Vertical Porosity and Velocity Fluctuations in Shallow-Water Surficial Sediments and Their Use in Modeling Volume Scattering

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Abstract

Variability in sediment porosity and velocity creates volume scattering which is a parameter used in high-frequency scattering models. High-resolution vertical profiles of sediment porosity and compressional wave velocity collected from 17 diverse sites on continental shelves are used to calculate vertical autocorrelation functions. Porosity and velocity fluctuations in the upper 20-35 cm of sediment exhibit correlation lengths which are highly variable. The variance of the porosity fluctuations varies with sediment type. Data comparisons indicate that fluctuations in sediment porosity are due to biological and sedimentological processes and fluctuations in sediment velocity are due to hydrodynamic processes.

1. Introduction

Recent field work in the field of high-frequency acoustics has focused attention on the potential contribution of sediment volume scattering to bottom backscattering from a sea floor lacking significant interface roughness [1]-[5]. Failure of acoustic models to accurately predict high measured levels of backscattering at small grazing angles has been attributed to lack of consideration of sediment volume scattering [1], [4], [6]. Scattering from the sediment volume is created by fluctuations in sediment density or sound velocity, and Hines [7] and Jackson *et al.* [8] have derived models for predicting acoustic backscatter from the sediment volume. In each approach, characterizing the fluctuations in sediment porosity within the sediment fabric and assessing the variance of these fluctuations are essential for accurate model predictions. The variance of porosity fluctuations is used to address scattering magnitude and the correlation lengths of these fluctuations are used to determine the frequency and grazing angle dependence of the backscatter. The model of Jackson *et al.* [8] employs the correlation length derived from the sediment sound velocity and density fluctuations as model parameters.

The correlation length associated with sediment density and sound velocity fluctuations has been invoked as a physical parameter for volume scattering models by a number of authors [7], [9]-[12]. In each case, lack of sufficient physical property data forced the authors to extrapolate meager existing data and make assumptions in order to arrive at a value for correlation length. In the absence of actual physical measurements, Nolle *et al.* [9] and Hines [7] assume correlation lengths are related to mean grain size (in relation to the ensonifying wavelength). Moreover, Hines allows the porosity variance to be a free parameter in his model so as to fit the model to the data. Lyons *et al.* [4] uses input parameters estimated from core data, but relies on only one core as ground truth for each sediment type.

Fortunately, a large body of data on sediment porosity and compressional wave velocity does exist for a variety of sediment types as a result of the Naval Research Laboratory (NRL) shallow-water high-frequency and coastal benthic boundary layer programs. Since 1982, NRL scientists have collected physical and geoacoustic property data to support high-frequency field experiments in sandy and muddy sediments. Sediment porosity and compressional wave velocity as well as sediment grain size have been measured vertically at regular, closely spaced intervals from numerous diver-collected cores and boxcores in order to ascertain sediment variability. Geoacoustic data collected by NRL can be used to calculate parameters integral to the volume scattering models of Hines and/or Jackson: correlation functions of sediment porosity and velocity fluctuations, and variances of sediment porosity and velocity fluctuations.

2. Methodology

Collection of cores was accomplished with the goal of ascertaining the variability of surficial geoacoustic properties over a wide area selected as an experiment site. The locations of core collection were chosen randomly within the site to ascertain spatial variability of the parameters in the vertical dimension, yet be representative of the horizontal spatial variability throughout the site.

Cores on which geoacoustic and physical property measurements were made were collected with 6.1-cm diameter polycarbonate plastic cylindrical core liners. Each core was bevelled at one end to facilitate the careful manual penetration into the sediment. Cores were capped at both ends immediately upon collection to retain the water overlying the sediment and kept in an upright position during transport to the laboratory for analysis. Collection, measurement, and handling procedures were designed to minimize sampling disturbance and to maintain an intact sediment-water interface within the core samples. Of the 17 experimental sites, five sites were sampled from boxcores (Montauk Point, Quinault Range, Arafura Sea, Straits of Juan de Fuca, and Russian River), one was sampled by probes in diver-collected box cores (Long Island Sound), and the rest were sampled directly by divers [13]-[16].

Measurement of compressional wave velocity was made within 24 hours of collection, once the samples had equilibrated with laboratory temperature. Sediment compressional wave velocity was measured at 1-cm intervals using a pulse technique [15]. The probes used to measure sound velocity in box cores were piezoceramic transducer/receivers operated at a frequency of 70 kHz.

Samples were extruded from sediment cores upon completion of acoustic measurements and sectioned at 2-cm intervals (1-cm intervals in cores from L.I. Sound) to determine sediment porosity and grain size distribution. Porosity was determined from weight loss of sediment dried at $105^{\circ}C$ for 24 hours. Sediment grain size was determined from disaggregated samples by dry sieving for sand-sized particles and by use of a Micromeritics Sedigraph for silt- and clay-sized particles when samples were collected from muddy environments.

The length of the sediment within the cores varied between 9 and 48 cm, depending on the sediment type. The acoustic frequencies at which the models are employed dictate that the length of the cores need only extend to the acoustic penetration depth and the number of measurements made from the cores result in increments corresponding to at most half a wavelength in order to accurately and usefully derive the correlation length. However, only the uppermost 20 to 30 cm of most shallow-water sediments are penetrated and allow reradiation back to the receiver at these high-frequencies (20-180 kHz). The one- and two-cm increments over which the measurements were made are sufficient to resolve fluctuations capable of scattering sound energy over most of the range of relevant acoustic wavelengths (1.5-7.5 cm). To avoid the problems involved in calculating the correlation function for essentially a truncated series of data, the first-order autoregressive model of Diggle [17] for analysis of a large number of relatively short series of data is used. Because of the short spatial series, the autocorrelation coefficent is estimated by Burg's algorithm [18]. Correlation length of a data sequence was calculated after Yaglom [19] by

$$l = \left(\frac{1}{2} + \frac{\phi_1}{1 - \phi_1} \right) \Delta z, \tag{1}$$

where l is the correlation length, ϕ_1 is the autocorrelation coefficient and Δz is the sampling interval for the porosity and velocity fluctuations.

Although the NRL data were measured at 1- or 2-cm intervals, the assumption that the fluctuations have a correlation length of 1 cm or less was tested by the following procedure. All core data were separated into groups corresponding to location and sediment type. A linear regression was performed on each core to remove any trend due to depth gradients of sediment porosity or sound velocity. The residuals from each core were analyzed to determine if the residuals could be considered to be uncorrelated "white noise" as opposed to the alternative hypothesis, namely, that the residuals were generated by a first-order autoregressive process. If the residuals can be characterized as white noise, then the correlation length is equal to or less than the measurement interval. The Durbin-Watson test at the $\alpha < 0.05$ level of significance was used to choose between the two hypotheses. For sample sizes less than 15, a Monte-Carlo method (explained on p.304-305 by Conover [20]) was used to determine the percentage points for the Durbin-Watson statistic.

3. Results and Discussion

All environmental data were collected from diverse experiment sites located on or proximal to the continental shelf. The environments vary from a very fine sand off a beach near La Spezia, Italy at 6 m water depth to a clayey silt in the Juan de Fuca Canyon at 280 m water depth. Some sites exhibit more than one type of sediment and these sites are subdivided as to sediment texture in Table 1. Variances of the sediment porosity and sound velocity at each experimental site and sediment type reported in Table 1 are expressed as the mean of the individual variances from each core rather than a collective variance because the vertical variations of sediment velocity and porosity at any one point are of interest. From the sediment porosity and sound velocity data, correlation functions, and correlation lengths can be derived.

Experimental Site	Sediment Type	n	s_V^2	s_β^2
Long Island Sound	silty clay	3	51.72	0.0008
	clayey silt	3	137.54	0.0020
Mission Bay, CA	fine sand	10	247.63	—
	coarse sand	7	789.60	—
Montauk Point, NY	fine sand	2	198.20	0.00004
Quinault Range, WA	fine sand	7	233.73	0.0003
Charleston, SC	medium sand	10	169.48	0.0003
La Spezia, ITALY	silty clay	2	14.94	0.0023
	very fine sand	1	443.04	0.0007
Arafura Sea, AUSTRALIA	clayey sand	8	31.87	0.0016
Panama City, FL (I)	fine sand	13	226.77	0.0002
Panama City, FL (II)	coarse sand	4	192.89	0.0004
Panama City, FL (III)	coarse sand	18	428.49	0.0003
	fine sand	6	127.69	0.0002
	medium sand	2	153.64	0.0002
Jacksonville, FL (I)	medium sand	9	249.19	0.0001
Jacksonville, FL (II)	shelly sand	13	1180.57	0.0010
St. Andrew Bay, FL	clay	2	0.58	0.00003
	fine sand	2	19.29	0.00005
Straits of Juan de Fuca, WA	silty fine sand	4	144.12	0.0007
	medium sand	4	475.59	0.0004
	silty sand	8	1229.16	0.0026
	silty clay	4	5.33	0.0008
	clayey silt	4	8.24	0.0007
Russian River, CA	clayey silt	12	61.71	0.0015
Eckernförde Bay, FRG	silty clay	20	28.52	0.0002
Key West, FL	sand-silt-clay	11	100.49	0.0020
	sand-silt clay	4	120.10	0.0027
	coarse sand	2	606.00	0.0003

Table 1: Sediment type, number of sediment cores collected (n) and variances of compressional wave velocity (s_V^2) and porosity (s_β^2) at the 17 experimental sites. (velocity variance is expressed as $(m/s)^2$; porosity variance is expressed as the square of the fractional porosity).

3.1. Correlation Functions

Frequency and grazing angle dependence in the volume scattering are determined by the correlation function of acoustic impedance fluctuations in the sediment [7]. Because impedance is the product of sediment density and sound velocity, measurements of both of these parameters can be used to calculate a correlation function. Porosity is used in the calculations instead of density because of the direct linear relation between density and porosity [15]. The data presented here are estimates that assume isotropy in the vertical and horizontal distribution of inhomogeneities.

Estimates of autocorrelation functions are made for sediment porosity and sound velocity fluctuations and examples are presented in Figs. 1-3. Due to the model chosen, autocorrelation functions derived from the sediment porosity and velocity data exhibit an exponential decay. Correlation functions having autocorrelation coefficients which did not pass the Durbin-Watson test for white noise residuals are not plotted. Most data series prove to be positively correlated. The majority of data series with uncorrelated, white noise for the least-square residuals are porosity measurements made at 2-cm intervals. Thus, many of the fluctuations of porosity may have correlation lengths less than 2 cm. The exponential autocorrelation function $R(\tau)$ is calculated as

$$R(\tau) = \phi_1^{\tau}, \tag{2}$$

where τ is the lag value in cm. The first-order autocorrelation coefficient ϕ_1 is evident in the figures as the value of the autocorrelation function at lag 1 cm.

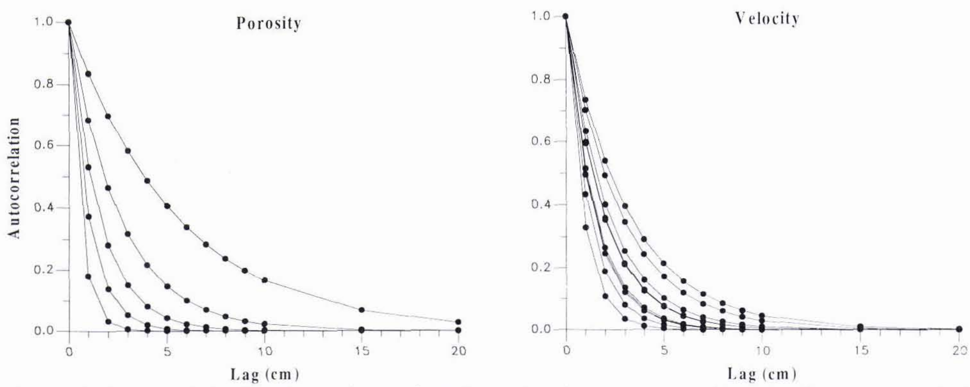

Figure 1: Autocorrelation functions estimated from fluctuations in sediment porosity and sediment sound velocity for cores collected in the Arafura Sea.

Figure 1 shows the autocorrelation functions for the sediment porosity and sound velocity data collected from the Arafura Sea. Autocorrelation functions calculated for velocity fluctuations exhibit steeper decay than those calculated for porosity fluctuations. The difference in the decay of the functions is probably due to the bimodal grain size distribution of the sediments. Sediments at the site are essentially sand- and gravel-sized particles (averaging 55% of sample weight) embedded in a silty clay matrix. Variation in mean grain size within the site is due to differences in proportions of coarser components. The coarse material consists of sand- and gravel-sized mollusk shells, shell fragments, and carbonate rocks. Sediment sound velocity exhibits little variability, whereas porosity and mean grain size exhibit much greater variability [3]. The relative constancy of the velocity data is indicative of the homogeneous silty clay matrix supporting the carbonate inhomogeneities. In contrast, the inhomogeneities which are embedded in the matrix create the variability in porosity and grain size. Hence, the autocorrelation functions derived from porosity fluctuations exhibit a wider spread of decay rates and associated correlation lengths than those derived from velocity fluctuations.

Autocorrelation functions calculated for measurements of Eckernförde Bay sediment are displayed in Fig. 2. The nature of the sediment porosity fluctuations yield autocorrelation functions which decay rapidly and are clustered together, indicating small correlation lengths. Eckernförde Bay sediment is a silty clay with high porosity and high concentrations of organic matter. Fluctuations in porosity, however, are confined to the uppermost 1-2 cm of sediment where the deposit-feeding animals flourish in a thin zone restricted by oxygen availability [21]. Below this oxygenated layer, the sediments exhibit strong chemically reducing conditions which inhibit the activities of most animals that cause porosity fluctuations. Sediment sound velocity fluctuations yield autocorrelation functions with divergent decay rates. The bay is open to the Baltic Sea to the east and the shallow depth allows the sediments to be subject to storm-induced sediment transport events. The sediment structure is characterized by coarser laminae deposited by storms [22]. Fluctuations in sediment sound velocity reflect the presence of these laminae and the autocorrelation functions diverge into three groups corresponding to fluctuations with correlation lengths of approximately 1, 2.5 and 10 cm.

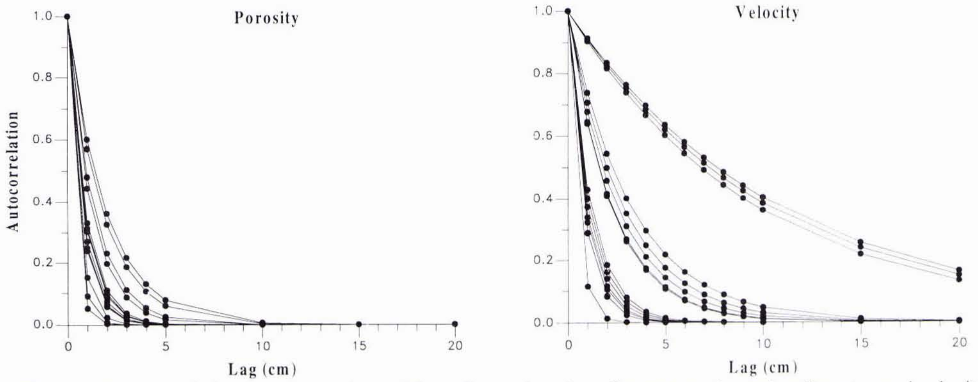

Figure 2: Autocorrelation functions estimated from fluctuations in sediment porosity and sediment sound velocity for cores collected in Eckernförde Bay.

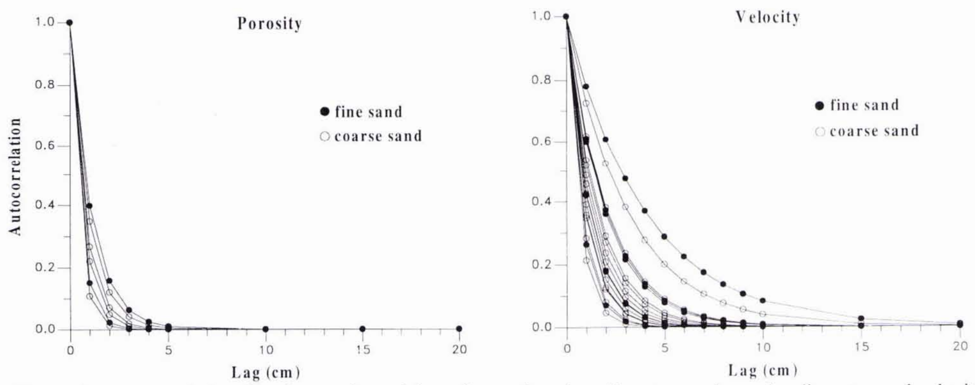

Figure 3: Autocorrelation functions estimated from fluctuations in sediment porosity and sediment sound velocity for cores collected at the Panama City (III) site.

A range of sediment grain sizes from the Panama City (III) site are represented in the autocorrelation functions displayed in Fig. 3. Porosity fluctuations in coarse and fine sands yield autocorrelation functions that decay rapidly without exception (porosity data from medium sand did not survive the Durbin-Watson test). There is no discrimination in terms of decay rate between the two sediment types. Generally, sands produce porosity autocorrelation functions with rapid decay rates and resultant short correlation lengths. Sediment sound velocity fluctuations in fine, medium and coarse sands from the Panama City (III) site yield autocorrelation functions with various decay rates, but no divergence into separate decay rates according to grain size.

The correlation lengths corresponding to each autocorrelation curve are plotted as a function of mean grain size of the sediment from each experiment site in Fig. 4. The data in Fig. 4 reveal the greatest amount of variation in the correlation lengths occurs in porosity measurements made in muds consisting of mixtures of sand, silt and clay (5 to 7 ϕ). This is not an unexpected result but indicates that stable predictions of density fluctuations in these type of sediments may be difficult to achieve with reasonable confidence. Porosity measurements made in coarser grained sediments ($< 5\ \phi$) exhibit the least variation in correlation length. There is no discernible trend related to grain size in the correlation lengths for velocity measurements plotted in Fig. 4, but values of correlation lengths are smaller than calculated for porosity measurements. Values of velocity correlation lengths are smaller than porosity correlation lengths due chiefly to the smaller increment over which velocity is measured. A higher level of correlation in velocity measurements may be explained by the ability of the autocorrelation function to resolve repeating patterns at correlation lengths less than 2 cm when the increment is only 1 cm.

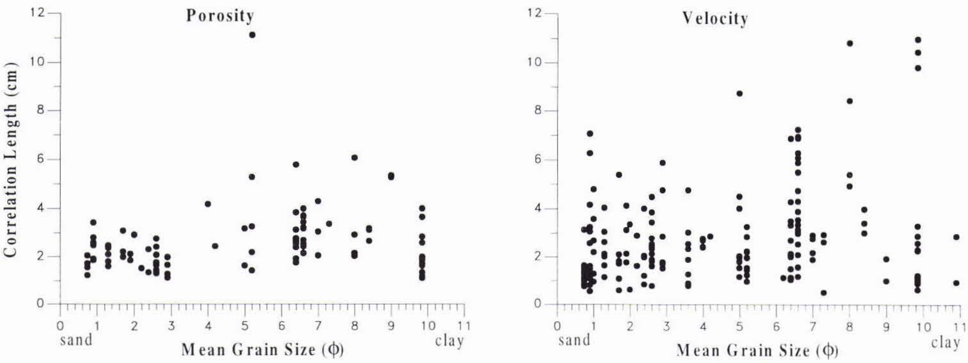

Figure 4: Plots of correlation length as a function of mean grain size (ϕ) calculated from porosity fluctuations and sound velocity fluctuations.

3.2. Parameter Variance and Sediment Type

The variances of sediment porosity and sound velocity define the nature of the impedance fluctuations in the sediment and these impedance fluctuations are responsible for the scattering of the sound from the sediment volume. Values for sediment sound velocity and porosity variances are somewhat interdependent and are indicative of particular sediment types. Values given in Table 1 are plotted in two-dimensional variance space in Fig. 5. Some experimental sites exhibit high values for porosity variance, but low values for velocity variance. Other sites exhibit low values for porosity variance, but high values for velocity variance. Generally, the former sites are muds and the latter sites are sands. The dashed lines demarcating the four regions in Fig. 5 are arbitrarily located, but effectively illustrate the pattern created by the distributions of the two variances. The parabolic relationship between sediment compressional wave velocity and porosity depicted in Richardson and Briggs [13] explains some of the pattern of high variance from one parameter paired with low variance from the other parameter: low porosity variance and high velocity variance is typical of the nearly vertical segment of the parabola, high porosity variance and low velocity variance is typical of the flattened segment of the parabola.

Those sediments having low variances in both velocity and porosity are unlikely to exhibit significant volume scattering. The three sites exhibiting low values for variance in sound velocity and sediment porosity are from St. Andrew Bay in Panama City, Florida and Eckernförde Bay, Germany. One sediment is a well sorted, fine sand which is relatively homogeneous and loosely packed since it is under the influence of strong oscillatory tidal currents. The other two sediments are muds with low rigidity and high organic content from protected embayments. The sediments from the protected embayments lack heterogeneities due to the hydrodynamically quiescent environment and the resultant anoxic conditions which reduce biological disturbances of the sediment fabric. Backscattering strengths from Eckernförde Bay are in fact anomalously high for muds due to the scattering from a methane-gas-bubble layer 1 m below the sediment surface [23]. The variance data presented here, however, are indicative of the upper 35 cm of sediment which is devoid of methane gas bubbles and relatively homogeneous.

Sediments having high variances in both parameters, however, are very likely to exhibit volume scattering. Sites located in the upper right corner of Fig. 5 are either sands with shell hash mixed in the sediment matrix or mixtures of silt and sand or silt and clay. Backscattering levels measured from three of the sites in this corner of Fig. 5 are quite high [2], [24].

Those sites exhibiting high variance in sediment porosity but low variance in sediment sound velocity are muds with inhomogeneities such as shell hash or animal burrows [3]. Backscattering levels measured from the Arafura Sea, the California coast off the Russian River, and approaches to the Strait of Juan de Fuca are all anomalously high for muds [3], [24]. The sands in the upper left corner of Fig. 5 are mixed with larger fragments of shells or other carbonate debris. Some of the elevation in variance values in these sediments are due to measurement error caused by scattering of the high-frequency sound by shell fragments (Richardson and Briggs, 1993). Nevertheless, scattering of sound from the sediment volume is characteristic of sediments in this region of the plot.

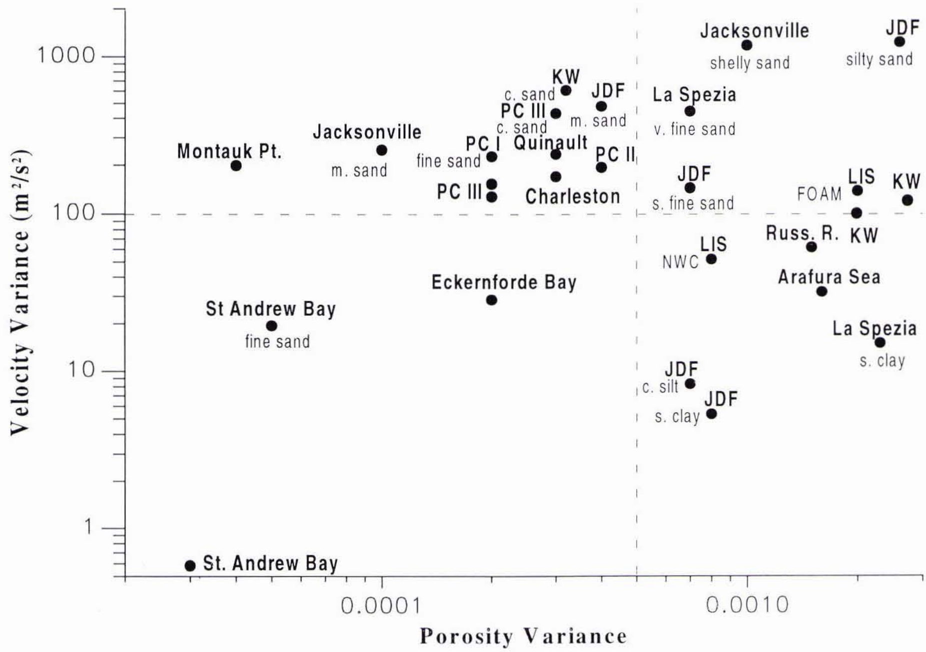

Figure 5: Plot of sediment sound velocity variance *vs.* sediment porosity variance for various experiment sites investigated.

Processes active on the continental shelf which tend to increase the variance of of the sediment porosity are primarily biological and sedimentological. Burrowing organisms such as polychaete worms and thalassinoid shrimp increase sediment porosity by building and maintaining irrigated tunnels within the sediment fabric. Sea cucumbers and heart urchins create a high-porosity, open sediment fabric by their ingestion and defecation of sediment as they burrow [25]. The presence of coarse shell hash layers within the sediment fabric decreases sediment porosity. Incorporation of mollusk shells in sediment fabric occurs during burial of coarse lag deposits by sedimentary events. Burial may occur through gradual or catastrophic settling of suspended material or migration of sand ripples over accumulations of coarser shells or shell fragments. The presence of burrows, reworked sediments and shells within the sediment fabric increases variance in porosity.

Variance of sediment sound velocity increases primarily as a result of hydrodynamic processes. Increasing fluid stress on the bottom caused by either oscillatory or unidirectional currents winnows the finer sediments and leaves coarser sediment behind. The episodic nature of hydrodynamic stress events, varying from regular tidal periods to occasional storms, creates layers of coarser sediments with higher values of sound velocity. Sites associated with higher values of velocity variance near the top of Fig. 5 are characteristic of higher stress regimes than sites associated with lower values of velocity variance. Hydrodynamic conditions vary from a quiescent lagoon in St. Andrew Bay at the lower left quadrant of the figure to continental shelf sediments subjected to winter storms at the Russian River, Charleston, Quinault, and Jacksonville sites at the upper portion of the figure.

4. Summary

Measurement of physical properties such as sediment porosity and density at small intervals downcore identifies inhomogeneities potentially creating sediment volume scattering. Fluctuations in sediment compressional wave velocity and sediment density are the most effective indicators of sediment fabric inhomogeneity because fluctuations in these two properties define sediment impedance differences.

Correlation functions derived from vertical gradients of sediment porosity and sound velocity are parameters determining the frequency and grazing angle dependence of sediment volume scattering in some models [4], [7]. The variance of sediment porosity and sediment sound velocity is a parameter determining volume scattering. Correlation length and variance of physical parameters depend on sediment type and the processes (deposition, transport, bioturbation) in effect at the particular location. Sediments with uniform sediment size tend to exhibit stable estimates for correlation length of sediment property fluctuations. Conversely, sediments with a wider range of grain sizes or bimodal grain-size distributions exhibit higher variance of the sediment sound velocity and diverse estimates for correlation length.

Although values for sediment sound velocity and porosity variances are somewhat interdependent, their relationship to each other provides information about sediment type and processes acting upon the sediments. Sediments having low variances in both velocity and porosity are unlikely to exhibit significant volume scattering. Sediments having high variances in both parameters are very likely to exhibit volume scattering. Sediments exhibiting contrasting magnitudes in variances of porosity and sound velocity are sediments containing inhomogeneities or exhibiting bimodal grain-size distributions. Although biological, sedimentological and hydrodynamic processes do not act exclusively, certain generalizations are apparent in the continental shelf data: biological and sedimentological processes increase the porosity variance, whereas hydrodynamic processes increase the sound velocity variance.

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