Blending single beam RoxAnn and multi-beam swathe QTC hydro-acoustic discrimination techniques for the Stonehaven area, Scotland, UK

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In this study we analysed sediment characteristics using two different acoustic systems: single beam RoxAnn system and multibeam QTC system. Using the new approach described here we have been able to capitalise on the seabed discrimination capabilities of both RoxAnn and QTC and combine them into a single synthesis of the habitat in the region.

***Research Highlights**

- We analysed and mapped the single-beam RoxAnn output.
- We analysed and mapped the multi-beam QTC-MultiView output.
- We developed a method to blend the two acoustic systems.
- We analysed the ground truthing samples to describe the acoustic classes identified.
- We developed a ‘blended map’ of accurate habitat classifications in the region.

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ABSTRACT

Surface properties of the seabed in a 180 km^2 area of coastal waters (14-57m depth) off northeast Scotland were mapped by hydro-acoustic discrimination using single and multi-beam echosounders linked to signal processing systems (RoxAnn for the single beam, and Questor Tangent Corporation (QTC) Multiview for the multibeam). Subsequently, two ground truthing surveys were carried out, using grab and TV sampling. The RoxAnn and QTC-Multiview outputs showed strong similarity in their classifications of seabed types. Classifications generated by QTC-Multiview were used to supervise those based on seabed roughness and hardness indices produced by the RoxAnn system and thereby develop a ‘blended’ map based on both systems. The resulting hydro-acoustic classes agreed well with a cluster analysis of data on sediment grain sizes from the grab sampling, and indicated that the area could be described by distinct regions of surface texture and surficial sediments ranging from muddy sand to boulders and rock.

Keywords: Sediment acoustic classification, RoxAnn system, QTC-Multiview system, ground truthing survey, seabed mapping, Scotland, UK.

1 INTRODUCTION

Habitat mapping is an important prerequisite for the sustainable management of marine ecosystems. Maps are required to assess environmental quality, develop management zoning schemes within marine protected areas, and to evaluate the impacts of disturbance (ICES, 2005). Despite intensive recreational and commercial use of the inshore marine environment off the east coast of Scotland (North Sea), knowledge of the seabed sediments and morphology is largely based on 1:250,000 scale maps produced from core and dredge surveys (several km between samples) and seismic data collected by the British Geological Survey (BGS) in the 1970s and '80s (e.g. Baxter *et al*. 2008). However, these maps do not necessarily resolve small scale seabed habitat features which may have important conservation issues (Diesing *et al*., 2009). The advent of marine spatial planning legislation, which essentially extends the long-standing principles of onshore planning systems into the marine environment, will require a more detailed knowledge of seabed habitats than is currently available. This requirement is likely to be most acute in inshore areas, as this is where most of the activity is concentrated.

Field Code Changed

Since the 1990's, 'acoustic ground discrimination systems' (AGDS) such as RoxAnn^{TM} (Stenmar Ltd, Aberdeen), and QTC Multiview^{TM} (Questor Tangent Corporation, Sidney BC, Canada), have emerged as important signal processing tools for extracting data on seabed properties from single and multi-beam echosounders respectively. RoxAnn, in particular, has been widely employed to map surficial sediments and associated benthic communities (Chivers *et al.*, 1990; Brown *et al.*, 2004 (a and b), 2005; Wilding *et al.*, 2003; Greenstreet *et al.*, 1997; Pinn and Robertson, 1998, 2001, 2003; Siwabessy *et al.*, 2000; Foster-Smith *et al.*, 1999, 2004; Collier and Brown, 2005). Other uses have included analyses of the physical impact of benthic trawls (Kaiser and Spencer, 1996; Kaiser *et al.*, 1998; Tuck *et al.*, 1998), locating fish spawning and nursery habitats (Cholwek *et al.*, 2000; Maravelias *et al.*, 2000; Reid and Maravelias, 2001) and mapping of contaminated sediments (MacDougall and Black, 1999; Rukavina, 2001). The signal processing in RoxAnn provides quantitative data on properties of the returning echo which relate to the roughness and hardness of the seabed, but is restricted to vertically oriented single beam echosounders where the acoustic beam is perpendicular to the seabed. However, a disadvantage of single beam echosounders is that they provide incomplete seabed coverage and poor spatial resolution, relying on interpolation between the tracks, unless a high density grid pattern is used when gathering the data. Multi-beam echosounder systems overcome the spatial coverage problem, but signal processing systems for multi-beam systems cannot provide the same level of seabed discrimination (e.g. Preston, 2003; Brown *et al*., 2005; Schimel *et al*., 2010). Hence, the prospect of linking single and swathe multi-beam data to produce a full coverage map with an accurate description of the seabed features is very appealing.

In our study, we conducted a combined single and multi-beam hydro-acoustic seabed discrimination survey to obtain data at high resolution, in a 18 km x 10 km strip along the east coast of Scotland (Fig. 1). Together with supplementary hydro-acoustic data, grab and TV sampling, the data allowed us to develop a detailed seabed map of the area which is an important point of access to the coastal zone for both recreational and small-scale commercial purposes. To accomplish the task we developed a methodology for combining different forms of hydro-acoustic data and seabed ground-truthing, which we describe here.

2 THE STUDY AREA

The study area was located off the town of Stonehaven, 18 km south of Aberdeen in the north-east of Scotland. The geology of the area is defined by the Highland Boundary Fault which traverses Scotland from the Isle of Arran, Firth of Clyde, in the south-west, to Stonehaven in the north-east (Anderson, 1947). The fault outcrops at the coast on the north side of Stonehaven Bay with exposed pillow lavas, shales and jasper. The coastline for 15 km north of the fault comprises cliffs of quartz-mica-schist, whilst for an equivalent distance to the south, the cliffs are higher (70m) and of red sandstone and conglomerate (Gillen and Trewin, 1987). The marine bathymetry is relatively flat between 2 and 20 km from the coast with depths of 45 – 60 m. The BGS 1:250,000 map Baxter *et al*. 2008) suggests that the inshore sediments in the area are relatively uniform and composed of sand and gravel. Muddy sediments are located further offshore in deeper water and around the major estuaries to the north and south of the area. However, this perception of the seabed morphology off Stonehaven does not accord with finer resolution local knowledge. For example, creel fishermen operating from Stonehaven deploy their gear in highly discrete areas to catch edible crab, and report the existence of rocky reef areas and softer, muddy areas suggesting a more diverse seabed habitat than indicated by the BGS data.

3 MATERIALS AND METHODS

3.1 Acoustic surveys: single-beam RoxAnn system and multi-beam swathe bathymetry system

During 11-13 December 2006, a hydro-acoustic survey was carried out by FRV Scotia off Stonehaven, Scotland (Fig. 1), between latitude 56° 54'N and 57° 03'N, with a distance from the shore between 2 and 12 km. The survey consisted of a set of 50 coast-parallel tracks with a mean separation distance of 160 m. During the survey two acoustic systems were run simultaneously (SIMRAD EK60 38 kHz scientific echosounder, and 95 kHz SIMRAD EM950 multi-beam sonar). Data from the EK60 echosounder were processed with a RoxAnn seabed discrimination system, whilst data from the multi-beam sonar were analysed using QTC-Multiview software.

Output from the RoxAnn signal processor was averaged over 10 s intervals along the survey track in order to smooth variation between successive pings of the echosounder, and this resulted in 18,300 individual observations. At the survey speed of the vessel of 8 knots, the mean along-track distance between single-beam foot-print centres of successive acoustic samples was 45 m. The RoxAnn system discards the leading part of the return echo from each sounder ping, which may come from subsurface sediment structures, and analyses the shape and energy of the trailing edge of the first, and the second seabed echo to determine the characteristics of the seabed surface. The first echo is a direct reflection from the seabed (specular return) whilst the second is reflected twice at the seabed and once at the sea surface. The tail of the first echo (E1) gives a measure of the bottom acoustic roughness while the energy from the whole second echo (E2), gives a measure of the bottom acoustic hardness (Chivers *et al.*, 1990; Hamilton *et al.*, 1999; Hamilton, 2001; Collier and Brown, 2005). RoxAnn data outputs are generally presented in a 2D scatter plot, roughness vs hardness. During signal processing, the sub-surface reflections are removed. Only the properties of the upper few cm of sediment are recorded (Chivers *et al.*, 1990), although the full penetration depth of the acoustic signal might amount to 20-40 cm depending on sediment type (Collins and Galloway, 1998). The advantage of using this method is that the roughness and hardness values represent two physical properties of the seabed. It is possible to extract these outputs singularly and develop a supervised classification; however, as with other systems, uncertainties in the evaluation may be caused by a seabed with overlapping bed features (e.g. sand/rocks/ripples overlapped by the signatures of rock and sand/rocks (Voulgaris and Collins, 1990; Collins and Voulgaris, 1993; Hamilton, 1999, 2001)).

The EM950 multi-beam sonar collected data at 1 s intervals resulting in >19,143,000 observations. The track separation distance (mean 160 m) was chosen such that in the water depths found in the survey area, there was overlap between the multi-beam swathes of adjacent tracks, providing 100% coverage of the area. In a multi-beam swathe bathymetry system, a pulse is transmitted in a wide beam normal to the track of the vessel. The reflected echoes are received in an orientation parallel to the vessel track across multiple narrow beams (1.5°) in a swathe of approximately 120° in the case of the EM950. This produces a swathe of data, collected over a wide range of grazing angles, which is normally several times the water depth. The QTC-MultiView system, extracting 132 acoustic variables (also called features) from the multi-beam backscatter, examines the shape, length, amplitude and other characteristics of the first echo that describe the image texture. Principal Component Analysis (PCA) is used to identify the main constituent features of these parameters, the first three principal components, being assigned as Q-values (Q1, Q2, and Q3) (QTC Multiview User's Manual and Reference, 2005). These three components often represent 90% to 95% of the variance of the complete data set (Preston *et al.*, 2009). The QTC-Multiview software assigned each data observation to one of a specified number of classes, based on the principal component scores (unsupervised classification). A high resolution view of the seabed is obtained, but although this automatic classification is an acceptable empirical method, the physical properties to which the principal components relate remain unknown to the users (Legendre, 2002).

The most inshore track of the survey came within 1 km of the shore, which was as close as the vessel was permitted, at the survey speed of 8 knots. Subsequently (6 March 2008), an additional survey was carried out to collect data from the near-shore zone, using RV ‘Clupea’ and a SIMRAD EK500 echosounder and RoxAnn signal processing unit, and an identical transducer to that installed on the ‘Scotia’. Because of the proximity to the coast, transects were conducted perpendicular to the shore and overlapped with the first acoustic survey tracks.

3.2 Hydro-acoustic data analysis

3.2.1 RoxAnn data

Since RoxAnn data were collected using different vessels and echosounders, the two datasets required to be inter-calibrated. We treated the more extensive ‘Scotia’ dataset as the standard, and for each data point extracted the nearest geographic neighbour in the ‘Clupea’ dataset which was within a 10 m radius. For each pair of points, hardness and roughness signals were compared to determine the mean correction factor (-0.4 ± 0.08 and 0.25 ± 0.07 for hardness and roughness respectively) to be applied universally to the ‘Clupea’ dataset so as to be consistent with the ‘Scotia’ data set.

The combined RoxAnn output data were initially analysed in a 2D scatter plot of roughness (E1) vs hardness (E2). A preliminary classification was made on the basis of a routinely used set of E1 and E2 intervals, which according to past experience indicated to represent major classes of seabed types (Chivers *et al.*, 1990). Charting values from different classes with different colours allows a visual interpretation of the acoustic data (Burns *et al*., 1989). Subsequently, the data were re-classified using seabed video and grain size data, allowing the E1 and E2 intervals to be adjusted to better describe the sediment characteristics in the survey region (supervised classification). The supervised map was created using the software *Surfer* ™.

3.2.2 QTC-MultiView data

The automatic assignment of swathe multibeam data points to seabed classes was performed by the QTC-Multiview software. Analyses were performed for a range of assumed number of classes (Hamilton *et al*., 1999). As the assumed number of classes was increased, so did the likelihood that some of the classes were unrelated to discernible features of the seabed surface due to, for example, the resolution of features due to sub-surface reflections (QTC MULTIVIEW User’s Manual and Reference, 2005). The optimum number of classes resolved all of, but not more than, the major spatial patterns identifiable in the ground truthing data. To a large part, this was judged visually. Results for the optimum number of classes were exported and mapped using the software *Surfer* ™.

3.2.3 Blending and gridding of RoxAnn & QTC data

To merge the data from the two acoustic systems used during the 'Scotia' survey, the 'nearest neighbour' observations in the QTC data set to each of the observations in the RoxAnn data set were located using a search algorithm developed in the statistical package R. The RoxAnn data were then sorted into groups according to the QTC classification and the roughness and hardness intervals extracted for each group. The QTC-supervised classifications of the RoxAnn data (see Results) were extracted and mapped using the software *Surfer* ™.

The QTC-supervised classification scheme developed from the Scotia survey was applied to the shallow water RoxAnn dataset from the 'Clupea' survey, and the classifications of the combined data were then projected onto a regular geographic grid (software *Surfer*™). The gridding involved overlaying the study area with an orthogonal matrix of square cells (equidistant on each side). For each cell, the proportion of the area represented by each sediment class was calculated as the percentage of acoustic data points which were assigned to each sediment class. We refer to this value as the class 'purity' of the sediment within a cell. Cells which contained homogeneous sediment were identifiable by a high proportion of data points from a particular sediment class (i.e. high purity level). By mapping the cells which contained greater than a given threshold of purity, we produced maps showing the main distributions of each sediment class. In such maps cells containing different sediment classes (i.e. low purity level) were essentially unclassified and represented transition zones between the different sediment classes. We developed maps based on all the combinations between grid cell sizes ranging from 100 m x 100 m to 500 m x 500 m, and purity levels ranging from 50% to 80%.

3.2.4 Internal accuracy of the acoustic maps

Internal accuracy assesses how well maps match with the ground truthing samples that have been used to classify the acoustic data (Foster-Smith *et al*., 1999). The acoustic classes corresponding to each of the grab samples locations were extracted from the acoustic datasets using a 'nearest neighbour' search algorithm developed in the statistical package R and the accuracies were measured as the number percentage of grab samples that matched the acoustic classifications.

3.2.5 Bathymetry analysis of the blended dataset

The seabed depth values in the QTC 'blended' dataset and of the shallow water RoxAnn data were used to develop a bathymetric map of the study area. The depth values recorded by the two acoustic systems were corrected for the tidal height at the time of each observation. Tidal heights were predicted using POLPRED Software (Continental Shelf Model CS3). For consistency with the RoxAnn and seabed classification data, the tidally corrected bathymetric data were gridded according to a 'nearest neighbour' algorithm (software *Surfer* ™) and contoured at 5 m depth intervals.

3.3 Ground truthing survey

Two ground-truthing surveys were carried out in April 2007 and September 2008, by the research vessels 'Clupea' and 'Alba na Mara' respectively. The aim of these surveys was to obtain samples of the seabed to describe the habitat types.

During the first survey fifty grab sampling locations were stratified by random assignment within each of nine spatial strata according to the classes identified by analysis of the hydro-acoustic data (see paragraph 4.4 in the results section for details). At each location, seabed samples were collected with a Day grab (0.1 m²). On recovery of the Day grab, seawater overlying any sediment was first siphoned off and a photograph taken of the exposed sediment. A 4-6 cm deep x 2.5 cm diameter sub-sample was then removed and frozen in a sealed plastic bag for grain size analysis. A closed circuit underwater television (CCTV) system was also deployed vertically beneath the vessel, whilst drifting for 30 minutes at 6 locations, to obtain visual data on the surface conditions of the seabed. Changes in the sediment characteristics and species presence were recorded along with depth and time linked to the logged positional data using an internal standard recording protocol. CCTV data were recorded onto digital tapes with annotation of location and depth by reference to the navigation data of the ship.

During the second ground truthing survey in September 2008, a further 55 random locations were sampled with the grab and the CCTV was deployed for 1-2 minutes at every station. Combinations of the grab and CCTV data were used to identify regions on the seabed with similar characteristics and macrofaunal communities (Pinn and Robertson, 2003).

3.4 Sediment grain size analysis

Sediment samples were freeze-dried and sieved in the laboratory using a sieve shaker through 8, 4, 2 and 1.4 mm mesh for 7 minutes; each sieved fraction was weighed to 0.01g. Sediments smaller than 2 mm were analysed by laser granulometry using a

Malvern Mastersizer granulometer (Malvern instrument). The cumulative weight percentage below each sieve fraction were calculated and combined with the cumulative volume percentage to obtain a full particle size range from fractions greater than 8000 µm to 0.49 µm. Before the blending process the sieve fractions are converted from percentage in weight to percentage in volume assuming that volume is equivalent to weight. The conversion and blending methods and calculations are supplied by Malvern. The full granulometry data were then extracted in a logarithmic scale ($\log_2$, in analogy with phi grain size unit ($\Phi = -\log_2(d)$, where 'd' represents the grain diameter)) in 29 grain size fractions.

Sediments were described using a classification based on a combination of the Udden-Wentworth scale (Udden, 1914; Wentworth, 1922) and Folk's classification system (Folk, 1954). Classification by the Udden-Wentworth scale is based on the median grain size, distinguishing sediments ranging from clay to boulders. In the Folk classification, sand:mud ratios between 1:1 and 9:1 are defined as 'muddy' sediments (sand refers to fractions smaller than 2 mm; mud refers to fractions smaller then 63 µm). Percentages of gravel between 1 and 5 %, and between 5 to 30% respectively, were defined as 'slightly gravelly' or 'gravelly'.

To more precisely describe the different sediment types present in the study area as a basis for a quantitative comparison with the acoustic classes, we used 'EntropyMax' software (Stewart *et al.*, 2009 and references therein). EntropyMax is essentially a k-means clustering algorithm that groups grain-size distribution data into self-similar clusters by testing for all possible groupings of samples, thereby minimising within-cluster variability whilst maximising between-cluster variability (e.g. Woolfe, 1995; Woolfe *et al.*, 2000; Orpin and Kostylev, 2006; Stewart *et al.*, 2009). The software also provides two statistics, which provide an aid when determining the number of clusters to be extracted.

4 RESULTS

4.1 Sediment grain size analysis

The sediment grain size analysis of all the grab samples dataset identified four groups as the optimum number that described the grain size distributions (Fig. 2) with a Rs statistic = 68%. The four grain size clusters identified could be described in terms of mean grain size (µm) and mud content percentages (in brackets):

1. Very Fine to Medium muddy Sand (122 ± 33 µm, 25 ± 9 %)
2. Medium to very Coarse Sand (539 ± 151 µm, 6 ± 6 %)
3. Gravelly Fine-Medium muddy Sand with pebbles (982 ± 921 µm, 14 ± 5 %)
4. Fine-Medium Sand (269 ± 51 µm, 6 ± 4 %)

However, the mean grain size was a poor descriptor of the most heterogeneous sediments found in the study area which showed multi-modal grain size distributions (group 2 and 3). A complete description of the grab sediment data is reported in Table 1.

4.2 RoxAnn output

Initially, the single-beam RoxAnn data were geographically mapped to visualise the spatial variations in E1-Roughness and E2-Hardness (Fig. 3 a and b). Roughness and hardness values were then extracted for the nearest neighbour RoxAnn data points to each grab and video sample location and along each video transect. The range of hardness values was then divided into intervals corresponding to sediment classes identified by the analysis of sediment samples (Table 1), and the roughness range divided into intervals according to seabed types identified from the video recordings (Tables 2 and 3). This process defined 5 intervals in the hardness dimension (vertical lines in figure 4) and 4 in roughness dimension (horizontal lines in figure 4).

The hardness and roughness categories were then defined in terms of sediment and seabed descriptors:

Hardness:

1. Very fine muddy sand (mud content percentage >35%, (E2: 0-0.4)
2. Very fine-fine Sand (mud content percentage <35%) (E2: 0.4-0.6)
3. Well sorted Fine-Medium sand (E2: 0.6-0.8)
4. Poorly sorted gravelly fine-medium-coarse sand with pebbles and cobbles (E2: 0.8-1.3)
5. Boulders (E2: 1.3-1.811)

Roughness:

1. Smooth sediment (E1: 0-0.5)
2. Slightly rippled sand and sediment with pebbles, cobbles and boulders (south of the area) (E1: 0.5-0.8)
3. Rippled sand and rough sediment due to the presence of cobbles with alcyonaria *Alcyonium digitatum* (southern shallow water) (E1: 0.8-1.4)
4. Boulders and rocks (E1: 1.4-2.0)

Finally, each grab sampling location and the corresponding entropy sediment group identified by the grain size analysis were plotted in RoxAnn data space according to values extracted for the nearest neighbour points in the RoxAnn dataset (Fig. 5 a and b). The maximum and minimum hardness and roughness values for each RoxAnn class were then adjusted according to the distribution of grab samples in the 2D RoxAnn space (a) and the grain size group (b) to match the sediment characteristics. The resulting supervised classification scheme discriminated 12 sediment classes (Fig. 5b, and 6a) which matched with ~75% of the ground truth samples, corresponded with the regional sediment type distribution and resolved two rocky reefs in the centre of the study area (Fig. 6a).

1. Smooth, very fine muddy sand
2. Smooth, very fine-fine muddy sand
3. Smooth, medium sand
4. Smooth, gravelly fine-medium muddy sand with pebbles
5. Boulders
6. Slightly rippled, fine muddy sand with ophiuroids present
7. Slightly rippled, fine-medium sand with ophiuroids present
8. Gravelly muddy sands with pebbles and cobbles with *A. digitatum* present
9. Rippled, fine sand
10. Rippled, medium sand. This classification category did not agree with the observed sediment proprieties in the southern shallow water
11. Gravelly muddy sand with cobbles and high concentration of *A. digitatum*
12. Gravelly muddy sand with boulders and high concentration of *A. digitatum*

4.3 QTC output

QTC-Multiview output for 2 to 10 classes were used to create distribution maps of sediment classes from the multi-beam data. The map identifying 6 classes was chosen as the most representative for further analysis because it best matched with ground truthing data and the similarity with class distributions from the RoxAnn data (Fig. 6b). Nearest neighbour observations to each grab sample location were then extracted from the full data set. Comparison of this subset of QTC-Multiview classified acoustic data with ground truth results showed 83% accuracy. The classes identified by the unsupervised QTC-Multiview analysis were assigned descriptors as follows:

1. Slightly rippled medium-coarse sand with shell fragments
2. Medium-coarse sand
3. Fine-medium sand
4. Smooth, very fine-fine muddy sand
5. Gravelly muddy sand with pebbles, cobbles and boulders and *A. digitatum*. This classification category did not agree with the observed sediment proprieties in the northern shallow water
6. Gravelly medium-coarse sand with pebbles. This classification category did not agree with the observed sediment proprieties in the northern shallow water

4.4 Blending and gridding of RoxAnn and QTC data

To merge the data from the two acoustic systems, the nearest neighbour observations in the multi-beam data set to each of the observation in the RoxAnn data set were located.

The RoxAnn data were then sorted into groups according to the QTC-Multiview classification (6 classes) and the roughness and hardness relationships plotted for each group. These plots showed a high level of overlap of the QTC classes in RoxAnn space. RoxAnn data points in three of the QTC classes (3, 5 and 6) were clearly not homogeneous and formed distinct sub-classes which were defined by sub-divisions of the roughness and hardness ranges (Fig. 7). On the basis of these sub-divisions, a new 9-class map was developed which matched with 83% of the ground truth samples (Fig. 8), the class descriptors being as follows:

1. Slightly rippled medium-coarse sand with shell fragments
2. Medium-coarse sand

3a. Slightly rippled, fine-medium muddy sand with burrows and with ophiuroids present

3b. Smooth, gravelly fine to coarse sand

4. Smooth, very fine to fine muddy sand

5a. Slightly rippled, fine-medium sand with ophiuroids present. This classification category did not agree with the observed sediment proprieties in the southern shallow water

5b. Gravelly muddy sand with pebbles, cobbles and boulders with *A. digitatum* present

6a. Rippled fine sand with ophiuroids present

6b. Gravelly medium-coarse sand with pebbles

We were unable to collect multi-beam sonar data in the shallow water: so on the map two further classes resulting solely from the RoxAnn analysis are shown (class 11 and 12).

The new ‘blended’ dataset was then combined with the shallow water RoxAnn dataset and projected onto a regular geographic grid. Clearly, the perception of landscape was likely to depend on an interaction between the grid cell resolution and the threshold level of purity for a cell to be defined as ‘belonging’ to a particular sediment class. High purity becomes a more demanding criterion as grid cell size is increased. Two contrasting maps are shown in Figures 9 a and b.

4.5 Bathymetry analysis of the ‘blended’ dataset

Depth in the surveyed area varied between 14 and 57 m (Fig. 10) and was highly correlated with the roughness acoustic property (Pearson correlation = 0.91). Individual sediment classes were generally distributed across a wide depth range, but fell into two groups based on the depth median (Fig. 11): classes 3a, 5a, 6a, 11 and 12 were predominantly found in areas shallower than 35 m, and classes 1, 2, 4, 3b, 5b, 6b were characteristically found in deeper water.

5 DISCUSSION

The BGS marine sedimentology maps of the Scottish east coast show the southern part of our study area, south of Stonehaven (56° 57’N), to be composed of coarse sediments (gravelly sand, muddy gravel, and muddy sandy gravel), and the entire northern part as undifferentiated sand. We conducted probably an order of magnitude more intensive grab sampling in our study area than was available for the construction of the BGS maps. This alone revealed the presence of previously undocumented muddy sediments in the northern half of the region and hints that harder rocky outcrops were present at various locations, although the presence of both of these features were well known to local fishermen. Video transects across the northern-most rocky reef (north-east of Stonehaven) showed boulders and pillow lava outcrops, and its location suggested a submarine extension of the Highland Boundary Fault visible on the nearby shore line. Key to the success of the RoxAnn and QTC-Multiview systems in revealing the full detail of sediment variability was the saturation of the survey area with measurements of a few continuous variables (sediment surface hardness and roughness) (Brown *et al*., 2005). The challenge in capitalising on the information content of these data was to convert these continuous measurements into a classification scheme that relates to the familiar descriptions applied to sediment grain size analyses (Greenstreet *et al*., 1997).

The acoustic discrimination methods provide only a small number of dimensions by which to resolve the nature of the seabed sediments – 2 dimensions from RoxAnn (E1 and E2), 3 dimensions from QTC-Multiview (the 3 principal component scores of each observation). The RoxAnn E1 and E2 values relate to seabed roughness and hardness respectively, but we do not know exactly what properties the QTC-Multiview components refer to. Hence, ground-truthing to establish the relationships between dimensions of the hydro-acoustic outputs and actual sediment characteristics is an essential part of the process. Many authors have illustrated these relationships for RoxAnn and QTC-Multiview separately, or compared the results from the two systems (Hamilton *et al*., 1999). Our aim was to increase the dimensionality available in the hydro-acoustic data by blending the results from RoxAnn and QTC-Multiview. This allowed us to resolve, for example, sub-classes of sandy sediments which were not distinguishable by either RoxAnn or QTC-Multiview alone. The results provide a description of the sediment types with an 83% degree of accuracy. This measure represents the internal accuracy, which indicates how well the acoustic classes describe the sediment properties: high levels of internal accuracy were found in other studies (e.g. Foster-Smith *et al*., 2004; Brown *et al*., 2005). However the external accuracy, using an independent ground truthing validation dataset it was not tested in this study.

A sound description of sediment classes from the grab sampling was an important pre-requisite for analysis of the hydro-acoustic data. Our samples showed a diverse range of sediments in the study area, which were difficult to classify due to variable degrees of sorting as indicated by multi-modal grain size distributions (e.g. group 2 and 3 in figure 2). Standard classification schemes such as the Udden-Wentworth scale (Udden, 1914; Wentworth, 1922) use median grain size (measured in phi, $\Phi=-\log_2(d)$, where 'd' represents the grain diameter), sorting level, skewness and kurtosis to describe the difference or similarity between the sediment samples (Woolfe, 1995). However, this scheme does not readily accommodate mixed sediments with multi-modal grain size distributions. For this reason we applied a combined classification system based on both the Folk and Udden-Wentworth scale to fully describe the sediment samples collected (Table 1). In addition, we subjected the grain size distributions to statistical analysis to identify the natural groupings of samples. Multi dimensional scaling and Principal Component Analysis (PCA) are sometimes used to measure the similarity in grain size fractions and identify groups of sediment types (Clarke and Ainsworth, 1993; Warwick and Clark, 1993; Greenstreet *et al*., 1997; Wilding *et al*., 2003; Brown *et al*., 2004a). However, we employed the entropy-based methodology which ~~was~~ proved to be a useful tool when analysing heterogeneous, multi-modal sediments that characterised our study area identifying the optimum number of groups that describe the sample distributions (e.g. Woolfe, 1995; Woolfe *et al.*, 2000; Orpin and Kostylev, 2006; Stewart *et al*., 2009).

There were some limitations to our analysis of sediment grain size data. In particular, we retained only 200 g of material from each grab sample for gain size analysis which is a limitation on the accuracy of the composition of coarse sediments with pebbles and cobbles (grain diameter > 10 mm) which were present in the southern part of the study area (see MESH standards and protocols at www.searchmesh.net),.

There were also limitations as to how closely we could relate grab sample data to individual data points in the RoxAnn data. It was not possible to position the grab samples used for ground-truthing to within 40 m accuracy, given the strength of the tidal stream and the lack of a dynamic positioning system on the vessels. Hence, there was almost never an exact match (to within 5 m) between the location of the single-beam acoustic and ground-truthing grab samples which is one of the main problems in the interpretation of the RoxAnn data. The use of the multi-beam system solved this problem by providing full coverage data. Both systems can however still provide incorrect acoustic class assignment due to heterogeneous seabed with overlapping sediment types within acoustic classes (Chivers *et al*., 1990; Foster-Smith *et al*., 1999; Pinn and Robertson, 2003; Brown *et al*., 2005; Preston, 2009). Nevertheless, both acoustic outputs showed close correlation with the ground truthing results, with a degree of accuracy >75% proving that these systems work well at distinguishing the heterogeneous seabed types. In addition to the problem of in-exact spatial coincidence, there was a large time gap within and between acoustic surveys (December 2006 and March 2008) and ground-truthing surveys (April 2007 and September 2008). However the analysis of the data did not show consistent changes between ground-truthing surveys. Moreover, for another purpose of study (data not shown), core sediment was collected in seven strategic locations in the study area over a year (from June 2008 to July 2009) and statistical tests of station grain size distributions did not change significantly. Hence, we assumed that the grain size distributions in the study area did not change significantly over time as a result of the topographical area configuration, with turbulent zones in the shallow waters where the sediment is characterised by well sorted sand, depositional area with muddy sand and reef and rocky areas.

The hardness property (E2) satisfactorily categorized the sediments classified as ‘very fine muddy’, ‘fine muddy sand’, ‘well sorted fine-medium’, ‘poorly sorted sands with pebbles and cobbles and ‘boulders’ (Fig. 3a). The roughness property (E1) identified a category of high roughness (Fig. 3b, class 4, red), which identified boulders and rocks. In Fig. 3a two reefs were also identified in the centre of the study area. Reef 1 to the North was rougher and steeper (Fig. 3b) than Reef 2. A mismatch between the sediment properties and the RoxAnn classification (Fig. 6a, class 10, blue) was found in the southern inner corner of the area which is characterised by the presence of boulders with a high concentration of *A. digitatum* (Hayward and Ryland, 1995) embedded in muddy sediments. Two further surveys were carried out in 2008 to better explore the shallow water area: a RoxAnn survey in March and a ground truthing survey in September. The new acoustic dataset identified different classes in this area (Fig. 6a, class 11 and 12, grey and black), with higher values of hardness and roughness, which better agreed with the video. There are several possible reasons that can lead to single-beam system miss-classifications (Wilding *et al*., 2003; Brown *et al*., 2005). In agreement with previous studies we speculate that the different acoustic response between the two RoxAnn surveys in this shallow water area could be due to a different range of depths analysed (Kloser *et al*., 2001; Brown *et al*., 2005), different survey track orientations and vessel speed (Wilding *et al*., 2003), high heterogeneity of the seabed in the area (Brown *et al*., 2005) and possible changes of *A. digitatum* density distribution at different times (December 2006 and March 2007). In contrast to other studies we did not use interpolation methods to create a full coverage map from the single-beam RoxAnn data (Greenstreet *et al*., 1997; Foster-Smith *et al*., 2004; Brown *et al*., 2005). However, the internal accuracy of our RoxAnn supervised map was comparable with the findings of other studies (e.g. Foster-Smith *et al*., 2004; Brown *et al*., 2005). Our results confirmed that despite the inherent limitations of the single-beam approach such as incomplete coverage of the seabed and low resolution for small and high heterogeneous regions (Brown *et al*., 2005), the RoxAnn system performed well for providing distribution maps at broad scale with accurate seabed classifications (Foster-Smith *et al*., 2004).

QTC-MultiView output successfully identified the sediment ‘texture’ characteristics, splitting into different classes the smooth muddy substrates (Fig. 6b, class 4, dark green), sand with ripples, burrows, ophiuroids and starfish, (Fig. 6b, class 3, light blue), shell fragments (Fig. 6b, class 1, light green) and the substrate with gravels and pebbles in the area to the south (Fig. 7b, class 5, red) with a high accuracy of 83% comparable with other case studies using the same acoustic multi-beam system (e.g. Preston, 2009). The system proved particularly sensitive to the presence of shell and shell fragments (Schimel *et al*., 2010), but did not perform well at separating the sediment grain size compositions and roughness levels for classes 3, 5 and 6 (Fig. 7), which had a high inter-class variation of hardness and roughness values. This confirmed the finding of other authors and underlined the high capability of QTC-MultiView to discriminating sediment ‘habitat’ that can differ in terms of hardness and roughness properties (McGonigle *et al*., 2009, Preston, 2009). Other authors also suggested that the mis-identification of different sediment grain size classes may be attributed to a high degree of bioturbation (Borgeld *et al*., 1999, Urgeles *et al*., 2002), in our case due to the presence of ophiuroids and starfish in the shallow waters.

In the shallow water areas, neither of the two systems produced classifications that agreed particularly well with the observed sediment properties. In the north-centre shallow waters the QTC-MultiView classifications (Fig. 6b, class 5, red) did not agree with the observed sediments. Although QTC-Multiview uses many parameters to inform the decision on separate substrate types, it is still possible for two differing substrates to provide similar combinations of parameters (Preston, 2009). In this case the mis-classification could be determined by the abnormally high backscatter (generally an index of gravelly sediment) due to the grazing angles of the beams in shallow water (Dartnell and Gardner, 2004; Preston *et al*., 2003). Nevertheless, our study confirmed that the single-echo shape approach of QTC-MultiView and the double-echo energy approach of RoxAnn can provide similar classifications under most conditions (Hamilton, *et al*., 1999; Preston *et al*., 2003). In this study, the two systems were run concurrently, on the same vessel: this permits us to reduce factors that can introduce differences between the acoustic outputs such as different vessel noise, speed, transect direction and weather conditions, increasing the likelihood of similar classification.

The gridded visualisation of the sediment landscape (Fig. 9) clearly showed how the sediment classes clustered in different regions of the study area: at a 400 m x 400 m grid resolution the class 3a and 3b represented a transition between very fine and fine-medium sand and between fine and medium-coarse sand respectively. Class 5a was a transition between sediments of low (slightly rippled) and high roughness (rippled) recorded during the shallow water RoxAnn survey. The two rocky reefs in the centre of the area and the class 2 sediments localised around them (Fig. 8), were not resolvable at 400 m x 400 m grid cell size because of the high variability in sediment classes at small spatial scales in the vicinity of the reefs. A resolution of 200 m x 200 m or less was required to reveal these small scale features (Fig. 9).

A final point to emerge from our study was that grain size characteristics were not correlated with depth. For example, fine sands and medium-coarse sands, with *A. digitatum* present, were found throughout the depth range (e.g. Fig. 11, classes 3a, 3b, 5a and 1). On the other hand, sediment roughness was highly correlated with depth (Fig. 5b and 10), such that seabed roughness increased with shallower depths and the smoothest sediments were confined to the deepest water. This relationship may be related to depth variations in inshore areas between the centre and north end of the study area (Fig. 10), where wave action, coupled with tidal effects, create larger ripples in the shallow sandy sediment class (Fig. 8, class 6a).

6 CONCLUSION

Previous studies analysed and compared visually and statistically the performance of different mapping systems in one area (e.g. Hamilton *et al*., 1999; Preston, 2003; Foster-Smith, 2004; Brown *et al*., 2005; Schimel *et al*., 2010). In this study we took a step further developing a method to blend two acoustic dataset collected simultaneously from two different systems. Using the approach described here we have been able to capitalise on the seabed discrimination capabilities of both RoxAnn and QTC multi-beam and combine them into a single set of habitat classifications in the region. RoxAnn and QTC differ in the aspects of sediment to which they respond – in particular the single beam echosounder will have deeper penetration into the seabed than the swathe system (which operates at a higher frequency and gathers data over a wide range of grazing angle). However, the RoxAnn signal processing filters out sub-bottom reflections to concentrate on the properties of the seabed surface. The results show a highly diverse sediment habitat in the study area, ranging from rocky reef systems to soft muddy sand.

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FIGURE CAPTIONS

Fig.1. Location map of the study area.

Figure 2. Entropy-based grain size grouping identifing four groups. Within-class variability is indicated by standard deviation (error bars) from each grain size mean fraction. In bracket is indicated the number of samples within each group.

Figure 3. Hardness supervised map identifying 5 classes with the grab sample stations collected during the ground truthing survey on April 2007 (a). Class 1, very fine muddy sand (mud content percentage >35%); class 2, very fine-fine sand (mud content percentage <35%); class 3, well sorted fine-medium sand; class 4, poorly sorted gravelly fine-medium-coarse sand with pebbles and cobbles; class 5, boulders.

Roughness supervised map identifying 4 classes with grab-video sample stations recorded during ground truthing surveys on April 2007 and September 2008 (b) (video transects are indicated with arrows and roman numerals). Class 1, smooth sediment; class 2, slightly rippled sand and sediment with pebbles, cobbles and boulders (south of the area); class 3, rippled sand and rough sediment due to the presence of cobbles with alcyonaria *Alcyonium digitatum* (southern shallow water); class 4, boulders and rocks.

Figure 4. 2D scatter plot Roughness versus Hardness of the RoxAnn acoustic surveys. Vertical and horizontal lines indicated 5 and 4 intervals in the hardness and roughness dimensions respectively.

Figure 5. Correspondence between ID grab station (a) and grain size entropy group (b) in RoxAnn space as a function of supervised roughness and hardness classes (in bold). Grab station numbers collected during the first (April-07, vessel 'Clupea') and the second (September-08, vessel 'Alba na Mara') ground truthing surveys are followed by the letter C and A respectively.

Figure 6. RoxAnn supervised map identifying 12 sediment classes (a). Class 1, smooth, very fine muddy sand; class 2, smooth, very fine-fine muddy sand; class 3, smooth, medium sand; class 4, smooth, gravelly fine-medium muddy sand with pebbles; class 5, boulders; class 6, slightly rippled, fine muddy sand with ophiuroids present; class 7, slightly rippled, fine-medium sand with ophiuroids present; class 8, gravelly muddy sands with pebbles and cobbles with *Alcyonium digitatum* present; class 9, rippled, fine sand; class 10, rippled, medium sand; class 11, gravelly muddy sand with cobbles and high concentration of *A. digitatum*; class 12, gravelly muddy sand with boulders and high concentration of *A. digitatum.*

QTC map identifying 6 sediment classes (b). Class 1, slightly rippled medium-coarse sand with shell fragments; class 2, medium-coarse sand; class 3, fine-medium sand; class 4, smooth, very fine-fine muddy sand; class 5, gravelly muddy sand with pebbles, cobbles and boulders and *A. digitatum*; class 6, gravelly medium-coarse sand with pebbles.

Figure 7. QTC classes plotted in a RoxAnn space roughness (E1) versus hardness (E2).

Figure 8. Combined RoxAnn & QTC map. Class 1, slightly rippled medium-coarse sand with shell fragments; class 2, medium-coarse sand; class 3a, slightly rippled, fine-medium muddy sand with burrows and with ophiuroids present; class 3b, smooth, gravelly fine to coarse sand; class 4, smooth, very fine to fine muddy sand; class 5a, slightly rippled, fine-medium sand with ophiuroids present; class 5b, gravelly muddy sand with pebbles, cobbles and boulders with *A. digitatum* present; class 6a, rippled fine sand with ophiuroids present; class 6b, gravelly medium-coarse sand with pebbles.

Figure 9. Purity maps: 400 m x 400 m grid cell size at 50% of purity level (a) and 200 m x 200 m grid cell size at 80% of purity level (b). For colour legend refer to Figure 8.

Figure 10. Bathymetry map generated from the surveys. Data are interpolated according to ‘nearest neighbour’ method using the program Surfer.

Figure 11. Depth distribution in each class. For the class descriptors refer to paragraph 4.4.

TABLES

Table 1. Sediment descriptors of grab samples collected during the first (April-07) and the second ground truthing surveys (September-08).

Entropy group	Station	Ground truthing survey	Longitude	Latitude	Description	Mean grain size (µm)	% Below 63 µm
1st	22	Apr-07	-2.081	57.023	Very Fine muddy Sand	72	43.9
1st	25	Apr-07	-2.092	56.999	Very Fine muddy Sand	72	43.9
1st	23	Apr-07	-2.094	56.993	Very Fine muddy Sand	80	40.8
1st	2	Sep-08	-2.087	57.02	Very Fine muddy Sand	80	38.2
1st	18	Apr-07	-2.091	57.009	Very Fine muddy Sand	82	37.3
1st	1	Sep-08	-2.096	56.993	Very Fine muddy Sand	83	37.3
1st	26	Apr-07	-2.098	56.986	Very Fine muddy Sand	91	36
1st	1	Apr-07	-2.073	57.045	Very Fine muddy Sand	90	35.2
1st	60	Sep-08	-2.088	57.016	Very Fine muddy Sand	99	34.1
1st	49	Apr-07	-2.11	56.995	Very Fine muddy Sand	90	33.9
1st	20	Apr-07	-2.082	57.006	Very Fine muddy Sand	102	33.1
1st	3	Sep-08	-2.073	57.037	Very Fine muddy Sand	99	28.7
1st	74	Sep-08	-2.121	56.98	Very Fine muddy Sand	105	28.1
1st	32	Apr-07	-2.119	57.028	Very Fine muddy Sand	121	27.9
1st	27	Apr-07	-2.12	56.975	Very Fine muddy Sand	106	26.7
1st	6	Sep-08	-2.118	56.973	Very Fine muddy Sand	106	26.6
1st	15	Apr-07	-2.063	57.038	Slightly Gravelly Fine muddy Sand	126	26.4
1st	11	Apr-07	-2.155	56.974	Very Fine muddy Sand	111	25.1
1st	10	Apr-07	-2.136	56.981	Slightly Gravelly Very Fine muddy Sand	120	23.2
1st	7	Sep-08	-2.086	56.988	Fine muddy Sand	142	22.3
1st	93	Sep-08	-2.116	57.005	Fine muddy Sand	135	22.2
1st	5	Apr-07	-2.158	56.97	Slightly Gravelly Very Fine muddy Sand	122	20.6
1st	8	Sep-08	-2.066	57.026	Fine muddy Sand	154	20.6
1st	24	Apr-07	-2.082	56.991	Fine muddy Sand	175	19.9
1st	12	Apr-07	-2.111	57.018	Fine muddy Sand	152	19.6
1st	21	Sep-08	-2.093	57.036	Fine muddy Sand	157	18
1st	32	Sep-08	-2.121	57.014	Fine muddy Sand	147	18
1st	35	Sep-08	-2.114	57.038	Fine muddy Sand	155	18
1st	48	Apr-07	-2.091	56.972	Slightly Gravelly Fine muddy Sand	185	17
1st	48	Sep-08	-2.146	56.973	Fine muddy Sand	126	16.8
1st	31	Apr-07	-2.167	56.955	Fine muddy Sand	151	16.1
1st	34	Sep-08	-2.129	57.013	Fine muddy Sand	169	15.6
1st	21	Apr-07	-2.159	56.951	Fine muddy Sand	152	15.2
1st	20	Sep-08	-2.138	56.983	Fine muddy Sand	130	14.3
1st	28	Apr-07	-2.176	56.948	Fine muddy Sand	173	13.6
2nd	4	Apr-07	-2.138	56.931	Gravelly Medium muddy Sand	334	21.9
2nd	7	Apr-07	-2.169	56.921	Medium muddy Sand	409	14.8
2nd	25	Sep-08	-2.135	56.917	Gravelly Medium muddy Sand	392	10
2nd	16	Apr-07	-2.046	57.026	Slightly Gravelly Medium Sand	410	9.3
2nd	13	Apr-07	-2.143	56.926	Gravelly Coarse Sand	548	6.8
2nd	43	Sep-08	-2.158	56.981	Coarse Sand	820	4.8
2nd	2	Apr-07	-2.141	56.938	Medium Sand	376	4
2nd	36	Apr-07	-2.14	56.911	Gravelly Coarse Sand	688	3.3
2nd	47	Apr-07	-2.136	56.913	Gravelly Coarse Sand	804	2.3
2nd	44	Apr-07	-2.125	56.925	Slightly Gravelly Coarse Sand	556	2.1
2nd	17	Apr-07	-2.09	56.938	Gravelly Coarse Sand	540	1.9

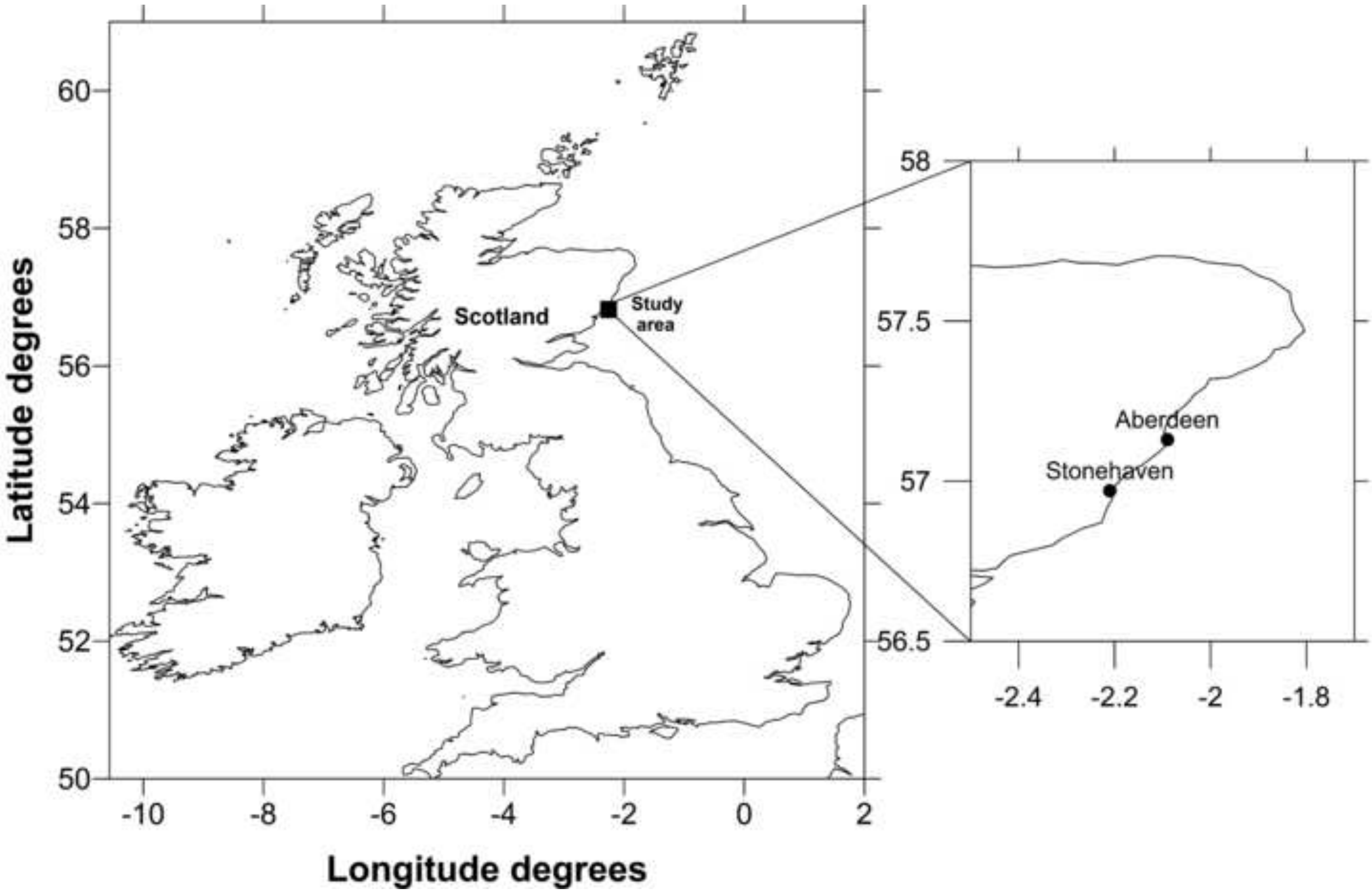
2nd	3	Apr-07	-2.129	56.923	Slightly Gravelly Coarse Sand	525	1.8
2nd	46	Apr-07	-2.124	56.928	Slightly Gravelly Coarse Sand	574	1.3
2nd	43	Apr-07	-2.158	56.989	Coarse Sand	565	0
3rd	22	Sep-08	-2.082	56.909	Gravelly Medium muddy Sand	257	25.7
3rd	24	Sep-08	-2.142	56.902	Gravelly Very Coarse muddy Sand	1984	21.5
3rd	38	Apr-07	-2.076	56.91	Muddy Gravel with pebbles and cobbles	1056	19.7
3rd	15	Sep-08	-2.052	57.035	Gravelly Fine muddy Sand	196	19.6
3rd	45	Sep-08	-2.066	56.931	Gravelly Medium muddy Sand	272	16.2
3rd	35	Apr-07	-2.082	56.93	Gravelly Coarse muddy Sand with cobbles	519	15.2
3rd	123B	Sep-08	-2.079	56.946	Gravelly Medium muddy Sand	312	15.2
3rd	33	Sep-08	-2.172	56.919	Gravelly Medium muddy Sand	282	15
3rd	27	Sep-08	-2.113	56.901	Gravelly Coarse muddy Sand	978	13.3
3rd	28	Sep-08	-2.156	56.913	Gravelly Medium muddy Sand	442	13.2
3rd	26	Sep-08	-2.14	56.896	Gravelly Very Coarse muddy Sand	1677	13.1
3rd	37	Apr-07	-2.161	56.911	Gravelly Very Coarse muddy Sand with pebbles and cobbles	589	11.7
3rd	33	Apr-07	-2.157	56.905	Gravelly Coarse muddy Sand with pebbles and cobbles	811	11
3rd	39	Apr-07	-2.083	56.911	Muddy Gravel with pebbles	3393	10.7
3rd	17	Sep-08	-2.077	56.94	Gravelly Medium muddy Sand	344	10.4
3rd	29	Sep-08	-2.105	56.913	Gravelly muddy Granule	2591	10.3
3rd	34	Apr-07	-2.126	56.909	Gravelly Coarse Sand with pebbles and cobbles	986	4.8
4th	13	Sep-08	-2.071	57.011	Fine muddy Sand	217	13.8
4th	12	Sep-08	-2.084	56.978	Slightly Gravelly Fine muddy Sand	198	12.9
4th	40	Apr-07	-2.056	56.966	Gravelly Fine muddy Sand with pebbles	231	12.6
4th	50	Apr-07	-2.13	56.96	Slightly Gravelly Fine muddy Sand	238	11.8
4th	9	Apr-07	-2.155	56.945	Medium muddy Sand	256	10.9
4th	14	Apr-07	-2.059	57.036	Slightly Gravelly Fine muddy Sand	240	10.8
4th	47	Sep-08	-2.149	56.95	Medium Sand	276	9.7
4th	16	Sep-08	-2.074	56.901	Gravelly Medium Sand	314	9
4th	18	Sep-08	-2.052	56.944	Gravelly Medium Sand	278	8.8
4th	30	Sep-08	-2.173	56.962	Fine Sand	200	8.7
4th	4	Sep-08	-2.146	56.946	Medium Sand	270	8
4th	19	Apr-07	-2.101	56.965	Medium Sand	272	7.2
4th	82	Sep-08	-2.121	56.96	Medium Sand	313	6.7
4th	113	Sep-08	-2.171	56.963	Fine Sand	216	6.3
4th	14	Sep-08	-2.036	57.012	Medium Sand	251	6
4th	5	Sep-08	-2.073	56.965	Medium Sand	256	5.9
4th	44	Sep-08	-2.046	56.983	Slightly Gravelly Medium Sand	263	5.7
4th	29	Apr-07	-2.171	56.962	Fine Sand	204	5.5
4th	9	Sep-08	-2.048	57.008	Fine Sand	240	5.5
4th	46	Sep-08	-2.101	56.931	Gravelly Medium Sand	386	4.9
4th	31	Sep-08	-2.155	56.993	Medium Sand	267	4.7
4th	8	Apr-07	-2.088	56.962	Medium Sand	300	4.6
4th	19	Sep-08	-2.164	56.93	Medium Sand	337	4.1
4th	6	Apr-07	-2.116	56.953	Slightly Gravelly Medium Sand	300	3.9
4th	45	Apr-07	-2.038	57.005	Medium Sand	313	3.7
4th	10	Sep-08	-2.128	56.932	Gravelly Medium Sand	334	3.3
4th	37	Sep-08	-2.15	57.009	Fine Sand	210	2.4
4th	38	Sep-08	-2.169	56.984	Medium Sand	330	1.4
4th	Ray	Sep-08	-2.158	56.924	Medium Sand	384	0.6
4th	36	Sep-08	-2.146	57.019	Fine Sand	206	0
4th	39	Sep-08	-2.177	56.974	Medium Sand	252	0

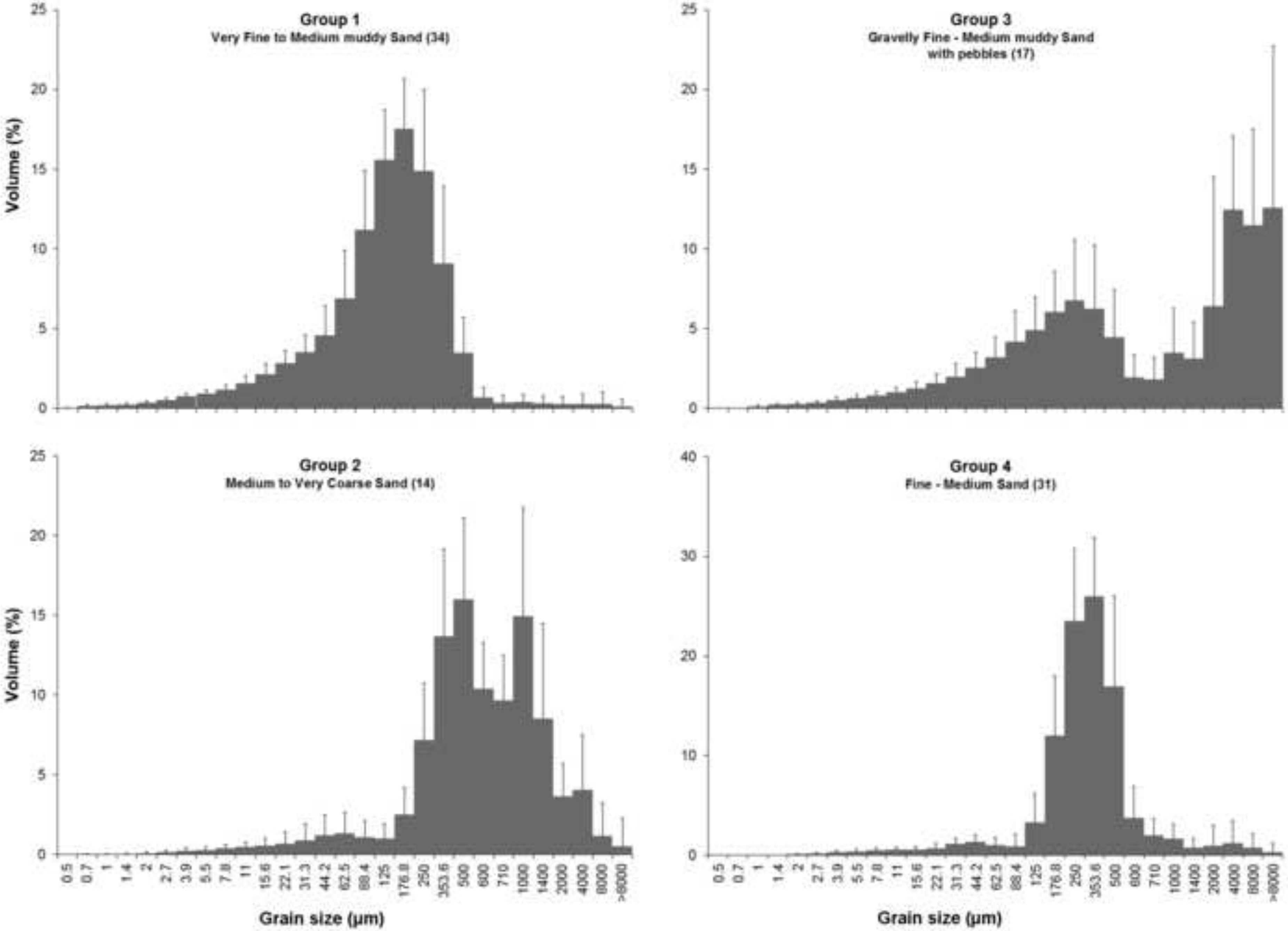
Table 2. Sediment descriptors of video transects carried out during the first ground truthing survey on April 2007

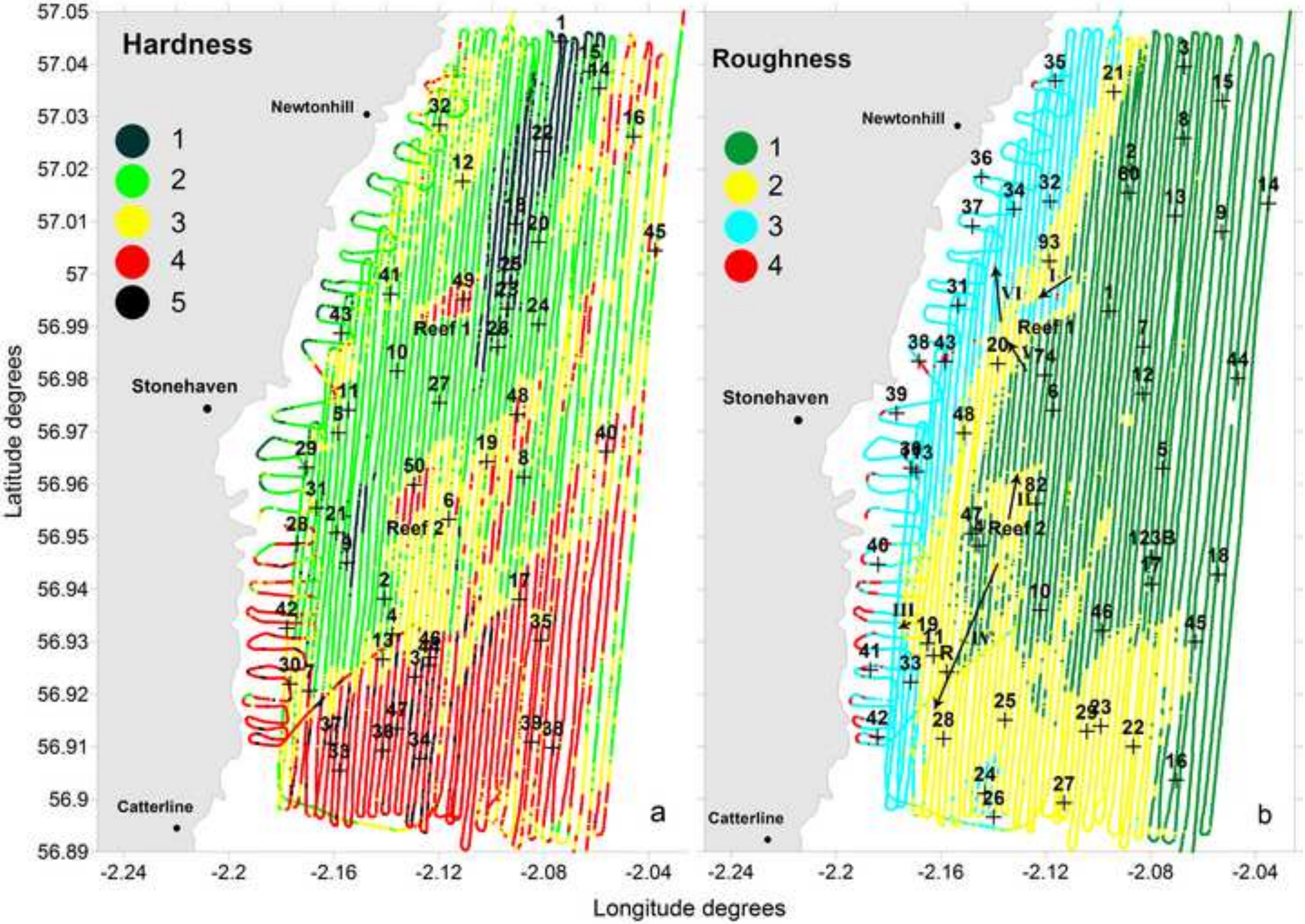
Transect	**Start Longitude**	**Start Latitude**	**End Longitude**	**End Latitude**	**Duration**	**Average depth (m)**	**Description**
I	-2.111	57.000	-2.123	56.996	34	40	From sandy sediment with ripples to boulders with *Alcyonium digitatum*
II	-2.135	56.953	-2.132	56.961	36	41	Sandy rippled sediment with cobbles, boulders and *A. digitatum*. Starfish and squat lobster present
III	-2.173	56.933	-2.176	56.933	29	36	Rippled sand with starfish. At the end harder sediment with an increasing of cobbles and *A. digitatum*
IV	-2.139	56.945	-2.163	56.918	29	45	Slightly rippled sand with shell fragment and starfish. At the end shell fragment on fine sand with *A. digitatum* present
V	-2.128	56.981	-2.135	56.987	31	39	Slightly rippled muddy sediment with burrows, ophiuroids and starfish
VI	-2.138	56.991	-2.140	57.001	30	30	From rippled muddy sand to sandy sediment. Ophiuroids and starfish present in all transect

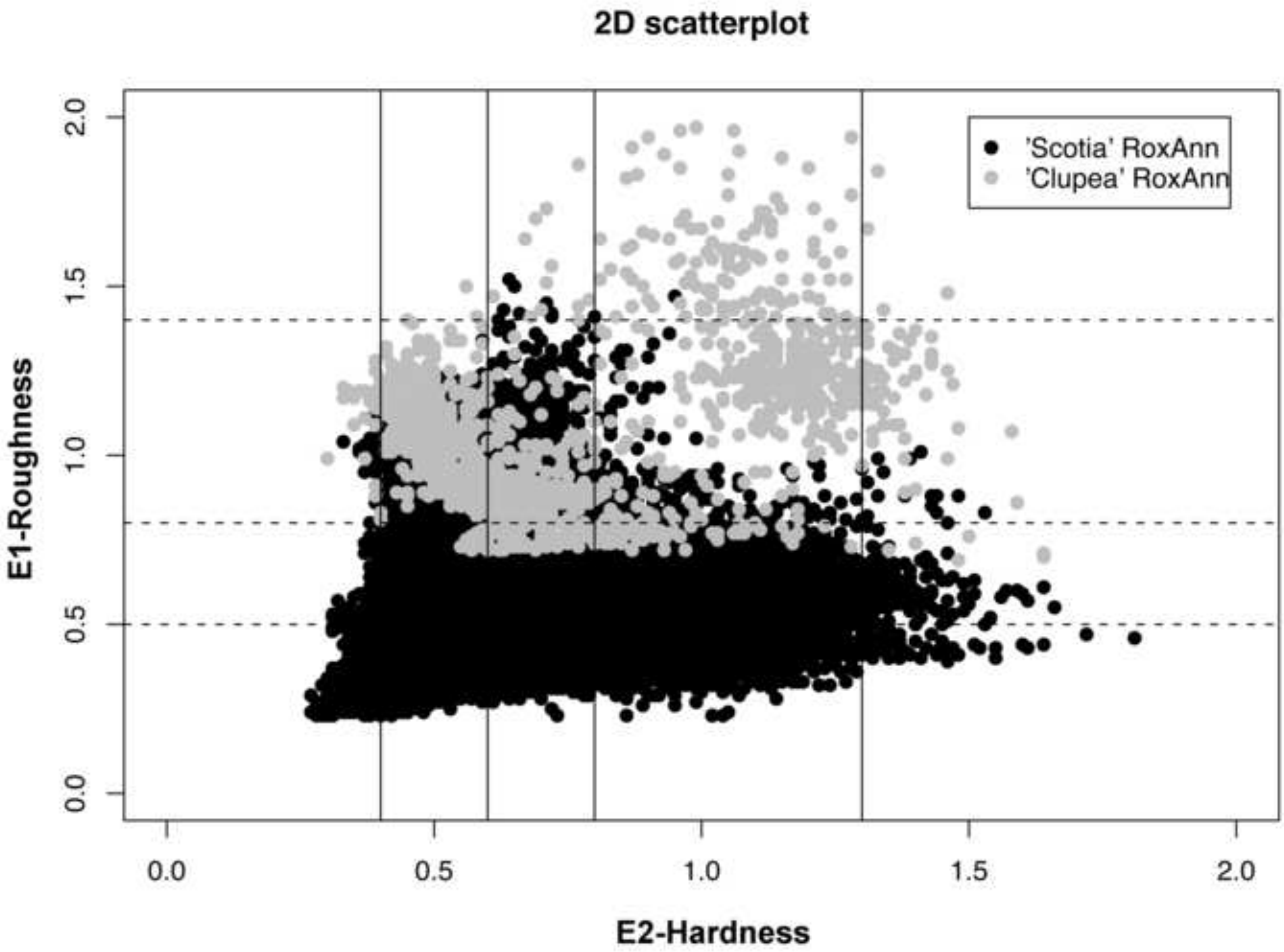
Table 3. Sediment descriptors of short video transects carried out during the second ground truthing survey on September 2008

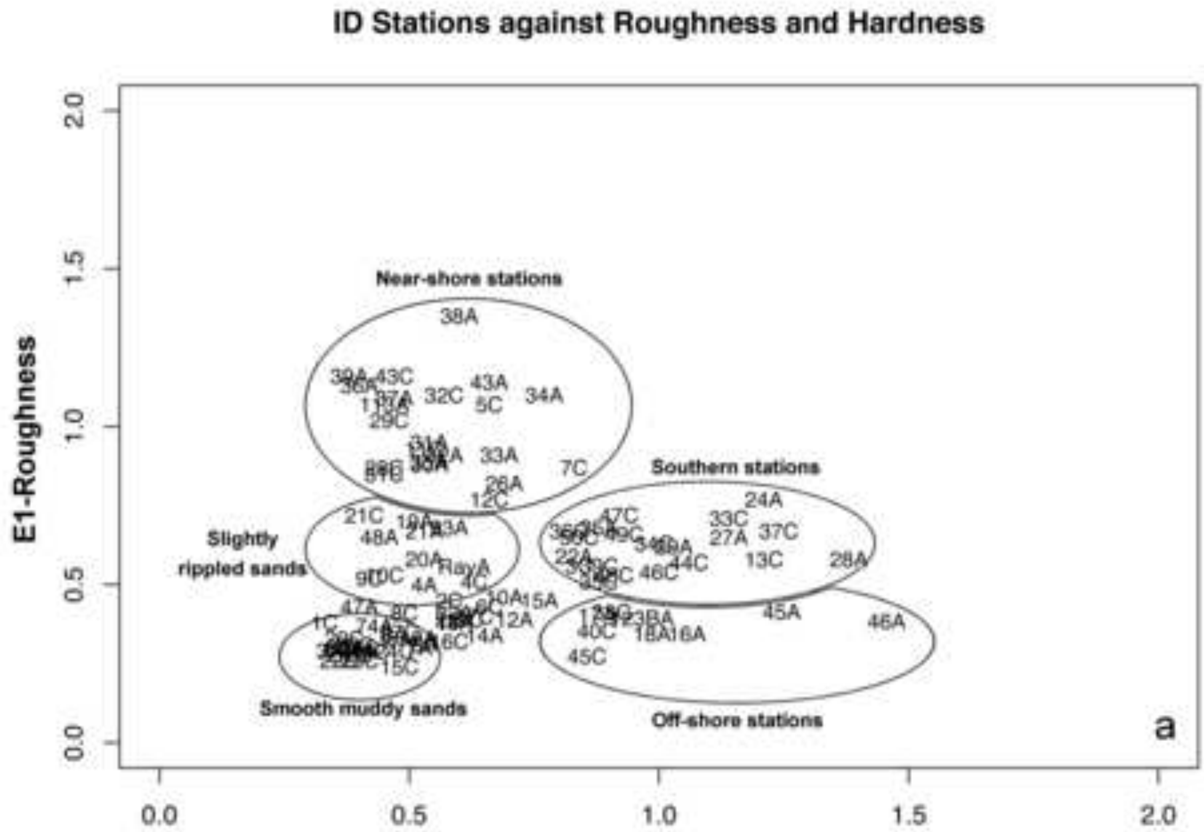
Station	Longitude	Latitude	Depth (m)	Description
1	-2.096	56.993	51	Smooth muddy sand
2	-2.087	57.020	46	Smooth muddy sand
3	-2.067	57.039	50	Smooth muddy sand with burrows
4	-2.146	56.948	38	Slightly rippled sand with some shell fragments
5	-2.075	56.963	53	Slightly rippled sand
6	-2.117	56.974	44	Smooth muddy sand
7	-2.083	56.986	50	Smooth muddy sand
8	-2.067	57.026	53	Smooth muddy sand
9	-2.053	57.008	56	Slightly rippled sand with shell fragments and flat fish present
10	-2.122	56.936	42	Smooth sand with shell fragments
11	-2.163	56.927	35	Medium sand with shell fragments
12	-2.083	56.977	49	Smooth muddy sand with some shell fragments and few cobbles
13	-2.071	57.011	52	Smooth muddy sand with some cobbles
14	-2.035	57.013	58	Slightly rippled sand with some shell fragments
15	-2.053	57.033	50	Gravel muddy sediment with shell fragments *A. digitatum* present
16	-2.070	56.904	51	Smooth sediment with pebbles and cobbles
17	-2.080	56.941	51	Smooth sediment with pebbles and cobbles
18	-2.054	56.943	53	Smooth sediment with pebbles and cobbles
19	-2.165	56.930	38	Rippled coarse sand
20	-2.138	56.983	33	Slightly rippled muddy sand with shell fragments
21	-2.094	57.035	32	Slightly rippled muddy sand with shell fragments and fish
22	-2.087	56.910	42	Pebbles, cobbles and some boulders with *A. digitatum* present
23	-2.099	56.914	42	Pebbles, cobbles and some boulders with *A. digitatum* present
24	-2.143	56.901	41	Pebbles, cobbles and some boulders with *A. digitatum* present
25	-2.135	56.915	43	Pebbles, cobbles and some boulders with *A. digitatum* present
26	-2.140	56.897	41	Pebbles and cobbles with *A. digitatum* present
27	-2.113	56.899	43	Pebbles, cobbles and some boulders with *A. digitatum* present
28	-2.159	56.911	43	Pebbles and cobbles with *A. digitatum* present
29	-2.104	56.913	42	Pebbles and cobbles with *A. digitatum* present
30	-2.171	56.963	22	Rippled sand with ophiuroids present
31	-2.154	56.994	22	Rippled sand with ophiuroids present
32	-2.118	57.014	31	Rippled sand with ophiuroids and shell fragments present
33	-2.171	56.922	37	Cobbles and boulders with starfish, big *A. digitatum* and squat lobsters
34	-2.132	57.012	26	Rippled sand with ophiuroids present
35	-2.116	57.037	22	Rippled sand with ophiuroids present
36	-2.145	57.019	16	Rippled sand with ophiuroids present
37	-2.148	57.009	18	Rippled sand with ophiuroids present
38	-2.168	56.983	16	Rippled coarse sand with shell fragments
39	-2.177	56.973	13	Rippled sand with ophiuroids present
40	-2.184	56.945	20	Cobbles and boulders on muddy sediment with small *A. digitatum*
41	-2.187	56.925	28	Cobbles and boulders and *A. digitatum*
42	-2.184	56.912	31	Cobbles and boulders and *A. digitatum*
43	-2.158	56.983	21	Rippled sand with starfish
44	-2.047	56.980	55	Rippled medium/coarse sand with shell fragment
45	-2.063	56.930	52	Smooth sediment with pebbles and cobbles
46	-2.099	56.932	46	Smooth sediment with pebbles and cobbles and big shell fragments present
47	-2.148	56.951	38	Slightly rippled sand
48	-2.151	56.970	32	Slightly rippled sand
60	-2.088	57.016	48	Smooth muddy sand
74	-2.120	56.981	44	Smooth muddy sand
82	-2.124	56.956	44	Smooth sand with shell fragments
93	-2.119	57.002	37	Slightly rippled muddy sand
113	-2.169	56.962	27	Rippled sand with ophiuroids present
Ray	-2.158	56.924	39	Medium sand with shell fragments
123B	-2.079	56.946	49	Smooth sediment with pebbles and cobbles

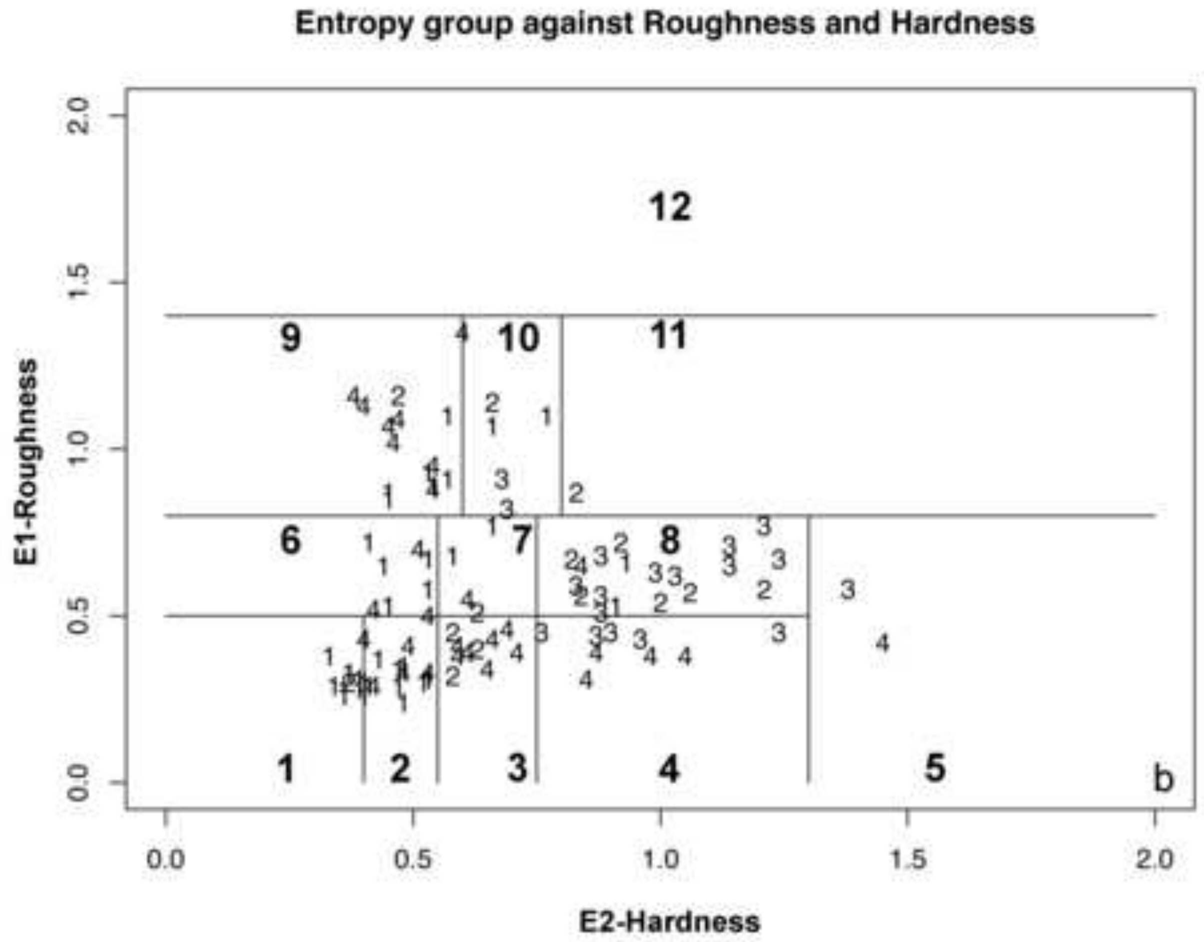

60
58
56
54
52
50
-10
-8
-6
-4
-2
0
2
Latitude degrees
Longitude degrees
Scotland
Study area
58
57.5
57
56.5
-2.4
-2.2
-2
-1.8
Aberdeen
Stonehaven

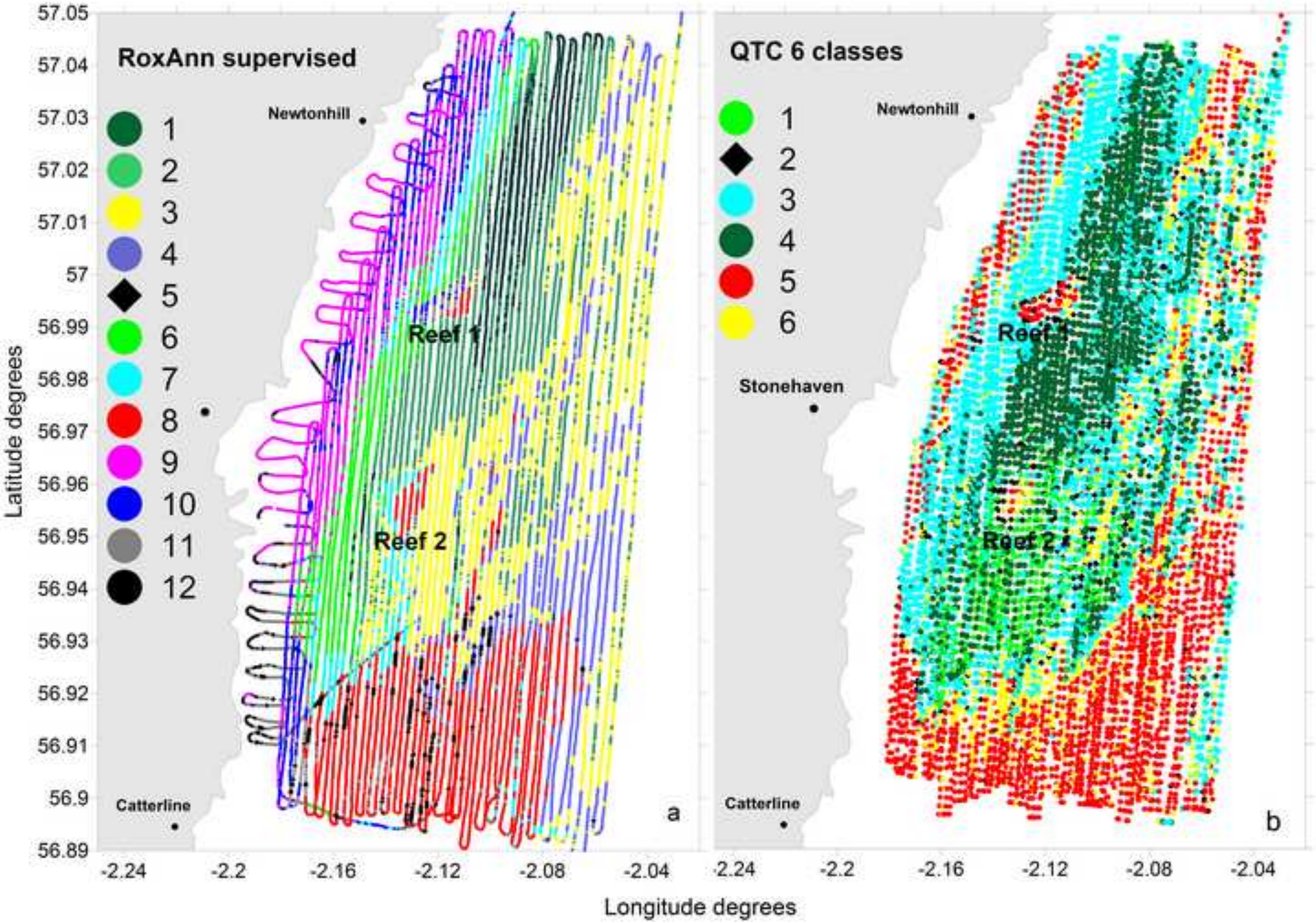

Group 1
Very Fine to Medium muddy Sand (34)
Group 3
Gravelly Fine - Medium muddy Sand
with pebbles (17)
Group 2
Medium to Very Coarse Sand (14)
Group 4
Fine - Medium Sand (31)
Volume (%)
Volume (%)
0
5
10
15
20
25
0
10
20
30
40
0.5
0.7
1
1.4
2
2.7
3.9
5.5
7.8
11
15.6
22.1
31.3
44.2
62.5
88.4
125
176.8
250
353.6
500
600
710
1000
1400
2000
4000
8000
>8000
Grain size (µm)
Grain size (µm)

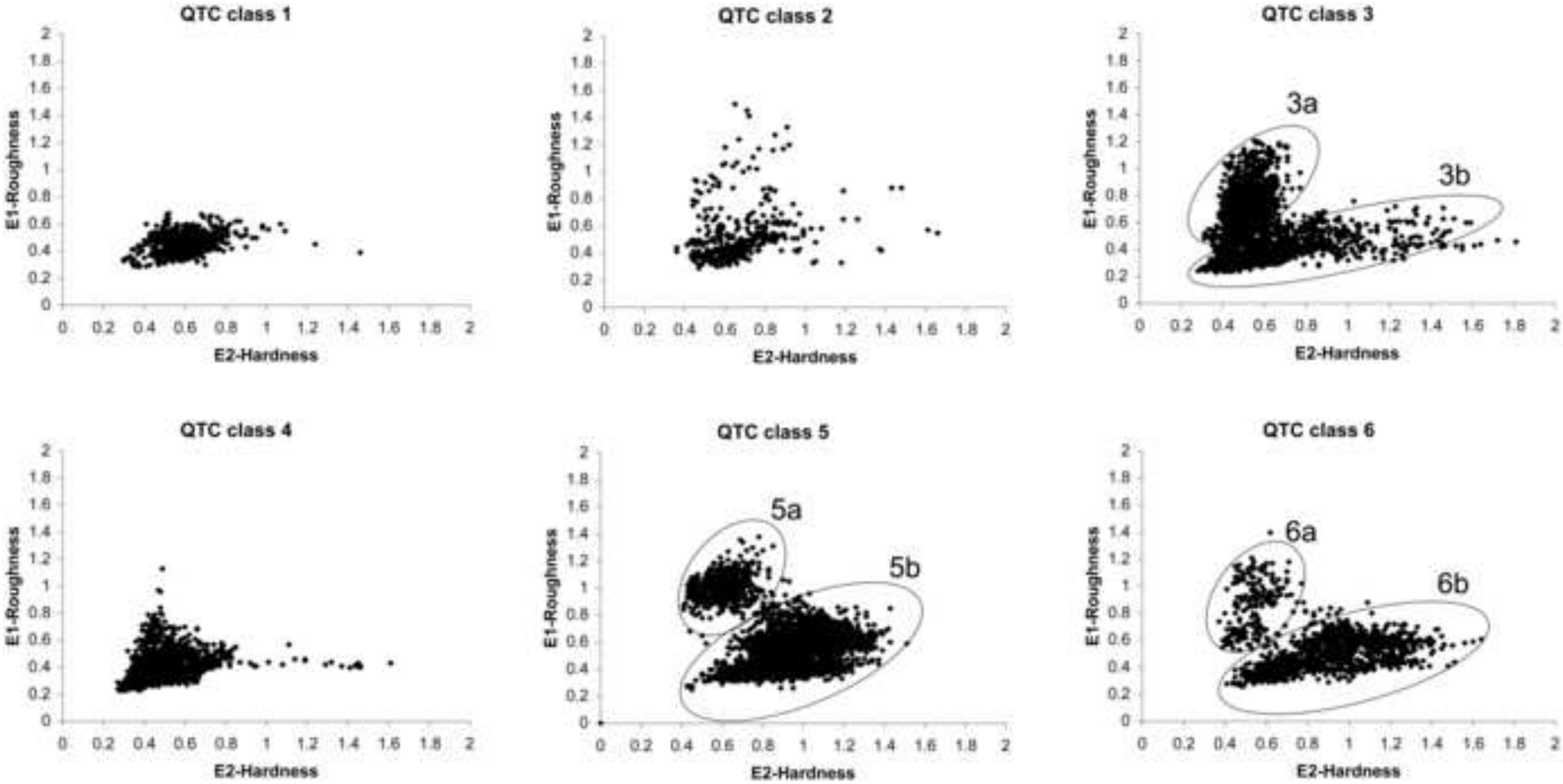

Hardness
1
2
3
4
5
Roughness
1
2
3
4
Newtonhill
Stonehaven
Catterline
Reef 1
Reef 2
I
II
III
IV
V
VI
R
a
b
Latitude degrees
Longitude degrees
57.05
57.04
57.03
57.02
57.01
57
56.99
56.98
56.97
56.96
56.95
56.94
56.93
56.92
56.91
56.9
56.89
-2.24
-2.2
-2.16
-2.12
-2.08
-2.04

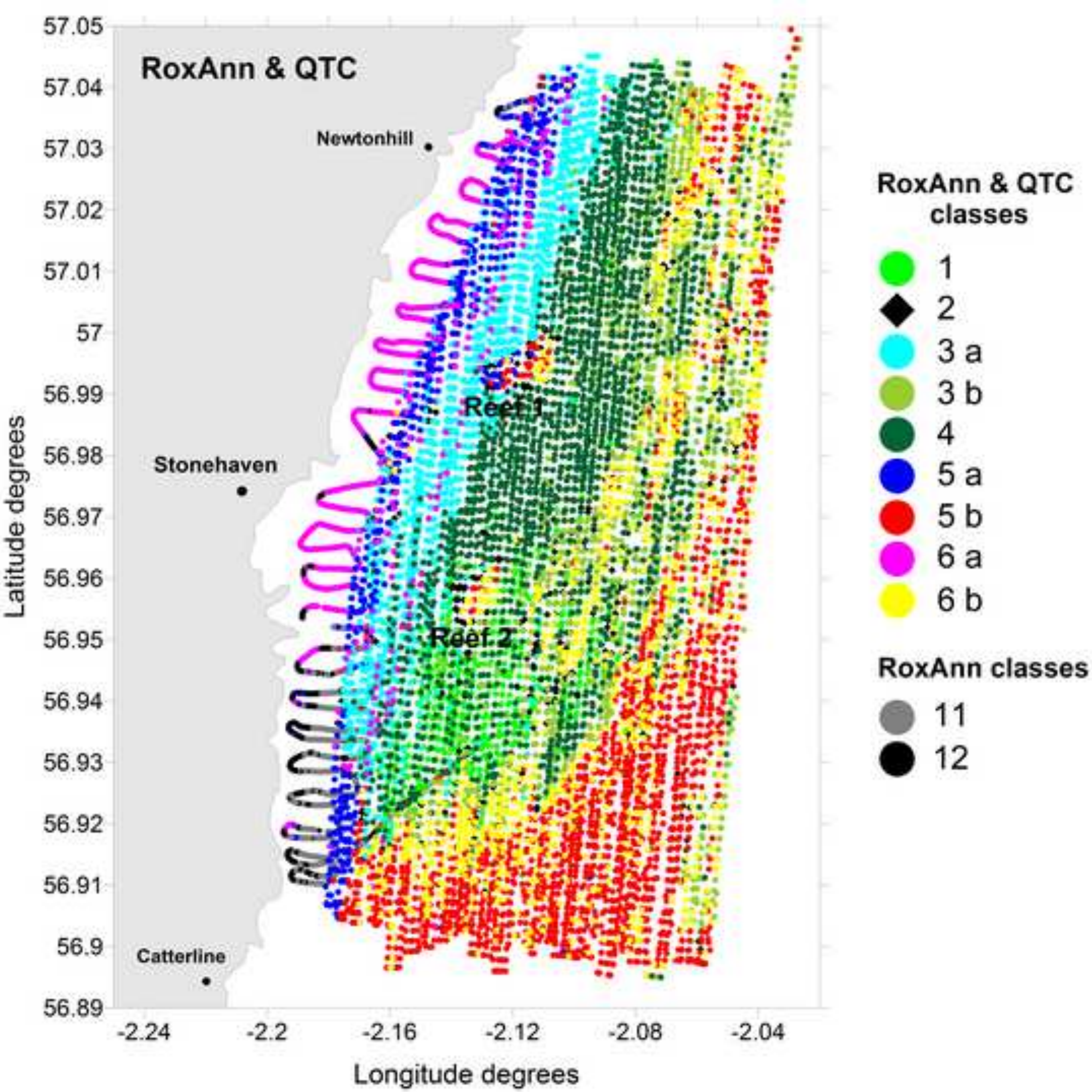

2D scatterplot
'Scotia' RoxAnn
'Clupea' RoxAnn
E1-Roughness
E2-Hardness
0.0
0.5
1.0
1.5
2.0
0.0
0.5
1.0
1.5
2.0

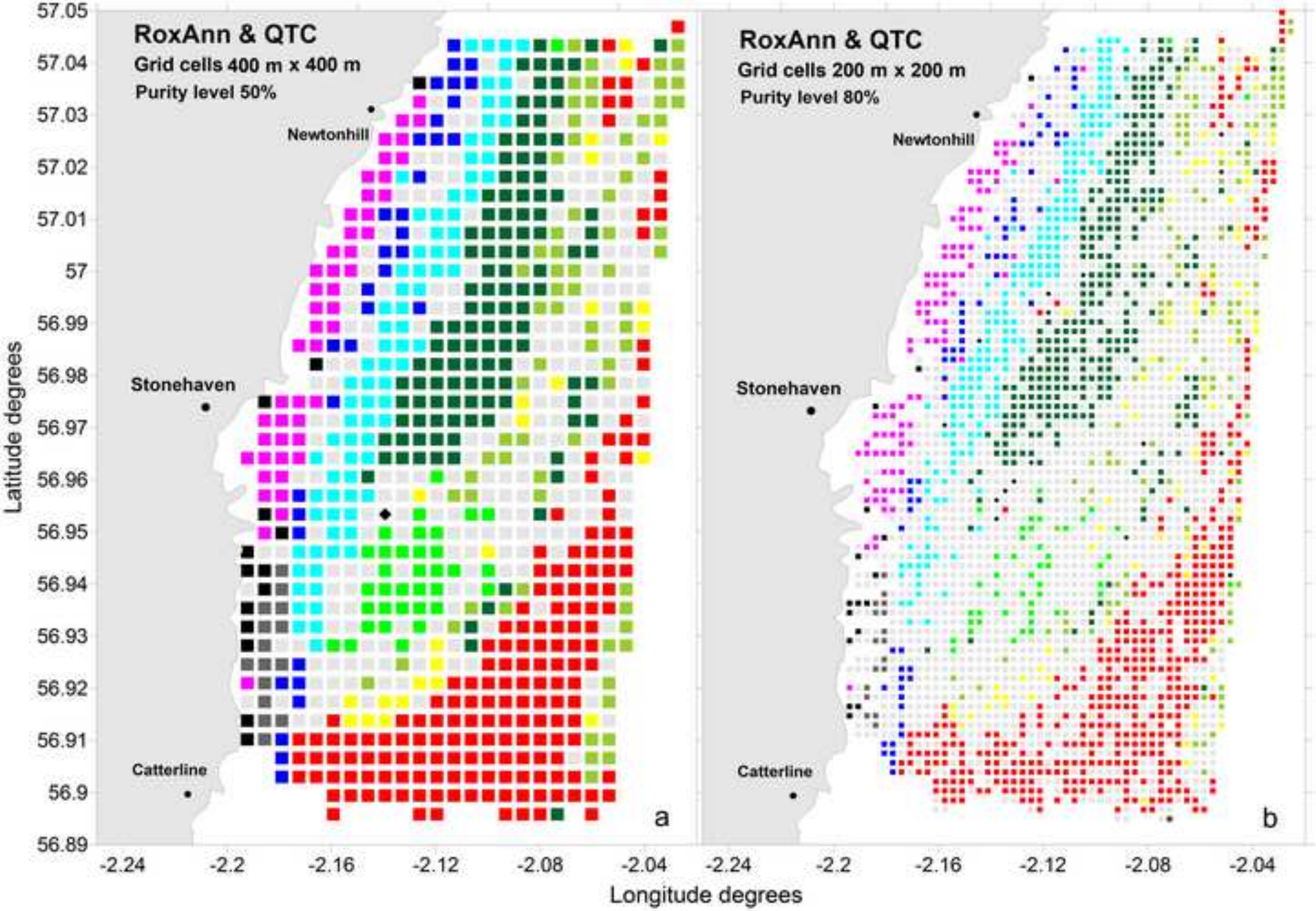

ID Stations against Roughness and Hardness


Entropy group against Roughness and Hardness


RoxAnn supervised
1
2
3
4
5
6
7
8
9
10
11
12
Newtonhill
Reef 1
Reef 2
Catterline
a
QTC 6 classes
1
2
3
4
5
6
Newtonhill
Stonehaven
Reef 1
Reef 2
Catterline
b
Latitude degrees
57.05
57.04
57.03
57.02
57.01
57
56.99
56.98
56.97
56.96
56.95
56.94
56.93
56.92
56.91
56.9
56.89
-2.24
-2.2
-2.16
-2.12
-2.08
-2.04
-2.24
-2.2
-2.16
-2.12
-2.08
-2.04
Longitude degrees


QTC class 1
QTC class 2
QTC class 3
3a
3b
QTC class 4
QTC class 5
5a
5b
QTC class 6
6a
6b
E1-Roughness
E2-Hardness
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


RoxAnn & QTC
Newtonhill
Stonehaven
Catterline
Reef 1
Reef 2
57.05
57.04
57.03
57.02
57.01
57
56.99
56.98
56.97
56.96
56.95
56.94
56.93
56.92
56.91
56.9
56.89
Latitude degrees
-2.24
-2.2
-2.16
-2.12
-2.08
-2.04
Longitude degrees
RoxAnn & QTC classes
1
2
3 a
3 b
4
5 a
5 b
6 a
6 b
RoxAnn classes
11
12


RoxAnn & QTC
Grid cells 400 m x 400 m
Purity level 50%
RoxAnn & QTC
Grid cells 200 m x 200 m
Purity level 80%
Newtonhill
Stonehaven
Catterline
a
b
Latitude degrees
Longitude degrees
57.05
57.04
57.03
57.02
57.01
57
56.99
56.98
56.97
56.96
56.95
56.94
56.93
56.92
56.91
56.9
56.89
-2.24
-2.2
-2.16
-2.12
-2.08
-2.04

Figure(s)

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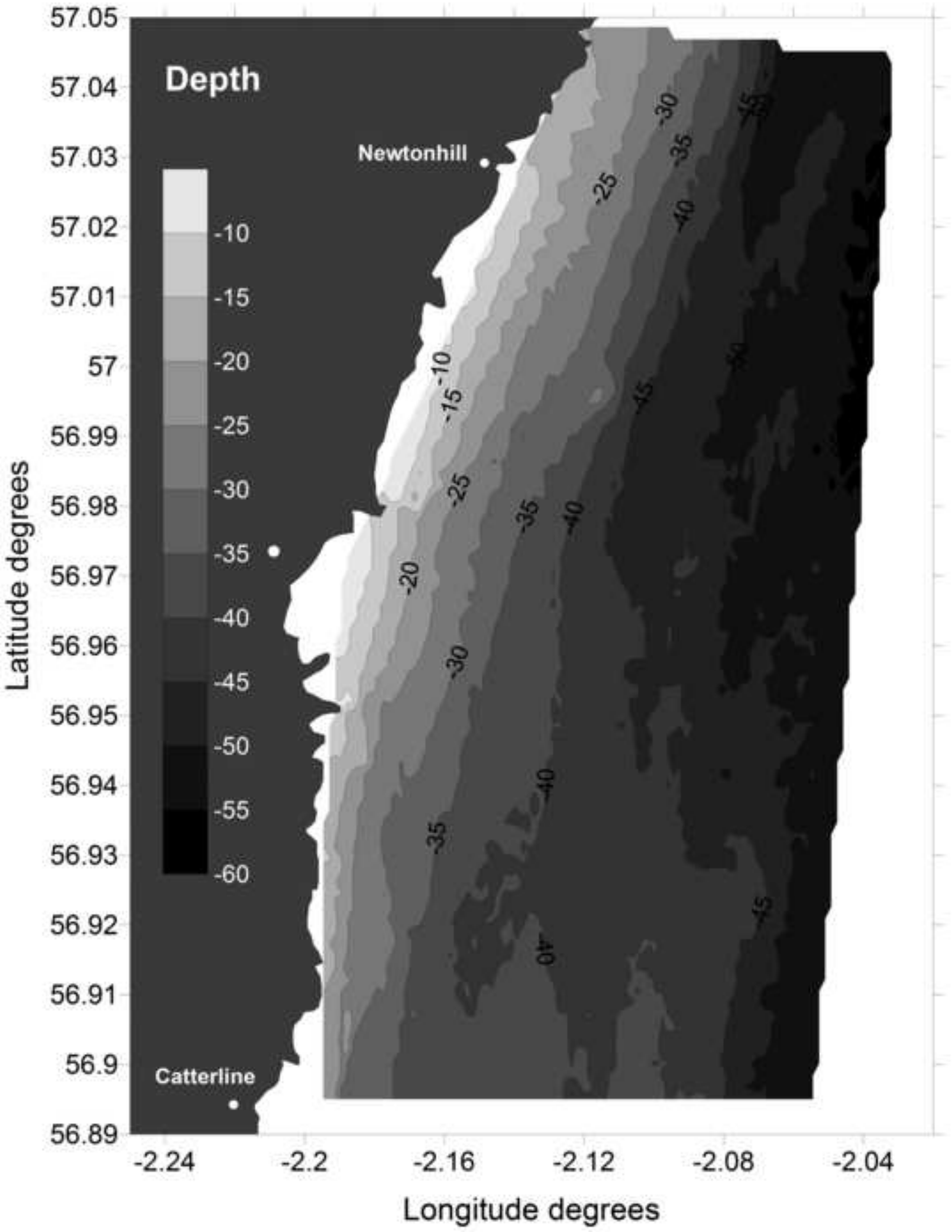

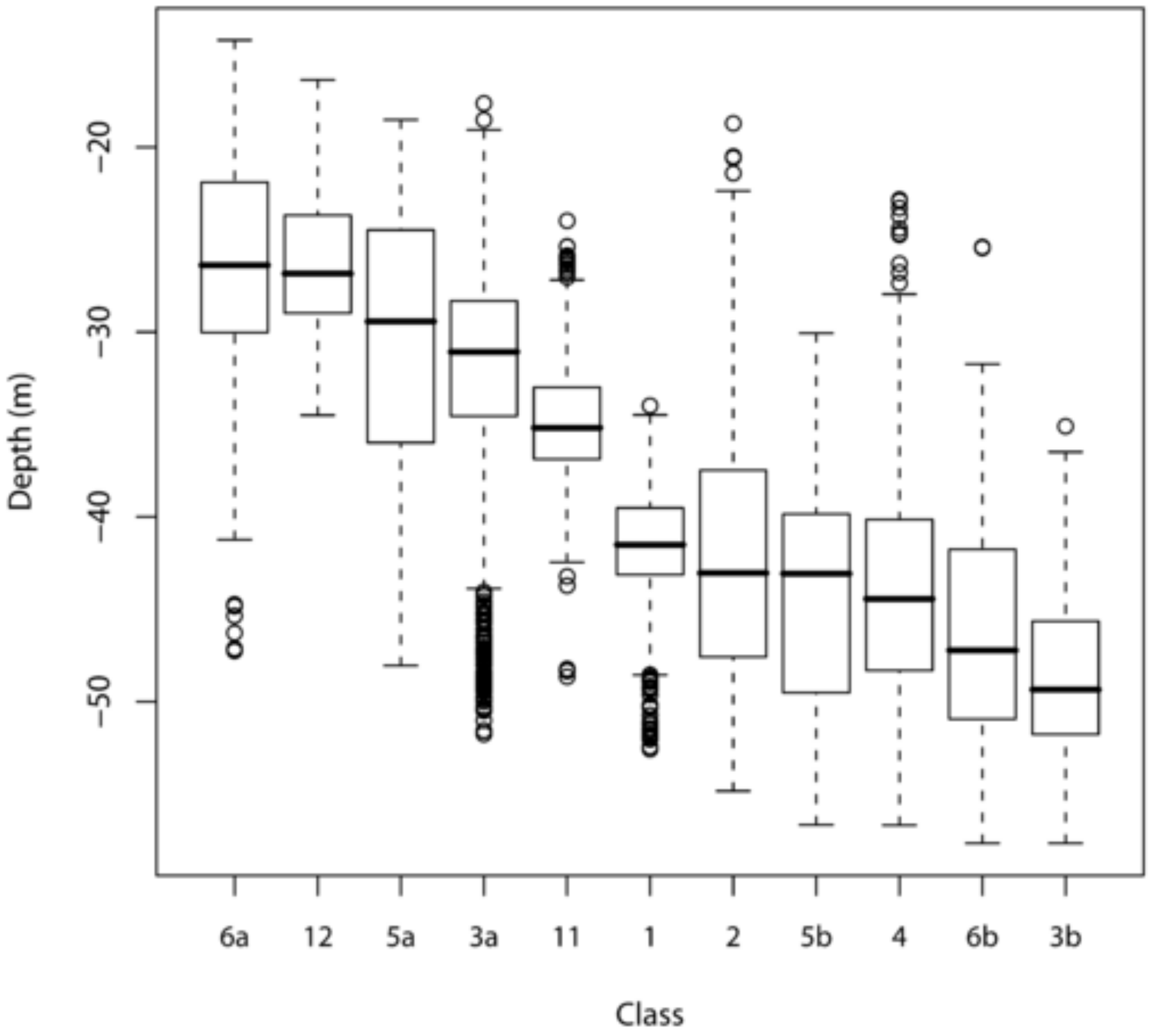
Depth (m)
−20
−30
−40
−50
6a
12
5a
3a
11
1
2
5b
4
6b
3b
Class