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# ON THE USE OF ACOUSTIC IMPEDANCE VALUES TO DETERMINE SEDIMENT PROPERTIES

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## 1. INTRODUCTION

Numerous systems have been developed over the past 25 years for remote classification of sediments. The generation of acoustic impedance as a function of depth is the principle behind operation of most normal-incidence acoustic classification systems. A typical high-resolution seismic system (15 kHz) used to classify sediments is described by Lambert *et al.* [1]. Profiles of sediment impedance are determined from echo return amplitude and pulse character using acoustic multilayer theory. Physical and/or empirical models are then used to convert these in-situ estimates of sediment impedance to sediment type or values of sediment physical (porosity, grain size, bulk density, permeability), geoacoustic (compressional and shear wave velocity or attenuation, acoustic reflectivity) or engineering (shear strength) properties. In this paper we assume *a priori* that a )ustic sediment classification techniques give accurate estimates of in-situ sediment impedance. We will instead examine the empirical and physical models that are used to estimate sediment type or values of sediment properties from the in-situ sediment impedance.

Perhaps the most widely used empirical relationships between sediment acoustic and physical properties were developed by Edwin Hamilton in the 1960's and 1970's [2]. Bachman [3] summarized Hamilton's relationships with an emphasis on the prediction of sediment physical properties from sediment acoustic impedance. This approach is the inverse of Hamiltion's, where sediment physical properties are used to predict sediment geoacoustic properties [4].

Several factors complicate the apparent straightforward prediction of values of sediment properties from remotely sensed sediment impedance. Firstly, impedance is the product of sediment sound speed and sediment bulk density, two quantities that are dependent on temperature, porewater salinity and water depth. Because empirical relationships are based on measurements made at (or corrected to) common environmental conditions, it is imperative that estimates of sediment properties be corrected for differences in model and in-situ conditions. Secondly, sediment sound speed also varies with frequency. These empirical relationships are usually constructed from high-frequency (100-400 kHz) acoustic measurements which can differ from the lower frequencies (3.5-30 kHz) at which most remote acoustic measurement systems operate. Depending on the sediment type, determination of frequency dispersion of sediment sound speed may be critical. Thirdly, both sediment physical and acoustic measurements are based on laboratory measurements. Sediment samples from cores are often disturbed during collection, handling and analysis, resulting in field measurements that differ from in-situ measurements. Fourthly, some empirical relationships are generated from data not restricted to surficial sediments. Impedance *vs.* grain size relationships developed from long core samples differ from empirical predictions based on surficial sediment samples. Finally, variability of sediment properties occurs on various spatial scales and affects interpretion of acoustic classification data.

In this paper new empirical relationships between sediment impedance and sediment physical properties are presented. All sediments were hand-collected by divers or carefully sub-cored from undisturbed box cores to minimize sediment disturbance, The large number of sediment samples were collected in a wide range of environments over the last 12 years. All data are based on samples collected from the upper 0.5 m of sediment. The in-situ effects of sediment temperature, salinity and water depth are eliminated by the introduction of an environmentally independent index of impedance (IOI). The effects of frequency-dependent impedance will be the subject of future papers.

## 2. EXPERIMENTAL AND ANALYTICAL METHODS

Geoacoustic and physical property measurements were made from sediments collected in polycarbonate plastic cores that were 6.1-cm in diameter and 45-cm long. 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. The cores penetrated to a depth of 9 to 40 cm into the sediment, depending on the sediment texture. Of the 11 experimental sites, four sites were sampled from boxcores (Montauk Point, Quinault Range, Arafura Sea, and Russian River) and the rest were sampled directly by divers [5-13].

Measurement of sediment sound speed was made within 24 hours of collection, once the samples had equilibrated with laboratory temperature. Sediment sound speed and attenuation were measured at 1-cm intervals using a pulse technique [8]. Time delay measurements of a 400-kHz cw pulse were made on cores through the sediments and a distilled water reference using an Underwater Systems model USI-103 transducer-receiver head. Differences in time delay between distilled water and sediment cores were used to calculate sediment sound speed. Sediment compressional wave attenuation was calculated as 20 log of the ratio of received voltage through distilled water to received voltage through sediment. Sound speeds were corrected to a common temperature, salinity and pressure (23°C, 35‰, 1 atm) after Hamilton [14].

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°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 [10].

Values of sediment sound speed are expressed as the ratio of measured sediment speed to measured speed of the overlying water in the core (same temperature, salinity, and depth). Values of attenuation are expressed in units of dB $m^{-1}kHz^{-1}$ and are identical to the constant, $k$, described by Hamilton [15]. Sediment impedance, $Z$, is calculated as the product of the measured values of sediment sound speed and the calculated values of sediment density and has the units of g $cm^{-2}$ $s^{-1}$. Density is calculated from sediment porosity, grain density and seawater density [8]. Values of the index of impedance (IOI) are calculated as the product of the sediment velocity ratio and the sediment density. The $V_p$ ratio is unitless, therefore the IOI has units of density (g cm$^{-3}$).

### 3. RESULTS AND DISCUSSION

Sediment physical and geoacoustic properties were measured on 211 cores collected at 11 different sites worldwide. Table 1 lists the locations from which surficial sediment cores were collected, the sediment characteristics including the average measured values of sound speed ($V_p$ ratio), sound attenuation ($k$), porosity and mean grain size ($\phi$) and the average calculated values of impedance ($Z$) and index of impedance (IOI). The number of data pairs ($V_p$ ratio and porosity) acquired in order to calculate impedance values is tabulated as the number of data points at each location. This number represents the frequency with which porosity values were measured at the same core depth interval as sediment sound speed values.

As suggested in an examination of similar data [13], sediment physical and geoacoustic properties are quite variable on scales of a kilometer or less. The large-scale variability of sediment properties is exhibited by the Long Island Sound, Mission Bay, St. Andrew Bay and La Spezia locations. These locations are divided into sedimentary provinces where a particular sediment type predominates. Small-scale variability of sediment properties within a particular sediment type is demonstrated in Table 2. The coefficient of variation of the $V_p$ ratio, attenuation ($k$), porosity mean grain size ($\phi$), bulk density ($\rho$) and IOI is calculated as the standard deviation divided by the mean and expressed as a percentage. The coefficient of variation (CV) of impedance ($Z$) is identical to the CV of the IOI because the CV's of the components are the same. Several general observations can be made pertaining to this variability. Sound speed (or velocity ratio) is the least variable sediment property; compressional wave attenuation is the most variable. However, in locations such as Jacksonville (II), St. Andrew Bay and La Spezia (Tellaro) mean grain size exhibits great variability due to occurrence of discrete layers of different sediment types. The variability of sediment impedance (or IOI) appears correlated with the variability of sediment bulk density rather than sound speed. Overall variability of all sediment properties is lower at muddy rather than sandy sites. The greatest variations are found at sandy sites that contained considerable amounts of shell material or at sites that contained mixtures of sand and mud.

The variability of sediment physical and geoacoustic properties presented in Table 2 was determined from replicate sediment samples collected from sites generally within an area with a 100-m radius. Except for the La Spezia and Panama City (II) data, replicate cores were collected within a short (usually a week) period of time. Coefficients of variation calculated for cores collected within a week of each other at the La Spezia and Panama City (II) sites were similar to the longer term data sets. We therefore suggest that the CV's presented in Table 2 represent variability that can be expected at scales used to characterize sediment physical properties remotely by acoustic methods. Given the high variability of compressional wave attenuation, precise prediction of this geoacoustic property may be difficult.

Table 1. Data sources and mean values of geoacoustic and physical properties.

| Experimental Site | Water Depth (m) | Location | | Sediment Type | No. of Data Pts. | *Vp* Ratio | Atten. (*k*) | Porosity (%) | $\phi$ | Z (g cm$^2$ s) ($\times 10^5$) | IOI (g cm$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Long Island Sound | | | | | | | | | | | |
| NWC | 16 | 41°11'N | 73°55'W | silty clay | 45 | 0.977 | — | 78.2 | 8.4 | 2.066 | 1.351 |
| FOAM | 10 | 41°14'N | 73°45'W | clayey silt | 75 | 0.986 | — | 74.2 | 7.3 | 2.185 | 1.429 |
| Mission Bay, CA | 18 | 32°46'N | 117°14'W | fine sand | 30 | 1.097 | 0.47 | — | 3.6 | — | — |
| | 18 | | | coarse sand | 26 | 1.148 | 0.29 | — | 1.0 | — | — |
| Montauk Point, NY | 35 | 41°04'N | 71°35'W | fine sand | 14 | 1.139 | 0.22 | 37.1 | 2.0 | 3.604 | 2.356 |
| Quinault Range, WA | 49 | 47°34'N | 124°35'W | fine sand | 72 | 1.112 | 0.43 | 41.6 | 2.9 | 3.376 | 2.207 |
| Charleston, SC | 20 | 32°25'N | 79°49'W | med. sand | 62 | 1.123 | 0.73 | 39.4 | 1.7 | 3.468 | 2.267 |
| Arafura Sea, AUSTRALIA | 47 | 10°01'S | 137°50'E | clayey sand | 127 | 0.988 | 0.84 | 70.5 | 5.2 | 2.281 | 1.492 |
| Panama City, FL | | | | | | | | | | | |
| I | 34 | 29°51'N | 85°47'W | fine sand | 91 | 1.133 | 0.59 | 39.9 | 2.6 | 3.483 | 2.277 |
| II | 29 | 29°41'N | 85°41'W | coarse sand | 75 | 1.111 | 1.04 | 40.8 | 0.9 | 3.358 | 2.195 |
| Jacksonville, FL | | | | | | | | | | | |
| I | 21 | 30°38'N | 80°57'W | med. sand | 79 | 1.146 | 0.53 | 37.2 | 1.3 | 3.586 | 2.345 |
| II | 26 | 30°36'N | 80°53'W | shelly sand | 118 | 1.113 | 1.42 | 40.0 | 0.8 | 3.429 | 2.242 |
| St. Andrew Bay, FL | 13 | 30°08'N | 85°45'W | f.sand/clay | 33 | 1.036 | 0.42 | 67.5 | 5.5 | 2.489 | 1.626 |
| | 10 | 30°10'N | 85°43'W | clay | 56 | 0.993 | 0.10 | 87.4 | 10.9 | 1.868 | 1.220 |
| | 10 | 30°08'N | 85°43'W | fine sand | 26 | 1.139 | 0.24 | 39.0 | 2.2 | 3.516 | 2.297 |
| Russian River, CA | 90 | 38°39'N | 123°29'W | clayey silt | 141 | 1.009 | 0.56 | 63.4 | 6.4 | 2.470 | 1.615 |
| La Spezia, ITALY | | | | | | | | | | | |
| Santa Teresa | 8 | 44°05'N | 9°53'E | silty clay | 28 | 0.982 | 0.28 | 65.8 | 8.7 | 2.402 | 1.570 |
| Portovenere | 13 | 44°03'N | 9°51'E | silty clay | 22 | 0.982 | 0.16 | 67.1 | 9.4 | 2.347 | 1.535 |
| Venere Azzura | 5 | 44°05'N | 9°54'E | v.fine sand | 55 | 1.096 | 0.38 | 44.8 | 4.2 | 3.226 | 2.110 |
| Tellaro | 18 | 44°01'N | 9°55'E | silty sand | 43 | 1.051 | 0.46 | 50.0 | 6.0 | 2.952 | 1.930 |
| Monasteroli | 16 | 44°05'N | 9°46'E | v.fine sand | 9 | 1.076 | 0.53 | 45.8 | 5.1 | 3.137 | 2.051 |
| Diga | 7 | 44°05'N | 9°52'E | silty clay | 7 | 0.968 | 0.14 | 68.0 | 10.0 | 2.259 | 1.477 |
| Viareggio | 22 | 43°49'N | 10°07'E | silty clay | 9 | 0.988 | 0.24 | 60.7 | 9.0 | 2.495 | 1.632 |

Table 2. Coefficients of variation (%) for sediment physical and geoacoustic properties.

| Experimental Site | Vp Ratio | Atten. (k) | Porosity | $\phi$ | $\rho$ | IOI |
|---|---|---|---|---|---|---|
| Long Island Sound | | | | | | |
| NWC | 0.4 | — | 1.6 | 2.4 | 1.5 | 1.4 |
| FOAM | 0.8 | — | 7.5 | 11.8 | 6.3 | 6.8 |
| Mission Bay, CA | | | | | | |
| fine | 1.1 | 14.8 | — | 10.8 | — | — |
| coarse | 1.0 | 25.7 | — | 7.4 | — | — |
| Montauk Point, NY | 1.0 | 16.6 | 3.2 | 3.7 | 1.0 | 1.4 |
| Quinault Range, WA | 1.2 | 43.6 | 5.1 | 3.5 | 1.8 | 3.1 |
| Charleston, SC | 1.0 | 37.9 | 4.8 | 19.1 | 1.6 | 1.9 |
| Arafura Sea, AUSTRALIA | 0.4 | 34.7 | 5.8 | 14.9 | 4.5 | 4.6 |
| Panama City, FL | | | | | | |
| I | 0.9 | 16.4 | 3.1 | 4.2 | 1.0 | 2.0 |
| II | 1.6 | 30.5 | 6.3 | 12.1 | 2.7 | 4.1 |
| Jacksonville, FL | | | | | | |
| I | 1.0 | 31.3 | 4.1 | 6.1 | 1.3 | 2.1 |
| II | 1.8 | 27.7 | 7.8 | 81.6 | 2.6 | 3.3 |
| St. Andrew Bay, FL | | | | | | |
| f.sand/clay | 4.9 | 71.6 | 28.4 | 58.3 | 19.8 | 24.2 |
| clay | 0.1 | 24.9 | 2.0 | 3.7 | 2.3 | 2.3 |
| fine sand | 0.3 | 25.5 | 2.1 | 3.5 | 0.6 | 0.8 |
| Russian River, CA | 0.5 | 14.6 | 6.2 | 7.1 | 3.8 | 4.3 |
| La Spezia, ITALY | | | | | | |
| Santa Teresa | 1.5 | 80.3 | 13.0 | 9.8 | 9.2 | 11.5 |
| Portovenere | 0.4 | 35.4 | 6.2 | 2.1 | 4.4 | 4.3 |
| Venere Azzura | 1.9 | 23.8 | 5.6 | 35.2 | 2.2 | 4.3 |
| Tellaro | 4.2 | 39.8 | 9.8 | 36.6 | 4.3 | 8.0 |
| Monasteroli | 2.6 | 15.3 | 6.8 | 27.6 | 1.9 | 3.7 |
| Diga | 0.2 | 88.9 | 2.4 | 0.8 | 1.8 | 1.8 |
| Viareggio | 0.6 | 51.2 | 7.5 | 2.2 | 4.6 | 4.9 |

Polynomial or linear regressions are constructed for the various geoacoustic and physical property measurements made at all locations in Table 1. The regression equations, coefficient of determination ($r^2$) and the F-value for the regression equations are tabulated in Table 3. The coefficient of determination is used to indicate the proportion of variation of one variable determined by the variation of the other. In every case in Table 3 the calculated F-value shown in Table 3 exceeds the tabulated F-value with appropriate degrees of freedom by more than a factor of four, indicating that the regression generates a "truly satisfactory prediction" [3].

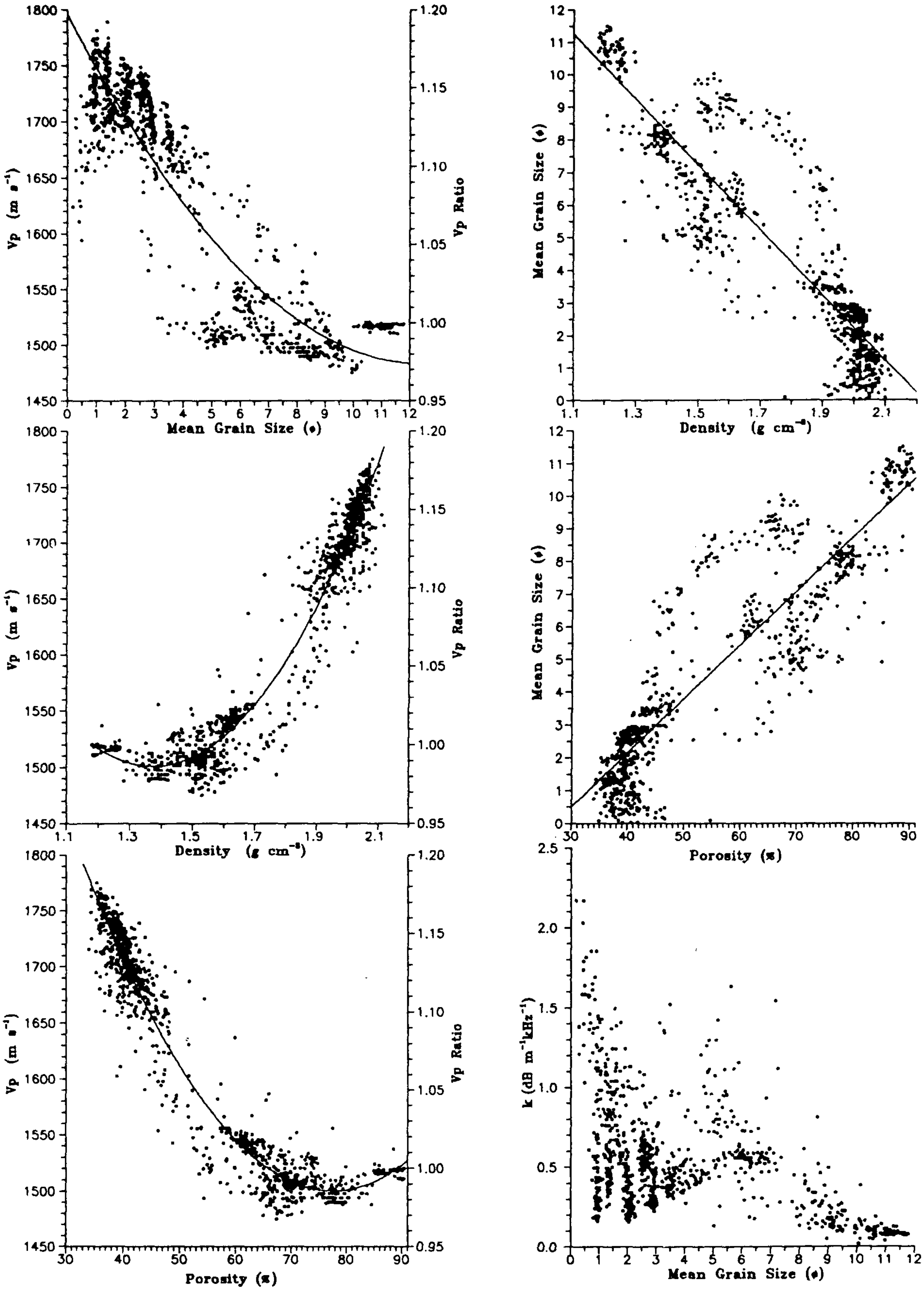


FIG 1. Relationships between geoacoustic and physical properties.

USE OF ACOUSTIC IMPEDANCE VALUES

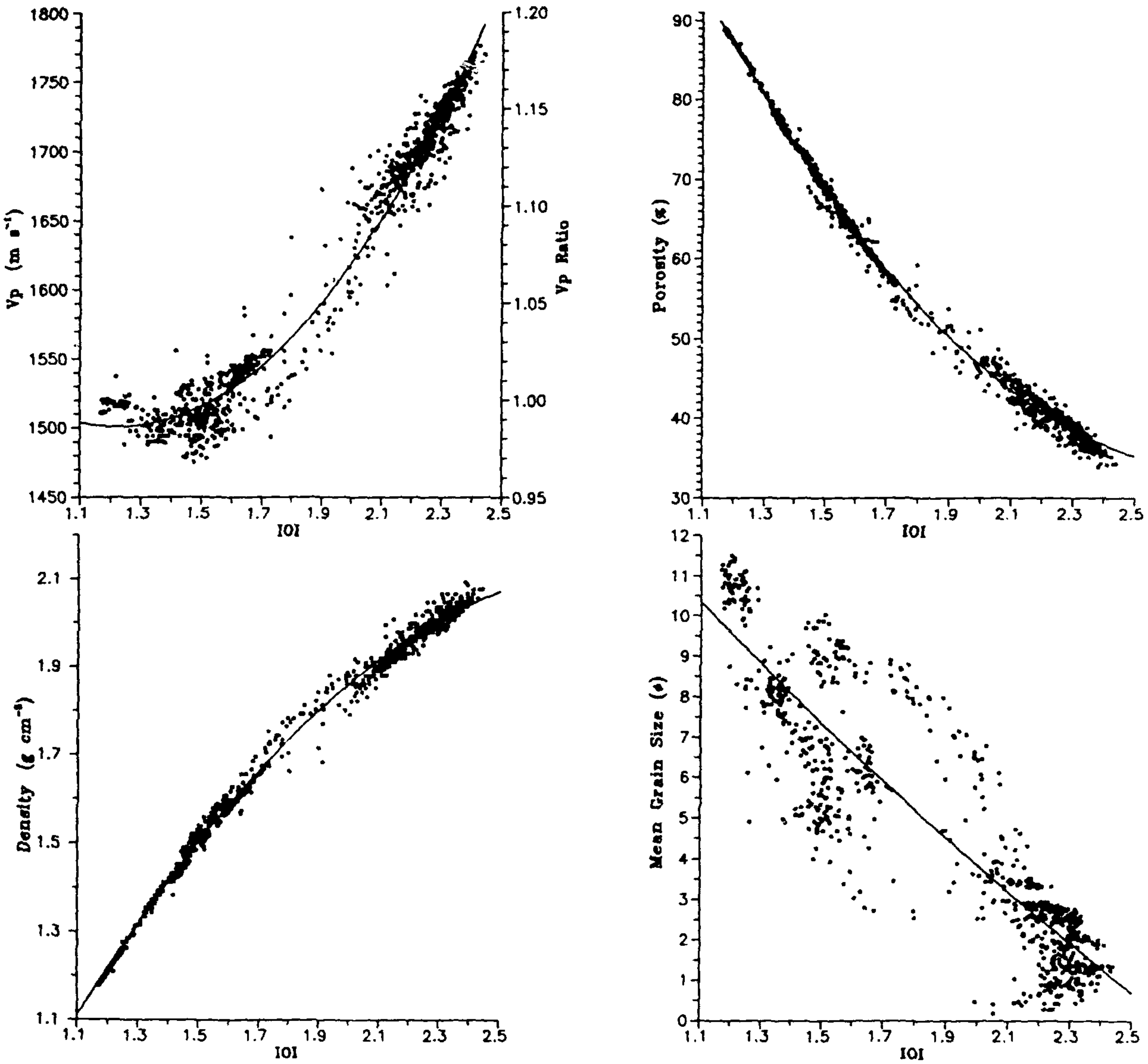


FIG 2. Relationships between geoacoustic and physical properties and IOI.

Data are concentrated in two regions in the regression plots corresponding to sands and muds. The intervening data are widely dispersed and correspond to various mixtures of coarse and fine sediments (Figs. 1, 2). Data dispersion due to over-consolidated clays are indicated in the plots by fine-grained sediments (high $\phi$ values) with low porosity or high bulk density values. Values of $V_p$ ratio are regressed against values of physical and geoacoustic properties and displayed in Table 3, but regressions predicting sound speed in m s$^{-1}$ are obtained by multiplying the regression coefficients by the the sound speed in water for the particular environment of interest. A curious similarity in the relationships between the $V_p$ *vs.* bulk density data and the $V_p$ vs. IOI data is noticeable in Figs. 1 and 2. The similarity is apparent in the mean grain size *vs.* bulk density data and the mean grain size *vs.*

IOI data. This is a result of the fact that the variations in bulk density values exert a strong influence on calculated values of IOI. Attenuation ($k$) is not correlated with mean grain size (Fig. 1) or any other geoacoustic and physical property. Empirical relationships between sediment physical and geoacoustic properties exist, but these relationships are only correlative, not causal.

Table 3. Regression equations and statistics.

| Regression Variables | Regression Equation | $r^2$ | F value |
|---|---|---|---|
| $Vp$ Ratio *vs.* $\phi$ | $Vp = 1.180 - 0.034\phi + 0.0013\phi^2$ | 0.820 | 2378.27 |
| $Vp$ Ratio *vs.* $n$ (%) | $Vp = 1.574 - 0.015n + 0.0001n^2$ | 0.954 | 11710.7 |
| $Vp$ Ratio *vs.* $\rho$ (g cm$^{-3}$) | $Vp = 1.623 - 0.936\rho + 0.3417\rho^2$ | 0.944 | 9629.79 |
| $Vp$ Ratio *vs.* Z x $10^5$ (g cm$^{-2}$ s) | $Vp = 1.174 - 0.207Z - 0.0560Z^2$ | 0.972 | 19634.0 |
| $\phi$ *vs.* $IOI$ | $\phi = 20.23 - 9.48IOI + 0.667IOI^2$ | 0.828 | 2116.18 |
| $n$ (%) *vs.* $IOI$ | $n = 202.14 - 120.70IOI + 21.598IOI^2$ | 0.996 | 142632 |
| $\rho$ (g cm$^{-3}$) *vs.* $IOI$ | $\rho = -0.502 + 1.802IOI - 0.3050IOI^2$ | 0.996 | 126646 |
| $Vp$ Ratio *vs.* $IOI$ | $Vp = 1.173 - 0.315IOI + 0.1296IOI^2$ | 0.972 | 19708.0 |
| $\phi$ *vs.* $n$ (%) | $\phi = -4.55 + 0.169n$ | 0.805 | 3792.13 |
| $\phi$ *vs.* $\rho$ (g cm$^{-3}$) | $\phi = 22.85 - 10.275\rho$ | 0.809 | 3920.22 |

The Index of Impedance is a very good predictor of sediment sound speed, bulk density, porosity and mean grain size. The $r^2$ values for the regressions in Fig. 2 range from 0.805 to 0.996. Hence, IOI can be used with confidence to predict sediment type. The over-consolidated clays separate from the main trend of the data in the mean grain size *vs.* IOI relationship as a field of high $\phi$, high IOI values (Fig. 2). The apparent uniqueness of these data is significant to the prediction of sediment characteristics from impedance measurements.

Sediment compressional wave attenuation ($k$) is not predicted satisfactorily by IOI (the regression is not shown in Fig. 2). Some or all of the following explanations may apply for a lack of correlation between attenuation and IOI. Firstly, attenuation is a highly variable parameter of shallow-water sediments and is therefore notoriously difficult to predict. Secondly, the proportion of attenuation due to scattering of acoustic energy is large in relation to the attenuation due to friction (*i.e.*, intrinsic attenuation) when the grain sizes are large compared with the acoustic wavelength. This effect causes a wide dispersion of measured attenuation values, especially when shells are a constituent of sediments) [9,10,13]. Thirdly, attenuation is strongly affected by any sediment disturbance which may occur during sampling or handling. Finally, the attenuation measurement techniques on small (6.1-cm diameter) cores may be called into question.

Relationships between impedance and various sediment parameters are similar in trend and dispersion to the relationships depicted in Fig. 2 for IOI. The impedance values in Table 1 and the equation in Table 3, however, were calculated from data that were adjusted to a single temperature, salinity and depth. The adjustment to the sound speed data accounts for the similarity in the $r^2$ values for impedance and IOI regressions. The significance in using IOI instead of impedance for predictions is accentuated in environments where there is a large seasonal change in bottom water conditions. Different values in impedance from a particular area result from seasonal variation in temperature and salinity. For example, a fine sand from La Spezia, Italy impedance varies from 3.22 x $10^5$ g $cm^{-2}s^{-1}$ in winter to 3.27 x $10^5$ g $cm^{-2}s^{-1}$ in summer. A mud (silty clay) from Long Island Sound, USA varies from 2.00 x $10^5$ g $cm^{-2}s^{-1}$ in winter to 2.06 x $10^5$ g $cm^{-2}s^{-1}$ in summer. By contrast, values of IOI for surface sediments from La Spezia and Long Island Sound are 2.145 and 1.376 g $cm^{-3}$, respectively, regardless of season.

The *de facto* correction of impedance values for environmental conditions using sound speed ratio values instead of in-situ sound speed values does not significantly improve predictions for different sediment types. In comparison to naturally occurring variability of sediment properties, the magnitude of the correction is small. In fact, the same amount of data dispersion around the predicted regression line occurs in plots of impedance values and IOI values.

Empirical relationships among sediment physical and geoacoustic properties presented here are similar to those reported by Bachman [3] for continental terrace sediments. Predicted sound speed in sands, however, were lower (25 to 75 m $s^{-1}$) than those predicted by Bachman's empirical relationships. Both Bachman's and our empirical relationships yield approximately the same sound speed predictions for muddy sediments. As expected for sandy sediments, the acoustic impedance (Z) estimates reported here are slightly lower than predictions made by Bachman. Therefore, for a given measured acoustic value of impedance or IOI our relationships indicate that sandy sediments have slightly lower porosity, higher bulk density and smaller mean phi size (larger grain diameter) values than predicted from Bachman's relationships.

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