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Single-beam acoustic ground discrimination of shallow water habitats: 50 kHz or 200 kHz frequency survey?

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Abstract

The single-beam acoustic ground discrimination system QTC View, Series V, was used in the Bay of Cadiz, Southwest Spain, for the identification and mapping of the bottom acoustic diversity. The acoustic data were obtained through two successive surveys, each conducted with one of the following echo sounder frequencies: 50 kHz and 200 kHz. The performance of each survey frequency for the identification of the sedimentary gradients was analyzed. The surveys were conducted during high tide given that the majority of the surveyed area is shallower than 5 m, although depth may occasionally reach 20 m in specific areas located in a navigation channel. The acoustic data obtained at the two different frequencies were, individually, submitted to manual clustering and a final solution consisting of three acoustic classes was reached for both datasets. However, only the geographical distribution of the acoustic classes obtained with 50 kHz echo sounder frequency was coincident with the spatial distribution of the superficial sediment groups (silty medium sand, very silty fine sand and mud), identified through multivariate analysis of the grain-size data of ground-truth sediment samples. The results obtained with the 200 kHz echo sounder frequency did not match the sedimentary gradients obtained for the area surveyed, not even the separation of muddy and sandy areas.

Keywords: acoustic seabed classification; sediment types; echo-sounder frequency; QTC VIEW Series V; Bay of Cadiz; Spain

1. Introduction

Several studies using the single-beam acoustic seabed classification system QTC VIEW™ Series IV have revealed its ability to distinguish various bottom types and associate them with distinct acoustic properties. These works showed that the acoustic response may depend namely on the surface roughness, sediment grain size, the presence/absence of shell debris and some infaunal species, texture properties of the sediment and sediment porosity, while being independent of depth (Collins and Lacroix, 1997; Collins and Galloway, 1998; Hamilton et al., 1999; Preston et al., 1999; Preston, 2001; Self et al., 2001; Anderson et al., 2002; Ellingsen et al., 2002; Freitas et al., 2003a,b, 2005, 2006). In comparison with the traditional point sampling techniques, besides its non-intrusive properties, this acoustic system has the advantage of collecting data almost continuously and thus sample seabeds that could otherwise be missed by point data.

Nevertheless, the employment of this acoustic system (QTC VIEW, Series IV) is limited to survey depths ranging from 10 to 500 m. Although most studies would not use this type of equipment to exploit deeper areas, its use in waters shallower than 10 m is in much more demand, namely due to the portability of the whole system and its ability to be deployed from very small boats. For such situations, the QTC VIEW™ Series V was developed, enabling seabed classification in less than 1 m of water (QTC VIEW Series V User Manual, 2004). Moreover, in comparison with the Series IV, Series V has the capability of full echo-length data logging

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and real-time echo trace viewer, thus providing adequate quality assurance during data acquisition.

Up to the present, few works have been done with this new equipment and, in addition, some of them revealed no successful or limited results. Riegl et al. (2005a,b), in the Indian River Lagoon (Florida, USA), showed that the acoustic system QTC VIEW V was capable, within limits, not only of differentiating sediment types but also to detect algae and seagrass. In a study conducted in the Arabian Gulf (Dubai, UAE), Riegl and Purkis (2005), showed that the same acoustic system was a useful complementary tool to remote-sensing observations, revealing to be able to produce maps of outlining coral areas in adjacent deeper areas beyond optical resolution with the limitation that acoustic maps will resolve fewer habitat classes and have lower accuracy. Moyer et al. (2005), working in Broward County (South Florida, USA) showed that the same system was able to accurately sense the spatial extend of three different coral reef communities while no evidence of depth-contamination on the acoustic data was found. On the other hand, Hutin et al. (2005), using the same acoustic system to remotely detect a scallop bed in the St. Lawrence Estuary (Québec, Canada) showed that it failed not only to discriminate the sediment pattern, but also to highlight the biological assemblages that characterise the surveyed area. Moreover, the acoustic classifications obtained by those authors showed to be significantly related to bottom depth. Preston et al. (2006), reported the effectiveness of the same acoustic system to detect seaweed and seagrass beds, whereas Gleason et al. (2007), surveying an area near Carysfort Reef, Florida (USA), indicated that this ground discrimination system was able to distinguish between hard bottom and sediment areas and, thus, the acoustic system revealed to be a potential useful tool for the identification and mapping of the grouper habitat.

With the exception of the works by Riegl et al. (2005a,b) and Riegl and Purkis (2005), in the Indian River Lagoon, none of the previously mentioned studies were conducted exclusively in less than 10 m of water. The scarcity of such type of studies relies in the fact that bottom classification from such shallow areas are challenging for several reasons, namely the need of a sampling rate fast enough to capture the details in very short echoes, the requirement of a remarkable dynamic range to capture larger amplitudes of such shallow echoes, and the avoidance of the clipping phenomenon between the outgoing pulse and the incoming echo, the risk of which will be higher in a shallower depth (Preston and Collins, 2000).

The present study analysis the performance of the acoustic system QTC VIEW Series V to identify the seabed habitats in a shallow water system, the Inner Basin in the Bay of Cadiz, SW Spain, the depth of which is shallower than 5 m, except in the navigation channels, characterized by turbid water and a mixture of macroalgae and phanerogams covering extensive bottom areas (Rueda and Salas, 2003). Two different echo sounder frequencies, 50 kHz and 200 kHz, were used in successive surveys and their results compared. All the above mentioned studies also used either one or both survey frequencies, but none was specifically concerned with their comparison and usefulness to attain the desired objectives.

2. Materials and methods

2.1. Study area

The acoustic survey covered the entire Inner Basin of the Bay of Cadiz, located in Southwest Spain, between 36° 23′–36° 37′N Latitude and 6° 8′–6° 15′W Longitude (Fig. 1). As described by Rueda and Salas (2003), the Bay of Cadiz comprises the Inner Basin, mostly very shallow but occasionally reaching up to 20 m depth in the navigation channel, and the Outer Basin, with maximum depth of 17 m. The Outer Basin is highly exposed to waves, winds and tidal currents, and is characterized by sandy sediments with significant gravel and sand content (Carrasco et al., 2003). The Inner Basin is less exposed, but is strongly influenced by tidal currents. The bottom is dominated by muddy sediments and almost entirely covered by the macroalgae *Caulerpa prolifera* and the seagrass *Cymodocea nodosa* (Carrasco et al., 2003; Rueda and Salas, 2003).

2.2. Sampling

2.2.1. Acoustic data

The acoustic data was obtained with the acoustic system QTC VIEW Series V aboard a small boat (approximately 4 m). Two consecutive surveys were undertaken in the same area, using 50 kHz and 200 kHz echo sounder frequencies. The vessel trajectory for both surveys is shown in Fig. 2. In

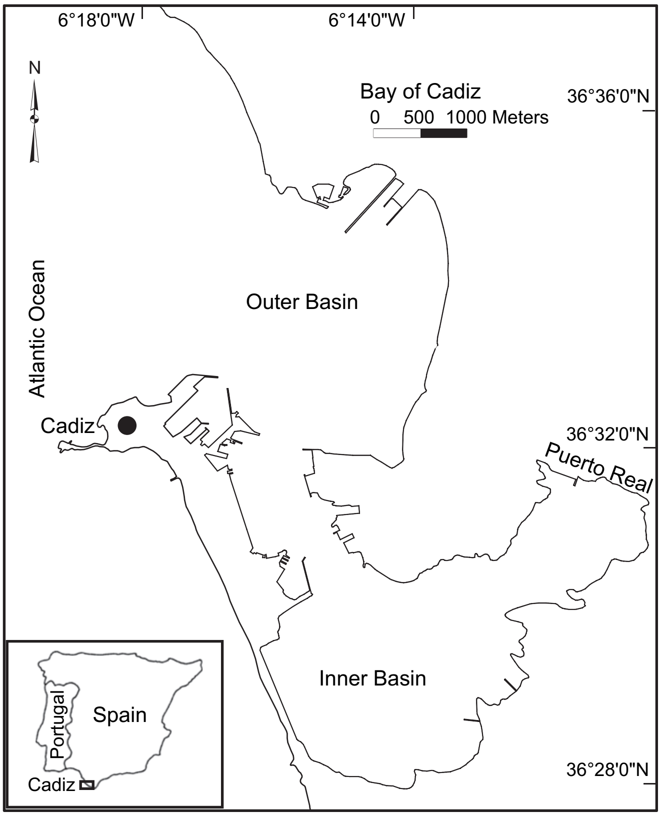

Fig. 1. Study area: the Bay of Cadiz (Outer and Inner Basins), Southwest Spain.

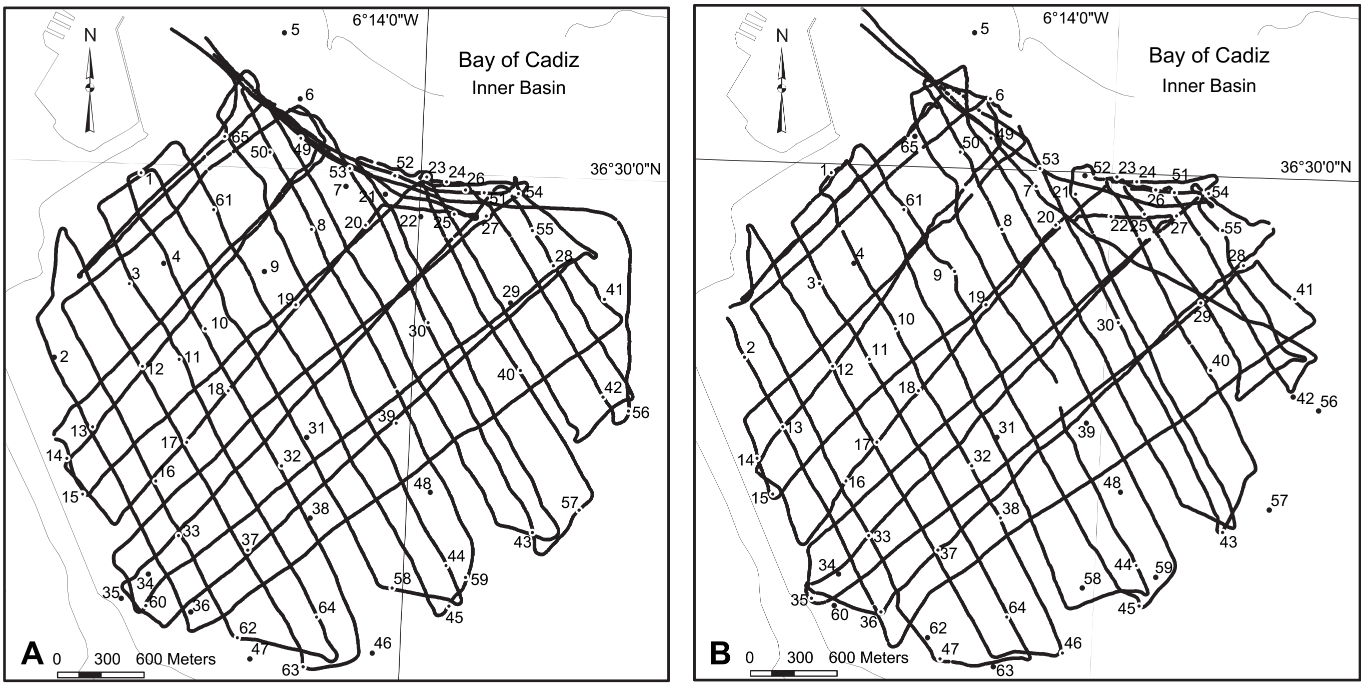

Fig. 2. Study area showing the acoustic survey lines, using 50 kHz (A) and 200 kHz (B) echo sounder frequencies, and the sampling sites for the study of superficial sediments.

both cases, the acoustic seabed classification system was connected to a Suzuki ES-2025 echo sounder. The transducer was mounted at the side of the boat and the survey speed did not exceed 6 Knots. The echo sounder and QTC VIEW settings for both surveys are given in Table 1. A differential Global Position System (GPS) acquired the positioning, which was logged continuously along with the acoustic data. The acoustic system includes a computer for data acquisition, display and storage.

2.2.2. Sedimentary data

Sediment samples for ground truth were collected at 65 sites with an Ekman grab (with unit sampling area of approximately 0.03 m^2), after the acoustic surveys were completed (cf. Fig. 2). The sampling sites were positioned as close as possible to the survey lines and spread over the entire survey area in order to cover as much as possible the whole range of distinct echoes.

2.3. Laboratory analysis

The sediment grain-size analysis was performed by wet and dry sieving, using the following major procedures (Quintino et al., 1989): (1) chemical destruction of organic matter with H_2O_2; (2) measurement of the total sediment dry weight, followed by chemical dispersion with tetra-sodium pyrophosphate (30 g/l) and wet sieving through a 63 μm mesh screen; (3) measurement of the second dry weight of the material left on the 63 μm mesh screen; and (4) dry sieving of the sand fraction (particles with diameter from 63 μm to 2 mm) and the gravel fraction (particles with diameter above 2 mm), through a battery of sieves spaced at 1 ϕ size intervals ($\phi = -\log_2$ the particle diameter expressed in mm). The silt and clay fraction (fine particles, with diameter below 63 μm) was expressed as a percentage of the total sediment (dry weight).

Table 1
Survey base settings for the echo sounder (Suzuki ES-2025) and the QTC VIEW Series V, for both survey frequencies. AGC = Automatic Gain Control

Parameter		Survey frequencies	
		50 kHz	200 kHz
Echo sounder	Beam width	24°	9°
	Transmit power	100 Watt	100 Watt
	Pulse duration	300 μs	300 μs
	Ping rate	5 per s	3 per s
QTC VIEW	Base gain	AGC	AGC

2.4. Data analysis

2.4.1. Acoustic classes

The acoustic signal generated by the echo sounder travels through the water column, reflects from the seafloor and the QTC VIEW Series V software acquires the first returning echo. The system contains a head amplifier that applies to the received signal both the Time Varying Gain (TVG) to compensate for absorption and spreading of the signal in the water column, and the Automatic Gain Control (AGC), which ensures that the echo signal stays within the dynamic range of the acquisition system (QTC VIEW Series V User Manual, 2004). The analogue waveform output from the QTC VIEW head amplifier is then digitized and recorded using a 5 MHz analogue to digital card installed in the data acquisition computer. Positions and times are also logged, along with system information such as AGC gains. Each echo is logged as a full-waveform time series (modulated carrier) and as an envelope, in qtc5fwf_raw and qtc5env_raw files respectively. Both have been down-sampled from the original sample rate. The envelopes were first formed using the Hilbert Transform (Preston and Collins, 2000) and then further down-sampled as part of a process to compensate the echoes for depth changes (Preston et al., 2007). The water depth must be known for compensation, that is, the echoes must have been picked, and should not be repicked later in the classification process. Using QTC IMPACT™ v3.4 software, the output files generated by the QTC VIEW (FWF and ENV files) were classified. In this study we used the qtc5fwf_raw and the qtc5env_raw files for, respectively, the 200 kHz and 50 kHz echo sounder frequency datasets analysis. Within QTC IMPACT the 200 kHz envelope dataset was created using the "Generate Envelope Dataset" feature.

The first step in classification is stacking consecutive echoes to reduce the consequences of ping-to-ping variability (Moyer et al., 2005). Stacking is the process of aligning echoes by their bottom picks and adding them in groups (groups of 5 in this work). Dividing the sum by 5 is an unnecessary step. The stacked echoes are submitted to a series of algorithms resulting in 166 variables (the Full Feature Vectors, FFV) that characterise each stacked echo. The dataset of all stacked echoes described by their 166 variables is then submitted to Principal Component Analysis (PCA), producing, for each echo, a reduced description consisting of three values (Q1, Q2, Q3) that correspond to the coordinates of the three first PCA axes. At the end, each stacked echo is represented by a single point in a three-dimensional diagram (Q-Space), at coordinates determined by the shape of the echo (QTC IMPACT User Manual, 2004). Finally, the "cloud" of points in Q-Space that characterises the acquired acoustic information is divided into acoustic classes, using a clustering procedure. Echoes from similar bottom types tend to form a cluster and each different cluster corresponds to a different acoustic class. The positions of the clusters in the Q-space indicate how acoustically similar are the seabed they represent.

Both acoustic datasets (50 kHz and 200 kHz) were classified with Manual Clustering, available within QTC IMPACT™. With this process, the QTC file is classified into the number of acoustic classes that best characterise the acoustic diversity of the study area. Manual cluster uses iterative *k*-means clustering algorithms that attempt to find the optimal number of clusters as well as the optimal assignment of points into those clusters. Initially a single class, or cluster, is displayed. This is then split along either the primary, secondary, or tertiary axis of its distribution in Q space, and the new clusters can then be assessed with several descriptors which help the user to decide how further divide the dataset. One of these descriptors is Total Score which is the sum of the scores (a product of the number of members or individuals in each cluster and its variance) of each cluster. Each score indicates how well that cluster's distribution conforms to a Gaussian along each axis. As the splitting process proceeds, Total Score decreases. By plotting the Total Score against the number of splits, the point of inflection in the resulting curve indicates the optimal splitting level (QTC IMPACT User Manual, 2004). Beyond the inflection point indicates over-splitting. A complementary indication of the optimal split level is given by the Cluster Performance Index rate which measures the ratio of the distance between the cluster centres to the extent of the clusters in Q-Space, and tends to be maximal at the optimal split level (Kirlin and Dizaji, 2000). CPI rate is obtained by calculating the change in CPI from one split to the next:

$$\text{CPI rate} = \frac{\text{CPI}(n) - \text{CPI}(n-1)}{\text{CPI}(n-1)}$$

The optimal number of splits is indicated by the greatest rate of change in CPI from one split to the next. The splitting process proceeds as long as the results of splitting improve the overall statistical description of the clusters.

Although important for the final classification result, these two descriptors must be taken as indicators, as it is acknowledged that the Total Score inflection point does not always coincide with the maximum CPI rate. Also, as with any other classification procedure, the final number of classes should also consider on how interpretable they are through ground-truth data, and finally, the mismatch between crossing survey tracks was used as an additional indicator of over-splitting.

The final acoustic solution files were imported into a geographical information system environment (Arc View v8.1, Minami, 2000) in order to produce maps of acoustic diversity.

2.4.2. Validation of the acoustic classes

For each site, the amount of sediment in each grain-size class (in mm: >2; 1–2; 0.5–1; 0.25–0.5; 0.125–0.25; 0.063–0.125; <0.063) was expressed as a percentage of the whole sediment, dry weight. These results were used to calculate the median value, P_{50}, expressed in phi (ϕ) units, corresponding to the diameter that has half the grains finer and half coarser. The grain-size classes and the median data were used in the validation of the acoustic classes. For the validation procedure, the sediment samples were divided into groups of samples representing the acoustic classes. This was visually appreciated in a GIS environment, by representing the sediment samples on top of the acoustic diversity and assigning a sediment sample to a given acoustic class only if its geographical position could be attributed to that acoustic class. The groups of sediment samples representing the acoustic classes were then tested for statistical differences, under the null hypothesis that there is no significant difference between the groups. This test was conducted with the sediment groups representing the acoustic classes obtained with both survey frequencies and was performed with the one-way multivariate ANOSIM procedure (Clarke and Warwick, 2001), in PRIMER v6 (Clarke and Gorley, 2006). ANOSIM (Analysis of Similarities) is a non-metric multivariate hypothesis testing procedure, based in the calculation of the statistic *R*, which relates the within to the between group distances, in a triangular distance matrix between sediment samples. The triangular [sites × sites] distance matrix was obtained by calculating the normalized Euclidean distance between every pair of sediment samples. The *R* statistic varies from −1 to +1 and approaches the value 0 when the null hypothesis is true (no detectable differences among the groups). R presents the value $+1$, rejecting the null hypothesis, when all the distance values between groups are larger than all the within groups distances, indicating that the difference between samples from different groups is always larger than that between samples of the same group. R will present the value -1 in the opposite situation (in practice, R lies mainly between 0 and $+1$ and although may present negative values, these are never close to -1). The R value from the global test and the pair-wise tests is accompanied by a significance value obtained by calculating the probability of the true R value against a series of R values obtained after a permutation procedure (Clarke and Warwick, 2001).

2.4.3. Sedimentary gradients

The sediment data matrix, including for each site the seven grain-size classes and the median, was also analysed by classification and ordination analysis in order to identify spatial patterns in the superficial sediment types. The [sites × sites] normalized Euclidean distance matrix was submitted to classification analysis using the average-clustering algorithm and to ordination analysis using non-metric multidimensional scaling (NMDS, Clarke and Gorley, 2006). The sedimentary affinity groups identified were characterised and reported on top of the acoustic diversity maps, using a GIS environment. The NMDS diagrams are accompanied by a stress value which quantifies the mismatch between the distances among data points in the Euclidean distance matrix and in the ordination diagram. Ordination diagrams with stress value below 0.10 are considered to represent very accurately the original distance matrix (Clarke and Warwick, 2001). Finally, the median and the percent content of fines (particles with diameter below 63 μm) were used to classify the sediment according to the Wentworth scale (Table 2). The final sediment classification adopted the description "clean", "silty" or "very silty", for those samples with a silt and clay fraction ranging from 0% to 5%, from 5% to 25% and from 25% to 50%, respectively, of the total sediment, dry weight (Doeglas, 1968; Larsonneur, 1977).

3. Results

3.1. Acoustic classes

The majority of the survey occurred in shallow water, with exception of the navigation channel. Almost 90% of the area sampled with the acoustic system is located in depth up to 5 m (Fig. 3). The minimum water depth that could be safely sampled was close to 2 m, due to the presence of macrophytes.

Table 2
Sediment classification, adapted from Wentworth (Doeglas, 1968) and Larsonneur (1977). (Φ (phi) $= -\log_2 x$, being x expressed in mm)

Median (Φ)	Sediment classification		Fines content (%)		
			<5	5–25	25–50
(−1)–0		Very coarse			
0–1		Coarse			
1–2	Sand	Medium	Clean	Silty	Very silty
2–3		Fine			
3–4		Very fine			
≥4	Mud		Above 50%		

The results of the acoustic classification with both echo sounder frequencies are shown in Table 3. According to the CPI rate, the optimal classification for both frequencies corresponds to the second split (three acoustic classes), where this descriptor presents its maximum value. Concerning the Total Score, the values diminish as splitting occurs, more abruptly initially, but never reach an inflection point, thus not giving a coherent indication about the optimal split level. In this way, we decided to accept as optimal acoustic classification 3 acoustic classes for both frequencies, as suggested from the CPI rate approach. Also, for both frequencies, an increasing mismatch between the acoustic classes at the intercept point of the survey lines was observed when more than 3 acoustic classes were considered, thus indicating undesirable noise in the classification result. The geographic distribution of the three acoustic classes obtained for both frequencies is shown in Fig. 4.

3.2. Validation of the acoustic classes

The ground-truth samples assigned to each acoustic class in both survey frequencies and the R values, with the associated statistical significance, obtained in the global and the pair-wise ANOSIM tests between the ground-truth groups of samples are given in Table 4. For the 50 kHz frequency, the global and the pair-wise test values are all statistically significant although only marginally in the comparison of the samples representing the acoustic groups B and C (cf. Table 4). For the 200 kHz frequency, neither the global R nor the pair-wise R values are statistically significant, indicating that the 200 kHz frequency is not related to the ground-truth sediment data, but to some other bottom characteristics.

Table 5 summarises the sediment characteristics of the 3 acoustic classes obtained with the 50 kHz survey frequency. Class A corresponds to sediments with mean fines (silt + clay) content close to 80%. From the 42 individual sediment samples assigned to this acoustic class (cf. Table 4), 4 do not conform to this description. These include 2 samples of very silty very fine sand (46% and 49% fines content and $P_{50} = 3.8\phi$ and 3.9ϕ respectively), one sample of silty fine sand (19% fines content and $P_{50} = 2.2\phi$) and one sample of clean medium sand (less than 1% fines content and $P_{50} = 1.6\phi$). The average sediment in the acoustic class B, according to the mean P_{50} and grain-size values given in Table 5, is at the borderline between a very silty, fine and very fine sand (43% mean fines content and $P_{50} = 3.0\phi$). From the 10 individual sediment samples used in the validation of this acoustic class, 6 fit this classification, 3 correspond to mud (more than 50% fines content) and one sample corresponds to silty medium sand (20% fines content and $P_{50} = 1.3\phi$). The average sediment in the acoustic class C is at the borderline between a very silty, medium and fine sand (29% mean fines content and $P_{50} = 2.0\phi$). From the 7 individual sediment samples used in the validation of this acoustic class, 6 correspond well to

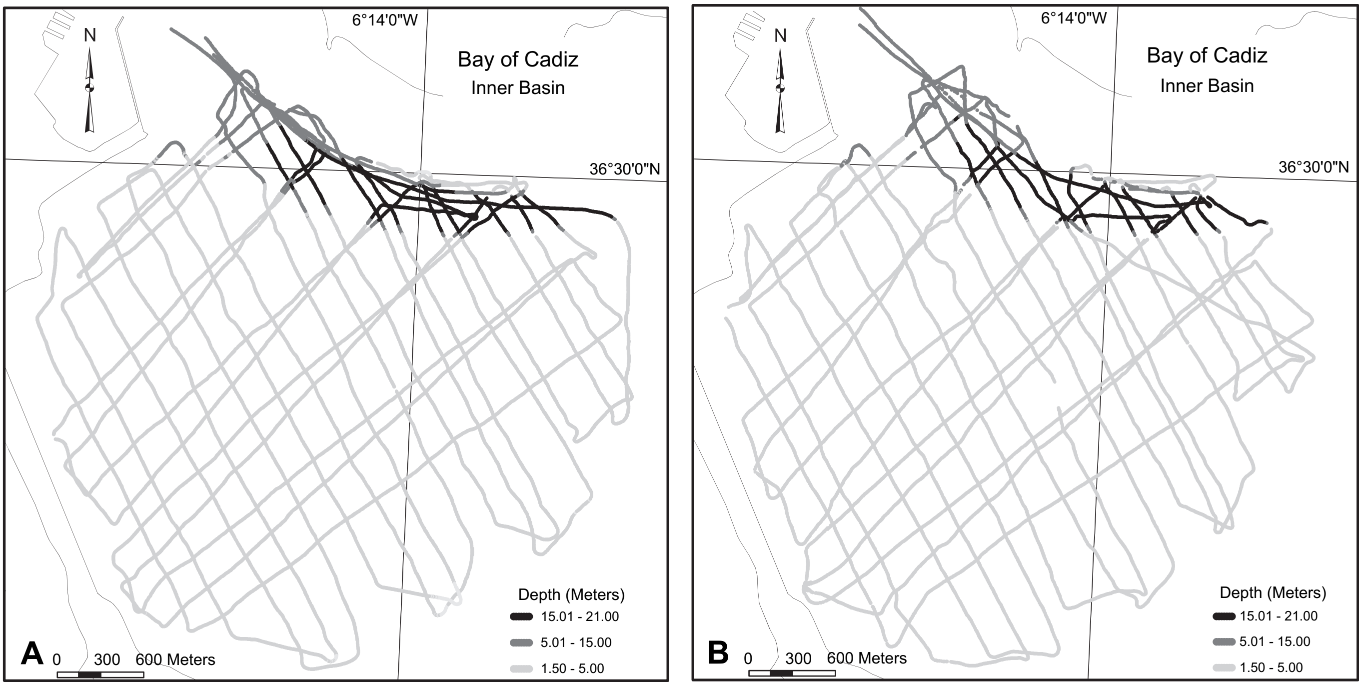

Fig. 3. Survey depth, as registered during data acquisition with both echo sounder frequencies (A = 50 kHz; B = 200 kHz). The survey was conducted during mid to high water.

this description, and one sample corresponds to very silty very fine sand (49% fines content and $P_{50} = 3.3\phi$).

Assigning the sediment ground-truth samples to the groups which represent the two initial acoustic classes, issued from the first acoustic split at both frequencies, and comparing the groups using the same one-way ANOSIM approach, showed no major difference from the previous results: the *R*-statistic and the associated significance presented the values 0.661 ($p < 0.0001$) and −0.013 ($p = 0.522$), for the comparison of the two groups of sediment samples representing the two initial acoustic classes obtained respectively with 50 kHz and 200 kHz. This indicates that the acoustic diversity obtained with the 200 kHz echo-sounder frequency totally failed to relate to the sedimentary ground-truth data even in very broad terms.

3.3. Sedimentary gradients

The multivariate analysis of the sediment data showed four affinity groups, as shown in the classification and ordination diagrams presented in Fig. 5. Table 6 summarises the grain-size and median characteristics of such groups. Groups A1 and A2 correspond to mud, with 67% and 87% fines content respectively. All the 28 sediment samples included in group A2 and 8 out of the 9 sediment samples included in group A1 agree to that description. Group A1 also includes one sample which corresponds to very silty very fine sand (46% fines content and $P_{50} = 3.8\phi$). The mean sediment sample in group B1 corresponds to silty medium sand (cf. Table 6). This group includes 9 sediment samples, 7 of which agree with this classification. The remaining 2 samples correspond to very silty fine sand (38% and 43% fines content, with $P_{50} = 2.2\phi$ and 2.4ϕ, respectively). The mean sediment sample in group B2 corresponds to very silty fine sand (cf. Table 6). This group includes 10 sediment samples, 6 of which agree to this description. The other 4 samples correspond to very silty very fine sand with mean 48% fines content and 3.7ϕ median value.

The sediment groups are represented on top of the acoustic diversity maps for both surveys frequencies in Fig. 6. Whereas no obvious match can be observed between the 200 kHz acoustic diversity map and the superficial sediment types (cf.

Table 3

Clustering results for the 50 kHz and 200 kHz echo sounder frequencies. Acoustic classification statistics, obtained up to the fifth split (six classes). Total score = sum of the scores of the individual classes; CPI = cluster performance index; CPI rate = [CPI(n) − CPI(n − 1)]/CPI(n − 1), where n is the split number

Split	Number of classes	50 kHz			200 kHz		
		Total score	CPI	CPI rate	Total score	CPI	CPI rate
0	1	1,224,226.01	–	–	1,020,816.06	–	–
1	2	255,268.44	2.62	–	118,007.03	1.82	–
2	3	208,194.21	15.49	4.91	90,976.84	12.16	5.68
3	4	118,979.68	46.94	2.03	78,422.94	23.56	0.94
4	5	101,920.20	95.93	1.04	60,853.34	32.93	0.39
5	6	68,454.13	124.46	0.29	53,214.13	47.65	0.45

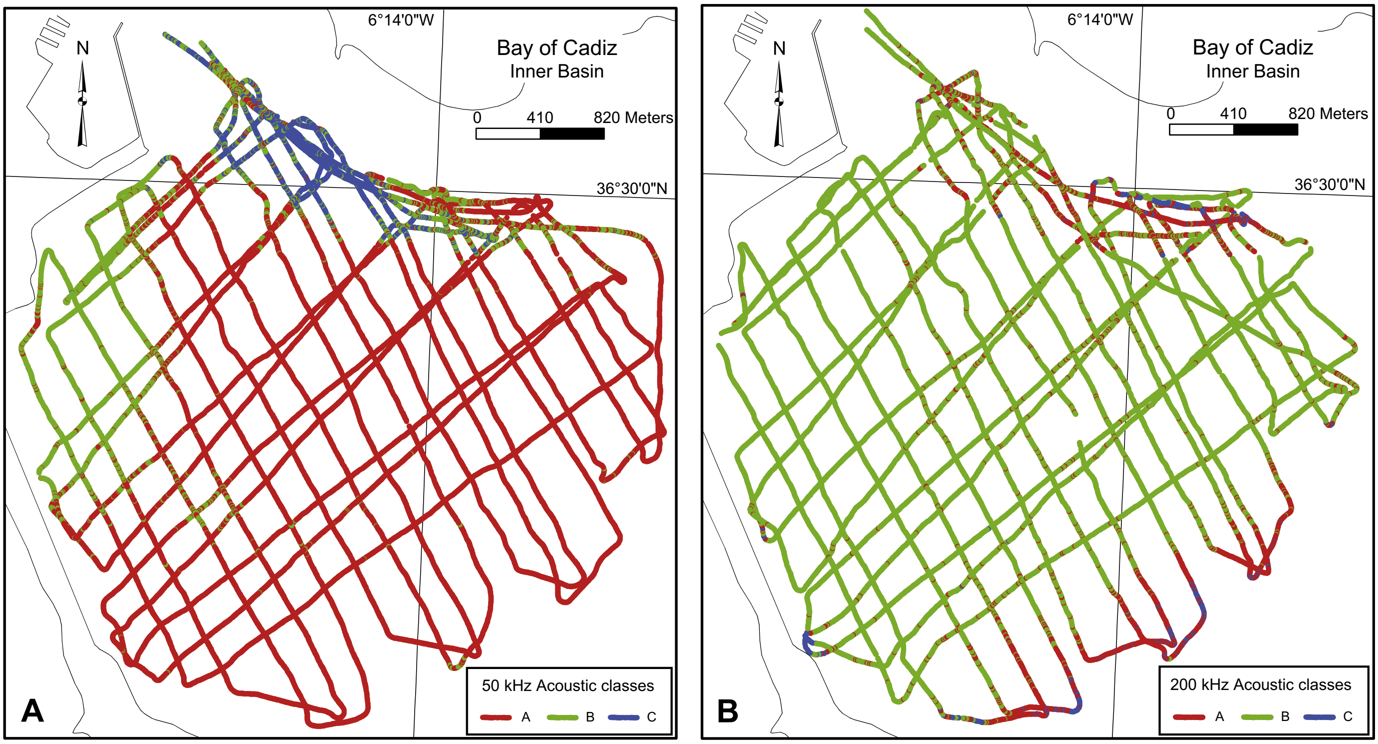

Fig. 4. GIS representation of the acoustic diversity at the Inner Basin, Bay of Cadiz, obtained with 50 kHz (A) and 200 kHz (B) echo sounder frequencies.

Fig. 6B), the 50 kHz acoustic diversity is closely related to the distribution of the sediment types showing that the acoustic classes captured the predominant sediment types (cf. Fig. 6A). The acoustic class A, the predominant class that covers all the central part of the Inner Basin, corresponds to mud (sediment groups A1 and A2). The acoustic class B, located on the upper south margin, and characterized by average sediment at the borderline between a very silty, fine and very fine sand corresponds well to the sediment group B2, identified as very silty fine sand. The acoustic class C, characterized by average sediment at the borderline between very silty, medium and fine sand, is located at the beginning of the navigation channel, in a high energy area, and corresponds to the area occupied by sediment group B1, silty medium sand.

The first split of the 50 kHz dataset creates two acoustic classes that mainly correspond to a separation between the mud and the sandy areas (figure not shown). The third acoustic class, obtained with the second split, corresponds to the separation of one of the previous classes (class B) into two classes (B and C) that are related with the separation within the sandy sediments (silty medium sand from very silty fine sand), indicating that only the detailed subdivision amongst the mud sediment samples (groups A1 and A2), couldn't be detected by the acoustic system surveying at 50 kHz. On the contrary, the acoustic diversity obtained with the 200 kHz echo-sounder frequency totally failed to relate to the sedimentary pattern even in very broad terms, i.e., was unable to distinguish the mud from the sand sediments.

4. Discussion

The acoustic ground discrimination system QTC View Series IV has been successfully used to discriminate superficial sediment types in many different areas, namely in the Portuguese coastal shelf (Freitas et al., 2003a,b, 2005, 2006). The recently developed acoustic system QTC View Series V extends to shallow water the survey abilities of this ground discrimination system, but has only seldom

Table 4
Global and pair-wise *R*-statistic values with associated significance, obtained in a one-way ANOSIM analysis of the sediment samples, assigned to groups according to the 50 kHz and 200 kHz acoustic classes

	R-statistic (associated *p* value)				Sediment samples in the acoustic classes		
	Global	A–B	A–C	B–C	A	B	C
50 kHz	0.655 (0.001)	0.575 (0.001)	0.821 (0.001)	0.191 (0.041)	4, 8–11, 15–20, 26, 28–44, 51, 52, 54–64	1, 2, 3, 12, 13, 22–25, 27	6, 7, 21, 49, 50, 53, 65
200 kHz	0.034 (0.289)	−0.039 (0.649)	0.096 (0.138)	0.150 (0.101)	7, 20, 22, 25, 42–45, 51–53, 55, 63, 64	1–4, 6, 8–19, 24, 28–34, 36–41, 47, 49, 50, 60–62, 65	21, 23, 26, 27, 35, 46, 54

Table 5
Mean values and associated standard deviations (std) for the grain-size and the median (P_{50}) data of the sediment samples included in the 3 acoustic classes obtained with the 50 kHz acoustic frequency

Acoustic classes		2.000 mm (%)	1.000 mm (%)	0.500 mm (%)	0.250 mm (%)	0.125 mm (%)	0.063 mm (%)	<0.063 mm (%)	P_{50} (ϕ)
A	Mean ($n = 42$)	3.84	1.84	1.32	2.21	5.81	5.74	79.24	>4
	std	4.065	1.976	1.559	4.560	8.991	5.717	20.365	–
B	Mean ($n = 10$)	13.55	5.11	5.59	11.47	14.60	6.33	43.35	2.98
	std	7.308	2.321	3.095	5.957	5.015	4.075	15.051	0.932
C	Mean ($n = 7$)	15.60	6.27	8.09	24.64	13.93	2.47	29.01	2.00
	std	8.920	2.531	3.843	15.253	4.218	2.031	13.756	0.690

been used and tested under such circumstances, the study by Riegl et al. (2005a,b) being one exception. In this work, the Series V equipment was used in the Inner Basin of the Bay of Cadiz, SW Spain, a shallow water system with turbid water and seabed dominated by muddy sediments covered with macroalgae and phanerogams, namely *Caulerpa prolifera* and *Cymodocea nodosa* (Carrasco et al., 2003; Rueda and Salas, 2003). Although the acoustic bottom classification on shallow areas is technically more demanding (Preston and Collins, 2000), this study revealed the ability of the acoustic ground discrimination system, to capture the main superficial sediment pattern and distinguish the sediment types that characterise this shallow water area. This result however was obtained only when surveying at 50 kHz. The acoustic diversity obtained at 200 kHz echo sounder frequency totally failed to identify the sedimentary pattern even in very broad terms, i.e., was unable to distinguish the mud from the sand sediments.

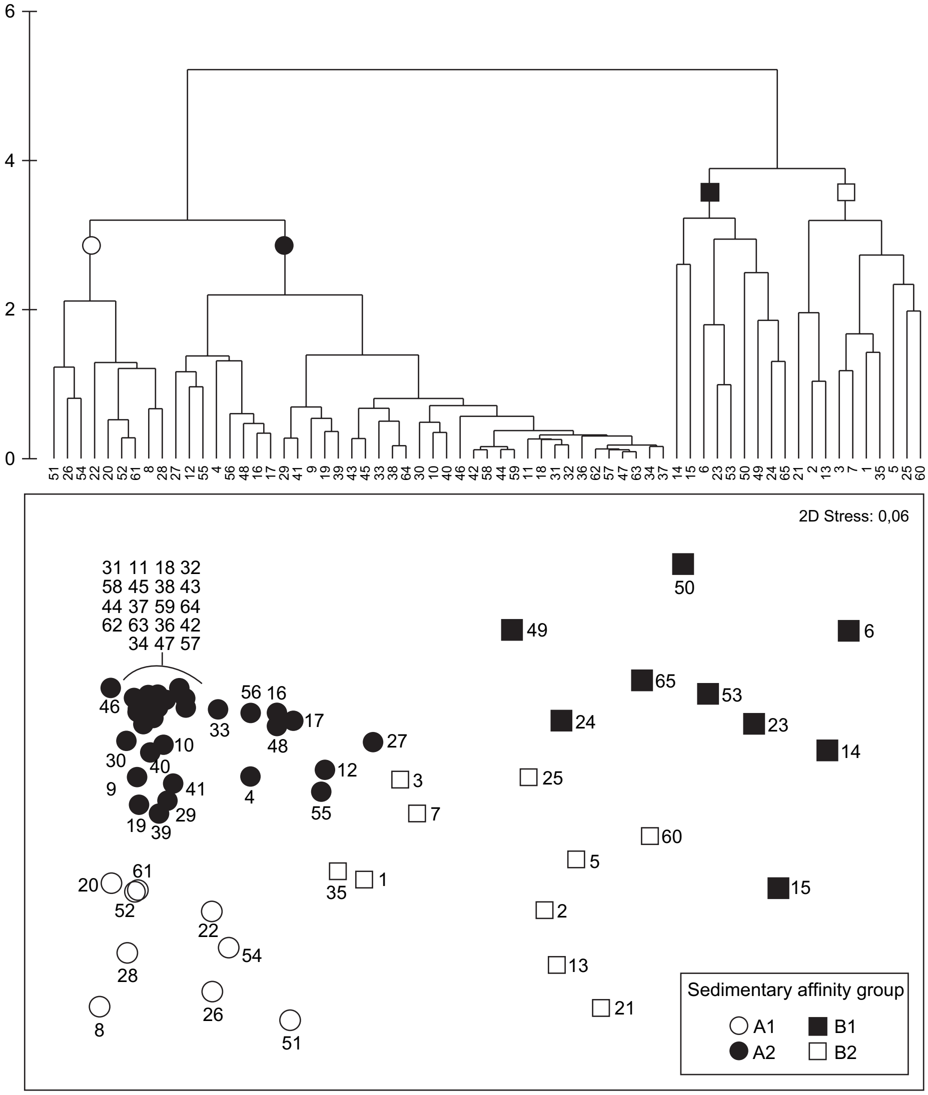

Fig. 5. Classification and ordination diagrams issued from the analysis of the sediment data, identifying the affinity groups A1, A2, B1 and B2.

Table 6
Grain-size and median mean values in the sediment groups, A1, A2, B1 and B2, identified by classification and ordination analysis

		Groups			
		A1	A2	B1	B2
Sampling sites		8, 20, 22, 26, 28, 51, 52, 54, 61	4, 9–12, 16–19, 27, 29–34, 36–48, 55–59, 62–64	6, 14, 15, 23, 24, 49, 50, 53, 65	1, 2, 3, 5, 7, 13, 21, 25, 35, 60
Gravel	>2.000 mm	1.96	3.97	14.00	15.36
Sand	1.000–2.000 mm	0.84	1.86	6.87	5.27
	0.500–1.000 mm	0.63	1.26	9.82	4.84
	0.250–0.500 mm	1.16	1.43	29.72	10.30
	0.125–0.250 mm	12.58	2.09	17.47	20.95
	0.063–0.125 mm	15.82	2.95	1.96	6.27
Fines	<0.063 mm	67.02	86.45	20.16	37.00
Median (Φ)		>4.0	>4.0	1.69	2.82
Sediment classification		Mud	Mud	Silty medium sand	Very silty fine sand

Overall, the results achieved with the present study are in agreement with those presented by Collins and Rhynas (1998), concerning acoustic seabed classification using different echo sounder frequencies. These authors indicated that lower echo sounder frequencies (up to 100 kHz) exhibit small signal losses in the water column, transmitting more energy into the seabed, leading the signal to penetrate deeper (tens of centimetres) into the seafloor and carry more information back to the transducer. Frequencies higher than 100 kHz suffer greater attenuation in the water column and therefore do not transmit as much energy into the seabed resulting in reduced penetration (few centimetres). In a situation, as in the present case, when the seabed is covered by underwater vegetation, this effect may eventually be enhanced, meaning that the lower energy frequency (50 kHz) will be more able to acquire information from the sediment. Therefore, if the two frequencies are "sampling" in different places relative to the vertical structure of the sediment water interface, the 50 kHz will acquire information from the sediment column while the 200 kHz may respond to a more superficial layer, eventually the underwater vegetation layer that covers the sediment. At this stage however it is not possible to relate the 200 kHz acoustic pattern to known habitat properties in the Inner Basin of Cadiz.

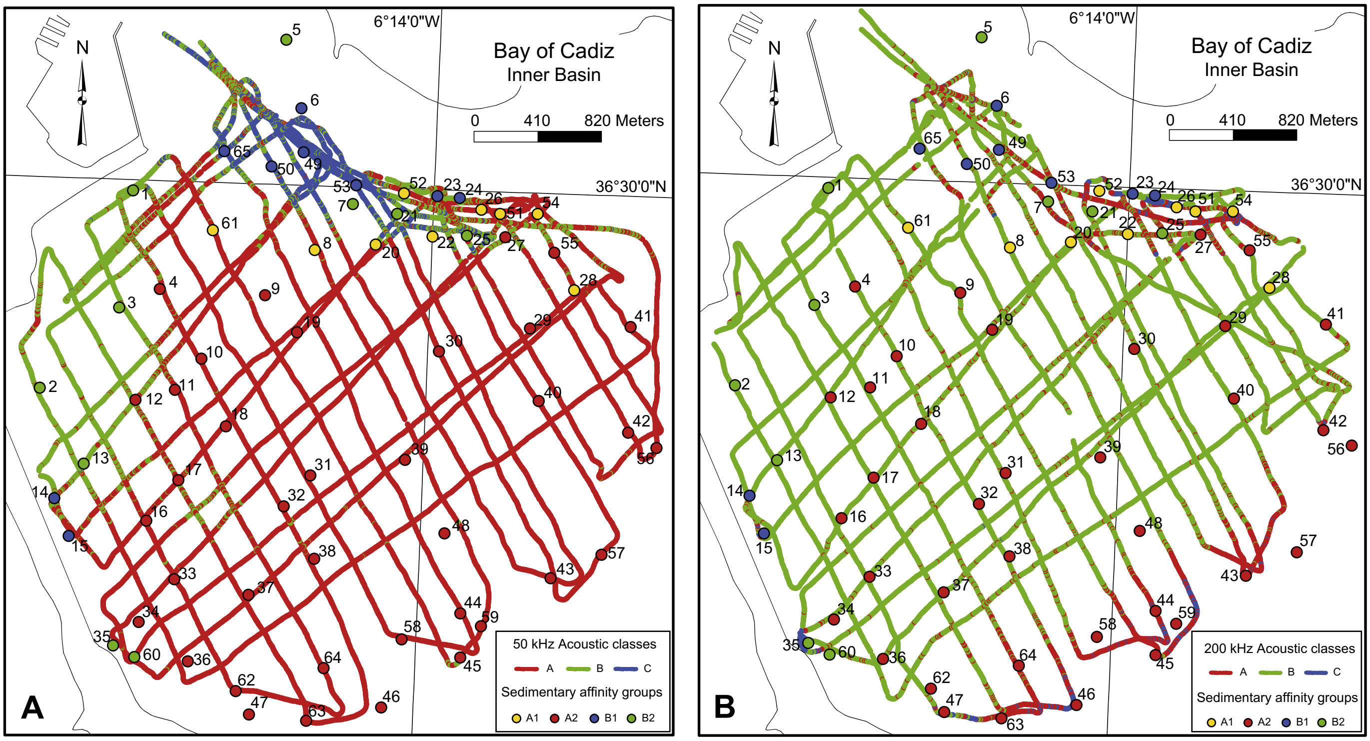

Fig. 6. Representation of the sediment groups (A1 and A2 = mud; B1 = silty medium sand; B2 = very silty fine sand), on top of the acoustic diversity maps obtained at 50 kHz (A) and 200 kHz (B).

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References

Anderson, J.T., Gregory, R.S., Collins, W.T., 2002. Acoustic classification of marine habitats in coastal Newfoundland. ICES Journal of Marine Science 59, 156–167.

Carrasco, M., López-Ramírez, J.A., Benavente, J., López-Aguayo, F., Sales, D., 2003. Assessment of urban and industrial contamination levels in the bay of Cádiz, SW Spain. Marine Pollution Bulletin 46, 335–345.

Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User Manual/Tutorial. PRIMER-E, Plymouth, 190 p.

Clarke, K.R., Warwick, R.M., 2001. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation, second ed. PRIMER-E, Plymouth, UK.

Collins, W.T., Galloway, J., 1998. Seabed classification and multibeam bathymetry: tools for multidisciplinary mapping. Sea Technology 39, 45–49.

Collins, W.T., Lacroix, P., 1997. Operational philosophy of acoustic waveform data processing for seabed classification. Proceedings of Coastal Open Space Utilization (COSU '97) International Conference, Singapore, Malaysia 1, 225–234.

Collins, W.T., Rhynas, K.P., 1998. Acoustic Seabed Classification Using Echo Sounders: Operational Considerations and Strategies. Proceedings of the Canadian Hydrographic Conference '98, Victoria, B.C., Canada. Canadian Hydrographic Service, Ottawa, Ontario, 384-390 pp.

Doeglas, D.J., 1968. Grain-size indices, classification and environment. Sedimentology 10, 8–82.

Ellingsen, K.E., Gray, J.S., Bjørnbom, E., 2002. Acoustic classification of seabed habitats using the QTC VIEW™ system. ICES Journal of Marine Science 59, 825–835.

Freitas, R., Rodrigues, A.M., Quintino, V., 2003a. Benthic biotopes remote sensing using acoustics. Journal of Experimental Marine Biology and Ecology 285–286, 339–353.

Freitas, R., Silva, S., Quintino, V., Rodrigues, A.M., Rhynas, K., Collins, W.T., 2003b. Acoustic seabed classification of marine habitats: studies in the Western Portuguese coastal shelf. ICES Journal of Marine Science 60, 600–609.

Freitas, R., Sampaio, L., Rodrigues, A.M., Quintino, V., 2005. Sea-bottom classification across a shallow water bar channel and near shore shelf, using single beam acoustics. Estuarine, Coastal and Shelf Science 65, 625–632.

Freitas, R., Sampaio, L., Oliveira, J., Rodrigues, A.M., Quintino, V., 2006. Validation of soft bottom benthic habitats identified by single-beam acoustics. Marine Pollution Bulletin 53, 72–79.

Gleason, A.C.R., Eklund, A.M., Reid, R.P., Koch, V., 2007. Acoustic signatures of the seafloor: tools for predicting grouper habitat. NOAA Professional Papers National Marine Fisheries Services 5, 38–47.

Hamilton, L.J., Mulhearn, P.J., Poeckert, R., 1999. Comparison of RoxAnn and QTC-View acoustic bottom classification system performance for the Cairns area, Great Barrier Reef, Australia. Continental Shelf Research 19, 1577–1597.

Hutin, E., Simard, Y., Archambault, P., 2005. Acoustic detection of a scallop bed from a single-beam echosounder in the St. Lawrence. ICES Journal of Marine Science 62, 966–983.

Kirlin, R.L., Dizaji, R.M., 2000. Cluster Order Using Clustering Performance Index Rate, CPIR. Proceedings of IEEE Nordic Signal Processing Symposium (NORSIG 2000), Kolmarden, Sweden, 85–88.

Larsonneur, C., 1977. La cartographie des depots meubles sur le plateau continental français: méthode mise au point et utilisée en Manche. Journal Recherche Océanographic 2, 33–39.

Minami, M., 2000. Using Arc Map. ESRI ed., New York, 528 p.

Moyer, R.P., Riegl, B., Banks, K., Dodge, R.E., 2005. Assessing the accuracy of acoustic seabed classification for mapping coral reef environments in South Florida (Broward County, USA). Revista de Biología Tropical 53 (Suppl. 1), 175–184.

Preston, J., 2001. Shallow-water bottom classification. High speed echo-sampling captures detail for precise sediment. Hydro International 5, 30–33.

Preston, J.M., Collins, W.T., 2000. Bottom classification in very shallow water by high-speed data acquisition. Proceedings of MTS/IEEE Oceans '2000, IEEE, Providence, USA 2, 1277–1282.

Preston, J.M., Collins, W.T., Mosher, D.C., Poeckert, R.H., Kuwahara, R.H., 1999. The strength of correlations between geotechnical variables and acoustic classifications. Proceedings of MTS/IEEE Oceans '99, IEEE, Seattle, USA 3, 1123–1127.

Preston, J., Inouchi, Y., Shioya, F., 2006. Acoustic classification of submerged aquatic vegetation. In: Jesus, S.M., Rodríguez, O.C. (Eds.), Proceedings of the Eighth European Conference on Underwater Acoustics, ECUA 2006. CINTAL, Carvoeiro, Portugal, ISBN 989-95068-0-X, pp. 317–322.

Preston, J.M., Rosenberger, A., Collins, W.T., 2007. Bottom classification in very shallow water. In: Papadakis, J.S., Bjorno, L. (Eds.), Proceedings of the Underwater Acoustic Measurements: Proceedings of Technologies & Results, 2nd International Conference and Exhibition. Foundation for Research and Technology – Hellas, Crete, Greece, pp. 815–822. ISBN 978-960-88702-5-2.

QTC IMPACT User Manual, 2004. QTC IMPACT™ Acoustic Seabed Classification. User Manual, Version 3.40. Quester Tangent Corporation, Marine Technology Centre, Sidney, B.C., Canada, 153 p.

QTC VIEW Series V User Manual, 2004, November 2004. QTC VIEW Acoustic Data Acquisition. User Manual, Version 2.10. Quester Tangent Corporation, Marine Technology Centre, Sidney, B.C., Canada, 68 p.

Quintino, V., Rodrigues, A.M., Gentil, F., 1989. Assessment of macrozoobenthic communities in the lagoon of Óbidos, western coast of Portugal. Scientia Marina 53, 645–654.

Riegl, B.M., Purkis, S.J., 2005. Detection of shallow subtidal corals from IKONOS satellite and QTC VIEW (50, 200 kHz) single-beam sonar data (Arabian Gulf; Dubai, UAE). Remote Sensing of Environment 95, 96–114.

Riegl, B.M., Moyer, R.P., Morris, L., Virnstein, R., Dodge, R.E., 2005a. Determination of the distribution of shallow-water seagrass and drift algae communities with acoustic seafloor discrimination. Revista de Biología Tropical 53 (Suppl. 1), 165–174.

Riegl, B.M., Moyer, R.P., Morris, L.J., Virnstein, R.W., Purkis, S.J., 2005b. Distribution and seasonal biomass of drift macroalgae in the Indian River Lagoon (Florida, USA) estimated with acoustic seafloor classification (QTC View, Echoplus). Journal of Experimental Marine Biology and Ecology 326, 89–104.

Rueda, J.L., Salas, C., 2003. Seasonal variation of a molluscan assemblage living in a *Caulerpa prolifera* meadow within the inner Bay of Cádiz (SW Spain). Estuarine, Coastal and Shelf Science 57, 909–918.

Self, R.F.L., A'Hearn, P., Jumars, P.A., Jackson, D.R., Richardson, M.D., Briggs, K.B., 2001. Effects of macrofauna on acoustic backscatter from the seabed: field manipulations in West Sound, Orcas Island, Washington, U.S.A. Journal of Marine Research 59, 991–1020.