Empirical Predictions of Seafloor Properties Based on Remotely Measured Sediment Impedance

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Abstract. Numerous acoustic systems have been developed over the past 25 years for remote classification of the seabed. Many systems use inversions of echo returns to estimate seafloor impedance and then use empirical relationships to predict other seabed properties from values of impedance. New regressions are presented, separately for siliciclastic and carbonate sediments, which allow prediction of sediment grain size, porosity, bulk density, percent sand and gravel and sound speed ratio and attenuation from values of an index of impedance (product of sound speed ratio and bulk density). This index is independent of pore water temperature and salinity and water depth. The regressions are based on nearly 800 cores collected from 67 shallow-water sites around the world (12 carbonate and 55 siliciclastic sites). Data are typically restricted to the upper 30 cm of sediment. The regressions based on the nearly 4,500 common data points from core measurements (3,922 for siliciclastic and 621 for carbonate sediments) do not vary significantly from the regressions for siliciclastic sediments first presented by Richardson and Briggs (1993) or between carbonate and siliciclastic sediments suggesting the empirical predictions universally apply to coastal sediments. Sound speed dispersion, sediment disturbance during core collection and measurement, inequalities between sample size (acoustic footprint vs. core diameter), spatial variability, and regression error all affect the accuracy of sediment property predictions.

INTRODUCTION

Many acoustic sediment classification systems use the amplitude of echo returns to estimate seafloor impedance. Empirical relationships between seafloor impedance and sediment physical properties are then used to map seafloor physical properties such porosity, bulk density, percent sand and gravel, or mean grain size and geoacoustic properties such as sound speed and attenuation. In this paper, we provide an update to the empirical relationships first given by Richardson and Briggs [1] to predict values of seafloor properties from a temperature-independent index of acoustic impedance. In the 1993 paper, the authors analyzed 1,243 measurements of impedance and physical properties from 211 cores collected from 22 sediment types at 11 siliciclastic sites. For this paper the data set has been expanded to over 4,500 measurements from 67 shallow water sites, with both siliciclastic and carbonate sediments represented (Tables 1 and 2). Our first objective is to determine if the almost-5-times-larger data set collected over a wider range of sediment types yields differences in empirical relationships between an index of impedance and related sediment physical and geoacoustic properties. The second objective is to determine whether these empirical regressions yield different predictions from carbonate and siliciclastic sites as suggested by Richardson and colleagues from the analyses of sediments collected from the Florida Keys [2].

METHODS FOR SEDIMENT COLLECTION AND LABORATORY DATA ANALYSES

Sediment geoacoustic and physical property measurements were made from sediments collected with 45-cm-long, 5.9-cm-inside-diameter, clear, polycarbonate coring tubes. Most sediments were collected by divers but sediments collected from eight sites (Montauk Point, Quinault Range, Arafura Sea, Russian River, Eel River, North Sea , TOSSEX, and Straits of Juan de Fuca), which were too deep for diving operations, were subsampled from 0.25m^2 spade box cores. Cores were capped at both ends immediately after collection to retain the overlying water and kept in an upright position during transport to the laboratory for analysis. Collection, measurement, and handing procedures were designed to minimize sampling disturbance and to maintain an intact sediment-water interface within the coring tube.

Sound speed and attenuation were measured on sediment at 1-cm intervals within the core tubes, usually within 24 hours of collection, using time-of-flight and amplitude of pulsed 400-kHz sine waves transmitted across the core tube [3]. Sediment sound speed is calculated from the differences in time-of-flight between sediment and distilled water within identical core tubes, the measured inside diameter of the core tube (5.9 cm), and the sound speed within the distilled water. Attenuation is measured as 20 log of the ratio of the mean amplitude of the waveform transmitted through water to those transmitted through sediment. Sound speeds are reported as the unitless sound speed ratio (V_p *ratio*) which is the ratio of measured sound speed to the sound speed of pore water at the same temperature, salinity and pressure. Attenuation is expressed in units of dB m^{-1}kHz^{-1} (k) after Hamilton [4].

Sediments were then extruded from sediment cores and sectioned at 2-cm intervals to determine sediment porosity and grain size distribution. Porosity was determined from weight loss of sediments dried at 105° C for 24 hours and corrected for residual salt. Grain density was determined using a pyncnometer. Sediment bulk density was calculated from the porosity and densities of pore water and sediment grains. Sediment grain size was determined from disaggregated samples by dry sieving for sand-sized particles and by either pipette methods or Micromeritics sedigraph for silt- and clay-sized particles.

Sediment impedance (Z, kg m^{-1}s^{-1}) is the product of sediment sound speed and bulk density. Sediment sound speed is dependent on pore water temperature and salinity and pressure (water depth). Furthermore, sound speed in sediment at a single site can vary up to 10% over the range of seasonal conditions expected in coastal waters [1]. Therefore, the pore-water-independent Index of Impedance (IOI), which is the product of the sediment bulk density and velocity ratio, is used to calculate empirical relationships between sediment impedance and other sediment physical properties.

RESULTS AND DISCUSSION

Sediment physical and geoacoustic properties were measured on over 800 cores collected from 67 shallow-water sites around the world (12 carbonate and 55 siliciclastic sites). The total of 4,582 collocated measurements is nearly 5-times the number of measurements used by Richardson and Briggs [1] to determine similar empirical relationships between the index of impedance (IOI) and sediment physical and geoacoustic properties and includes measurements in carbonate sites (609) as well as siliciclastic sites (3973). Sediment at the 55 siliciclastic sites ranged from very-high-porosity clays (such as Eckernförde Bay, Baltic Sea or St. Andrew Bay, Florida) to coarse sands in the northeastern Gulf of Mexico (Table 2). Siliciclastic sampling sites were generally associated with high-frequency acoustic bottom scattering experiments and include sites in the Mediterranean, Baltic and North Seas, and along the entire range of Atlantic, Pacific and Gulf coasts of the US [1,3,5]. Carbonate sampling sites are geographically restricted to tropical waters along the southern coastline of Florida [2] and Hawaii but, nevertheless include several sediment types (Table 1).

The Index of Impedance (*IOI*) provides excellent predictions of sound speed ratio, bulk density, and porosity for both carbonate and siliciclastic sediments (Figures 1 and 2; Tables 3 and 4). This is not surprising as *IOI* is the product of velocity ratio (V_pR) and bulk density, and both sediment bulk density and porosity are determined from the same wet loss measurements. Predictions of V_p, V_pR, bulk density and porosity for carbonate and siliciclastic sediments vary less than 14 m s^{-1}, 0.001, 0.04 g cm^{-3}, 4% respectively, over the full range of values of *IOI* suggesting regressions for each parameter derived from the entire data set is appropriate (Table 5). The coefficients of determination (r^2) between *IOI* and sediment mean grain size and percent sand and gravel are lower for carbonates than siliciclastic sediments. The lower values of r^2 between *IOI* and grain size properties due to scatter in the data justify combined regressions using all carbonate and siliciclastic data in spite of up to 0.6 phi and 17% differences in predicted mean grain size and percent sand and gravel. Based on the data presented, attenuation is poorly predicted from impedance.

TABLE 1. Mean values of sediment physical and geoacoustic properties from carbonate sites located in southern Florida and in Hawaii. Sediment properties include sound speed ($\boldsymbol{V_p}$, m s^{-1}), sound speed ratio ($\boldsymbol{V_pR}$, no units), attenuation ($\boldsymbol{\alpha}$, dB m^{-1}; $\boldsymbol{k}$, α kHz^{-1}), mean grain size ($\boldsymbol{M_z}$, phi) porosity ($\boldsymbol{\eta}$, %), density ($\boldsymbol{\rho}$, g cm^{-3}) and the Index of Impedance (***IOI***, g cm^{-3}). Sites are ordered as increasing values of ***IOI***.

Site	*Vp*	*VpR*		M_z			*k*	*IOI*	Sediment
Hawaii/mud	1495.3	0.977	68.6	8.67	84.02	1.296	0.171	1.267	calc. silty clay
MarqKeys	1555.6	1.017	391.3	6.15	59.66	1.726	0.978	1.755	calc. s-s-clay
SG98-5	1560.8	1.020	322.3	5.85	59.59	1.748	0.806	1.783	calc. s-s-clay
DTortugas	1561.8	1.021	343.0	6.62	59.00	1.755	0.858	1.792	calc. s-s-clay
LFK/fine	1581.3	1.034	365.8	5.40	57.19	1.759	0.914	1.818	calc. s-s-clay
Hawaii-4	1609.7	1.052	246.2	3.88	56.42	1.771	0.615	1.864	calc. silty sand
SG98-2	1669.4	1.091	383.1	1.57	49.47	1.921	0.958	2.096	crse. skel. sand
Hawaii/crse	1639.4	1.072	695.2	0.74	45.18	1.960	1.738	2.100	crse. coral sand
Hawaii-2	1671.6	1.093	438.3	2.33	47.68	1.933	1.096	2.112	calc. med. sand
LFK/crse	1704.7	1.114	488.9	0.54	41.97	2.054	1.222	2.289	crse. coral sand
RebShoal	1733.1	1.133	279.1	1.26	43.85	2.022	0.698	2.290	carbonate sand
SG98-3	1777.3	1.162	236.7	1.66	40.92	2.067	0.592	2.401	ooid/skel. sand

TABLE 2. Mean values of sediment physical and geoacoustic properties from 55 siliciclastic sites world-wide. Sediment properties include sound speed (***V_p***, m s^{-1}), sound speed ratio (***V_pR***, no units), attenuation (**α**, dB m^{-1}; ***k***, α kHz^{-1}), mean grain size (***M_z***, phi) porosity (***η***, %), density (***ρ***, g cm^{-3}) and the Index of Impedance (***IOI***, g cm^{-3}). Sites are ordered as increasing values of ***IOI***.

Site	*Vp*	*VpR*		*M_z*			*k*	*IOI*	Sediment Type
SABay	1518.9	0.993	38.7	10.94	89.14	1.170	0.097	1.162	clay
Eck93	1515.5	0.991	72.3	9.88	87.40	1.188	0.181	1.177	silty clay
CLBight	1521.9	0.995	114.0	8.10	86.50	1.223	0.285	1.216	silty clay
JDF7	1507.2	0.985	114.2	8.50	83.43	1.313	0.285	1.294	silty clay
LISound	1503.1	0.982	—	7.64	76.64	1.411	—	1.386	clayey silt
Orcas	1511.9	0.988	179.1	8.08	75.22	1.403	0.448	1.387	clayey sand
Diga	1480.4	0.968	58.0	10.05	69.12	1.506	0.145	1.458	silty clay
JDF4	1521.7	0.995	206.8	6.93	74.35	1.470	0.517	1.462	glacial till
Arafura	1511.4	0.988	347.8	5.24	71.63	1.494	0.869	1.476	clayey sand
Portovenere	1501.7	0.982	66.2	9.45	68.30	1.546	0.166	1.518	silty clay
STeresa	1502.4	0.982	122.3	8.78	66.98	1.569	0.306	1.541	silty clay
RussRiver	1545.5	1.010	231.8	6.35	64.35	1.597	0.579	1.613	clayey sand
Viareggio	1511.3	0.988	99.5	8.98	61.74	1.634	0.249	1.615	silty clay
Eck94	1609.7	1.052	210.7	4.59	59.38	1.659	0.527	1.745	sand-silt-clay
EelRiver	1554.6	1.016	190.7	7.17	57.32	1.745	0.477	1.773	clayey silt
ATB/G40	1651.9	1.080	219.8	2.56	56.61	1.716	0.549	1.853	fine sand
JDF1	1617.6	1.057	238.5	4.37	55.37	1.800	0.596	1.903	silty fine sand
Tellaro	1614.4	1.055	184.7	6.08	50.70	1.820	0.462	1.921	sand-silt-clay
Monasteroli	1652.4	1.080	220.2	5.12	46.62	1.891	0.550	2.042	sand-silt-clay
JDF6	1668.2	1.090	314.3	2.94	47.56	1.922	0.786	2.096	fine sand/s-s-c
Tirrenia	1683.1	1.100	127.6	3.72	45.76	1.906	0.319	2.097	v.fine sand
VAzzura	1686.4	1.102	156.5	4.14	45.17	1.911	0.391	2.106	muddy sand
SG98-6	1649.6	1.078	632.5	0.08	43.47	2.001	1.581	2.158	shell/coral hash
JDF5	1701.5	1.112	213.8	2.31	45.44	1.946	0.534	2.164	fine sand/s-s-c
LTB	1716.8	1.122	317.1	2.54	43.57	1.929	0.793	2.165	fine sand
Quinault	1709.3	1.117	177.2	2.94	41.76	1.971	0.443	2.202	fine sand
PC93	1708.5	1.117	404.0	0.98	40.93	2.008	1.010	2.242	coarse sand
PCII	1716.4	1.122	391.2	0.85	41.09	2.000	0.978	2.244	c. sand/sh. hash
TBay/crse	1754.2	1.147	610.2	1.36	44.85	1.966	1.526	2.254	coarse/fine sand
KB/lyn	1709.2	1.117	586.9	0.90	40.14	2.020	1.467	2.256	shell hash
Charl/fine	1728.4	1.130	281.0	1.97	39.94	2.001	0.703	2.260	fine sand
SG98-10	1752.1	1.145	164.1	1.62	40.69	1.979	0.410	2.266	medium sand
Charl/crse	1729.1	1.130	308.1	1.44	39.63	2.006	0.770	2.267	medium sand
PC84	1742.9	1.139	241.7	2.61	40.08	1.998	0.604	2.276	fine sand
SWEAT	1747.6	1.142	213.3	2.23	40.38	2.007	0.533	2.292	fine sand
SG98-9	1747.1	1.142	206.7	1.56	39.45	2.010	0.517	2.295	medium sand
TBay/fine	1746.0	1.141	206.1	2.92	40.16	2.013	0.515	2.297	fine sand
ATB/B14	1752.6	1.146	107.2	2.15	39.52	2.006	0.268	2.298	fine sand
SG98-1	1713.0	1.120	430.2	0.84	40.66	2.053	1.076	2.299	shell hash
IRB	1745.2	1.141	281.2	1.77	40.63	2.023	0.703	2.307	medium sand
SG98-8	1747.1	1.142	265.7	2.14	39.65	2.026	0.664	2.314	shelly fine sand
PCB I&II	1755.1	1.147	176.1	2.34	39.72	2.018	0.440	2.315	fine sand
NS	1735.0	1.134	226.1	1.87	41.07	2.046	0.565	2.320	medium sand
MVCO	1755.1	1.147	154.5	2.52	38.49	2.028	0.386	2.327	fine sand
PCB99	1764.2	1.153	133.5	2.24	39.33	2.020	0.334	2.329	fine sand
MonPt	1744.4	1.140	92.1	2.04	37.21	2.045	0.230	2.332	fine sand
KB/bar	1758.2	1.149	254.4	1.33	37.28	2.047	0.636	2.352	medium sand
Duck	1758.8	1.150	116.2	2.53	39.54	2.051	0.291	2.357	fine sand
JDF2	1771.6	1.158	179.5	2.03	39.10	2.039	0.449	2.361	medium sand
PE99	1770.7	1.157	153.0	1.28	37.08	2.052	0.383	2.375	medium sand
PE00	1774.1	1.160	149.5	1.21	37.32	2.050	0.374	2.377	medium sand
SAX99	1766.3	1.154	177.5	1.27	37.27	2.066	0.444	2.385	medium sand
NoSea	1779.0	1.163	155.7	1.93	37.56	2.054	0.390	2.388	med/fine sand
TOSSEX	1762.7	1.152	161.8	1.93	35.64	2.075	0.404	2.391	med/fine sand
HoodCanal	1767.1	1.155	184.6	1.34	36.46	2.108	0.462	2.435	medium sand

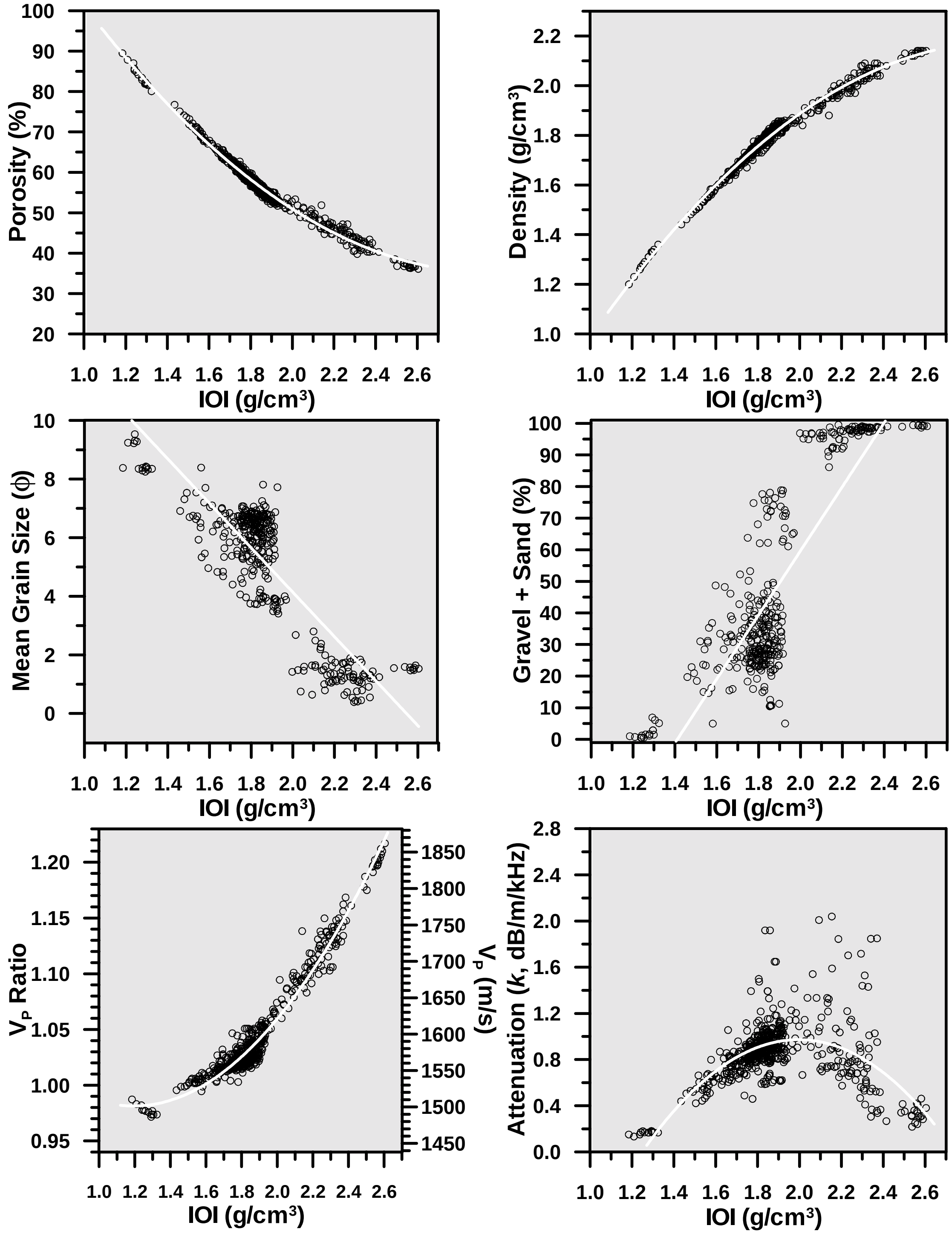

FIGURE 1. Empirical relationships used to predict sediment physical and acoustic properties from the Index of Impedance *(IOI)* for carbonate sediments. Data and regressions (Table 1, Table 3) are based on 69 cores collected from 12 sites around southern Florida and in the Hawaiian Islands.

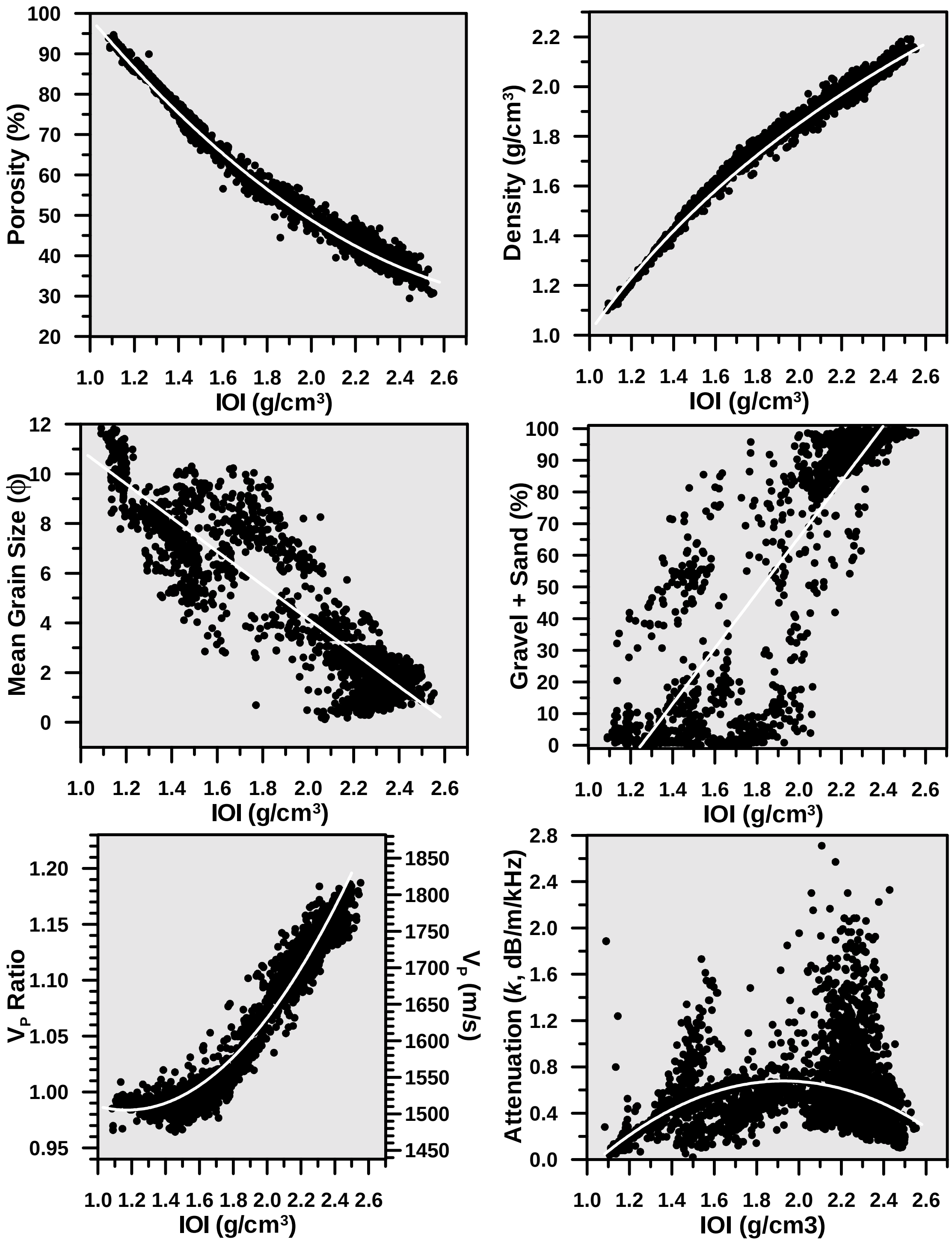

FIGURE 2. Empirical relationships used to predict sediment physical and acoustic properties from the Index of Impedance (*IOI*) for siliciclastic sediments. Data and regressions (Table 2; Table 4) are based on over 3,900 measurements made on cores collected from 55 shallow-water sites world-wide.

TABLE 3. Empirical Predictive Relationships for Sediment Physical and Geoacoustic Properties Based on the Index of Impedance (IOI) for Carbonate Sediments. Coefficient of determination (r^2) is given for each regression.

Parameter	Regression	r^2
Sound Speed Ratio	= 1.164 - 0.3001(IOI) + 0.1253(IOI)^2	0.96
Attenuation (k)	= -5.96 + 6.94(IOI) – 1.174(IOI)^2	0.43
Porosity (%)	= 186.18 – 102.20(IOI) + 17.29(IOI)^2	0.99
Density (g cm^{-3})	= -0.52 + 1.81(IOI) – 0.305(IOI)^2	0.99
Mean Grain Size (θ)	= 19.3 -7.6(IOI)	0.75
Sand and Gravel (%)	= -143.2 + 101.4(IOI)	0.73

TABLE 4. Empirical Predictive Relationships for Sediment Physical and Geoacoustic Properties Based on the Index of Impedance (IOI) for Siliciclastic Sediments. Coefficient of determination (r^2) is given for each regression.

Parameter	Regression	r^2
Sound Speed Ratio	= 1.149 - 0.2821(IOI) + 0.1203(IOI)^2	0.97
Attenuation (k)	= -2.61 + 3.41(IOI) – 0.885(IOI)^2	0.16
Porosity (%)	= 178.60 – 94.60(IOI) + 14.86 (IOI)^2	0.99
Density (g cm^{-3})	= 1.01 + 1.22LN(IOI)	0.99
Mean Grain Size (θ)	= 17.7 -6.8(IOI)	0.85
Sand and Gravel (%)	= -109.6 + 87.7(IOI)	0.82

TABLE 5. Empirical Predictive Relationships for Sediment Physical and Geoacoustic Properties Based on the Index of Impedance (IOI) for Siliciclastic and Carbonate Sediments Combined. Coefficient of determination (r^2) is given for each regression.

Parameter	Regression	r^2
Sound Speed Ratio	= 1.164 - 0.3001(IOI) + 0.1253(IOI)^2	0.97
Attenuation (k)	= -3.31 + 4.33 (IOI) - 1.138 (IOI)^2	0.22
Porosity (%)	= 174.16 - 89.12(IOI) + 13.37 (IOI)^2	0.99
Density (g cm^{-3})	= 1.02 + 1.21LN(IOI)	0.99
Mean Grain Size (θ)	= 17.9 - 6.0(IOI)	0.84
Sand and Gravel (%)	= -113.4 + 89.1(IOI)	0.81

CONCLUSIONS

The Index of Impedance (*IOI*) can be used to predict accurately sound speed, density, and porosity in seafloor sediments and, with a lesser degree of accuracy, predict mean grain size and percent sand and gravel. The lower values of the coefficient of determination (r^2) between *IOI* and mean grain size (percent sand and gravel) compared to sediment bulk density, porosity, or sound speed reflect the lack of fundamental physical relationship between mean grain size and either sediment bulk density or sound speed (Fig. 3). The coefficients of determination (r^2) are 0.84 and 0.64, respectively. In muddy sediments, consolidation (dewatering) lowers porosity and increases density without a change in mean grain size. In sands, porosity can vary up to 10%, depending on packing [7]. Given the same packing a uniform assemblage of spheres would theoretically achieve the same porosity regardless of grain diameter (size). Using values of mean grain size as an index, especially in the silt-size range, may be very misleading because of major differences in sorting (standard deviation of the particle size distribution). Well-sorted sediment composed of wholly silt-size particles may have the same mean grain size as poorly sorted sediment with a mixture of sand- and clay-size particles. The resultant density and sound speed of these two sediments, however, might be very different. Given the aforementioned issues, it is perhaps amazing that empirical regressions between grain size-related parameters and sediment density, porosity, sound speed, or impedance have any predictive value.

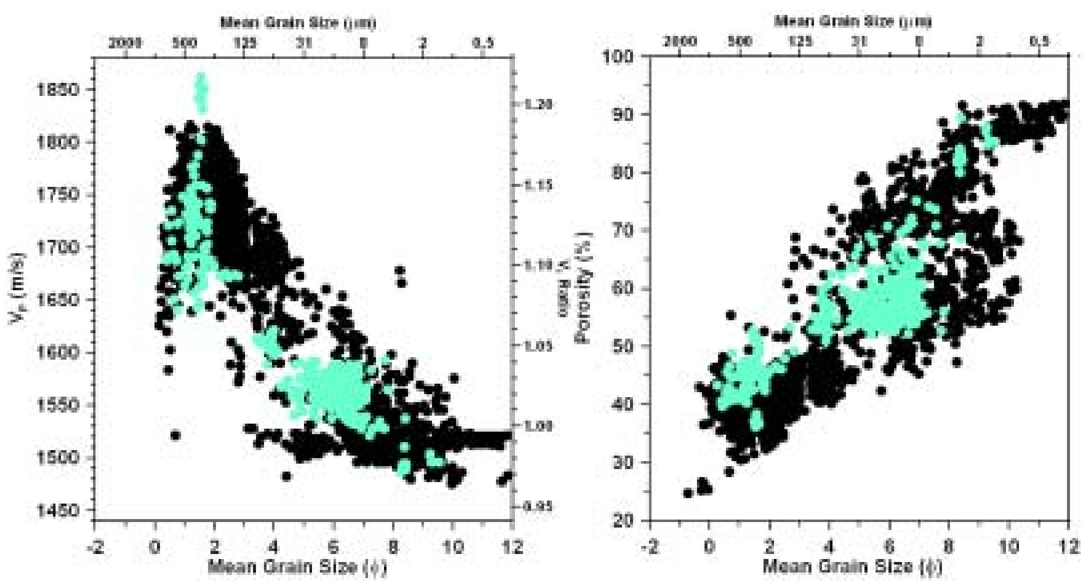

FIGURE 3. Scatter diagrams of mean grain size versus porosity and sound speed (V_p). The lighter colored symbols, which represent carbonate sediments, overlay the darker colored symbols, which represent siliciclastic sediment. Mean grain sizes less than 4 phi are in the sand grain size, 4-8 phi are silt sized particles and greater than 8 phi are clay-sized particles.

The use of different empirical *IOI* regressions for carbonate sediments than for siliciclastic sediments may be justified for some specific carbonate sites where intra-particulate porosity is high [2] but is not justified for more generalized relationships for all coastal sediments, based on the data presented here. Therefore, the regressions based on the combined data set (Table 5) are recommended for general use. The regressions presented by Richardson and Briggs [1] in 1993 do not significantly differ from those regressions developed from the much larger data sets from siliciclastic sediments used here (Tables 4 and 5). Mean absolute differences between the 1993 and 2004 *IOI* regressions were as follows: 1.4% for porosity, 0.0108 g cm^{-3} for bulk density, 0.13 phi for mean grain size, 0.0025 for velocity ratio and 3.8 m s^{-1} for sound speed. A regression between IOI and percent sand and gravel was not calculated by

Richardson and Briggs [1]. Attempts to predict compressional wave attenuation from *IOI* at these high acoustic frequencies (400 kHz) have failed because of the high, but unknown, contribution of scattering to the overall measured attenuation. Intrinsic attenuation probably does not exceed the lower level of the curvilinear fits given in Figures 1 and 2. However, it is notable that attenuation in the carbonate sediments is on average 0.14 dB m^{-1} kHz^{-1} (56 dB m^{-1} @ 400 kHz) higher than for siliciclastic sediments.

Poro-elastic models predict that sound speed is dispersive, especially in sandy sediments [6]. The empirical relationships presented here were developed using sound speeds measured at 400 kHz. Typical echo sounders operate at 3.5 to 30 kHz, where sound speeds and thus impedance values may be lower. This dispersion effect is more pronounced in sand compared to muddy sediments. In the example given by Williams et al [7] for the sand sediment of the SAX99 experiments, measured sound speeds were 25-75 m/s higher at 400 kHz than over the 3.5- to 30-kHz frequency band. The calculated values of IOI, given the mean sediment density of 2.066 g cm^{-3}, would be 2.4 g cm^{-3} at 400 kHz and 2.3 g cm^{-3} at 3.5 kHz. Based on this amount of sound speed dispersion, sediment properties predicted at 3.5 kHz would be different than from measured sound speeds (400 kHz): porosity is 2.6% higher, bulk density is 0.05 g/cm^3 lower, mean grain size is 0.69 phi units higher (finer), and sound speed is 44 m/s higher.

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