

Seabed habitat mapping employing single and multi-beam backscatter data: A case study from the western continental shelf of India

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Abstract:

Acoustic backscatter from multi-beam echo-sounder (MBES) and dual-frequency single-beam echo-sounding systems (SBES) operable at 95 kHz and 33/210 kHz, respectively, were used to study the distribution of sediment texture and benthic macro-fauna along the central part of the western continental shelf of India (off Goa). To characterize the continental shelf seafloor, single-beam and multi-beam backscatter signals were acquired along with grab sediment samples. The relationships between processed acoustic backscatter strength, grain size, and benthic macro-fauna abundance were demonstrated employing clustering technique (PCA) and Geographic Information System (GIS) based mapping. The clustering analysis delineated that the backscatter values at three frequencies are strongly correlated with both substrate type and faunal functional groups. The preferences of deposit feeders (soft body benthic macro-fauna) for the fine-sediment regions and filter feeders (hard body benthic macro-fauna) for coarse sediment regions were linked to the variations in sediment granulometry as well as backscatter strengths in the study area. This study further demonstrates the utility of high frequency backscatter data employing echo-sounding systems towards the interpretation of seafloor sediments and benthic habitat characteristics across large areas of seafloor.

Keywords: backscatter strength, habitat mapping, multi-beam, single-beam.

1. Introduction

Space based marine remote sensing is a conventional technique for oceanographic applications. Many dynamical properties of the open ocean and the variability in the coastal zones can be mapped and effectively monitored using remote sensing techniques. Likewise, the application of acoustic remote sensing using high frequency SBES and MBES sonar imagery could provide a wealth of data for ocean multidisciplinary studies such as seabed classification and related benthic habitat studies (Kloser *et al.*, 2001; Tegowski, 2005; Brown and Blondel, 2009). The technological solutions associated with both SBES and MBES for acoustic seabed classification and benthic habitat mapping are currently an active area of research and have become an essential tool in ecosystem based management of marine environment (Anderson *et al.*, 2008).

Considering the ecological aspects of benthic habitat present in the seafloor, there is always a need to develop cost-effective methods to study their distribution at large spatial scales. Studies investigating the distribution of benthic habitat usually involve the direct collection of samples using grab or diving in order to classify the species and to assess biomass. Although such methodology provides the most accurate representation, it is time consuming and can only assess small areas (Quintino *et al.*, 2009). Hence, the acoustic remote sensing method for the study of benthic habitat has become more common and is mainly used for mapping purpose. Among the acoustic systems, SBES, which provides normal incidence backscatter values is more cost affordable. Many studies based on SBES to characterize benthic habitat have been carried out in the past (Anderson *et al.*, 2002; Freitas *et al.*, 2003; Chakraborty *et al.*, 2007; Quintino *et al.*, 2009). Moving beyond techniques that employ the SBES systems, many recent studies reported in scientific literature document how MBES has been successfully used for studying seafloor (Chakraborty *et al.*, 2004; van Walree *et al.*, 2005; Brown *et al.*, 2011; Hamilton and Parnum, 2011) and related habitat environment (Brown and Blondel, 2009; McGonigle *et al.*, 2009; De Falco *et al.*, 2010; Kloser *et al.*, 2010; Ierodionou *et al.*, 2011). In this work, an attempt has been made to understand the interaction between the seafloor sediment and benthic macro-fauna at multiple frequencies employing MBES and dual-frequency SBES operable at 95 kHz and 33/210 kHz, respectively.

Marine benthos present in the seafloor can roughly be divided into micro and macro organisms. In this study, only the macro benthos was included. Their presence in the seafloor can alter the backscatter in many ways: i) by changing the positions of the hard body fauna such as bivalves and

gastropods, which may scatter the sound signal due to strong impedance mismatch between the sediments and / or their body parts (Jumars *et al.*, 1996), and ii) by alteration of local density of the sediment-water interface, including displacements responsible for producing or erasing the small-scale features. Such changes arise due to burrowing and tube building by soft body fauna mainly dominated by polychaete worms (Kogure and Wada, 2005). Moreover, the micro benthic organisms frequently are producers of gas which in the form of bubbles trapped in the top layer of sediments can again strongly influence scattering process of acoustic wave (Pouliquen and Lyons, 2002; Holliday *et al.*, 2004). The scattering strength is high when the spatial scale of the scattering animal or its modifications in the sediment properties are comparable to acoustic wavelength applied (De and Chakraborty, 2011). In the present study, the backscatters at three acoustic frequencies (33, 95, and 210 kHz) along with sediment texture and benthic macro-faunal information are utilized to understand the interrelationship between acoustic backscatter, grain size, and benthic macro-faunal abundance. To address these issues, field experiments were carried out in the shallow water coastal area of the western continental shelf of India.

2. Materials and methods

2.1. Acoustic data acquisition

Bottom backscatter data was acquired over substrates ranging from clayey silt to sand in the central part of the western continental shelf of India (Fig. 1) with calibrated SBES and MBES. The importance of benthic production has been studied in this part of the study area (Chakraborty *et al.*, 2007; Ingole *et al.*, 2010), and it allowed us to analyze the effect of interaction between the acoustic signal and benthic macro-fauna present in the seafloor. Separate cruises were conducted to acquire the data. The dual-frequency (33 and 210 kHz) echo waveform data were acquired using a hull-mounted normal incidence RESON-NS 420 SBES during the cruise of RV “Sagar Purvi” in February 2007. The 33 and 210 kHz echo waveforms were collected using transmission pulse lengths of 0.97 and 0.61 ms with respective beam widths 20° and 9°. Meanwhile, 95 kHz MBES data were acquired using the EM1002 echo-sounding system installed onboard RV “Sagar Sukti” in April 2007. The Simrad EM1002 is a phase interpolated beam-forming MBES with 128 transducer elements forming 111 beams in a semicircular array of 45 cm radius. This echo-sounder was calibrated following a “patch test” to minimize navigational and motion errors as described in the Simrad EM1002 installation manual. The line spacing was around three to four times water depth to provide sufficient overlap between adjacent lines. An Applied Microsystems SV Plus velocimeter was used to carry out sound speed calibration

profiles of the water column. Fig. 1 shows the 12 locations where the single-beam, multi-beam, and sediment sample data were collected. The seafloor depths for the present study generally varied between 29-109 m.

2.1.1. Single-beam data processing

A typical echo record (basically a voltage trace) consists of a transmission pulse, reflection from water column, and reflections from seafloor. The voltage fluctuations at the starting point represents the transmission pulse, and the next fluctuation represents a direct reflection from the seafloor. The direct reflection has two distinct parts, the initial part and the tail part. The initial part of the echo trace is the reflection from the water-seafloor interface (interface scattering), and the tail portion represents the energy backscattered from the sediment volume (volume scattering). Since both, the lower (33 kHz) and the higher (210 kHz) frequency channels of the SBES are to be digitized, the raw analogue output on the receiver circuit board was tapped and connected to a PCL 1712L 12-bit A/D converter with a sampling frequency 1 of MHz. These data points were then converted from binary to ASCII format within a range -5 to +5 V, and Hilbert transformation was employed to obtain the echo envelope data from the echo trace at each location. However, the shape of such echo envelope depends on various factors such as natural variability of the seafloor, transducer heave, and noise due to echo-sounder instability. Therefore, several post processing steps such as visual check, echo alignment and echo averaging are essential for obtaining good averaged echo envelopes for further utilization (De and Chakraborty, 2009).

The first step in the post processing is to select good echo envelopes (with minimum distortion) by removing saturated and clipped echo-envelopes through visual checks. This is achieved by careful selection of the echo envelopes, characterized by a well defined initial rise and amplitude followed by a slow decay. In addition, the data having voltage response saturates at ± 5 V and those with prominent multi peaks are discarded. Indeed, an echo-envelope presenting only one important peak, with amplitude between 2.5 and 5 V are qualified for further processing steps. Due to the transducer heave motion and small variations of seafloor depth over consecutive pings (while recording the backscatter data), initial rise times of the echo envelopes are not same. Hence, it is essential to align all echo envelopes before carrying out further processing. The alignment is based on identifying and indexing a temporal feature on an echo envelope. The initial rise time and the time of peak amplitude are considered as an important temporal feature of an echo. After identifying this temporal feature, all echoes within the ensemble are

shifted in time to align with the (selected) feature. Finally, echo envelope averaging is carried out on the aligned echoes to obtain stable acoustic signals, which are useful for comparison with theoretical models as well as for backscatter strength computation (De and Chakraborty, 2010). For this purpose, echo envelopes are averaged using 20 successive envelopes with 95% overlap (i.e. the echoes are averaged in a moving average sense with sequences 1-20, 2-21, and so on till the end of the number of consistent echo envelopes available in the dataset).

2.1.2. Depth correction and backscatter strength computation

Apart from the processing steps described in the preceding paragraph, the echo envelope data requires additional correction for the sonar footprint dimension prior to backscatter strength computation. The footprint diameter increases in proportion to the water depth, and hence the backscatter area and echo duration increase as well (van Walree *et al.*, 2005). As a result, an echo recorded at a greater depth is expanded in time and an echo recorded at a lesser depth is compressed along the time axis (compared to a reference depth). Consequently, the acoustic returns from the same seafloor sediment type lying at different depths do not have the same shape. To overcome this problem, time adjustments (Pouliquen 2004) are made on the averaged echo envelopes at a reference seafloor depth of 50 m (approximate average of all the spot depths) (De and Chakraborty, 2009, 2010, 2012). Finally, to compute backscatter strength (in dB) from the depth corrected backscatter signal of the dual-frequency echo-sounder, we follow Urick (1983), as referenced in Chakraborty *et al.* (2007):

$$\langle 10 \log_{10} S \rangle = \langle 20 \log_{10} U_A \rangle - V_{\text{tot}} - G_{\text{up}} - \text{SL} + \langle 40 \log_{10}(R) \rangle + 2\alpha_b R - 10 \log_{10} A,$$

where S is the backscatter strength, U_A the depth corrected backscatter signal obtained from particular locations, and V_{tot} the system gain utilized in the echo-sounder. For the source level (SL) and receiving sensitivity (G_{up}), two different sets of values were used for two frequencies (33 and 210 kHz). Similarly, for the attenuation coefficient (α_b), two values corresponding to 33 and 210 kHz were used with R and A as the vertical depth (m) and the beam-insonified area respectively.

2.1.3. Multi-beam data processing

Analogous to single-beam data, the multi-beam data also require prior processing to eliminate the artifacts which occurred during the data acquisition. During the time of data acquisition, the Simrad EM 1002 system primarily measures the time average of the received backscattered signal envelope in each of its 111 beams. The received signal envelopes are corrected for Time Varying Gain (TVG),

predicted beam patterns, and for the insonified area. This data then gets recorded in a packet format called “datagram” and is stored for every ping as estimates of the seafloor’s backscatter strength. However, such data recorded by the system is not directly usable for a correct estimation of the backscattering strength angular dependence. Hence, post processing is essential for the removal of Lambert’s law, corrections for actual bottom slope and the insonified area (Haris *et al.*, 2011).

To obtain a correct angular backscattering strength, the PROBASI-II (PROcessing BACKscatter Signal) algorithm (Fernandes and Chakraborty, 2009) was employed to raw backscatter data to make necessary corrections related to position, heading, bathymetry slope, seafloor insonified area, and also Lambert’s law corrections. To apply the above mentioned corrections, a batch file was created consisting of EM1002 echo-sounder’s raw data. The program first read this batch file and extracted specific data such as backscatter strength, bathymetry, heading, position, and beam angle required during the processing of backscatter intensities. Finally, after giving the appropriate corrections for position, heading, bathymetry slope, and insonified area, the effect of Lambert’s law was removed from the measured level given by the echo-sounder (Haris *et al.*, 2011). The processed multi-beam angular backscatter data (in decibels) for 20 consecutive pings, varying between the incidence angles of -65° to $+65^{\circ}$ were binned in equal angular bins of 1° intervals. The data was then averaged over the available number of samples within each bin. From the statistical point of view presented in this paper, the angular backscatter function is represented from 0° to 65° only (i.e. half of the MBES data is used). In addition to seafloor properties, the incidence angle at which backscatter is measured can strongly influence its intensity. Generally, backscatter strength near nadir (i.e. small incidence angles) has higher backscatter values compared to outer swath. This is because of differences between reflection near nadir and scattering at outer swath. To obtain representative backscatter values for each location, it was necessary to choose a reference angle which is minimally sensitive to slope correction and absorption errors (Kloser *et al.*, 2010). Hence, following Kloser *et al.* (2010) the backscatter values corresponding to 40° incidence angles were chosen for further analysis presented in this study.

2.2. Sediment sampling

Separate sediment samples were analyzed for textural and benthic studies using a Van-Veen grab, covering an area of 0.04 m^2 and penetration of 10 cm following standard protocol. For textural analysis, about 15-20 g sediment was removed from each grab sample with 4.0 cm diameter core tube. The sediment was repeatedly washed in distilled water until all the chloride ions detectable with 4%

silver nitrate were removed (Ingole *et al.*, 2002). These samples were treated with 10% sodium hexametaphosphate and kept overnight for dispersion before being subjected to grain size analysis. The acquired sediment samples were put through a 62 μm sieve to separate the sand from the mud fraction employing wet sieving. The size distribution (<62 μm) of the mud fraction was measured with a Malvern laser particle size analyzer (MASTERSIZER 2000). Since it was difficult to maintain uniform suspension of sandy material within the laser particle analyzer, the size distribution of the sand fraction was determined using standard dry sieving method (Folk, 1968). The shelf sediments also frequently contain shelly material, which have to be sieved prior to measurement by laser diffraction. The mean grain size $M_{\phi} = -\log_2 U_{\phi}/U_0$ (where $U_0 = 1\text{mm}$) was then calculated for each of the sediment sample locations.

The sediment samples for benthos identification were washed through a 0.5 mm mesh sieve, and all organisms retained on the sieve were collected and preserved in 10% seawater formalin-Rose Bengal solution for subsequent identification. These samples were again washed through 0.5 mm mesh in running water in the laboratory to clear adhering sediments. All organisms were sorted into major groups, preserved in 90% alcohol for further identification and counted group-wise. Specimens were identified to the lowest possible taxon. The average number of organisms from the samples was then converted to number per m^2 (No. m^{-2}). Biomass was determined by using the wet weight method after blotting. The obtained biomass (shell included) was then converted to $\text{g}\cdot\text{m}^{-2}$ (wet weight). The species identification was based on the work by Ingole *et al.* (2010). We have grouped benthic macro-fauna into two communities: i) soft body organisms, referred to as “deposit feeders”, which include majority of polychaete worms and related soft body species like nematode, oligochaetes, nemertinea, echurids and ii) hard body organisms, referred to as “filter feeders”, which include mainly bivalves and gastropods. Total organic carbon analyses were carried out on the freeze-dried sediments using a NCS 2500 (Model-EA/NA1110) CNS analyzer after removing inorganic carbon from the total sample.

2.3. GIS based classification

In order to have an overall picture of seafloor processes using ground truth and backscatter data at 33, 95, and 210 kHz, the comprehensive application of Geographic Information System (GIS) has been implemented over the study region (Mortensen *et al.*, 2009). Apart from the 12 study locations, to have a better picture about the general bottom environment of the study area, we have incorporated 14 more reference sites in the GIS based image classification having both single-beam acoustic (33 and 210

kHz) and sediment texture data. However, in the statistical analysis we have considered 12 locations (Fig. 1) having acoustic data at three frequencies as well as sediment texture data along with benthic macro-fauna information. For image data generation, we have used ArcGIS “Kriging” technique, which involves an interactive investigation of the spatial behavior of the phenomenon or data. Kriging is an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with z-values. Unlike other interpolation methods supported by ArcGIS Spatial Analyst, Kriging involves the spatial behavior of the phenomenon represented by the z-values before the best estimation method for generating the output surface. Kriging is based on the regionalized variable theory that assumes that the spatial variation in the phenomenon represented by the z-values is statistically homogeneous throughout the surface. This hypothesis of spatial homogeneity is fundamental to the regionalized variable theory.

3. Results and discussion

In this section, we compare the estimated backscatter strengths from SBES and MBES with weight percentage of the sediment fraction and the number density of benthic macro-fauna present in the seafloor. The establishment of traditional statistical techniques for the understanding of spatial and temporal dependence of benthic habitat on the acoustic backscatter has been proposed in the past (Jackson *et al.*, 1996). Similarly, in this study we have adopted the method Principal component analysis (PCA) for better understanding of the shelf seafloor processes. PCA is a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. This technique has three effects: it orthogonalizes the components of the input vectors (so that they are uncorrelated with each other), it orders the resulting orthogonal components (principal components) so that those with the largest variation come first, and it eliminates those components that contribute the least to the variation in the data set. The first several principal components have cumulatively mainly 80-90% of information but the rest of information is included in the principal components having higher indexes (Manly, 1994).

3.1. Ground-truth data

The percentage distribution of sediment compositions based on Shepard’s classification (Shepard 1954) shows the presence of four seafloor sediment types: clayey-silt, silt, silty-sand and sand with varied levels of mixing of three textural grades of sand, silt, and clay. Sediment texture was relatively coarse ($M_{\phi} < 4$) in the deeper depths (60-109 m). Fine-grained sediment ($M_{\phi} > 4$) was located at the shallow depth region (29-54 m). Table (1) provides location wise details about the sediment type,

biomass, and population density of benthic macro-fauna. For simplicity, in the following text silty-sand and sand sediments will be referred to as coarse sediments (with $M_{\phi} < 4\phi$); and clayey-silt and silt sediments will be referred to as fine sediments (with $M_{\phi} > 4\phi$).

3.2. Backscatter and grain size

Backscatter intensity data for three frequencies were compared with weight percentage of the individual grain size classes namely, sand, silt, and clay. The correlation coefficient R^2 between backscatter intensity and grain size classes is reported in Fig. 2. It is evident that, for three frequencies, the backscatter intensity is directly correlated with coarse fractions (sand within the range 62-2000 μm) and inversely correlated with finer fractions namely silt (2-62 μm) and clay (<2 μm). The relationship between backscatter intensity and the weight percentage of the sand fraction is depicted in Fig. 2a. As the percentage of the sand fraction increases, the backscatter intensity also increases linearly. Concurrently, the relationship between backscatter intensity and the weight percentage of the silt and clay is expressed in Figs 2(b) and (c), and shows that the backscatter intensity decreases with increasing weight percentage of both silt and clay fraction.

Several studies have compared backscatter responses to ground-truth sediment data in order to assess the ability of different acoustic technologies to classify seafloor types (e.g. Goff *et al.*, 2004; Ferrini and Flood, 2006; Simons and Snellen, 2009; De Falco *et al.*, 2010). The backscatter intensity from a muddy seafloor has been shown to be inversely linearly related to the percentage content of silt and clay (Goff *et al.*, 2004; Sutherland *et al.*, 2007). Fine sediments generally exhibit low backscatter intensity due to low density and sound velocity (De Falco *et al.*, 2010). However, the spatial variability of backscatter intensity along the seafloor characterized by coarse sediments has been shown to be mainly driven by the weight percent of coarse grains (sand) (Goff *et al.*, 2004; De Falco *et al.*, 2010). Coarse sediments are more likely to result in higher backscatter intensity due to scattering from coarse particles, lower porosity, higher density and sound velocity, and greater roughness of the water-sediment interface. The results of this study agree with those of De Falco *et al.* (2010), in that backscatter intensity and the proportion of the coarse fraction in sediments are strongly related. In this study, as with that of De Falco *et al.* (2010), a linear relationship between weight percentage of sand and backscatter intensity is also evident. However, for muddy seafloor, the present study indicates an inverse linear relationship between percentage content of silt and clay, thus supporting the findings of previous studies (Goff *et al.*, 2004; Sutherland *et al.*, 2007).

Benthic macro-fauna present in the seafloor can affect backscatter in several ways. Hard-bodied fauna may individually be a discrete scatterer and groups of these individuals can also scatter acoustic energy. The benthic fauna can both create and destroy seafloor roughness, and can create fluctuations in density or sound speed in the sediment. Moreover, benthic fauna can compact and dilate sediments, create density and sound speed gradients, and finally can also destroy layers created by sedimentary events (Diaz *et al.*, 1994). Most of these acts by benthic fauna are collectively referred to as bioturbation. Apart from the process of bioturbation, the acoustic energy used by the echo-sounder can penetrate into the sediments and are likely to be scattered from the buried inhomogeneities such as coarse sand particles, shell hash, mollusk shells, and buried layers of coarse materials. The intensity of the scattered energy depends on the sizes of these buried inhomogeneities relative to the impinging acoustic wavelength (De and Chakraborty, 2011). These phenomena might be responsible for higher backscatter strength, observed especially in coarse sediment region where the hard body organisms dominate.

Moreover, as evident from Fig. 2, the correlation coefficient (R^2) between backscatter intensity and grain size are much larger for the SBES measurements than for the MBES measurements. This is not a frequency related issue, as the SBES measurements are at 33 and 210 kHz, compared to 95 kHz for MBES measurements. More precisely, the low correlation of the multi-beam measurements may be due to the selection of reference angle from the MBES angular profile. In this study, to obtain representative backscatter value for statistical analysis, it was necessary to choose a reference angle which is minimally sensitive to slope correction and absorption errors. Accordingly, the backscatter values corresponding to 40° incidence angles were chosen for the analysis presented in this study (Kloser *et al.*, 2010). A generic representation of backscatter strength versus incidence angle with physical processes involved in seafloor backscattering is presented in Fig. 3. At frequencies (tens and hundreds of kHz) used by seafloor mapping sonar, the backscattering from the seabed can generally be attributed to two contributing factors (Fig. 3). Part of the energy is scattered by the interface relief, either by the subhorizontal facets at incidence angle close to the vertical or by microscale roughness at grazing incidence. The other part of the energy penetrates the sediments and is reflected back by volume heterogeneities. This process can become predominant at oblique incidence (Lurton, 2002).

3.3. Grain size and benthic habitat

The number density of both hard and soft body organisms were compared with weight percentage of the individual grain size classes. The correlation coefficient R^2 , which assesses the animal-sediment relationship is depicted in Fig. 4. It is evident that the number density of hard body organism is directly correlated with coarse fractions (sand within the range 62-2000 μm) and inversely correlated with finer fractions namely silt (2-62 μm) and clay (<2 μm). The relationship between number density of hard body organism and the weight percentage of the sediment fraction is depicted in Fig. 4(a). As the percentage of the sand fraction increases, the number density of hard body organism also increases linearly. Meanwhile, for fine region the number density of hard body organism decreases with increasing weight percentage of both silt and clay fraction (Figs. 4(b) and (c)). Conversely, the number density of soft body organisms is directly correlated with both silt and clay fractions and inversely correlated with coarse fractions (Figs. 4a-c). Lower correlations show that there could be many factors in combination that influence the distribution of benthic macro-fauna.

Two distinct feeding groups were observed from this study area: namely, deposit feeders (majority of polychaete worms and related soft body species like nematode, oligochaetes, nemertinea, and echurids) mainly in shallow region and filter feeders (hard body bivalves and gastropods) in deeper depths. However, a coexistence of deposit feeder along with filter feeders in the deeper regions is also observed. The dominance of deposit feeders in shallow depth could be due to their preference for the fine-grained sediment. However, the occurrence of filter feeders in coarse sediments of deeper depth suggests that this species is typical of this particular substratum. The dominance of deposit feeders in the fine-grained sediment has already been reported from Indian waters (Jayaraj *et al.*, 2007, 2008). Moreover, Ansari *et al.* (1977), and Jayaraj *et al.* (2007, 2008) have reported that fine-sediment such as clayey regions are not a favorable substratum for filter feeders. Sanders (1958) had suggested that the coarse region (sand sediment), where the filter feeders dominate, reflects the more pronounced under water current activity and brings more potential food to filter feeding organisms than would weaker currents. Conversely, fine sediment reflects the environment with feeble currents, which allow the fine particles to settle, so that only a small amount of organic matter in suspension is available as food for filter feeders, which in turn prevents them from inhabiting such environment and providing an adequate source of nutrition for deposit feeders only (Jayaraj *et al.*, 2008). The preferences of deposit feeders for the fine-sediment regions and filter feeders for coarse sediment regions indicates the influence of sediment texture on the feeding behavior of the organisms (Fig. 5).

3.4. Interrelationship between backscatter, grain size, and benthic macro-fauna abundance

The relationships between processed acoustic backscatter strength, grain size, and benthic macro-fauna abundance were demonstrated based on PCA. A dendrogram for 8 variables delineated two main clusters from the study area (Fig. 6(a)). A dendrogram consists of many U-shaped lines connecting variables in a hierarchical tree. The height of each U represents the distance between the two objects being connected. As it is evident from Fig. 6(a), Cluster 1 consists of coarse sediment texture (dominated by sand content) and high backscatter intensity values for three frequencies with dominant hard body benthos. Meanwhile, sediments from cluster 2 are characterized by relatively low backscatter values dominated by fine sediment texture (high percentage content of both silt and clay) with substantial occupancy of soft body organisms. In short, high backscatter intensity values, coarse sediments, and hard body organisms were the major components that contribute to cluster 1. Conversely, low backscatter intensity values, fine sediments, and soft body organisms were the major components associated with cluster 2. The location wise clustering of these variables is shown as biplot of PCA in three dimensional views (Fig. 6(b)). Here each of the variables is represented by a vector, and the direction and length of the vector indicates how each variable contributes to each of the clusters formed. As discussed in Section 3, PCA orthogonalizes the components of the input vectors so that they are uncorrelated with each other. It then orders the resulting orthogonal components (principal components, PC) so that those with the largest variation come first. Finally, it eliminates those components that contribute the least to the variation in the data set. The result of such implementation in the study area is shown in Fig. 6(b). Here, the variances are found to be 74.74, 10.83, and 9.38 %, respectively, for PC1, PC2, and PC3. The rest of information is included in the PCs having higher indexes, but they are insignificant to be represented. Preference of filter feeders for coarser sediment could be clearly seen in cluster 1, which was a sand dominating cluster (Locations: 7-12) with high backscatter values for 3 frequencies. Likewise, Preference of deposit feeders for fine sediment could also be clearly seen in cluster 2, which was a cluster with silt and clay as the dominant sediment texture (Locations: 1-6). The clustering analysis depicts that, both the backscatter and sediment texture can characterize the distribution of the organisms present in the seafloor (Figs. 7 and 8).

The benthos living in the seafloor however have complex population and community dynamics (Kloser *et al.*, 2010), and are affected by factors other than substrate type. To address these issues, we have mapped the variations of total organic carbon in the study area and related it to the distribution of biomass and benthic density. The variation of biomass from the study locations generally showed a

increase at 54 m water depth, with decreasing trend towards both shallow (<54 m) and deeper (>54 m) depths (Fig. 9(a)). However, a noticeable feature observed was the low biomass at the 29 m depth. Meanwhile, the distribution of benthic density was relatively high at depths 43, 54, and 60 m (Fig. 9(b)). Beyond 60 m the benthic density showed a decreasing trend with increasing water depth. The present findings of high and low biomass at respective water depths 54 and 29 m agree with earlier studies from Indian waters (Jayaraj *et al.*, 2007, 2008). Relatively high species richness and diversity observed in the coastal region (<100 m) could be due to the enrichment of coastal waters due to riverine flow and land runoff in the study area (Parulekar, 1973). The high percentage of fine grained sediments with relatively high organic carbon was a noticeable feature in the very shallow region (Fig. 10). It is to be noted that the distribution of organic carbon is governed by a set of physico-chemical, sedimentological and hydrographic conditions (Jayaraj *et al.*, 2007). Moreover, the study area receives relatively high annual rainfall, which can bring organic load through the rivers and discharges to the shallow water regions of the study area. This process might have also resulted in increased amount of both fine sediment and organic carbon in the shallow region. In this study, compared to deeper depths (43, 54, and 60 m) the benthic density was low at very shallow region (29 and 39 m) depth contours. The low biomass at very shallow depth (29 m), where the texture was clayey-silt with high organic carbon suggests that fine sediment and high organic carbon adversely affect the benthic density (Jayaraj *et al.*, 2007).

4. Conclusions

The Interrelationship between backscatter, grain size, and benthic macro-fauna abundance were demonstrated based on the acoustic data from dual frequency (33 and 210 kHz) SBES and MBES (95 kHz) in conjunction with the sediment grain size and benthic macro-fauna information. The sediment textural properties and benthic macro-fauna information were collected using a grab for ground truth data. The findings of this study show that the different seabed types of the western continental margin of India can be mapped using a combination of data, including backscatter intensity and ground-truth sediment information. The preferences of deposit feeders for the fine-sediment regions and filter feeders for coarse sediment regions indicate the influence of sediment texture and total organic carbon on the feeding behavior of the organisms. On the basis of PCA, two main clusters were distinguished from the study area. The locations from cluster 1 are characterized by high backscatter intensity values for three frequencies. Sediments from those locations are mainly coarse ($M_{\phi} < 4$) in nature, dominated by sand content with prominent occupancy of hard body benthos. However, locations from cluster 2 are

characterized by low backscatter intensity values for three frequencies. Sediments from those locations are mainly fine ($M_e > 4$) in nature, dominated by high percentage content of both silt and clay with substantial occupancy of soft body organisms. The objective of this study was to establish a link between acoustic backscatter, sediment texture and benthic habitat characteristics across the western continental shelf of India (off Goa). The backscatter data presented here provide information about the sediment texture and subsequently will also give information about the occupancy of the organisms present in the seafloor. From the PCA analysis and GIS based image classification, it can be deduced that a given location is suitable for occupancy or likely to be occupied by a given type of organism.

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Figure captions

Fig. 1. Study area shows the acoustic and sediment sample data acquisition locations and their sediment types: clayey-silt (cross), silt (square), silty-sand (closed-triangle) and sand (star). The depth contours are expressed in meters. The acoustic data was sampled with EM 1002 MBES and RESON-NS 420 SBES along the two tracks. The sediment samples for textural and benthic studies were collected using a Van-Veen grab. Locations of the two prominent estuaries (Mandovi and Zuari) and rivers (Chapora and Sal) are also plotted.

Fig. 2. Correlations showing the relationships between the backscatter at three frequencies and weight percentage of sediment types sand (Panel a), silt (Panel b), and clay (Panel c) collected from the Van-Veen grab.

Fig. 3. Generic representation of backscatter strength versus incidence angle (after Lurton, 2002) depicting the physical processes involved in seafloor backscattering. The angular backscatter data presented here is from the location 11, with silty-sand as the sediment type. The marked backscatter value at reference angle 40° was chosen for the statistical analysis carried out in this study. This particular reference angle is minimally sensitive to slope correction and absorption errors compared to other values in the angular profile.

Fig. 4. Correlations showing the relationships between the benthic macro-fauna and weight percentage of sediment types sand (Panel a), silt (Panel b), and clay (Panel c) collected from the Van-Veen grab.

Fig. 5. GIS based classification representing the animal-sediment relationship. The distributions of benthic macro-fauna in relation to the sediment types of the locations are clearly distinguished.

Fig. 6. Panel (a) represents a dendrogram for the clustering of benthic macro-fauna, backscatter at three frequencies, and sediment types of the study locations (8 variables). The nomenclature SB and HB denotes soft body and hard body benthic macro-fauna respectively. This dendrogram consists of U-shaped lines connecting 8 variables (in X- axis) in a hierarchical tree. The height of each U represents the distance (in Y- axis) between the two objects being connected. Panel (b) represents the location wise clustering of the same variables in three dimensional views. The first three principal components

cumulatively 94.95% representing the information in the data sets are presented. Here, each variable in the data set is represented by a vector, and the direction and length of the vector indicates how each variable contributes to each of the clusters formed.

Fig. 7. GIS based classification representing the backscatter-animal-sediment interrelationship at 33 kHz.

Fig. 8. GIS based classification representing the backscatter-animal-sediment interrelationship at 210 kHz.

Fig. 9. Panels (a), and (b) represents the depth wise spatial variations of biomass, backscatter, and benthic density in the study location.

Fig. 10. GIS based classification representing the distribution of total organic carbon in relation to the benthic macro-fauna and sediment types of the study locations. Locations of the two prominent estuaries (Mandovi and Zuari) and rivers (Chapora and Sal) which bring organic load in the shallow water regions of the study area are also plotted.

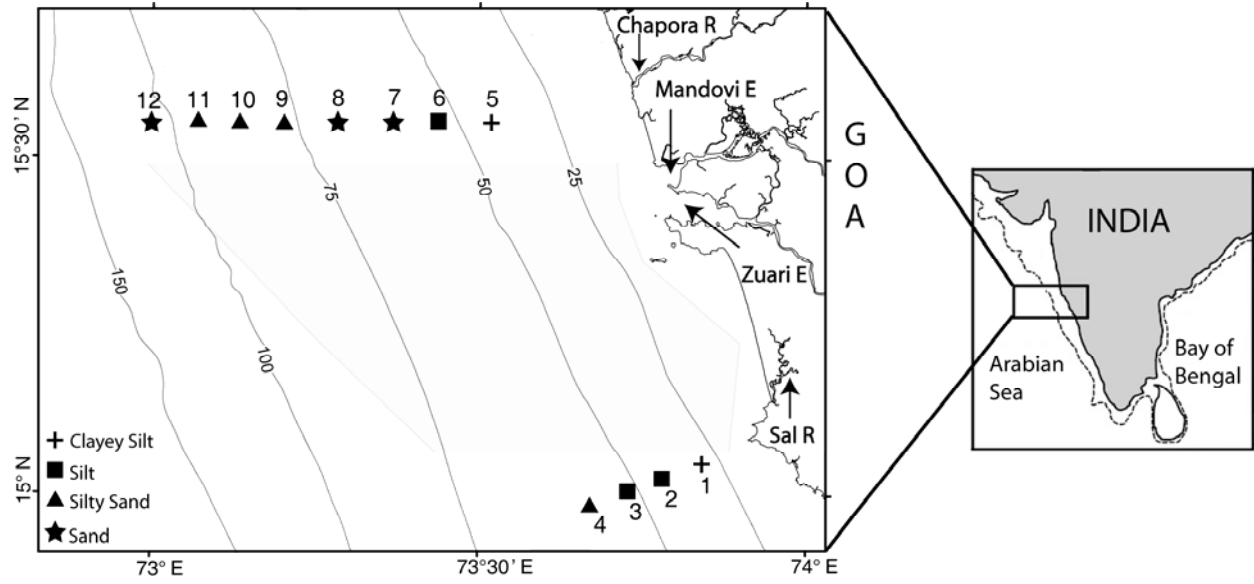


Fig. 1.

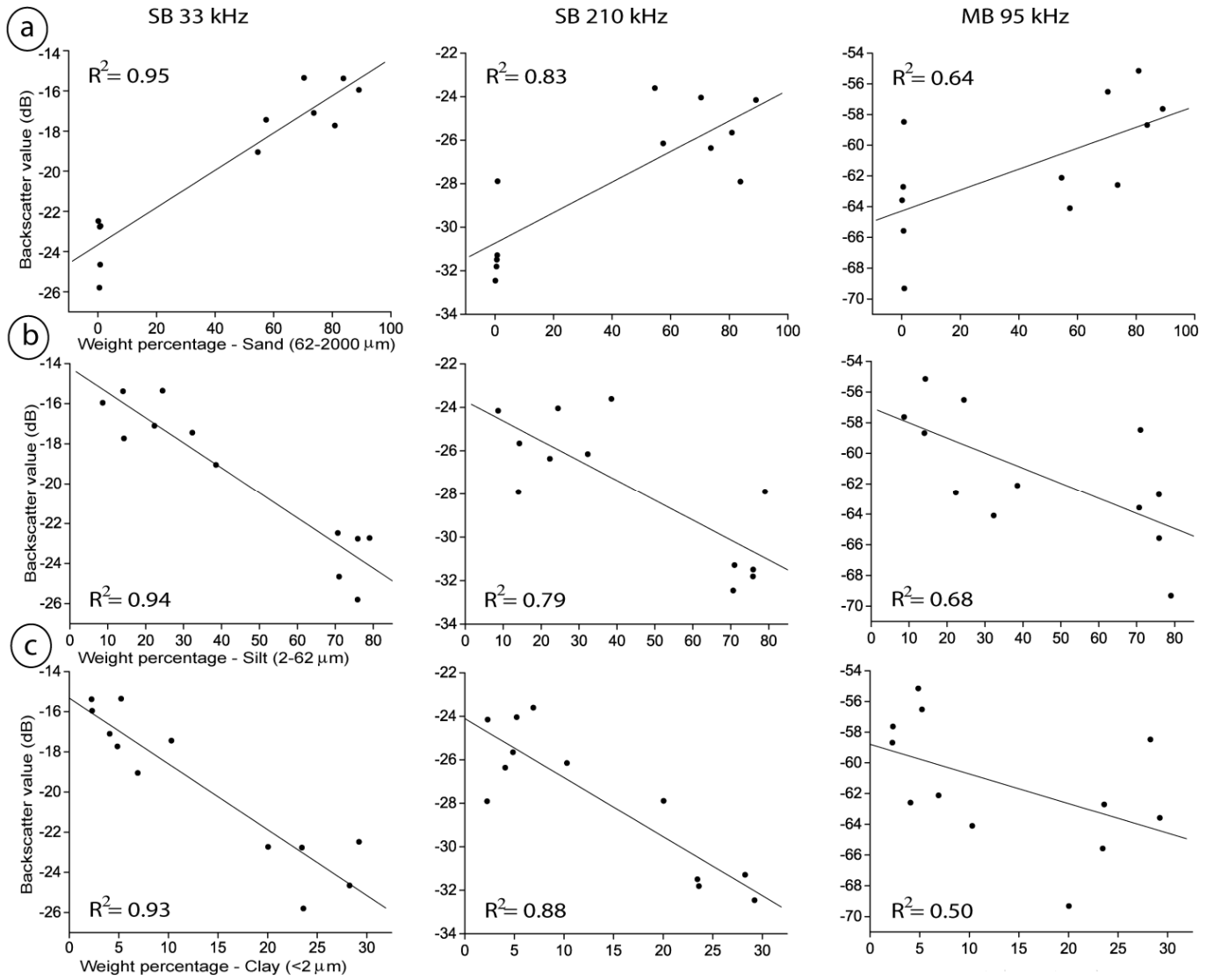


Fig. 2.

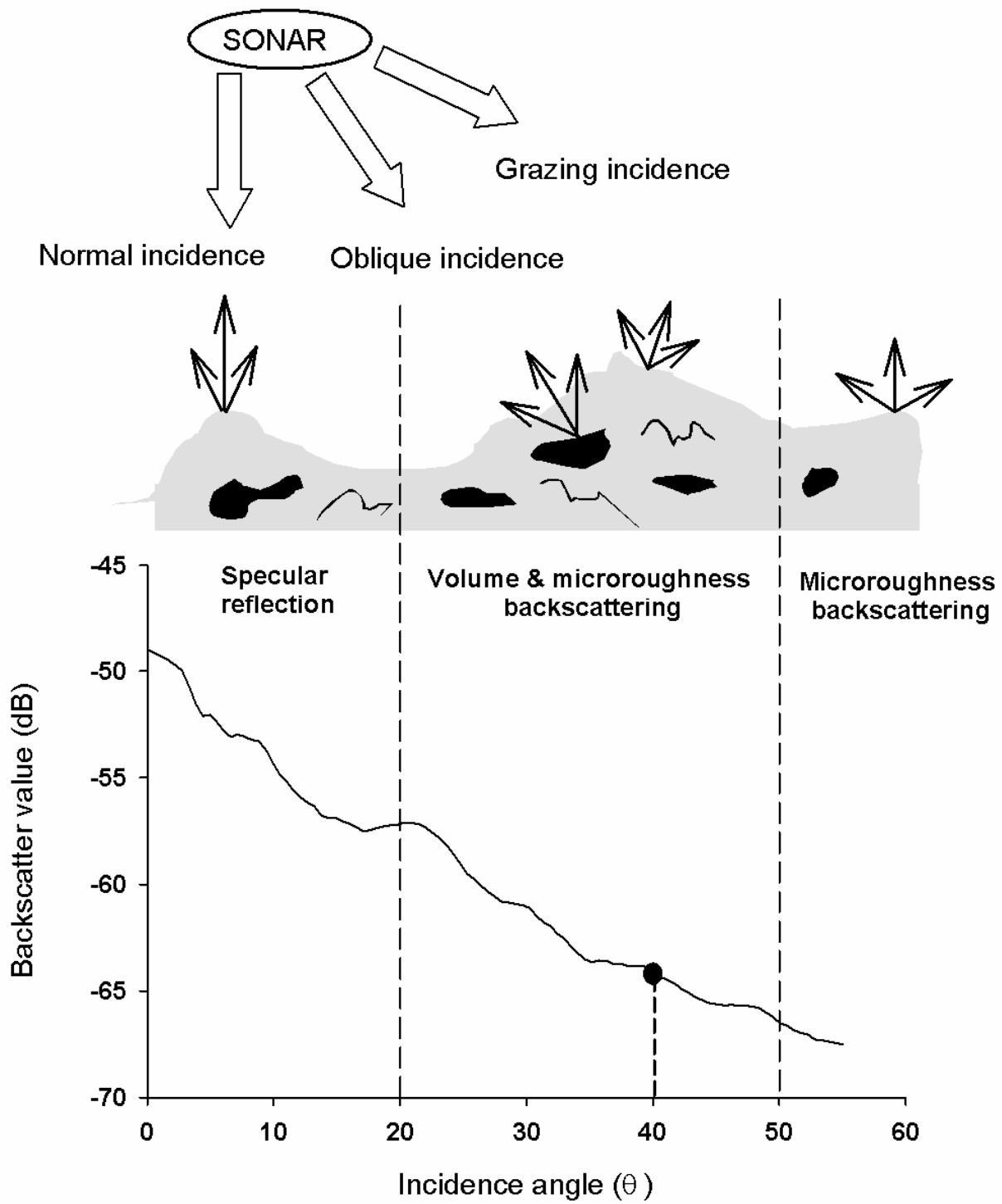


Fig. 3.

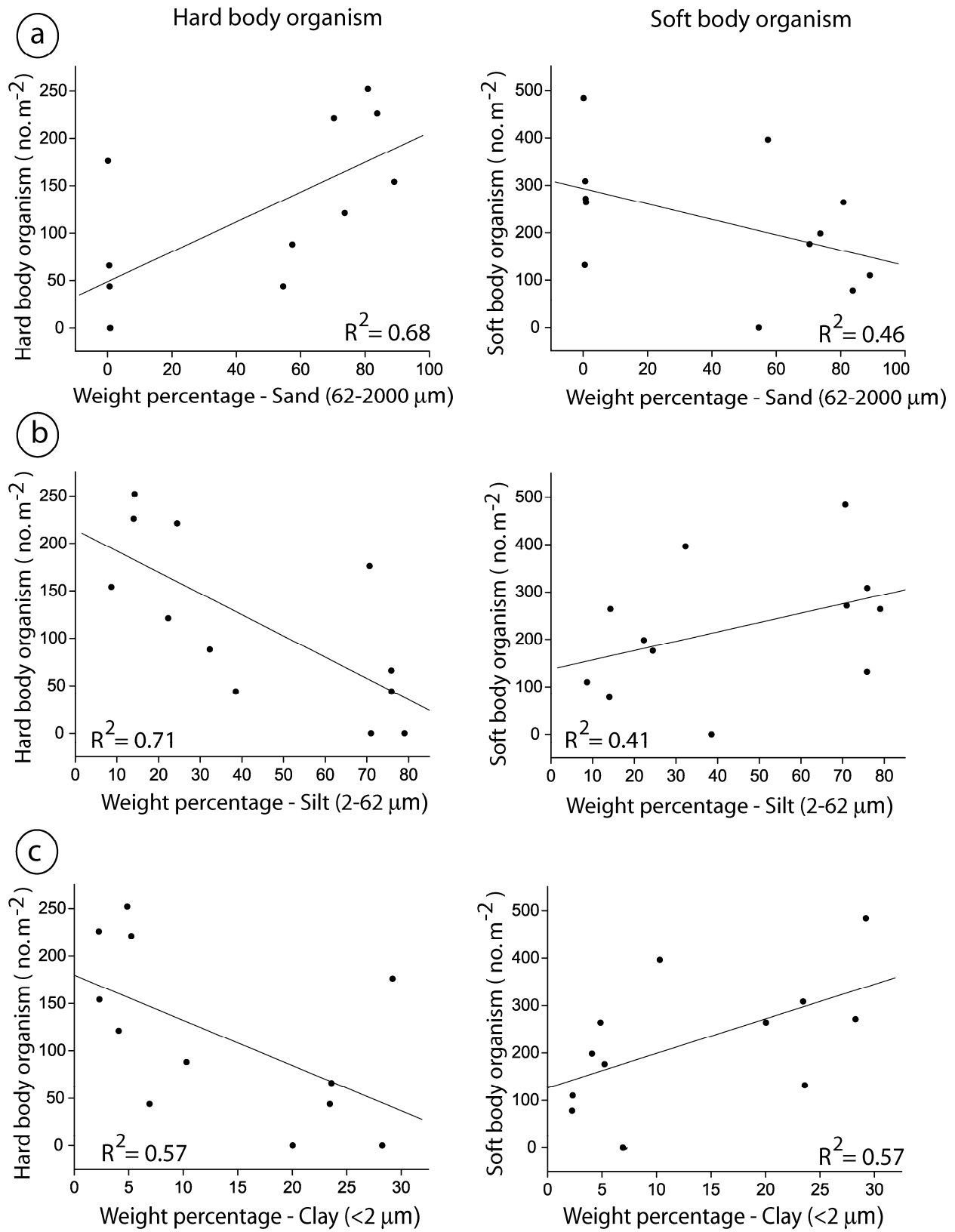


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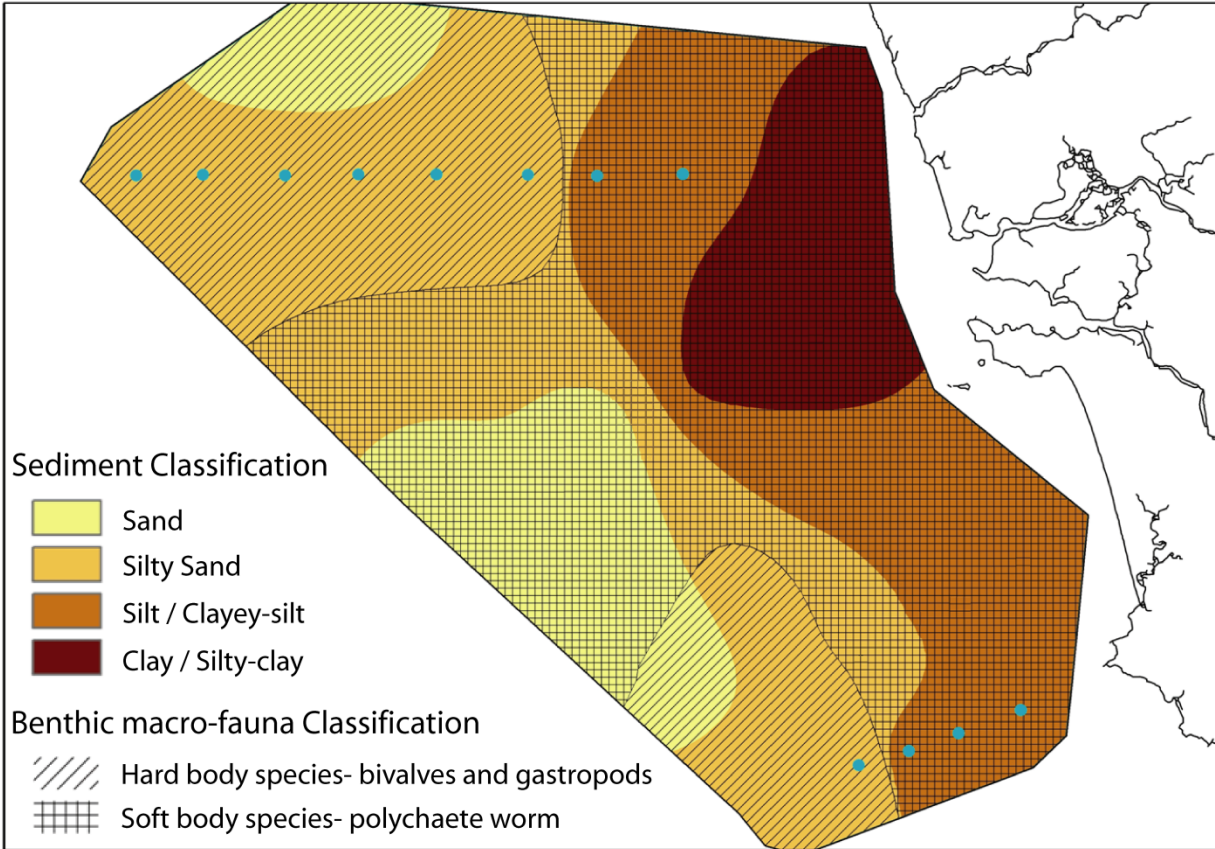


Fig. 5.

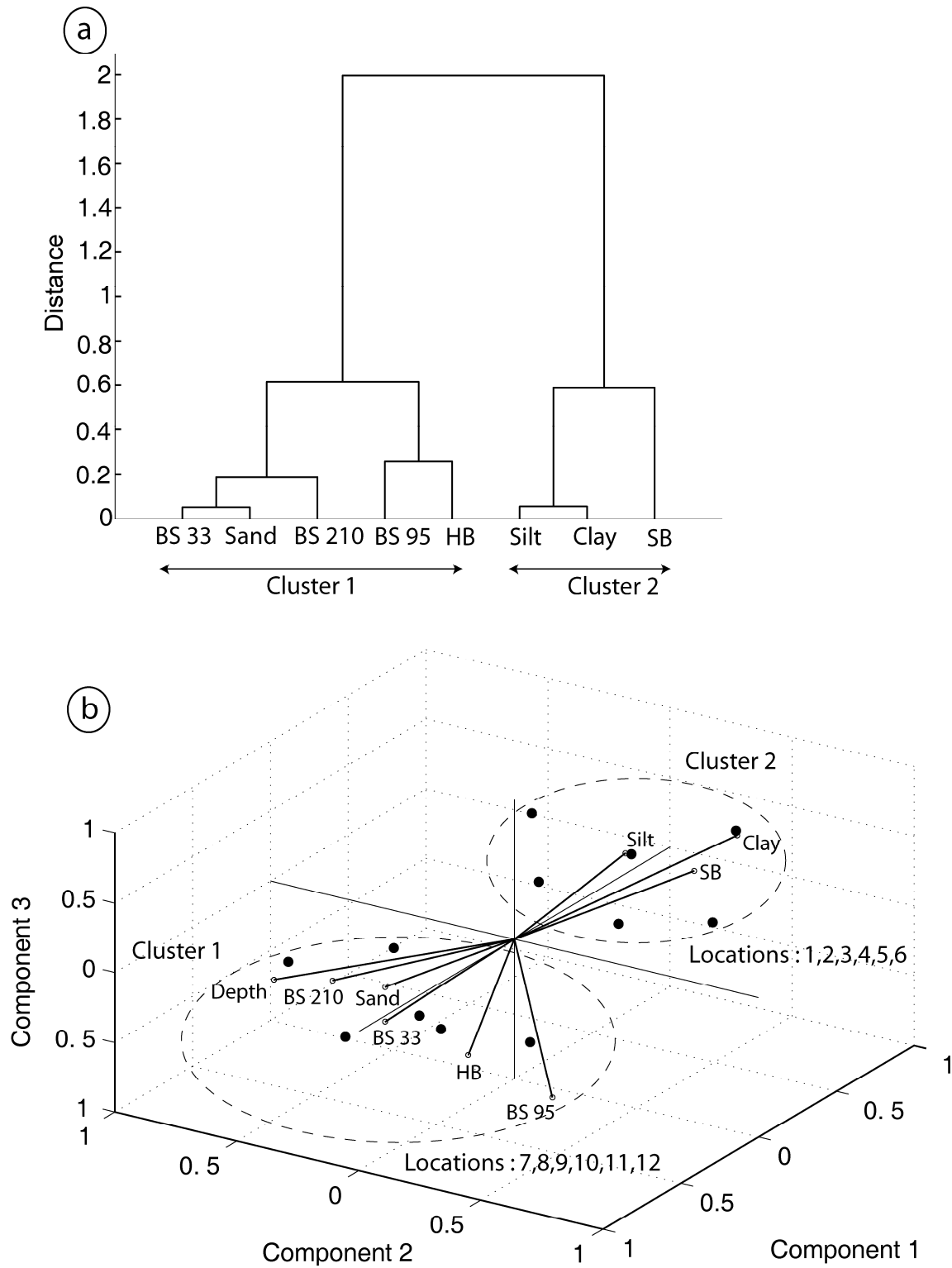


Fig. 6.

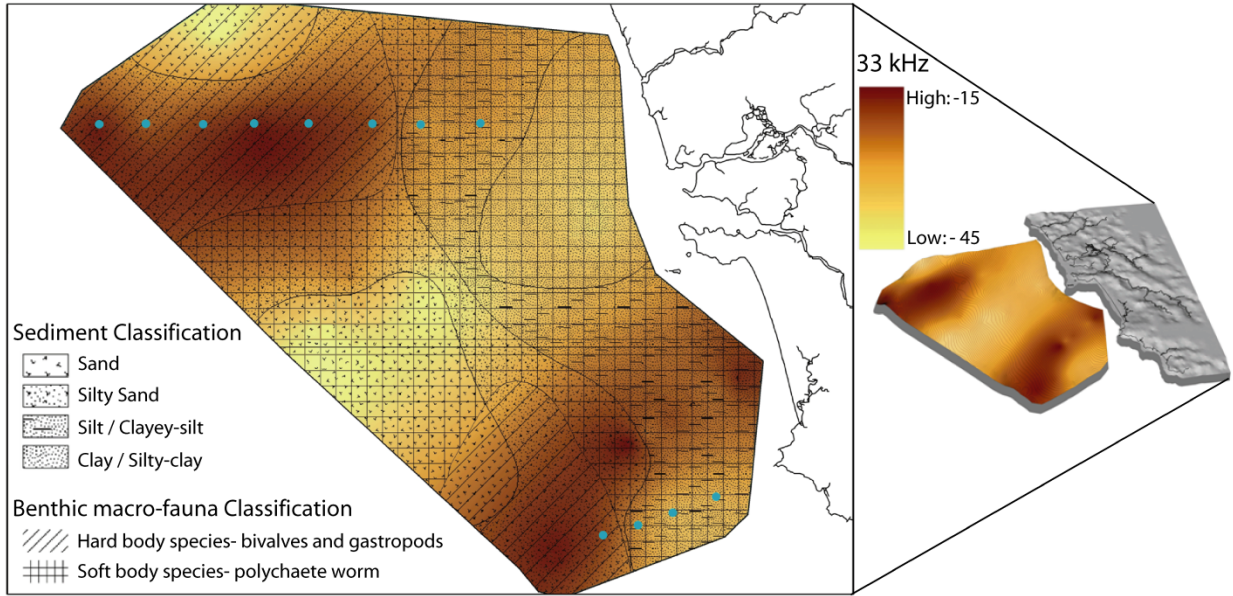


Fig. 7.

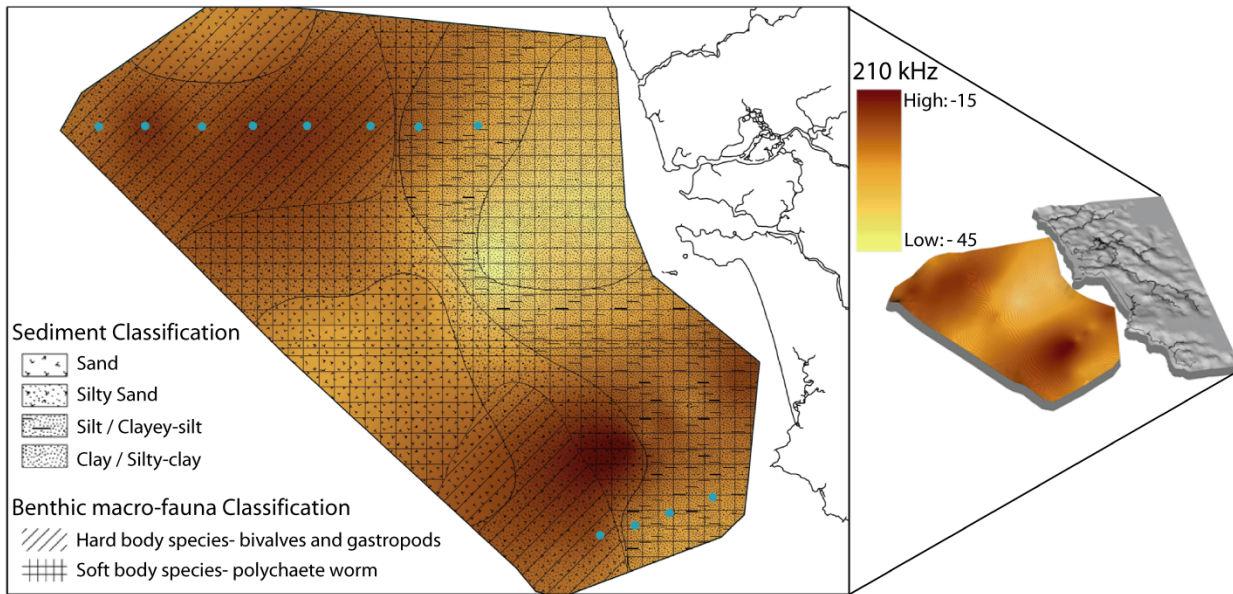


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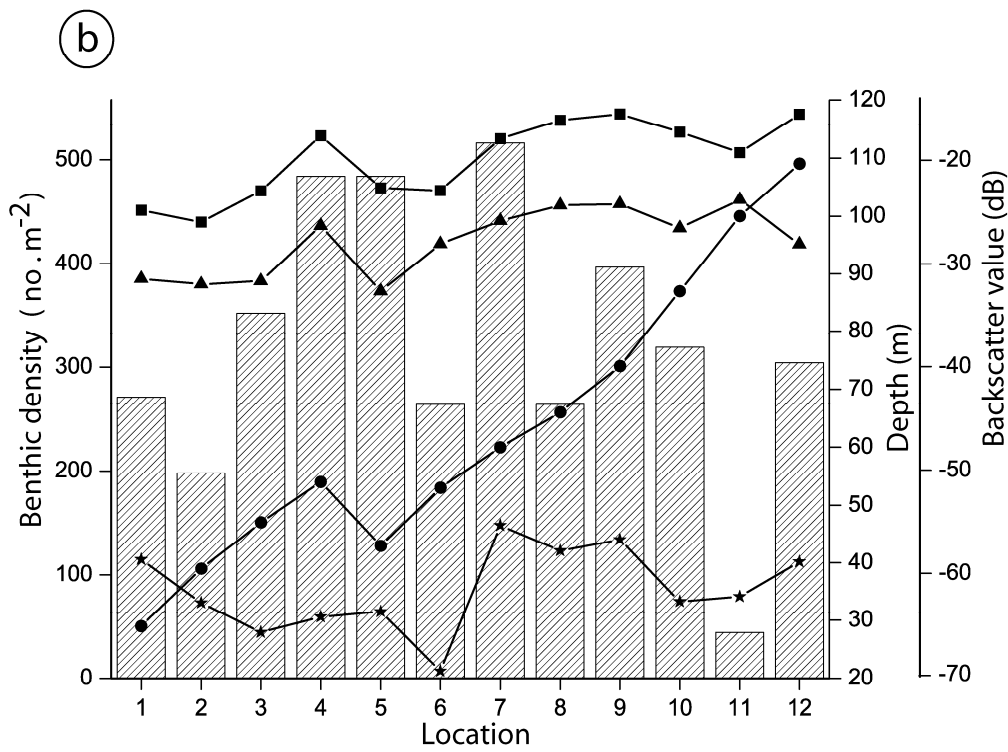
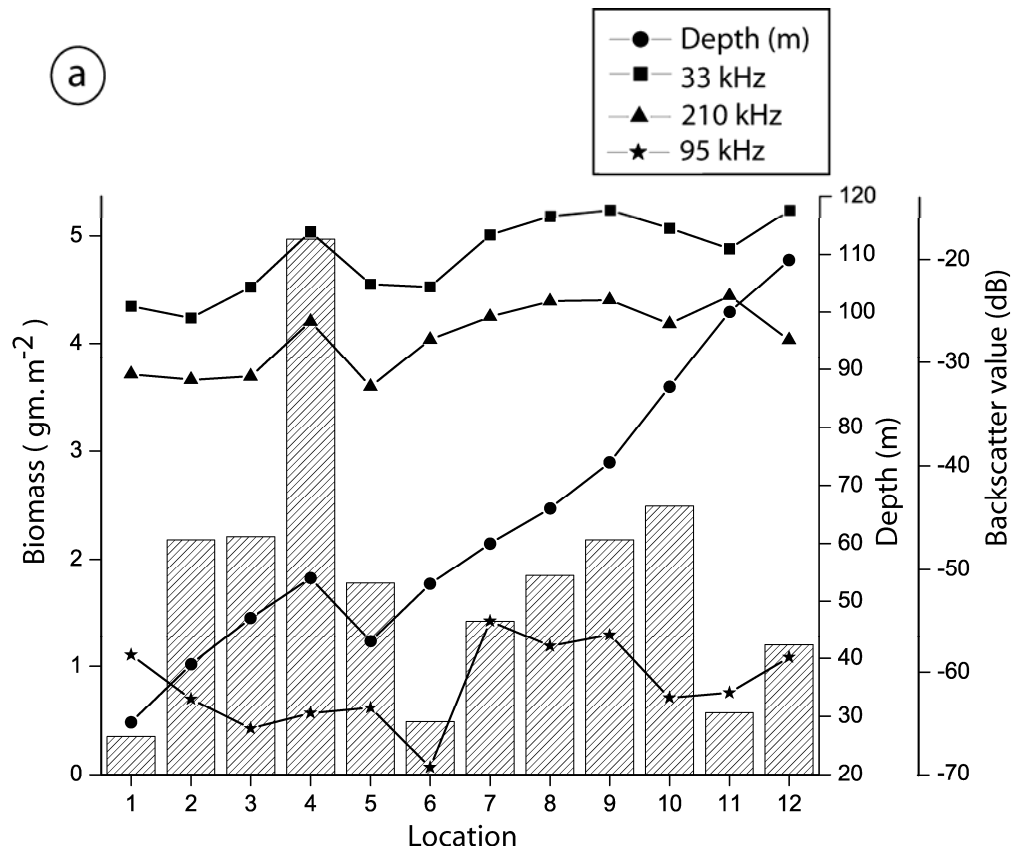


Fig. 9.

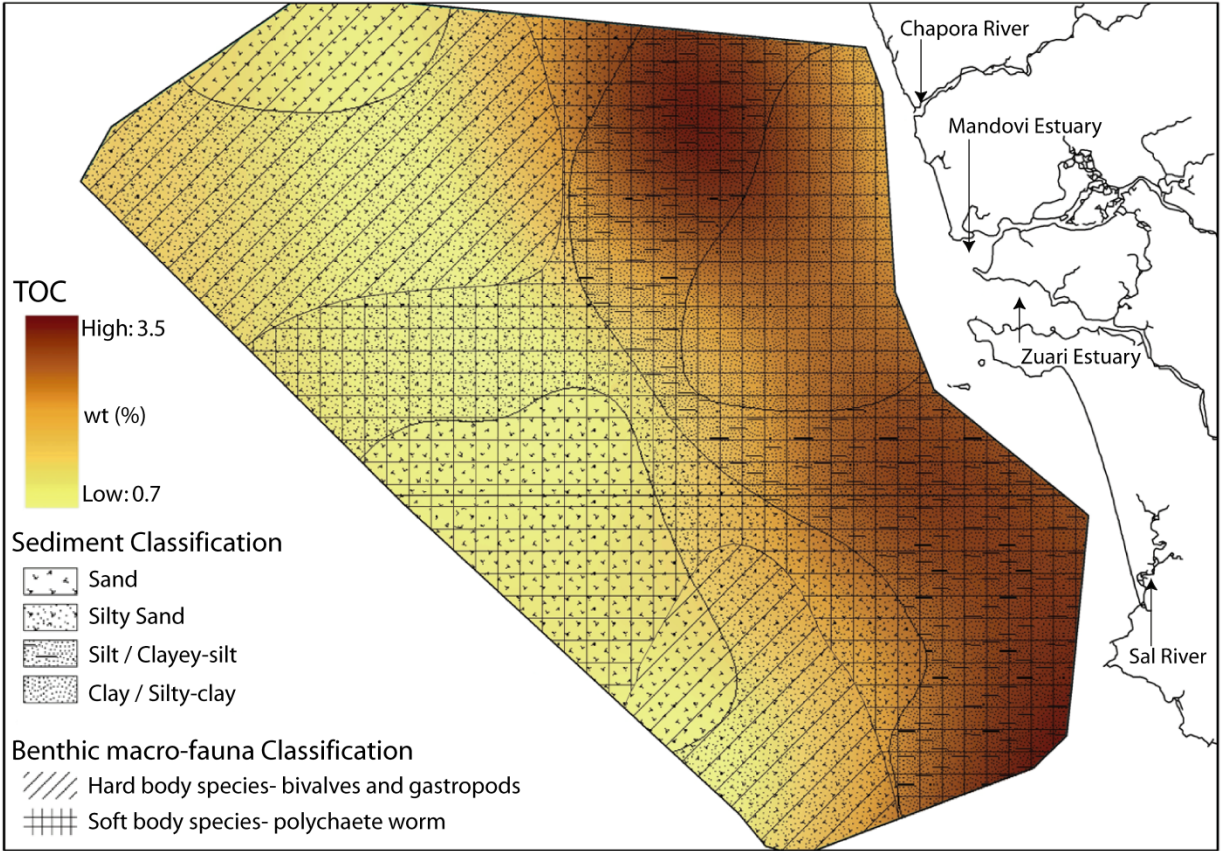


Fig. 10.

Table 1. Location wise distribution of sediment type, biomass, and benthic macro-fauna.

Location	M_{ϕ} (PHI)	Sediment type	Biomass (gm.m ⁻²)	Benthic density (no.m ⁻²)	SB ^a (no.m ⁻²)	HB ^b (no.m ⁻²)
1	6.66	Clayey-silt	0.35	271	271	00
2	6.42	Silt	2.18	198	132	66
3	6.50	Silt	2.21	352	308	44
4	4.02	Silty-sand	4.97	484	396	88
5	6.79	Clayey-silt	1.78	484	484	00
6	6.20	Silt	0.49	264	264	00
7	2.42	Sand	1.42	516	264	252
8	1.16	Sand	1.85	264	110	154
9	2.40	Silty-sand	2.18	397	176	221
10	1.99	Silty-sand	2.49	319	198	121
11	3.32	Silty-sand	0.57	44	00	44
12	2.07	Sand	1.20	304	78	226

^aSoft body organisms referred to as “deposit feeders”, which includes majority of polychaete worms and related soft body species like nematode, oligochaetes, nemertinea, and echurids.

^bHard body organisms referred to as “filter feeders”, which includes mainly bivalves and gastropods.