SPATIAL VARIABILITY OF SURFICIAL SHALLOW WATER SEDIMENT GEOACOUSTIC PROPERTIES

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ABSTRACT

Variability of surficial sediment geoacoustic properties was determined from cores collected at eight shallow-water continental shelf regions in the U.S., Italy and Australia. Highly porous muds found in low energy environments exhibited the lowest range of values in physical and acoustic properties; mixtures of sand and shell found in higher energy environments exhibited the highest range of values. Compressional wave attenuation consistently exhibited the highest variability followed by mean grain size, porosity and compressional wave velocity. Vertical variability was generally greater than horizontal variability for all properties measured. Sediment geoacoustic properties of most coastal marine sediments are controlled by the interaction of biological and hydrodynamic processes. Biological processes tend to dominate in finer sediments, whereas hydrodynamic processes control sediment geoacoustic properties in sandy substrates. Understanding these processes in various environments not only explains the spatial distribution of sediment geoacoustic properties but leads to improvement of predictive geoacoustic models.

INTRODUCTION

Knowledge of the spatial variability of surficial sediment geoacoustic properties is important to the prediction of acoustic scattering from the sediment-water interface and to the prediction of propagation of acoustic energy through the sediment[1]. It is within this surficial zone (upper 50 cm of sediment) that the most active and rapid diagenic changes in sediment properties are found. Gradients and variability of geoacoustic properties result from dewatering caused by overburden pressure, as well as active chemical, sedimentological, biological and hydrodynamic processes which mix and alter sediment properties[2,3].

For high frequency (>10 kHz) acoustic applications, geoacoustic properties of the upper tens of centimeters must be known, whereas for low frequency applications surficial geoacoustic properties provide the initial conditions used for prediction of depth gradients of sediment physical properties[1]. Accurate values, including variability, of surficial sediment geoacoustic properties are therefore required for geoacoustic models covering the wide range of frequencies of interest to those studying underwater acoustics, marine sedimentology, geophysics and marine geotechnique.

In this paper I compare data on the spatial variability of sediment geoacoustic properties among eight shallow-water continental shelf regions in the U.S, Italy and Australia. I also discuss the relative importance of biological, hydrodynamic and sedimentological processes in determining spatial distribution of these geoacoustic properties. Results are then compared to a similar study of geoacoustic properties of three sedimentary provinces in the Venezuela Basin (3500 to 5050 m water depth).

MATERIALS AND METHODS

Replicate sediment samples were collected from eight sites along the continental shelves of the United States, Italy and Australia (Table 1). Sediment types ranged from clayey-silts found in Long Island Sound and the Arafura Sea (off northern Australia) to coarse sands off San Diego, California. All sediments were collected with 6.1 cm (inside diameter) cylindrical cores either in situ by scuba divers or from relatively undisturbed 0.25 m^2 USNEL box core samples collected from deeper sites (Washington coast and Arafura Sea). Collection, measurement and handling procedures were designed to minimize sampling disturbance and maintain an intact sediment water interface with overlying sea water. Sediment compressional wave velocity and attenuation were measured after sediments equilibrated with laboratory temperature, usually one-half to two days after collection. Temperature and salinity of the overlying water were measured with a YSI model 43TD temperature probe and an AO Goldberg temperature-compensated salinity refractometer. Compressional wave velocity and attenuation were measured at 1 cm intervals on sediments in 129 subcores using a pulse technique.

*Table 1. Collection sites, including mean values of porosity, mean grain size, compressional wave velocity (V_p-ratio) and attenuation (dB/m at 400 kHz) (*unpublished data).*

Site	Date	Water Depth (m)	Substrate type	Porosity (%)	Grain Size (ϕ)	V_p-ratio	Attenuation (dB/m)	References
Long Island Sound	XIII 80							3,4
FOAM		10	clayey-silt	73.2	7.4	0.99	-	
NWC		16	clayey-silt	77.2	8.4	0.99	-	
San Diego, CA	IV - V 82							5
fine sand		18	very fine sand	-	3.5	1.10	188	
coarse sand		18	coarse sand	-	1.0	1.15	116	
Montauk Point, NY	V 82	35	fine sand	36.6	2.1	1.14	88	6
Quinault, Washington	IV 83	49	fine sand	41.2	2.9	1.11	160	7
Charleston S.C.	VI 83	18	medium sand	37.9	1.6	1.12	292	8,*
La Spezia, Italy	XI 83							8,9
MT		17	gravel	-	-1.6	1.20	-	
ST		8	silty-clay	69.8	8.9	0.98	104	
PV		13	silty-clay	67.6	9.4	0.98	64	
AV		5	very fine sand	43.3	3.6	1.10	136	
Arafura Sea	V 84	47	clayey-sand	69.2	5.3	0.99	336	*
Panama City, Florida	IX 84							10
pre-site		18-33	fine, medium sand	39.3	1.8	1.14	216	
experimental		33	fine sand	39.0	2.6	1.13	228	

Time delay measurements were made through sediments and a distilled water reference with a Hewlett-Packard 1743A dual time interval Oscilloscope. Signals were generated by driving a Underwater Systems, Inc. (Model USI-103) transducer-receiver head with a 400 kHz, 20 volts p-p sine wave triggered for 25μs duration every 10 ms with a Tektronic PG 501 Pulse Generator and FG 504 Function Generator. Differences in time delay between distilled water and sediment samples were used to calculate sediment compressional wave velocity (Vp). Compressional wave velocity was expressed as the dimensionless ratio of measured sediment velocity divided by the velocity in the overlying water that was calculated for the same temperature, salinity and depth[11]. This ratio is independent of sediment temperature, salinity and depth and therefore ideal for comparison to other geoacoustic properties. Attenuation measurements were calculated as 20 log of the ratio of received voltage through distilled water to received voltage through sediment[12]. Values of attenuation were extrapolated to a 1 m pathlength and expressed as dB/m.

After completion of the acoustic measurements, core samples were extruded and sectioned at 2 cm intervals for determination of sediment porosity and grain size distribution. Porosities were determined by weight loss of sediment dried at 105°C for 24 hours. Values were not corrected for pore water salinity. Salt-free porosity may be obtained by multiplying values by 1.012. Sediment grain size distribution was determined on disagregated samples by dry sieving for sand-sized particles and with a Micromeritics Sedigraph and/or pipette for silt and clay-sized particles. Grain size statistics were determined using the graphic formula of Folk and Ward[13].

RESULTS

Sediment geoacoustic data were measured on 129 cores that were collected for this study at eight different sites. I have restricted the data presentation to a summary of sediment geoacoustic properties from each site together with selected graphical representations of the spatial variability of sediment geoacoustic properties. Detailed data presentation can be found elsewhere[3-10].

Sediment samples were collected from two sites in Long Island Sound. Both sites were characterized by high porosity, fine grained, low velocity sediments. At the deeper (18 m) NWC site sediments, were characterized by a uniform distribution of geoacoustic properties (Table 2) on scales of centimeters to meters with no apparent depth gradients in the upper 20 cm. Richardson et al.[3] attributed this low variability to sediment mixing by macrofaunal animals that feed on bottom deposits (bioturbation). At the shallower FOAM site (10 m) sediments exhibited a much higher variability in sediment geoacoustic properties (Table 2). This higher variability was a result of storm induced erosional and depositional events creating laminations within the upper 35 cm of sediment. These laminations, each with different values of geoacoustic properties, were preserved because sediment mixing by macrofaunal animals at the FOAM site rarely extended below the upper few centimeters of sediment[3].

The shallow water samples collected off San Diego came from two distinct sediment types: a fine sand that had lower compressional wave velocity and higher attenuation than the coarser sand over which it was migrating. Of particular interest were the significant positive gradients in compressional wave velocity and attenuation with depth (Fig. 1) for both substrate types without a concordant change in mean grain size. These gradients probably resulted from increased packing and compaction of sands with depth in the sediment.

*Table 2. Coefficient of variation (CV) of porosity, mean grain size, compressional wave velocity ratio (Vp-ratio) and attenuation, calculated for eight shallow water and one deep-sea location (*data from the upper 2 cm of sediment only).*

Site	Porosity	Grain Size	V_p-ratio	Attenuation
Long Island Sound				
FOAM	7.33	11.53	0.82	-
NWC	1.50	1.91	0.35	-
San Diego				
fine sand	-	11.75	1.16	16.41
coarse sand	-	7.42	0.97	25.73
Montauk Point, NY	3.36	6.45	0.93	15.72
Quinault, Washington	4.98	3.63	1.19	33.08
Charleston S.C.	6.28	18.84	1.03	37.76
La Spezia, Italy				
ST	6.07	3.89	0.31	36.63
PV	6.86	1.80	0.34	36.11
AV	3.11	5.42	0.85	10.05
Arafura Sea	5.81	14.56	0.51	47.26
Panama City				
presite	5.60*	36.51*	1.07	33.03
experimental	3.72	6.14	0.87	15.59
Venezuela Basin				
carbonate	2.82	11.23	0.45	19.75
turbidite	9.88	16.22	1.67	105.88
hemipelagic	3.41	4.51	0.25	23.68

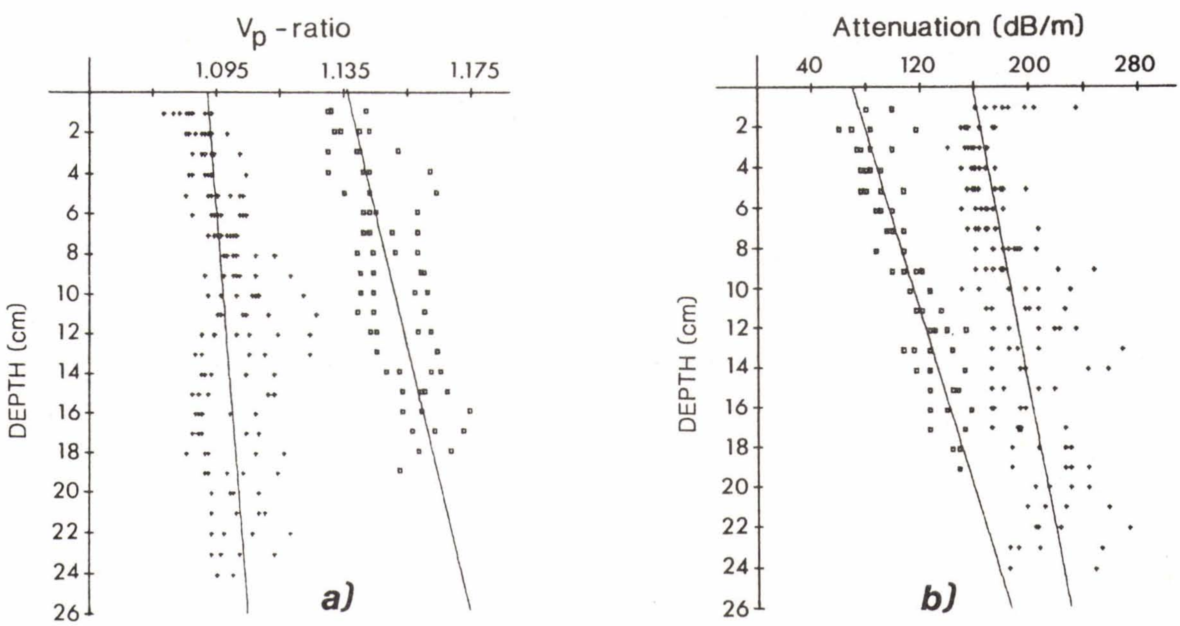

Fig. 1 Regressions of compressional wave velocity ratio (V_p-ratio) and attenuation (dB/m at 400 kHz) with depth for fine (+) and coarse (□) sand substrates found off San Diego, California.

The fine sand sediments collected in 35 m of water 25 km east of Montauk Point, Long Island, New York exhibited relatively low variability in sediment geoacoustic properties, especially attenuation. This low variability was attributed to mixing of sediments by an abundant population of sand dollars[6]. The positive gradient of compressional wave velocity with depth with little change in mean grain size was similar to gradients found in sediments from San Diego. Porosity generally decreased with depth supporting the argument that, for sand, positive gradients in compressional wave velocities can result from increased compaction. Surficial sediment samples collected within a 0.5 km^2 area around the prime collection site exhibited considerable variability in mean grain size (CV=108) because the study site was located at the base of a drowned barrier spit. At this site coarse grained lag deposits formed during the last glacial advance were covered intermittently by fine-grained sediments which were in equilibrium with current hydrodynamic conditions.

Fine sand surficial sediments collected in 50 m water depth on the continental shelf off Washington State exhibited little variation in values of geoacoustic properties from the surface to 12 cm depth (Fig. 2). Below 12 cm, the sediments had higher percentages of silt-sized particles that resulted in higher values of porosity, mean grain size, and attenuation as well as lower values of compressional wave velocity. Variability of geoacoustic properties was also highest below 12 cm depth. A high abundance of molluscan shells below 12 cm also contributed to higher variability of geoacoustic properties, especially attenuation.

Scuba divers observed two surficial substrate types in a one km^2 study area off the Charleston, S.C. coast. Fine to medium sand (mean grain size

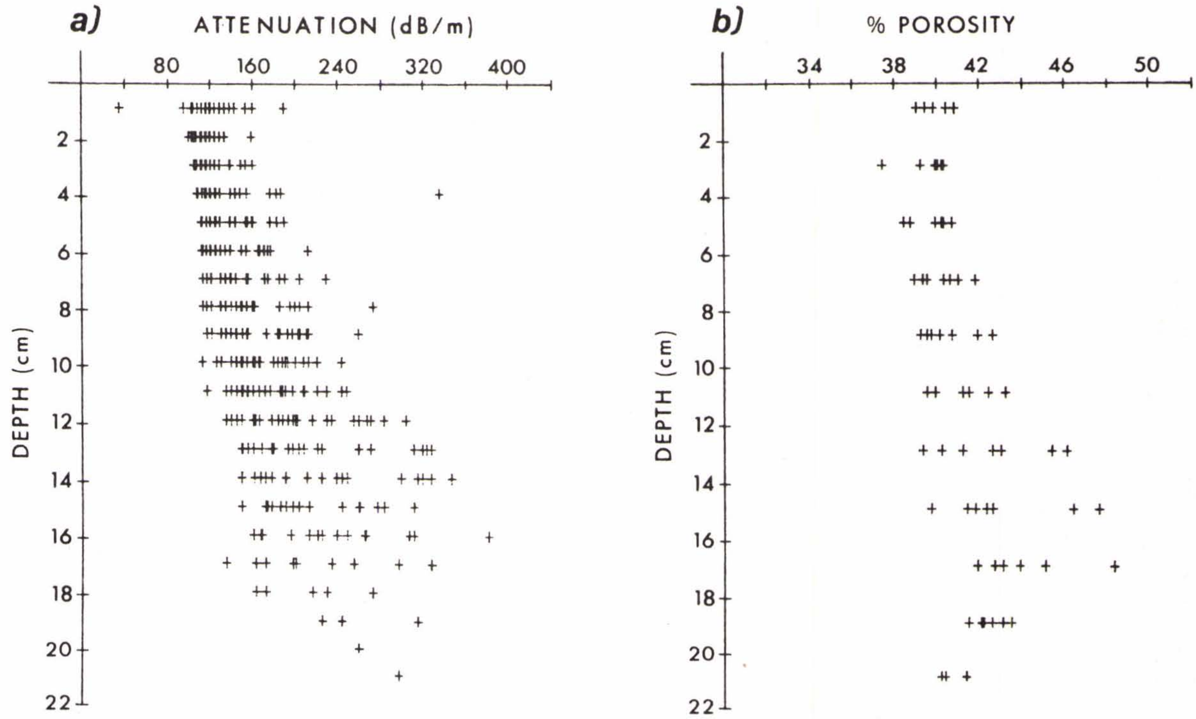

Fig. 2 Depth distribution of values of compressional wave attenuation (dB/m at 400 kHz) and porosity (%) for sediments collected in the Quinault acoustic tracking range - Washington.

1.8 to 2.2ϕ) with porosity values of 37 to 42% were found in troughs of shallow sand waves. The coarser (0.9 to 1.7ϕ) sediments on crests contained abundant shell material and generally had lower values of porosity (30 to 40%). Below 6 to 10 cm, shell material was abundant in all cores. Coefficients of variation for geoacoustic properties of the Charleston samples were higher than at most other locations (Table 2). Most of the variability at the Charleston site was associated with samples that had greater than 2% gravel-sized particles. If these samples are excluded, coefficients of variation are reduced to 0.72% for compressional wave velocity; 23.25% for attenuation; 5.19% for grain-size; and 2.20% for porosity.

Sediment samples were collected from four locations in the vicinity of La Spezia, Italy as part of an international program to compare various acoustical, geotechnical and geophysical measurement techniques[9]. Locations were chosen to include a wide spectrum of sediment types (Table 1). The Monasteroli site (MT) was located in a high energy environment next to the Ligurian coast. Sediments were composed of gravel-sized particles (75% by weight) making it difficult to collect adequate samples.

The coarser sediments (mean grain-size -1.57ϕ) probably originated from erosion of the nearby steep coastline[9]. Frequent storms winnowed finer material from the gravel sediments leaving only 0.17% silt-and clay-sized particles. Compressional wave velocity ratio (mean 1.20) and its coefficient variation (3.45%) were higher than at any other location. Porosity, mean grain size and attenuation were not accurately measured to permit the calculation of coefficients of variation. Sediments from the PV site located at the eastern entrance of the Portovenere channel were protected from physical disturbance, e.g. storms. Sediments were composed of silt and clay mixed with up to 5% gravel-sized shell particles. Compressional wave velocity and mean grain size values varied little (Table 2). However, the high coefficient of variation for porosity reflected 10 to 15% higher values of porosity found in the uppermost 4 cm of sediment. Both biological (bioturbation) and hydrodynamic processes probably maintained this higher surficial porosity. The Santa Teresa site (ST) was located in a small protected harbor on the eastern side of the Gulf of La Spezia. Samples consisted of very soft muds. Compaction of the upper 6 cm produced a negative gradient of porosity with depth without apparent change in sediment acoustic properties. The lack of vertical gradients in compressional wave velocity resulted in a low coefficient of variation. The Venere Azzurra site (AV) was located on a shallow (6 m), flat, hard-packed sandy bottom off Lerici in the Gulf of La Spezia. These well sorted and hard packed sediments had the lowest coefficient of variation for values of attenuation of any site listed in Table 2.

Twelve sediment cores were collected from a one km^2 area in the central Arafura Sea. The clayey-sand sediments contained an abundant quantity of both whole and broken gravel-sized molluscan shells (2 to 23%). The lack of orientation of shells suggested considerable biological mixing had occurred. Variability of mean grain size was a function of the patchy distribution of shells whereas variability of porosity was related to vertical gradients caused by bioturbation and by strong currents which resuspend sediments. Very high values of attenuation measured at 400 kHz (mean 336 dB/m) were a direct result of scattering of the high frequency signal from shell material. Even at 125 kHz values of attenuation were high (mean 65 dB/m) and highly variable (45.7%). Compressional wave velocity ratio appeared to be much less affected by shell material, and was controlled primarily by the clayey-sand matrix (0.989 at 125 kHz vs 0.988 at 400 kHz).

As part of a pre-site survey, 27 sediment cores were collected from a variety of sandy sites (18 to 33 m water depth) off Panama City, Florida. The upper 2 cm of sediments ranged from coarse to fine sand (0.42ϕ to 2.75ϕ) with a relatively narrow range of porosities (36.3 to 43.9%). The coefficient of variation for attenuation and compressional wave velocity were approximately the same as other sandy sites (see Table 2). As part of the acoustic experiment 15 cores were collected from a one km^2 area that had uniform surficial sediment properties[10]. As expected the coefficient of variation for all geoacoustic properties was lower than that calculated from the pre-site survey (Table 2, Fig. 3).

DISCUSSION

The data in Table 2 demonstrate that shallow-water geoacoustic properties of sediment can be quite variable on scales of a kilometer or less. Not evident from Table 2 are the spatial sources of this variation (either vertical or horizontal), the scales (cm to km) or the processes that create this variation. Understanding these relationships can increase the predictability of sediment geoacoustic properties in time and space.

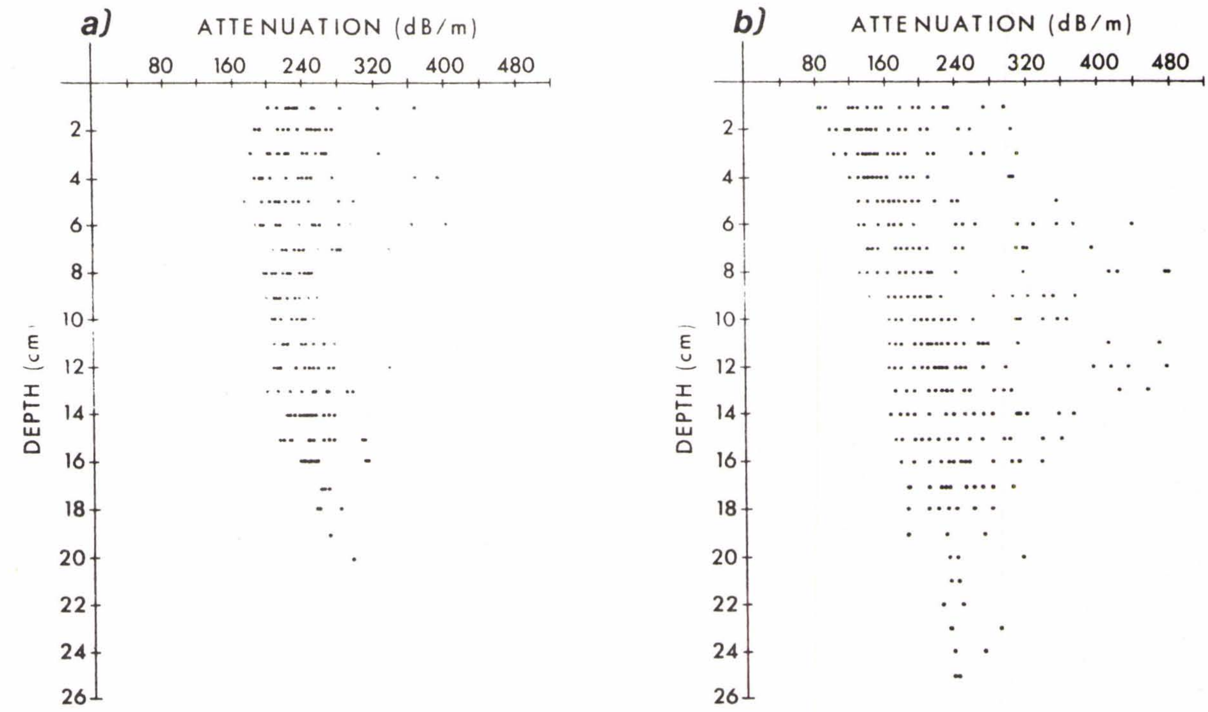

Fig. 3 Comparison of the variability and depth distribution of attenuation (dB/m at 400 kHz) for a one km² experimental site (a) and a larger presite survey area (b) off Panama City, Florida.

Several general observations can be made from the data presented in Table 2. Compressional wave attenuation consistently had the highest values of variation, and velocity the lowest. These results were expected given the previously reported range of values for compressional wave velocity and attenuation[12,14,15]. The coefficient of variation for mean grain size was generally higher than for porosity. The lowest coefficients of variation for mean grain size and compressional wave velocity were found at muddy sites, whereas attenuation and porosity exhibited the lowest coefficients of variation in fine hard packed sands. The highest variability of attenuation was found at sites with an high percentage of shell material.

Depth gradients in geoacoustic properties at several sites (FOAM, San Diego, Montauk Point, Washington and Charleston) accounted for a considerable percentage of variation of sediment geoacoustic properties. At the San Diego site compressional wave velocity and attenuation significantly correlated with depth (F-test, >0.001) for both fine and coarse sand substrates (see Fig. 1). The coefficients of variation for these properties after correction for depth gradients were 11.59 to 11.79 for attenuation and 0.72 to 0.79 for velocity. Depth gradients in geoacoustic properties at the San Diego and Montauk Point sites were the result of increased packing of sand-sized particles with depth[5,6]. At the FOAM site sediment laminations produced by storm induced erosional and depositional events resulted in the higher values of mean grain size and porosity and lowest values of compressional wave velocity between 5 to 15 cm depth in the cores[3,4]. Increased percentages of silt with depth at the Washington continental shelf site resulted in higher values of porosity and lower values of compressional wave velocity below 12 cm depth in the cores[7]. At both the Washington and Charleston sites the higher abundance of shell material with depth resulted in higher values of attenuation with depth[7,8]. Knowledge of the depth distribution of values of sediment geoacoustic properties can greatly increase predictability of these properties.

The magnitude of horizontal variation in geoacoustic properties varied considerably among sites. At the FOAM site in Long Island Sound horizontal patchy distribution of animals resulted in considerable variation in geoacoustic properties on scales of 10 to 100 meters[4]. At San Diego, sediments were classified as fine and coarse sands based on a mosiac created from overlapping tracks of side-scan sonar records[5]. Knowledge of the distribution of these two substrate types greatly reduced coefficients of variation of geoacoustic properties used in correlations with the values of acoustic bottom backscatter[16]. Side-scan mosaics from the Charleston, S.C. and Panama City sites also indicated considerable spatial variability in sediment types. The improved predictability of sediment geoacoustic properties for the Panama City site is clearly demonstrated in Table 2. At the Charleston site both horizontal and vertical variations in sediment geoacoustic properties must be taken into account to improve the predictability of sediment properties. Large scale horizontal variation, such as found in data collected from the Gulf of La Spezia, can usually be accounted for by utilizing detailed sediment distribution maps which are available for many continental shelf regions.

Table 3. Dominant factors affecting geoacoustic properties of sediment (xx = very important; x = important).

Experiment	Hydrodynamic Processes	Biological Processes	Relict (Inherited) Features
Long Island Sound	x	xx	
San Diego CA	xx		x
Montauk Point	x	x	xx
Quinault, Wash	xx		
Charleston S.C.	xx	x	x
La Spezia, Italy	xx		xx
Arafura Sea	x	xx	x
Panama City, Fl.	xx	x	

Sediment geoacoustic properties of many coastal marine sediments are controlled by the interaction of biological and hydrodynamic processes[3]. Table 3 presents the relative importance of these processes as well as that of relict (inherited) features in determining values and variability of sediment geoacoustic properties. Bioturbation (mixing of sediment by deposit-feeding animals) tends to reduce horizontal variation in sediment physical properties especially in fine grained sediments (NWC, Arafura Sea). The vertical gradients created by bioturbation are usually restricted to the upper 10 cm and are predictable on a seasonal basis given knowledge of biological processes present. A high abundance of tube dwelling species tends to stabilize the sediment surface, thus preserving the spatial variability of geoacoustic properties (FOAM). In fine sediment where the dominance of hydrodynamic and biological processes alternate horizontal and vertical variability is great and predictability poor (FOAM).

In sandy substrates, surface deposit feeding species, such as sand dollars, tend to reduce horizontal variability[5]. Feeding also reduces packing in the upper few centimeters increasing porosity and decreasing compressional wave velocity (Montauk Point, Panama City). At Montauk Point sand dollars were so abundant that they acted as surface point scatterers of acoustic energy[17]. The presence of surface and buried shell material contributes to considerable fine scale variation of geoacoustic properties (Quinault, Charleston, Arafura Sea and Panama City sites). The high values and variability of compressional wave attenuation associated with shell material are due to scattering from the shells as opposed to the intrinsic absorption described by Hamilton[12]. The distribution of shells in the sediment is controlled by both biological and hydrodynamic processes.

The random distribution and lack of preferred orientation of shells at the NWC and Arafura Sea sites suggests biological mixing processes were dominant, whereas hydrodynamic mixing processes control the distribution of shells at sandy sites (Charleston, Quinault and Panama City).

Large scale variability is generally controlled by hydrodynamic processes acting on given relict features. At the San Diego site a recently deposited fine-grained sand was found to be migrating over a coarser-grained offshore Pleistocene deposit[5]. At the Montauk Point site a light colored fine grained sand of modern origin discontinously covered a reddish granular sediment which was a lag deposit formed by the erosion of a drowned Pleistocene barrier spit[6]. At both locations the sand of modern origin was in dynamic equilibrium with recent storm events, whereas the coarser Pleistocene deposits were in equilibrium with winter storm events.

Hamilton and Bachman[14] presented data on geoacoustic properties from 340 sediment samples collected on the continental shelf and slope. They classified sediments into nine groups based on grain size. The coefficient of variation for porosity (range 5.0 to 13.8%; mean 10.3%) and compressional wave velocity ratio (0.7 to 3.2%; mean 2.3%) were much greater within those nine sediment classes than for the individual sites included in this study (Table 2). Direct measurements of geoacoustic properties are therefore preferred to predictions based on sediment type despite considerable fine-scale variability of geoacoustic properties demonstrated in this paper.

Briggs et al[18], using the same techniques employed here, characterized sediment geoacoustic property variability for three sedimentary provinces in the Venezuela Basin (3450 to 5050 m water depth) (see Table 2). Most of the variability was associated with vertical gradients of geoacoustic properties (cm) as opposed to horizontal variability (on scales of cm to km)[18]. As would be expected in the deep sea coefficients of variation for the carbonate and hemipelagic sites were lower than at most shallow-water sites, whereas the turbidite site had very high coefficients of variation. This variability resulted from the presence of alternating layers of pelagic and terrigeneous sediments. This study indicates the importance of considering the variability of geoacoustic properties for geoacoustic modelling of both deep-sea and shallow water sediments.

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