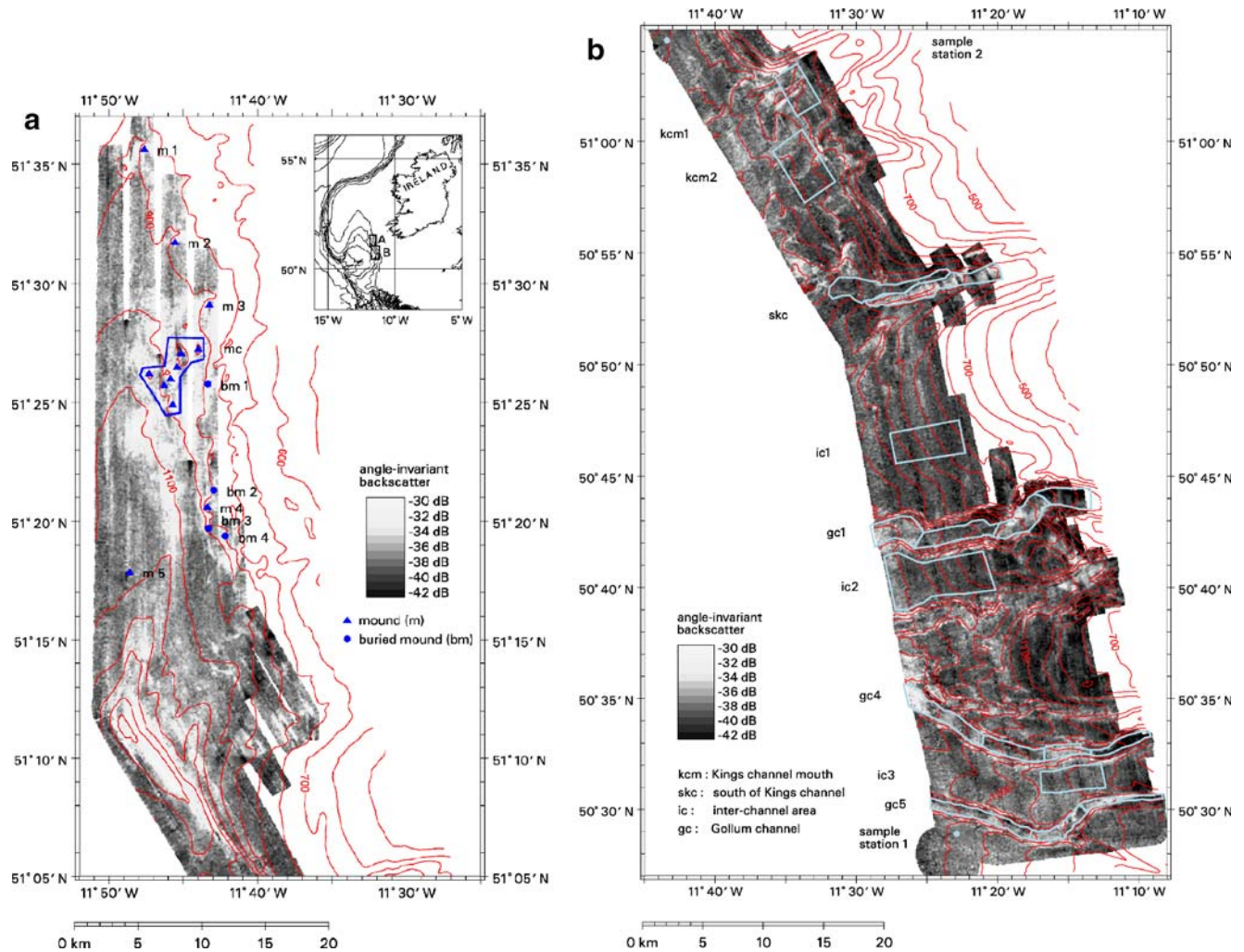
Fig. 2 Backscatter map of the angle-invariant backscatter data recorded in the deep-sea mode of the Hydrosweep DS-2 multibeam system. Hundred meter bathymetric contour lines are also accommodating this figure. **a** The locations of the mounds and buried mounds are drawn using *triangles* and *circles* respectively. **b** Gives the boundaries of the areas used for backscatter analyses

multibeam data acquired between 50°25′N and 51°40′N at the eastern margin of the Porcupine Seabight [8]. In order to maintain consistency in the backscatter processing, the area chosen for this backscatter study is lying within the deep-sea mode of the multibeam system (i.e. 800 m to higher depths) since the operational aspects e.g. transmission beams and reception beams, coverage, and pulse lengths are changing in different modes.

The morphology of the investigation area can broadly be separated into a mound region in the northern part and a channel region in the south. A clear difference in grey scale level can be noticed while comparing between the northernmost-end mound system and southern-end channel system (Fig. 2) of the study area. Towards the north of 50°15′N latitude, the bathymetric trace of the giant mounds is reported in [8]. Though, we have presented angle-invariant multibeam

backscatter data operated in the deep-sea mode, overlying bathymetry is presented for the entire area covered during the RV Polarstern expedition. Towards the northern part of the survey area (Fig. 2a), few blank parallel lines are seen which represent a data gap of the deep-sea mode due to the survey utilizing the medium depth mode which is not considered here. Relative backscatter values (since the multibeam Hydrosweep DS-2 system is not calibrated) varying from the highest backscatter −30 dB (light grey scale) to the lowest i.e. −42 dB (dark grey scale) are observed within the area. Mounds of the Belgica province are present in this northern part. Details of the Belgica mound province are also given in [17] (this volume). A complex grey scale i.e. combination of grey scales varying from light to medium is observed within the clustered mound area of seven mounds (areas coded mc, having an average value of −34 dB within the area marked in Fig. 2a). In addition, four isolated mounds having moderately higher backscatter are shown. Table 1 provides the dimensional aspects of these mounds along with the mean backscatter values acquired from the angle-invariant data. The backscatter level in the mound area is varying from the highest value (−32.20 dB) for the northernmost

Table 1 Statistical parameters of the areas under study including number of measurements, covered area and mean angle-invariant backscatter value (BS)

Area code	Number of measurements	Area covered [km²]	Mean angle-invariant BS [dB]	Remarks
m1	1,531	1.44	-32.20	500 m E–W, 850 m N–S, Ht 100/15 m
m2	1,451	1.34	-33.97	500 m E–W N–S, Ht 90/20 m
m3	3,103	3.59	-32.74	800 m E–W, 2,000 m N–S, Ht 90/50 m
m4	3,185	2.75	-33.88	700 m E–W, 1,400 m N–S, Ht 160/70 m
m5	1,952	1.74	-37.18	1,400 m E–W, 1,100 m N–S, Ht 70/20 m
mc	1,5429	14.67	-34.36	
bm1	967	0.98	-32.80	
bm2	856	1.01	-34.17	
bm3	813	0.88	-35.30	
bm4	1,022	1.22	-34.49	
kcm1	9,047	8.13	-37.80	
kcm2	15,329	15.46	-38.66	
skc up	11,534	11.03	-36.66	
skc low	8,268	10.09	-39.47	
ic1	14,773	15.54	-39.64	
ic2	22,339	29.26	-39.27	
ic3	13,001	10.11	-38.40	
gc1-1	3,812	7.45	-37.03	
gc1-2	6,338	7.82	-38.88	
gc1-3	9,120	7.61	-37.31	
gc1-4	5,756	6.11	-41.16	
gc4-1	4,874	8.68	-36.61	
gc4-2	5,271	5.78	-38.28	
gc4-3	4,092	3.37	-36.07	
gc4-4	5,004	3.46	-41.70	
gc5-1	9,510	7.03	-37.33	
gc5-2	5,735	4.65	-37.22	
gc5-3	2,365	1.77	-35.35	
gc5-4	1,901	1.28	-40.34	

The areas are coded as m (*mounds*), mc (*mound cluster*), bm (*buried mound*), kcm (*Kings channel mouth*), skc (*south of Kings channel*), ic (*inter-channel area*) and gc (*Gollum channel, channel number - channel section*). The sections of the Gollum channels are numbered from west to east. The remarks section gives extension and height of the individual mounds located in Fig. 2. Ht represents the height of the downslope/upslope side of the mounds respectively

mound (m1) to the lowest (−33.97 dB) for the mound (m2). Associated medium grey levels though negligibly close to the mound structures may be identified as a shadow zone, and are insignificant in the multibeam backscatter data. No correlation is obtained with the dimensional aspects of the mounds and backscatter values from this area. The seafloor in the wider surroundings of the mound cluster shows high backscatter but no further mound occurrences were found there. Thus, the lighter grey scale is not solely due to the existence of mounds but because surrounding seabed is also affected. Darker grey scale around −37 dB is seen for the associated background sediment areas. Patchy high-backscatter regions having light grey scales (−30 dB) are also observed in this mound-dominated channel areas. The channels within the seafloor slope closer to mound areas are due to the current scouring which leaves coarser material in the seafloor while sweeping away the fine materials. Parallel examinations of Fig. 2a and the bathymetry map of [8] around the mound structures indicate directions of coarse grained material flow along the depth contours. Reports about the existence of seafloor ripples or sediment waves in the mound-dominated ridge areas were made which are found to be perpendicular to the surface gradient [18, 19]. Sediment waves having a wavelength up to 100 m and a height varying from 1 to 2 m, are only visible in Digital Terrain Model analyses (Fig. 7a of [8]). OREtech side scan sonar (operating frequency 30 kHz; lines ORAT 4 and 9) from the Inter-governmental Oceanographic Commission (IOC) initiatives [6] indicates the presence of two suspected barrier reef mounds at the core sampling locations TTR7-AT-19G (51°17.43′N and 11°48.59′W) and 20G (51°17.82′N and 11°40.78′W) [20]. At TTR7-AT-19G top (0–5 cm) sediments of foraminiferal sand with silt are obtained. Sediment sample descriptions of the TTR7-AT-20G core are found to be similar to TTR7-AT-19G. We could locate the barrier reef mound (m5) at the sediment sampling location of TR7-AT-19G with low bathymetric height. Backscatter strength at the sediment sampling location TTR7-AT-19G is lower (−37.76 dB) and corresponds to the backscatter of background sediments. The TTR7-AT-20G location is situated on the lower 'terrace' slope, and is not considered for our study. Four buried mound structures of variable sizes occur in the study area having mixed backscatter levels varying from −32.80 dB to −35.30 dB for (bm1) to (bm4) (Fig. 2a). The backscatter levels of the buried mounds are comparable with the backscatter level obtained from the mounds. Bathyme-

try-wise, a pronounced depression is observed south of the mound province having very high backscatter. The presence of strong backscatter (−30 dB) at the slope in the topographically depressed area indicates the presence of active seafloor currents which may be guiding coarse material towards the depression. Two parallel low backscatter bands showing northeast to southwest orientation extend between 51°10'N and 51°20′N and have a width of about 1 km. Though no close link with the bathymetry is seen, the change in backscatter level indicates changes in sediment properties which may be related to down-slope currents and sediment transport.

The middle part of the investigation area is characterized by two canyons which cut the generally smooth-sloped margin, ending in a rather changeable deeper area (Fig. 2b). Twenty degree steep canyon flanks are observed and the southern canyon has a width of 2 km at the canyon bottom. Similarly, the northern channel (Kings Channel) shows a variable structure and a mean width of 4 km. We have chosen our study data at the mouth of this channel (kcm1). The second site was chosen slightly away from the channel mouth towards the area indicated as sediment slump (kcm2). Variability in sediment lithology is observed within the two chosen areas. In general, this area has a mixed backscatter level. However, a higher backscatter level (−37.80 dB) is seen for the (kcm1) area compared to the area (kcm2) i.e. −38.66 dB. The presented grey scale levels (Fig. 2b) of the backscatter data can establish the difference between the areas. In this region, the existence of current-generated symmetric seafloor ripple patterns (wavelengths varying from 0.1 to 0.3 m and height of 2.0–5.0 cm) affect the seafloor backscatter, associated with drop-stones, reported by [5]. However, towards the southern end of the Kings channel, areas devoid of current-generated ripples were seen to support bio-turbidity effects [5]. Dominant fine sand with associated fine materials is reported here. Grain size distribution indicates that the area has 'silty sand' similar to the mound site ([2, 5]). Distinctly different backscatter level variations are seen from the channel sections' (skc) top end (−36.66 dB) with respect to the associated lower seafloor channel end (−39.47 dB) towards the southern end of the Kings channel area. Though exact sediment distribution is unavailable from this area, we consider the seafloor to be 'silty sand' like in the Kings channel mouth area (kcm). However the 3 dB fall towards the western side of (skc) suggests significant changes of the seafloor micro-roughness in this channel.

The Gollum channel system is one of the very few lengthy leveed channel systems known from the NW European margin. It is a E-W striking tributary system with sinuosity and narrow steep sided channels. The continental seafloor towards the eastern side of this channel system varies between the depth of 400 and 800 m., whereas for the western side it is observed to be varying up to 1,700 m in the study area. The northernmost channel (gc1) of the five channel systems, is the widest and deepest (Fig. 2b). It reaches an incision of about 400 m, whereas the other channels have a depth of 200 m. The width of this extreme channel reaches up to 1.5 km at the bottom compared to the other channels having a width of 1 km [8]. Within these channels, various types of channel structures are observed. The northernmost channel shows straight characteristics, whereas the two southernmost channels show a distinct extent of meandering while proceeding to the southeast side (gc4 and gc5).

Tudhope and Scoffin [5] had reported the detailed morphological aspects of the Gollum channel system. According to their observations and understandings (based on the references of [21]), the channel floors having 0.0–0.3 m of thick blanketing deposit of flocculant fine grained organic detritus—the origin of phytoplankton, and its varying concentration in the channel floor are due to the funnelling into the topographic depression. The sediment beneath the phyto-detritus layer appeared to be monotonous white ooze. All the sediment samples (five stations) from various locations with varying water depth (400–2,800 m) are indicative of 'silty clay' sediments (10% fine sand, 15–20% silt and 70% clay). For the present study, backscatter data from three complete channel systems are considered out of the five channels surveyed i.e. the northernmost channel (gc1) and channel numbers (gc4) and (gc5) towards the southern end. Backscatter data of the channels (gc2) and (gc3) were not analysed because the high variability of the grey scale prevents to create seafloor segments that cover the entire incidence angle range of the backscatter data. Interestingly, indications of slope failure is seen in the backscatter plot within the intermediate area of the channel systems (gc2 and gc3), not considered for the present study. Indication of such slope failure was clearly absent in the bathymetric plot. In an examination of the angle-invariant backscatter data (Fig. 2b) for the northernmost steep channel (gc1), four segments are observed in terms of backscatter level variation indicative of sediment lithology. Towards the western-end section of this channel (gc1), section 1 shows moderately lighter grey scale (−37.03 dB) followed by the medium grey scale (−38.88 dB) in the channel section 2. Then again relatively higher backscatter (−37.31 dB) is observed in section 3. The dark grey i.e., lowest backscatter is observed for the flank section of this channel section 4 (−41.16 dB), having dominant ridge structures. Moderately lighter grey scale in certain parts of the Gollum channel system can be correlated with the presence of the white ooze having stiff gelatinous texture as observed by [5], and is dominant at the sections of the channel where it is constricted. In section 2 of this channel, medium grey level cannot confirm the presence or absence of a phyto-detritus layer. Similar ideas may be drawn about the grey scales for the other two channels (gc4 and gc5). For channel (gc4), the backscatter levels are varying from: −36.61, −38.28, −36.07 and −41.70 dB for the sections from 1 to 4 respectively. Similar variations are observed within the channel (gc5) also. However, the grey scale variations (sediment

lithology) within the channel sections suggest that the chosen segments are fairly homogenous.

Seafloor classification using angular backscatter response—a semi-empirical approach

The local variations in the shape of the angular backscatter strength can be determined by estimating 'mean angular backscatter response' with lines corresponding to standard deviations from the mean [11]. Regression fits to such angular backscatter curves from different seafloor areas can be utilized to compare their shape-related parameters. The 'slope' of the mean angular backscatter response curve (slope of the linear regression) along with the estimation of a predicted backscatter response at a known angle and the average ratio of the standard deviation to the mean i.e. coefficient of variation (CV) are important classification parameters. These estimated three parameters are utilized as classification parameters for the present study. The area angular backscatter response curves are computed by averaging the measured backscatter strength values within particular angle bins on a linear scale (Eq. 4 in [11]). Similarly, standard deviations from the average values are also computed using Eq. 5 in [11]. Figure 3 provides the mean angular variations in backscatter strength with respect to the incidence angle for specific areas (total six area types): cluster of mounds (mc), buried mound (bm2), channel mouth of the Kings channel system (kcm1), area between the channel 1 and channel 2 (ic2) within the Gollum channel area. Also, similar variations are presented for two adjacent sections (sections 1 and 2) of the Gollum channel (gc1) system seafloor having different textures (Fig. 2b). Distinctly different shapes of the backscatter response patterns are observed for these areas. In order to keep the homogeneity aspects, data of the close surroundings were selected around the mound and buried mound area. Due to the limited data amount from the buried mound area, fluctuations are seen in the mean angular response and standard deviation curves. The estimated standard deviation values from these areas indicate a small range of variations within 3.5 dB, also indicating generally homogenous seafloor. Predicted mean angular response for the 20° incidence angle (estimated by using regression fit) is found to be the highest (−34.76 dB) for the mound area (m1), and the lowest (−43.19 dB) for the Gollum channel area (gc4). Similarly, the absolute values of the slope for the buried mound areas (bm3) are found to be the highest (0.367) and the lowest for Gollum channel (gc4) section 1 seafloor (0.172) respectively. The coefficient of variation (CV) is comparatively higher (0.422) for the clustered mound (mc) area and the lowest (0.312) for the buried mound area (bm2). The estimated values are provided within Fig. 3 for different Porcupine Seabight area seafloor types, which gives enough ground to differentiate among seafloor facies. However, inclu-

sion of more data from different facies may provide a useful trend of the parameters for a specific type of seafloor in the study area.

Table 2 presents estimated parameters for different acoustic facies from the Porcupine Seabight. Most of the parameters are found to be dominant for the mound, buried mound and channel facies. Comparatively, limited activities may be underlined from the inter-channel area data.

In Fig. 4, three inter-parameter relationship plots for mound, buried mound, Kings channel mouth seafloor, Gollum channel seafloor and inter-channel areas are provided. Figure 4a provides a scatter plot of the slope of the angular backscatter curve versus a predicted backscatter value at 20° (regression fit) for all locations. Overall, a low correlation (correlation coefficient ∼0.2) among slope and predicted backscatter at 20° is seen amongst the data from seafloor areas of the Porcupine Seabight. As already explained, the predicted 20° degree angular backscatter is estimated by means of regression fit to the mean angular backscatter response curves following the methods given by [11]. This value is somewhat different from the average angular backscatter strength. We have estimated a correlation coefficient of 0.98 between the average backscatter strength and predicted backscatter values at 20° based on the data of all seafloor segments which indicates that the estimated 20° predicted backscatter response can be an alternative to the mean angular backscattering strength at least for our data. Within a limited change of slope values, variations in the 20° backscatter response is dominant for the Gollum channel seafloor which is indicative of a strong change of channel seafloor backscatter. Similarly, dominant variations of backscatter response are seen for generally higher slopes of the buried mound. However, for carbonate mounds (higher backscatter and moderate slope) and inter-channel seafloor areas (ic1–ic3) (low backscatter and moderate slope), data clusters were found to be localized within very closed areas. For the cluster of seven mounds, the slope and 20° predicted backscatter values are in accordance with the other isolated mound data. No significant parametric variations are observed between the Kings channel mouth areas (kcm1 and kcm2), whereas the other two data points from the channel system south of the Kings channel (skc) indicate higher variations. The significant changes of the backscatter values within limited slope values for the Gollum channel seafloor may indicate a presence or absence of a seafloor material contributing to the change. Occasional presence of white ooze within the channel seafloor is well correlated with the backscatter [21]. Figure 4b provides a plot of the CV values with respect to the predicted backscatter values at 20° incidence angle. The CV values are found to be decreasing with respect to the increase in the 20° backscatter response for mound area data, showing a fairly good correlation of ∼-0.8. Station TTR7-AT-19G (m5) is not considered because the backscatter data correspond to background sediment data. For the buried

Fig. 3 Mean angular backscatter response (*thick lines*) and associated standard deviation (*thin lines*) of six seafloor segments: mound cluster (*mc*), buried mound (*bm2*), Kings channel mouth (*kcm1*), inter-channel area (*ic2*) and two sections of the northernmost Gollum channel (gc1 sec 1, gc1 sec 2). The calculated parameters slope, mean angular response at 20° incidence angle (linear regression fit), coefficient of variation (*CV*) and number of measurements are given inside the figure box
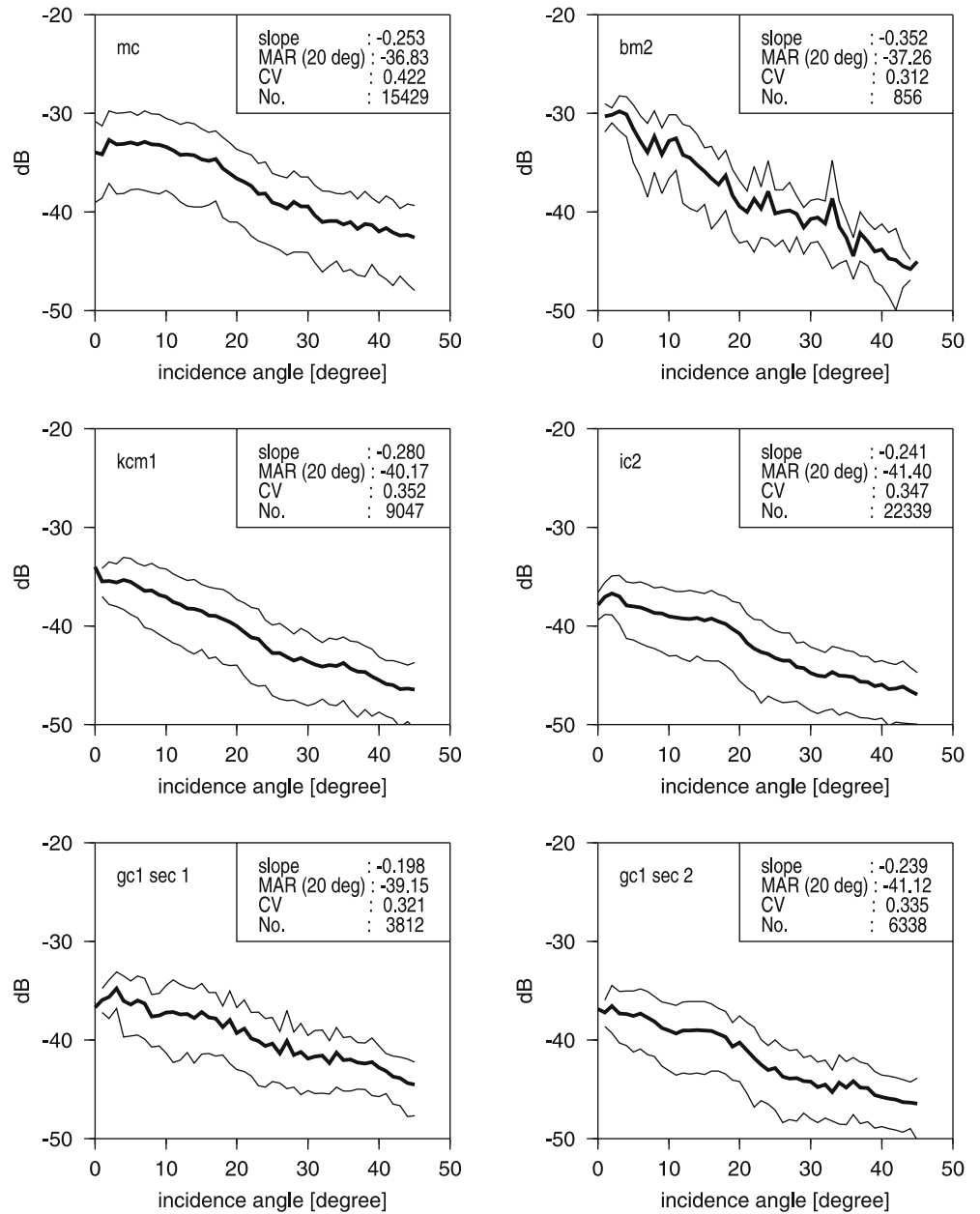

Table 2 Parameters of the different facies in the study area: backscatter strength (BS) at 20° incidence angle (linear regression fit), slope (linear regression fit), coefficient of variation (CV)

Area	BS (20°) [dB]	Slope [dB /deg.]	CV	Remarks
Mound	-34.76 to −39.40	-0.219 to −0.291	0.333–0.422	Highest BS and highest CV of all
Buried mound	-35.68 to −38.30	-0.185 to −0.362	0.312–0.367	Highest slope of all
Inter channel	-40.38 to −41.79	-0.229 to −0.254	0.336–0.349	–
Channel	-37.12 to −43.19	-0.172 to −0.258	0.312–0.392	Lowest slope and lowest CV of all

The remarks section gives specific aspects of the facies

mound areas, no such relation is seen i.e. CV is independent to the backscatter response. For Gollum channel area seafloor, higher variations of the backscatter response are found to be unrelated with the CV. Though very limited sites are available from the inter-channel areas, a very negligible fall in CV is seen with the backscatter response. On the whole, we presume that a moderate correlation among the CV and 20° predicted backscatter is observed for the total dataset. Figure 4c presents a plot of the CV versus slopes. No correlation is

Fig. 4 Statistical characteristics of the analysed seafloor segments. **a** Shows the slope of the linear regression fit of the backscatter data versus the backscatter strength (linear regression fit) at 20° incidence angle. **b** Shows the coefficient of variation (CV) versus backscatter strength at 20° incidence angle (linear regression fit) and the slope of the linear regression fit of the backscatter data versus the CV is shown in (**c**)
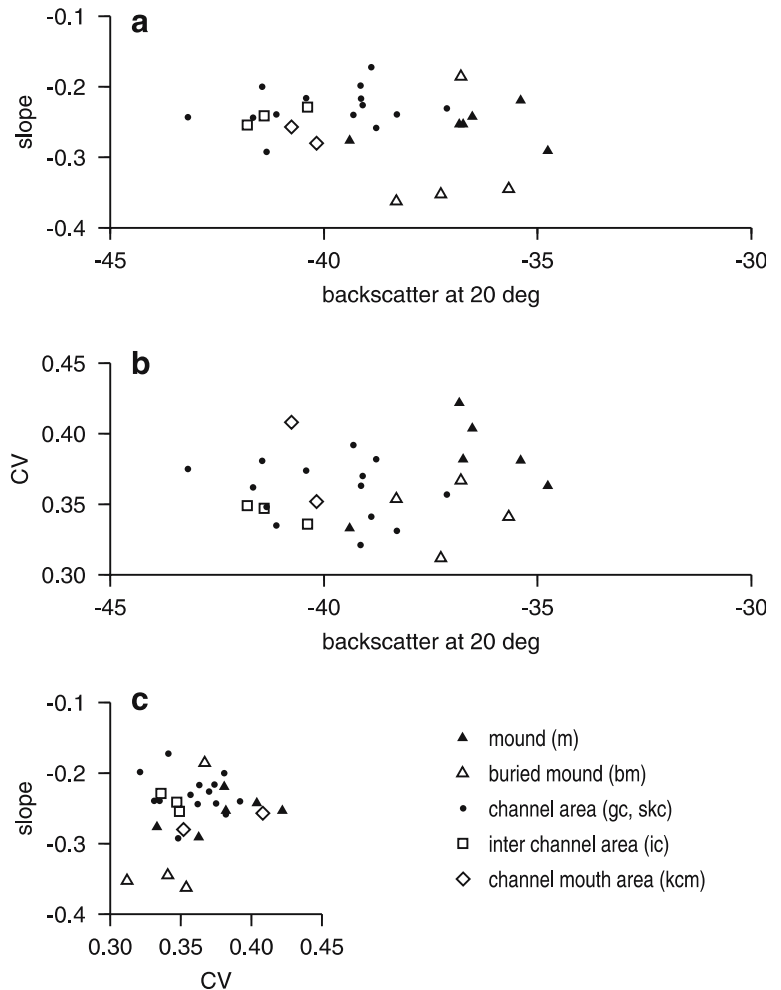
observed between these two parameters when the entire dataset is considered. For the mound and buried mound areas, a moderate and good correlation is seen respectively (∼0.5 to ∼0.65). Within the channel seafloor, poor correlation (∼-0.2) is observed between the CV and slope parameters. Overall, the slope of the backscatter curves does not show a significant change for various seafloor regimes within the Porcupine Seabight.

Conclusion

In this work, analyses of the multibeam angular backscatter data acquired in the eastern slope of the Porcupine Seabight area are carried out. Processing of the angular backscatter data using the 'NRGCOR' software is made for 29 locations to classify different geological provinces like: carbonate mounds, buried mounds, seafloor channels, and inter-channel areas. A detailed methodology is developed to produce angle-invariant (normalized) backscatter maps to clarify different seafloor sediment lithological aspects. Such a presentation has advantages above the raw angular backscatter data since the impact of the incidence angle is removed. The

presented angle-invariant backscatter map possesses 12 dB dynamic range in terms of grey scale and reflects the lithology of various seafloor features. A clear distinction is seen between the mound-dominated northern side (Belgica province) and the Gollum channel seafloor from the southern end of the site. A qualitative analysis of the calculated mean backscatter values i.e. grey scale levels, utilizing angle-invariant backscatter data generally indicates that backscatter values are highest (lighter grey scale) from the mound areas followed by buried mounds. The backscatter distribution also shows that mound structures not only impact their immediate vicinity, but also the wider surroundings illustrate mound-typical backscatter values (grey scale). However, mound-related backscatter patterns only exist within the depth range of the mounds. Patchy backscatter variations at 'off-mound' locations might correlate with inhomogeneous occurrences of corals in mound areas [7]. Reported contour currents are also supported by the backscatter data. High backscatter around the mounds was also stated in [7] based on 30 kHz OREtech sidescan data. However, by means of multibeam backscatter data analyses, the main part of the margin was covered. The backscatter values are the lowest from the inter-

channel areas (lowest grey scale level). Though moderate backscatter values (medium grey level) are observed from Gollum and Kings channel data, data show significant variability within the channel seafloor provinces. The segmentation of the channel seafloor provinces is made based on the computed grey scale levels for the present analyses as well as further studies based on the angular backscatter strength.

The application of the semi-empirical approach employed to the angular backscatter data provides three major parameters to classify the four major seafloor provinces of the Porcupine Seabight seafloor. Implementation involves the shape, variance and magnitude of the angular response applied to the measured multibeam angular backscatter strength data and provides effective classification and comparisons. The predicted backscatter response at $20°$ dB is the highest for the mound areas. The CV of the mean backscatter response is also the highest for the mound areas. This indicates higher seafloor roughness compared to the surrounding sediments. However, reduced volume roughness is also expected in the mound-associated areas. Interestingly, the slope values are found to be the highest for the buried mound area. However, the channel seafloor of moderate backscatter response presents lowest slope and CV values. Interestingly, a critical examination of the inter-channel areas indicates less variability within the estimated three parameters.

The present study is a semi-quantitative effort. In order to understand the complex seafloor conditions, we are working on this subject employing quantitative methods to estimate seafloor roughness parameters. However, the presently produced imagery provides good information for marine science because it shows the degree of variability in terms of acoustic sediment properties. The technique developed is essentially applicable for geological interpretation, because changing sediment properties can be related to areas of different seafloor facies. The extent and variety of the seafloor facies gives an indication for the geological interpretation of the upper part of the seafloor sediments and its spatial validity.

References

1. Croker PF, Shannon PM (1987) The evolution and hydrocarbon prospectivity of the Porcupine Basinn, offshore Ireland. In: Brooks J, Glennie KW (eds) Petroleum Geology of North West Europe. Graham and Trotsman, London, pp 633–642
2. De Mol B, Van Rensbergen P, Pillen S, Van Herreweghe K, Van Rooij D, McDonnell A, Huvenne V, Ivanov M, Swennen R, Henriet JP (2002) Large deep-water coral banks in the Porcupine Basin, southwest of Ireland. Mar Geol 188:193–231
3. Hovland M, Crocker PF, Martin M (1994) Fault associated seabed mounds (carbonate knolls?) off western Ireland and northwest Australia. Mar Pet Geol 11:232–246
4. Henriet JP, De Mol B, Pillen S, Vanneste M, Van Rooij D, Versteeg W, Crocker PF, Shannon PM, Unnithan V, Bouriak S, Chachkine P, the Porcupine-Belgica 97 shipboard party (1998) Gas hydrate crystals may help build reefs. Nature 391:648–649
5. Tudhope AW, Scoffin TP (1995) Processes of sedimentation in Gollum Channel, Porcupine Seabight: submersible observations and sedimentation analyses. Trans R Soc Edingburgh Earth Sci 86:49–55
6. Kenyon NH, Ivanov MK, Akhmetzhanov AM (eds) (1998) Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin. IOC Technical Series 52. UNESCO, p 178
7. Huvenne V, Blondel P, Henriet JP (2002) Textural analyses of sidescan sonar imagery from two mound provinces in the Porcupine Seabight. Mar Geol 189:323–341
8. Beyer A, Schenke HW, Klenke M, Niederjasper N (2003) High resolution bathymetry of the eastern slope of the Porcupine Seabight. Mar Geol 198:27–54
9. Kenyon NH, Akhmetzhanov AM (1998) Long-range sidescan sonar data. In: Kenyon NH, Ivanov MK, Akhmetzhanov AM (eds) Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin. IOC Technical Series 52. UNESCO, pp 34–39
10. Wheeler A, Degryse C, Limonov A, Kenyon N (1998) OREtech sidescan sonar data. In: Kenyon NH, Ivanov MK, Akhmetzhanov AM (eds) Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin. IOC Technical Series 52. UNESCO, pp 40–58
11. Hughes Clarke JE (1994) Toward remote seafloor classification using the angular response of acoustic backscattering: a case study from multiple overlapping GLORIA data. IEEE J Oceanic Eng 19(1):112–127
12. Gutberlet M, Schenke HW (1989) Hydrosweep: New era in high precision bathymetric surveying in deep and shallow water. Mar Geod 13:1–23
13. Anonymous (1994) Atlas Hydrosweep DS-2 Softwarepaket zur Bestimmung des Rueckstreumasses nach de Moustier (A system description from STN Atlas Electronik)
14. Vogt PR, Gardner J, Crane k (1999) The Norwegian-Barents-Svalbard (NBS) continental margin: Introducing a natural laboratory of mass wasting, hydrates, and ascent of sediment, pore water, and methane. Geo Mar Let19:2–21
15. de Moustier C, Matsumoto H (1993) Seafloor acoustic remote sensing with multibeam echo-sounders and bathymetric sidescan sonar systems. Mar Geophys Res 15:27–42
16. Hughes Clarke JE (1993) The potential for seabed classification using backscatter from shallow water multibeam sonars. Proc Inst Acoustics 15(part2):381–387
17. Wheeler AJ, Beyer A, Crocker P, Freiwald A, Geogheghan M, de Haas H, Huvenne VAI, Kozachenko M, Masson DSM, Schenke HW, White M (2005) The environmental context of carbonate mounds on the NW European Margin. Int J Earth Sci (This issue)
18. De Mol B, Friend P, Akhmetzhanov A, Ivanov M, de Haas H, Belenkaya I, Stadnitskaya A (1999) Porcupine Seabight: Short visit. In: Kenyon NH, Ivanov MK, Akhmetzhanov AM (eds) Geological Processes on the Northeast Atlantic Margin. IOC Technical Series 54, UNESCO, pp 34–47
19. Wheeler AJ, Bett BJ, Billet DSM, Masson DG (2000) High resolution side-scan mapping of deep-water coral mounds: surface morphology and processes affecting growth, Eos Transactions AGU, 81 (48), Fall Meet. Suppl., Abstract OS61B-16
20. Swennen R, Cronin B, Ivanov M, Kozlova E, Wheeler AJ, Akhmetzhanov A, Sautkin A, Van Rooij D, Zaragosi S, Mazurenko L, Degryse C, Sumida P, Satur N, Kennedy R, Akhmanov G, Belenkaya I, Pillen S, Naumov Yu, Stadnitskaya A, de Mol B, Balashova A, Saprykina A (1998) Bottom sampling results. In: Kenyon NH, Ivanov MK, Akhmetzhanov AM (eds) Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin. IOC Technical Series 52. UNESCO, pp 59–97
21. Lampitt RS (1985) Evidence for the seasonal deposition of detritus to the deep-sea floor and its subsequent resuspension. Deep Sea Res 32(8):885–897