Indian Journal of Geo-Marine Sciences
Vol. 44(2), February 2015, pp. 156-163

Seafloor micro-roughness, benthic macro-fauna, and sediment substrate: A study of their interrelationship using high-frequency echo-sounding systems

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Received 25 November 2014; revised 2 December 2014

The spatial variability of sediment geoacoustic inversion results, derived from dual-frequency single-beam (SBES) and multi-beam echosounder system (MBES) operable at 33/210 kHz and 95 kHz, respectively, have been analyzed to demonstrate the interrelationship among the sediment texture and benthic macro-fauna abundance. The correlationship among the derived acoustical and biological parameters was identified from the spatial map generated using ArcGIS and validated by applying Principal component analyses (PCA). Distinct interclass separation of the sediment provinces is revealed by the spatial variability in the computed inversion results, demonstrating a strong correlation with the backscatter and biologically active faunal functional group assemblages on the seafloor. The results obtained are indicative of bioturbation by benthic animals, resulting in variability in the data that should be taken into account to optimize the model-data matching procedure during inversion.

[**Keywords:** Geoacoustic inversion, single-beam, multi-beam, benthic macro-fauna]

Introduction

Acoustic remote sensing technique using high-frequency single-beam (SBES) and multi-beam echosounder system (MBES) has been recognized as an effective tool for studying the seafloor over a wide area[1]. The backscatter data acquired using the echo-sounding systems can be matched with the theoretical scattering models to interpret the fine scale seafloor information embedded in data[2-4]. The numerical approach employed for extracting information from the data is commonly referred to as inversion modeling. Inversion modeling primarily involves physics based approach to calculate upper-layer seafloor roughness parameters, namely, the sediment mean grain size (M_φ); spectral parameters at the water-seafloor interface (γ_2, w_2); and sediment volume parameter (σ_2)[5,6]. However, the study of the interaction of sound with the seafloor and the accompanying application of inversion modeling can provide new insights if the physical structure of the seafloor and the associated benthic communities with its diversity coexists[7].

The bottom dwelling benthic organisms often modify the physical properties of the sediment and create fine scale seabed structures[8]. The multiple processes that are continually occurring at the water-sediment interface and within the sediment volume significantly causes fluctuation in acoustic backscattering. The collective displacement and mixing processes of sediment substrates by the benthic macro-fauna are termed as bioturbation. The bioturbation can affect the sediment properties including derived parameters as follows: (a) due to the movement of the hard body fauna such as bivalves and gastropods that scatters the sound signal due to strong impedance mismatch between the sediments or their body parts[9], and (b) by altering the local density of sediment-water interface, including displacements responsible for producing or erasing the small-scale features. Such changes are caused by burrowing and tube building of soft body fauna, mainly dominated by polychaete worms[10,11].

Relatively high backscattering is expected when the spatial scale of the scattering animal or its modifications in the sediment substrates become comparable to the transmitting acoustic wavelength[5]. Besides, the SBES echo-envelope shape parameters such as peak along with its width, rise, fall time, and the tail part gets modified due to the bioturbation. Therefore, it is important to examine the role of bioturbation on the acoustic backscatter using high-frequency echo-sounding systems. In the present study, the spatial variability of the previously estimated sediment geoacoustic inversion results[5,6], using MBES and dual-frequency SBES operable at 95 kHz and 33/210 kHz, respectively, were analyzed along with the sediment texture and benthic macro-faunal information obtained at the same locations.

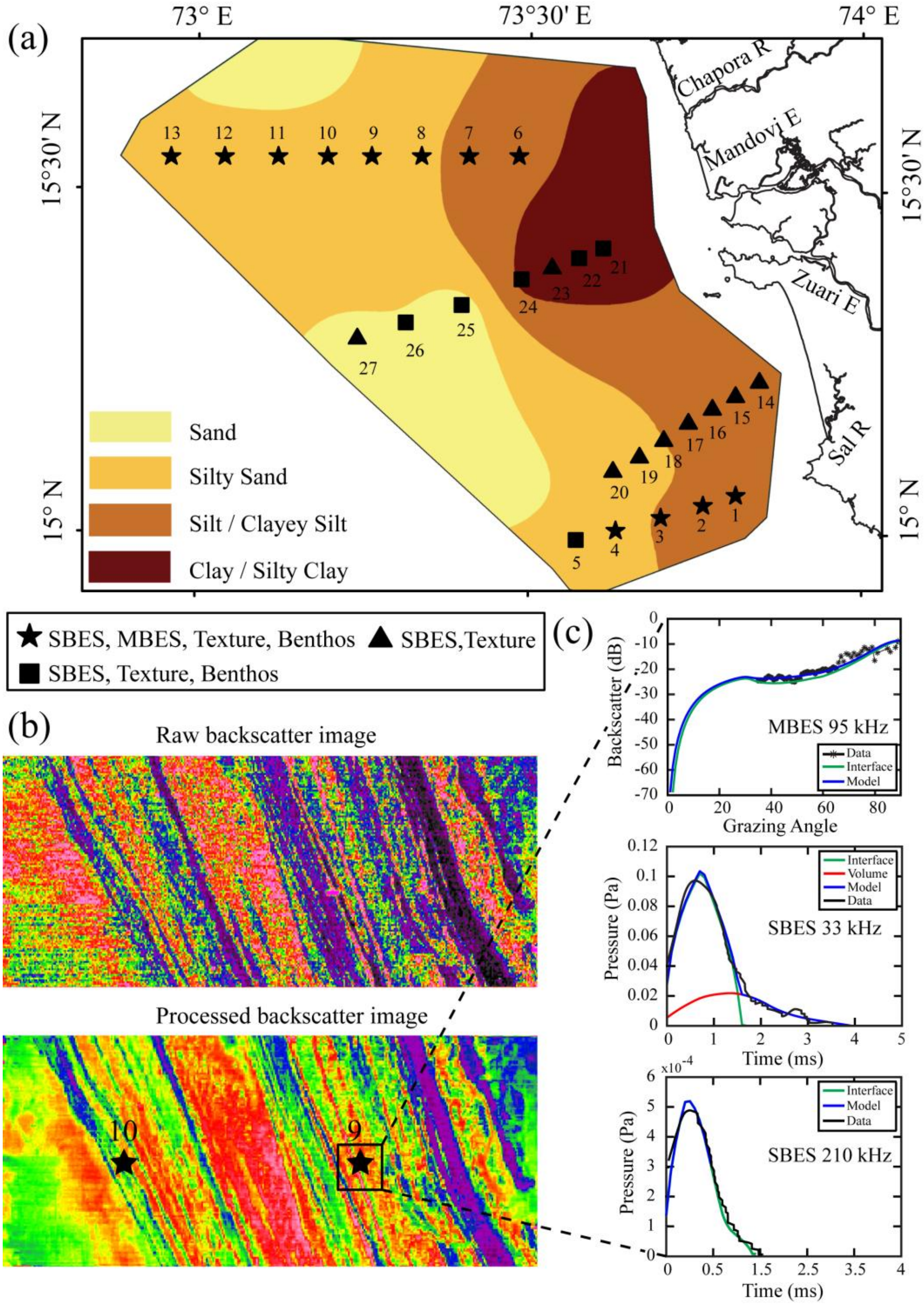

Fig. 1(a)–Shows the study area and type of data collected (modified from Haris *et al*.[6]). Panel (b) depicts the application of PROBASI algorithm to process EM 1002 MBES backscatter data. The processed SBES and MBES backscatter data used to carry out the inversion modeling are presented in (c). The inversion results are analyzed with the sediment texture and benthic macro-faunal abundance obtained at the same locations.

The results analyzed demonstrate the interrelationship among seafloor micro-roughness parameters, grain size, and benthic macro-faunal abundance[11] along the central part of the western continental shelf of India.

Materials and Methods

Acoustic data acquisition

Multi-frequency seafloor backscatter data were acquired over substrates ranging from clayey silt to sand, using calibrated SBES and MBES

(Fig. 1a). The dual-frequency (33 and 210 kHz) echo data were acquired using a hull-mounted normal incidence RESON-NS 420 SBES. The beam width of the echosounder transducer for 33 and 210 kHz is 20° and 9°, respectively, with respective pulse lengths of 0.97 and 0.61 ms. The 95 kHz angular backscatter data were acquired using EM1002 MBES. Simrad EM1002 is a phase interpolated beam-forming MBES with 128 transducer elements forming 111 beams in a semicircular array of 45 cm radius.

SBES data processing and time dependent inversion modeling

The recorded echo data were converted from binary to ASCII format within a range of −5 to +5 V prior to inversion modeling. Hilbert transformation was employed to obtain the echo envelope from the echo trace at each location. The shape of the echo envelope is generally influenced by various factors including natural variability of the seafloor, transducer heave, and noise due to echosounder instability. Therefore, several post-processing steps such as visual check, echo alignment and echo averaging were performed to obtain good averaged echo envelopes. The echo envelopes were averaged using 20 successive envelopes with 95% overlap (in a moving average sense with sequences 1–20, 2–21, and so on, utilizing all the consistent echo envelopes available in the data set). Finally, the voltage form of the aligned data was converted to a pressure signal, and the corresponding backscatter values were computed[12,13].

The bottom geoacoustic parameters suitable to discriminate seafloor types were determined by comparing the simulated data with the measured pressure signal[5]. The temporal backscatter model developed by Sternlicht and de Moustier[3] was employed to simulate the data. The model can generate the total backscatter intensity (measured at the transducer face) by summing the intensities from the water-sediment interface and sediment volume inhomogeneities. However, the interpretation of seafloor characteristics using the temporal model relies on a model-data matching paradigm that converges to a correct set of bottom parameters. The results obtained after inversion modeling were statistically analyzed, compared to the ground truth, and tested as new input parameters to conclude on model versus data performance fit[5].

MBES data processing and angular backscatter inversion modeling

EM 1002 MBES primarily measures the time average of the backscatter signal envelope in each of its 111 beams. The signal envelopes were corrected for time variable gain (TVG), predicted beam patterns, the insonified area, and gets recorded in a packet format called datagram. However, the raw data recorded by the MBES require post processing such as removal of Lambert’s law, correction of actual bottom slope, and the insonified area[6]. The necessary corrections were applied using PROBASI (PROcessing BAckscatter SIgnal) algorithm. The detailed post processing corrections have been described in Haris *et al*[6]. The processed angular backscatter data for 20 consecutive pings, varying between the incidence angles −65° to +65° were binned in equal angular bins of 1° intervals. The data was subsequently averaged over the available number of samples within each bin, and folded with respect to the normal incidence angle (Fig.1c)[6]. Generally, the backscatter of nadir has higher strength as compared to the outer swaths. Therefore, it is imperative to select a reference angle that is minimally sensitive to slope correction and absorption errors[14]. Accordingly, the backscatter values corresponding to the 40° incidence angle were utilized in the analyses[11].

The composite roughness model developed by Jackson *et al.*[2] was employed to compute geoacoustic parameters[6]. The model can simulate the total angular backscatter strength as a superposition of the incoherent surface roughness and volume scattering coefficients respectively. However, analogous to the temporal backscatter model, the interpretation of seafloor characteristics using the angular backscatter model also relies on a model-data matching procedure that converges to a correct set of bottom parameters. The results obtained after inversion modeling were statistically analyzed, compared to the ground truth as well as with the inversion results of 33 and 210 kHz obtained at the same locations[6].

Sediment sampling

Sediment samples were collected using a Van Veen grab, covering an area of 0.04 m^2 and penetration of 10 cm. About 20 g of sediment were taken from each grab sample to carry out the textural analyses using a 4.0 cm diameter core tube. The acquired sediment samples were subjected to wet sieving using a 62 µm sieve to

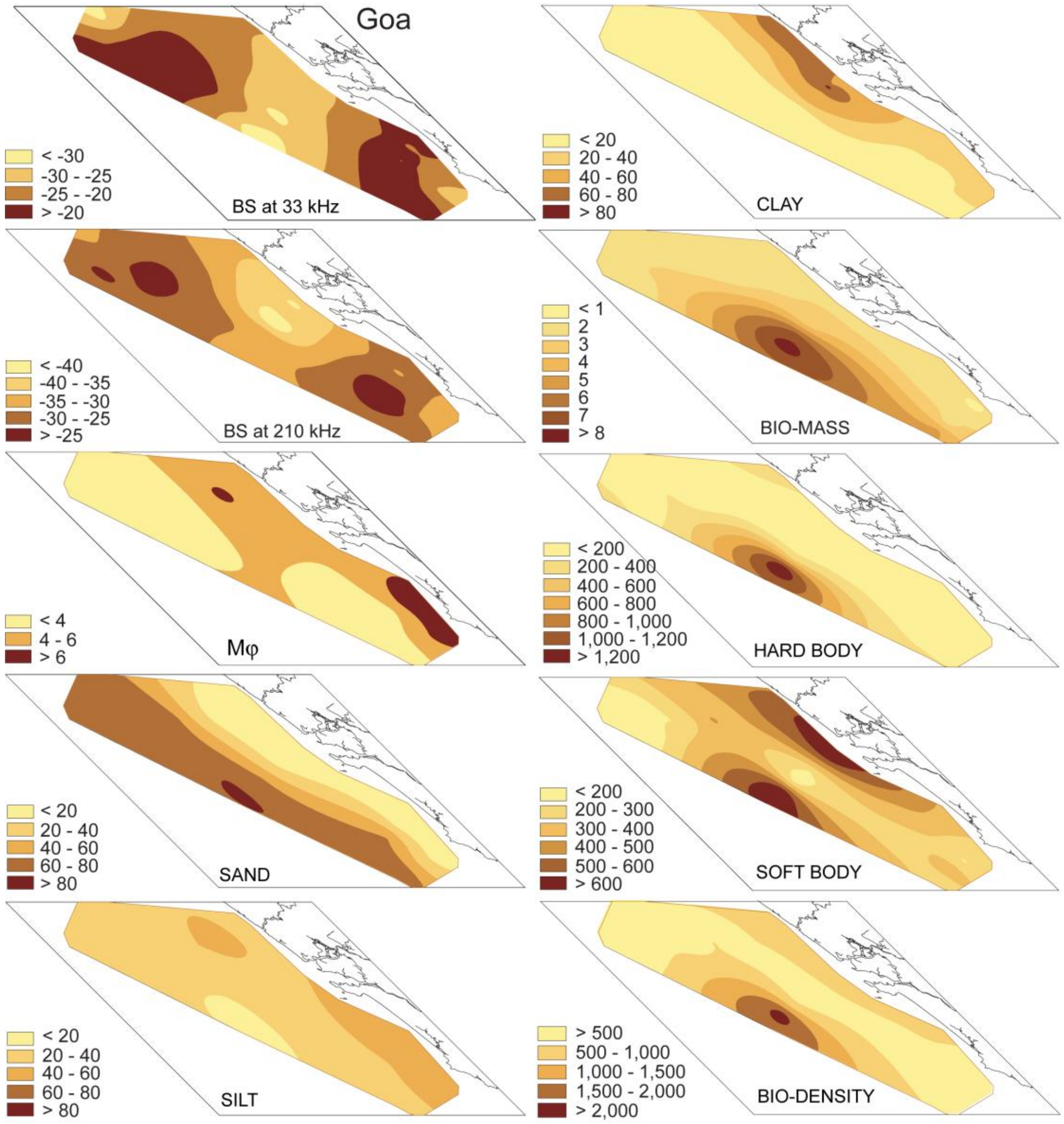

Fig. 2–GIS-based sediment distribution and benthic macro-faunal abundance map of the study area. The maps illustrate general environmental scenarios of the study region, including acoustical, physical, and biological properties.

separate the sand from the mud fraction. The size distribution of the mud fraction (< 62 μm) was measured with a Malvern laser particle size analyzer (MASTERSIZER, 2000). The size distribution of the sand fraction was determined using a standard dry sieving method. The mean grain size $M_{\varphi} = -\log_2 U_g/U_0$ (where $U_0 = 1$ mm) was 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. The organisms were sorted into major groups and counted group-wise. The specimens were identified to the lowest possible taxon. The average number of organisms from the samples was converted to number per m^{-2}. Biomass (shell included) were determined from the wet weight method after blotting and converted to g.m^{-2} (wet weight)[15]. We have grouped the benthic macro-fauna into two communities: (i) soft body infauna organisms, commonly referred as deposit feeders that include the majority of polychaete worms and associated species like nematode, oligochaetes, nemertinea, echurids and (ii) hard body epifauna organisms, commonly referred as filter feeders that include mainly bivalves and gastropods[11].

GIS based classification and PCA

The comprehensive application of Geographic Information System (GIS) has been implemented to generate spatial map of derived parameters along the study area. The Kriging technique involved in the map generation uses local data correlation structures (the variogram) to calculate the interpolation, and appropriately modeled in space from the original variable.

Principal component analyses (PCA) has been adopted to demonstrate the relationship between the measured and derived parameters. PCA is a robust statistical 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.

Results and Discussion

In the following sections, the geoacoustic inversion results derived from the MBES[6] and SBES[5] data have been compared with the sediment texture and benthic macro-faunal information. For simplicity, in the following text, silty-sand and sand sediments will be referred to as coarse sediments (with $M_\varphi < 4$); and clayey-silt and silt sediments will be referred to as fine sediments (with $M_\varphi > 4$).

Backscatter and mean grain size

The percentage distribution of sediment compositions indicates the presence of four seafloor sediment types: clayey-silt, silt, silty-sand and sand. The sediment texture was relatively coarse ($M_\varphi < 4$) in the deeper depths (60–109 m), and fine-grained sediment ($M_\varphi > 4$) was found in the shallow depth region (29–54 m) (Fig. 2). Statistically significant correlations observed among the measured and computed M_φ values demonstrates the success of inversion modeling carried out (Fig. 3). The multi-frequency inversion is advantageous because the studies[16] assessing the scattering models with the data acquired are rare so as to provide an evaluation of the model over a broader range of sediment types and frequency.

The backscatter strength from the seafloor is primarily controlled by the acoustic frequency, the acoustic impedance contrast between water and sediment, and the contributions from seafloor interface roughness as well as sediment volume inhomogeneity. Several studies[11,17,18] while comparing the backscatter response with the ground truth sediment data have concluded that the acoustically soft fine sediments ($M_\varphi > 4$) generally exhibit low backscatter intensity due to low density and sound velocity. On the flip side, the acoustically hard coarse sediments ($M_\varphi < 4$) results relatively higher backscatter intensity due to scattering from coarse particles, lower porosity, higher density and sound velocity, and greater roughness of the water-sediment interface (Fig. 4).

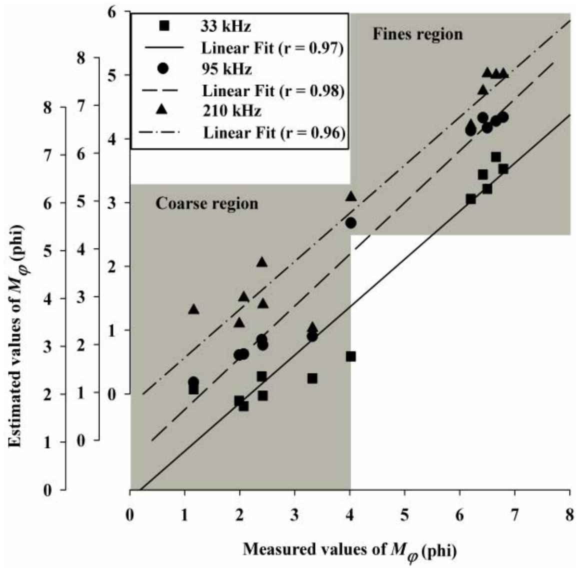

Fig. 3–Scatter plot demonstrating the success of inversion modeling carried out.

The benthic macro-fauna can compact and dilate the sediment, resulting modification in seafloor roughness, sediment density and fluctuations in the sound speed[19]. Besides, the hard body epifauna as an individual and group can scatter acoustic energy[20]. The collective biological processes might be controlling higher backscatter strength observed in the coarse sediment region with substantial occupancy of hard body organisms (Fig. 4).

Macrobenthos-sediment relationship

PCA indicates two major clustering patterns (Fig. 4). The number density of hard body organism is inversely correlated with the computed M_φ. Whereas, the soft body abundance is linearly correlated with the estimated M_φ. Two distinct feeding groups are observed from the study area: the deposit feeders in the shallow region (including polychaete worms and related soft body species like nematode, oligochaetes, nemertinea, and echurids) and filter feeders (hard body bivalves and gastropods) in deeper depths.

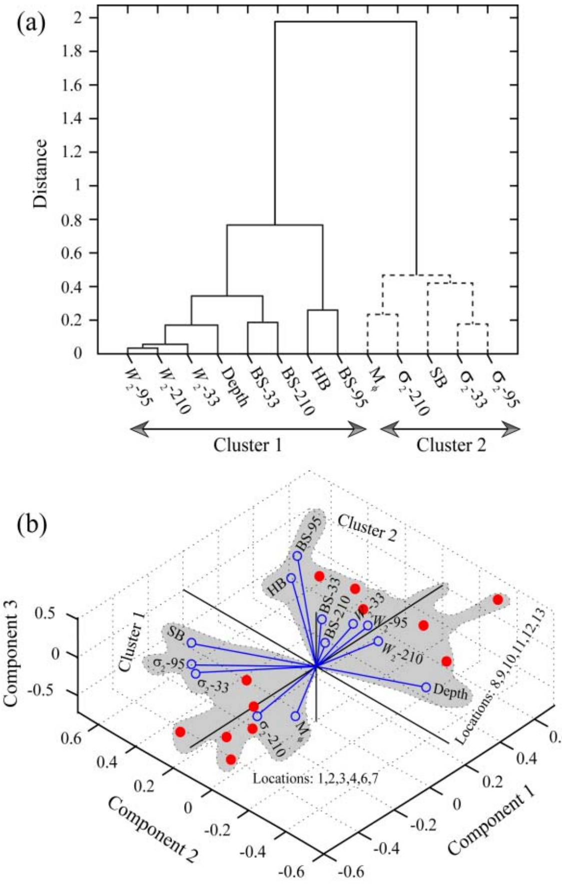

Fig. 4–The dendrogram in panel (a) and bioplot of PCA (b) illustrates the location wise clustering of measured and derived parameters. The acronym BS, SB, HB denotes backscatter, soft body and hard body benthic macro-fauna respectively.

Studies[15,21] have been conducted in past to report animal-sediment relationship along the Indian coast. Sanders[22] and Jayaraj *et al.*[21] suggested that the coarse sediment region reflects the environment with pronounced under water current activity (with filter feeder dominance). In contrast, the fine sediment region towards the shallow depth reflects the environment with feeble current. The weaker current allows the fine particles to settle down and provides an adequate source of nutrition for deposit feeders. Therefore, only a limited amount of organic matter would be available in suspension as the food source for filter feeders and inhibits them from inhabiting in such environments. The dominance of deposit feeders in the fine-sediment regions and filter feeders in the coarse sediment regions are well corroborated by the distinct trends observed in the computed backscatter and M_{φ} values (Fig. 4).

Macrobenthos-roughness relationship

The computed geoacoustic parameters[5,6] w_2 and σ_2, that account for the interplay of sediment interface and volume scattering have been analyzed with the macrobenthos abundance. The variation of geoacoustic parameters conforms to the shape of the SBES echo-envelope and MBES angular backscatter data (e.g., peak of the echo-envelope along with the width, rise, fall time, and tail part). The bioturbation occurring at the seafloor interface and sediment volume can modify the shape parameters, and the extend of bioturbation gets reflected in the computed parameters (w_2 and σ_2). The sensitivity analyses carried out on the shape of the echo-envelope data indicates lees-steep slope and reduced amplitude of the response curve with higher value of w_2. The higher w_2 has significant influence on the interface scattering and marginal effect on the tail part. The contribution of sub-bottom scattering is conspicuous near the tail of the echo-envelope with relatively higher σ_2 value. The fine sediment provinces are penetrated more deeply by the acoustic signal, consequently the sediment volume scattering increases in comparison with the interface scattering.

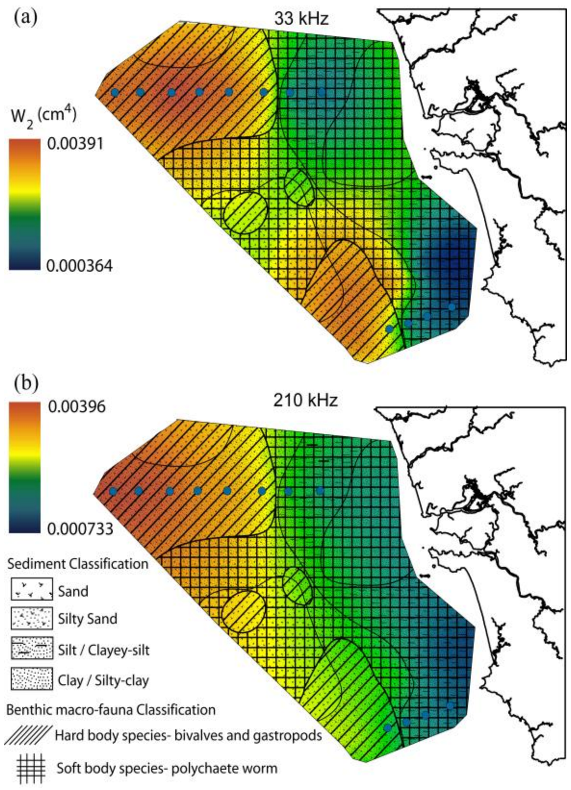

Fig. 5–GIS-based image classification representing the variation of interface roughness spectral parameter w_2 in relation to the benthic macro-fauna and sediment types at 33 (a) and 210 kHz (b).

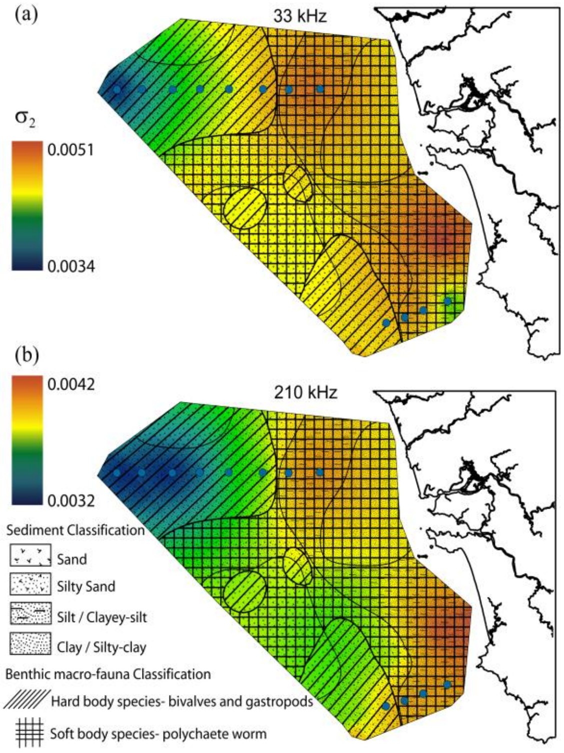

Fig. 6–GIS based image classification representing the variation of sediment volume scattering parameter σ_2 in relation to the benthic macro-fauna and sediment types at 33 (a) and 210 kHz (b).

With reference to the multi-frequency inversion modeling study carried out by Haris *et al.*[6], in the coarse sediment region, the w_2 values were restricted within the range 0.002 to 0.005 cm^4. In the fine sediment region, the w_2 values were found to be less than 0.001 cm^4. The corresponding GIS generated roughness map (Fig. 5) reveals relatively higher values of w_2 in the coarse sediment region with substantial occupancy of hard body organisms (Fig. 4). Likewise, the lower w_2 values are apparent in the fine sediment provinces with dominant soft body abundance. The average value of σ_2 computed at three acoustic frequencies[5,6] were found to be relatively higher in the fine sediment region as compared to the coarse sediment provinces. Correspondingly, GIS generated volume scattering map (Fig. 6) indicates comparatively lower σ_2 values in the coarse sediment region with significant occupancy of hard body organisms (Fig. 4). Conversely, the higher σ_2 values are evident in the fine sediment provinces with dominant soft body abundance.

The biologically active marine sediments get continually modified due to the collective activities of epifauna (hard body organisms that live on the sediment surface) and infauna (soft body organisms living within the sediment). The epifaunal activities basically include locomotion and home building that creates additional roughness at the sediment-water interface, causing relatively high interface scattering. On the other hand, the infaunal activity, including tube building is responsible for the vertical and the horizontal redistribution of solid material within the sediment volume. The process can create spatial and temporal inhomogeneities in sediment bulk properties (density, porosity, and compressibility). Such changes are mainly driven by burrowing and tube building by soft body infauna including polychaete worms. Accordingly, strong volume scattering is inevitable from the corresponding habitat region. In the present study, the high values of w_2 and σ_2 are attributed to the coarse and the fine sediment region, with the dominance of hard body epifauna and the soft body infauna respectively (Fig. 4).

Concluding comments

The multi-frequency sediment geoacoustic inversion results, derived from the MBES[6] and SBES[5] data have been analyzed to demonstrate the interrelationship among the sediment texture and benthic macro-faunal abundance. Two distinct feeding groups were observed in the coarse and fine sediment regions. The preference of hard body organisms to coarse sediment region causes the relatively high interface scattering due to the collective epifaunal activities including locomotion and home building. In the fine sediment region, the tube building infaunal activity generated by the soft body organisms creates spatial and temporal inhomogeneities in the sediment bulk properties, evidencing dominant sediment volume scattering as compared to the interface scattering.

Acknowledgements

The authors are thankful to Dr. S. W. A. Naqvi, Director, CSIR-NIO, for providing facilities to carry out this study. Financial support for this work was provided by NIOT (Ministry of Earth Sciences) under the *Ocean Acoustics Program*. The work of K. Haris was supported by the CSIR through a grant of research fellowship. This is CSIR-NIO contribution 5681.

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