The Acoustics of Marine Sediments

Megan S. Ballard

Postal:
Applied Research Laboratories
The University of Texas at Austin
PO Box 8029
Austin, Texas 78713-8029
USA

Email:
meganb@arlut.utexas.edu

Kevin M. Lee

Postal:
Applied Research Laboratories
The University of Texas at Austin
PO Box 8029
Austin, Texas 78713-8029
USA

Email:
klee@arlut.utexas.edu

For biologically active sediments, understanding geoacoustic properties is a multidisciplinary undertaking, involving both the measurement of acoustic properties and the quantification of biological effects.

Introduction

In contrast to electromagnetic waves, which are highly attenuated by seawater, acoustic waves can propagate long distances through the ocean. For this reason, sound waves are used underwater for navigation, communication, and remote sensing. For shallow-water propagation environments, which include extensive regions on continental shelves, acoustic propagation can be described as a waveguide bounded above by the sea surface and below by the seafloor. The geometry of the shallow-water waveguide is that of a broad, thin layer so that sound emitted from a source generally reflects from the waveguide boundaries many times before reaching a receiver. Because the distance that sound propagates from the source to the receiver can be equivalent to hundreds of water depths, the sound field is greatly influenced by the properties of the waveguide boundaries, and the acoustical properties of the seabed can be the dominant factor affecting propagation and scattering in shallow-water environments.

The geoacoustic properties of marine sediments have been studied for over a century, with papers covering this topic regularly appearing in *The Journal of the Acoustical Society of America* for the past 60 years. This article begins by providing background on the types of marine sediments, which can differ in their source (lithogenic: coming from land by erosion of rocks, vs. biogenic: derived from the hard parts of animals), predominate mineralogy (silicate vs. calcium carbonate), and grain structure (solid vs. porous) as well as the approaches used to model their acoustic properties. Next, the current state of measurement and modeling techniques is described and examples of applications are presented. The article concludes with a discussion of open questions and possible future directions for the field.

Types of Marine Sediments

Marine sediments are often classified according to grain size, with standardized definitions for sand (median diameter greater than 62.5 μm), silt (median diameter between 3.9 and 62.5 μm), and clay (median diameter less than 3.9 μm) (Wentworth, 1922). The composition of coarse-grained sediments (composed of sand- and silt-sized particles) differs greatly from that of fine-grained sediments (composed of clay-sized particles). The stress-strain behavior (how an elastic medium deforms under loading) of coarse-grained sediments is dominated by friction between the particles, which, along with viscous damping due to the thin layer of pore fluid (which may consist of freshwater or salt water as well as mucus and other animal byproducts) between the grains, is a mechanism for the attenuation of acoustic waves (Buckingham, 2014; Chotiros and Isakson, 2014). Muddy sediments made up of clay-sized particles consist of a colloidal suspension of microscopic, irregularly shaped platelets, which carry a surface charge linked to their cation exchange capacity. These suspensions result in open structures that cause mud to have high porosity (indicating high wa-

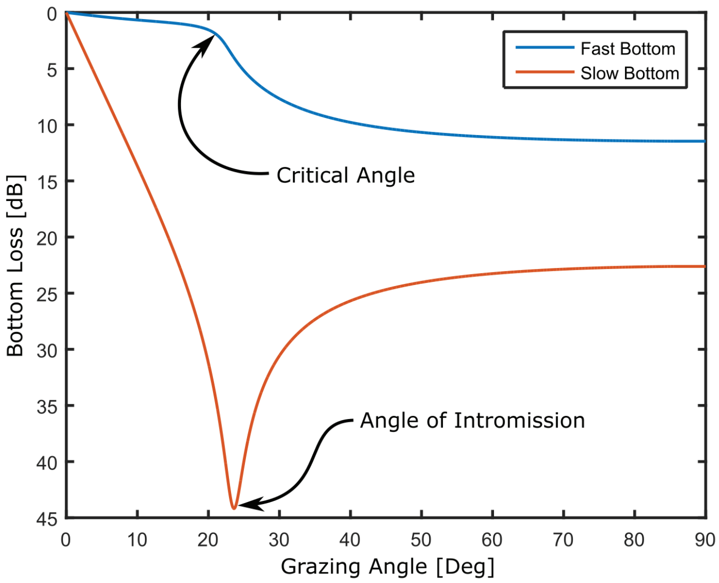

***Figure 1**. Examples of bottom loss (BL) calculated for "fast" and "slow" bottoms. BL is calculated as 10 $\log_{10}|R|^2$, where R is the complex reflection coefficient. For the coarse-grained sandy sediment (fast bottom: the sound speed in the sediment is faster than that in the overlying water), nearly all of the incident sound wave is reflected from seabed for grazing angles less than the critical angle (here about 20° relative to the horizontal direction). Much less sound is reflected from the fine-grained muddy sediment (slow bottom: the sediment sound speed is lower than that in the overlying water) because total sound transmission into the sediment occurs at the angle of intromission, which is at a grazing angle of about 22°.*

ter content and low bulk density) and exhibit gel-like behavior. For pure clay muds, the intrinsic attenuation can be very small (Holland and Dosso, 2013).

Coarse-grained sediments are characterized by a sound speed faster than that of the overlying water, and the angular dependence of the refection coefficient (the ratio of the amplitude of the reflected wave to the incident wave) at the water-sediment interface possesses a critical angle. For grazing angles smaller than the critical angle, there is total reflection of the incident wave (see **Figure 1**). For propagation environments with sandy seabeds, sound waves that reflect from the bottom with small angles relative to the horizontal direction can propagate for long distances with relatively little energy loss due to bottom interaction. On the other hand, fine-grained sediments are characterized by a sound-speed ratio (sound speed in the sediment compared with that of the overlying water) of less than one, giving rise to a reflection coefficient with an angle of intromission, which is the angle for which total transmission of sound into the seabed occurs. As a result, comparatively less sound is reflected from fine-grained sediments.

Although coarse- and fine-grained sediments have distinct acoustic properties, most naturally occurring marine sediments contain a mixture of sand-, silt-, and clay-sized particles in varying proportions. An example of sand grains coated with increasing quantities of clay platelets are shown in **Figure 2**. The addition of clay particles to a sandy sediment can have disparate effects on porosity and wave speed depending on the relative volume of clay particles. For low concentrations of clay particles (less than 20% by weight), the clay particles are located in the sand pore space and act to stiffen the pore-filling material. As a result, porosity decreases and velocity increases. In contrast, when the volume of clay particles is high (greater than 40% by weight), sand grains are suspended in the clay matrix. Therefore, porosity increases and velocity decreases with increasing clay content (Marion et al., 1992). Many natural marine sediments also contain free or trapped gas and/or organic content that can further alter the effective bulk properties of the sediment.

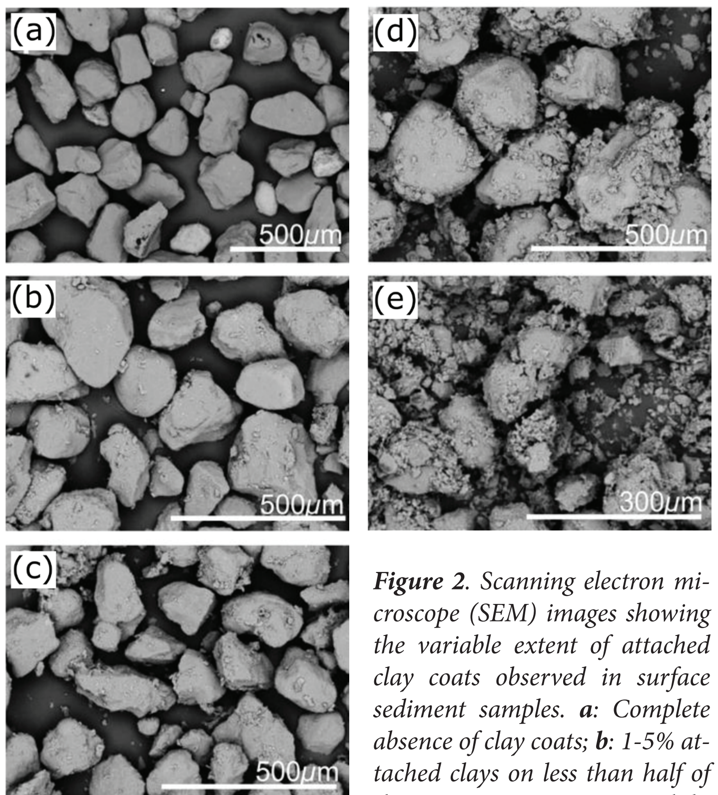

***Figure 2**. Scanning electron microscope (SEM) images showing the variable extent of attached clay coats observed in surface sediment samples. **a**: Complete absence of clay coats; **b**: 1-5% attached clays on less than half of the grains; **c**: every grain exhibits 5-15% clay coats coverage; **d**: clay coats observed on every grain, with the majority exhibiting extensive 15-30% coverage; **e**: extensive, >30% clay coats coverage observed on every grain. Adapted from Woolridge et al. (2017).*

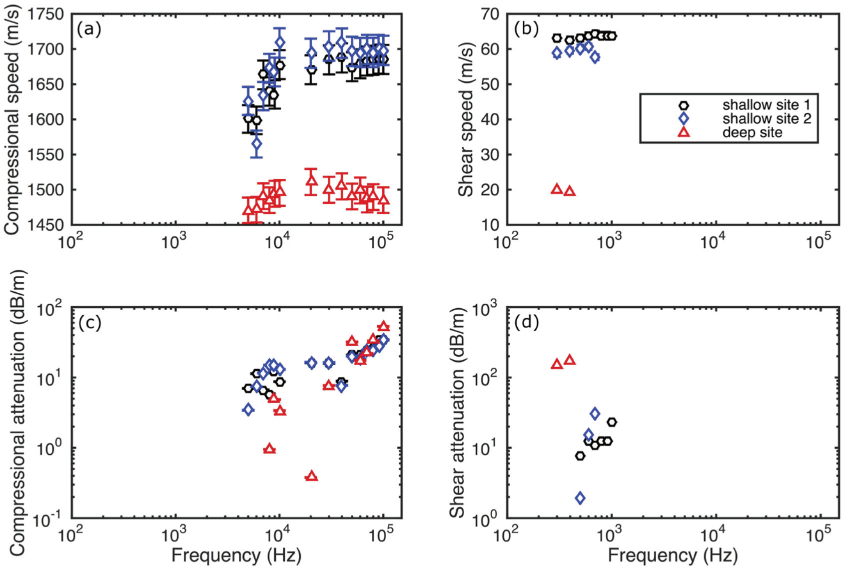

*Figure 3. Frequency-dependent compressional sound speed ratio (**a**), shear-wave speed (**b**), compressional-wave attenuation (**c**), and shear-wave attenuation measured* in situ *at two sites in Currituck Sound in North Carolina (**d**). **Black hexagons:** first site, first deployment; **blue diamonds:** first site, second deployment; **red triangles:** second site (further out in the Sound at greater water depth). The acoustic behavior from the two deployments at the first site is typical for fine-grained sandy sediment; however, it is markedly different at the second site even though the sediment grain sizes are similar. Adapted from Lee et al. (2016a).*

Direct Measurement Systems

Although many techniques have been developed to determine the geoacoustic properties of marine sediments, this discussion focuses on direct measurements for which wave speed and attenuation are calculated from measurements of travel time and the amplitude of a known signal. Although indirect measurements of sediment properties (including statistical inference techniques, for which geoacoustic properties are inferred from measurements of transmission loss, acoustic time series, reflection coefficient, and other parameters) are invaluable to the underwater acoustics community, these approaches are out of the scope of this article. The advantages of concentrating on direct measurements in the context of the current discussion are that (1) they have historically been more closely linked to measured physical properties and (2) parameter uncertainty is primarily attributed to the measurement system rather than to model mismatch.

Edwin L. Hamilton was an early pioneer of techniques based on acoustic probes inserted into the sediment, measuring compressional wave speed and attenuation in a variety of ocean bottom locations (Hamilton et al., 1956). Early *in situ* measurements of compressional-wave speed and attenuation in mud were also reported by Wood and Weston (1964). Numerous devices have been designed in recent years for *in situ* measurements of sediment compressional-wave properties, and they have been used to characterize the surficial sediment of the shallow ocean at a number of sites.

The *in situ* sound speed and attenuation probe (ISSAP) was designed to rapidly sample a large area by inserting a set of probes 15 cm into the seabed to obtain estimates of the compressional-wave speed and attenuation and then hopping to subsequent locations (Mayer et al., 2002). The sediment acoustic speed measurement system (SAMS), which uses a vibracore for a penetration depth of up to 3 m with an arbitrary step size, provides estimates of the compressional-wave speed and attenuation and has been used in offshore locations in support of ocean acoustic-propagation experiments (Yang et al., 2008). More recently, compact, manually deployed systems have been used to characterize compressional-wave properties of a variety of intertidal (Robb et al., 2006) and near-shore (Demoulin et al., 2015) sediments. A system capable of measuring shear-wave properties as well as compressional-wave properties has also been developed (Barbagelata et al., 1991). For deeper penetration into the seabed, measurement systems involving down-hole methods (Muir et al., 1991) or acoustic probes attached to the end of sediment-coring devices (Ballard et al., 2016) have been developed.

Examples of direct measurements collected 30 cm below the water-sediment interface in Currituck Sound in North Carolina are shown in **Figure 3** (Lee et al., 2016a). The measurements were collected at two field locations having distinctly different sediment types: a shallow site (approximately 1 m water depth a few hundred meters from the shore) with medium- to fine-grained sand and a deeper site (about 3 m water depth and out in the main channel of the Sound) with fine-grained sand with approximately 10% mud content. Two deployments of a measurement system consisting of a set of one compressional-wave source and three receivers and a set of one shear-wave source and three receivers were conducted a few meters apart at the shallow site and one measurement system deployment was performed at the deeper site. The measured wave properties at the two shallow-site deployments are statistically similar, as indicated by the overlapping error bars in **Figure 3a**. The compressional-wave speed at the deeper site was approximately 200 m/s slower compared with that at the shallower site, and the shear-wave speed was approximately 40 m/s slower. The shear-wave attenuation was also much greater at the deeper site, which limited the shear-wave measurements to frequencies below 500 Hz. It is believed that slower wave speeds and higher shear-wave attenuation at the deeper site were caused by the presence of vascular plants or algae, infauna, and their organic and inorganic byproducts that have the potential to alter the physical properties of the sediment (e.g., density, porosity, or shear strength) and pore fluid (e.g., viscosity) and thereby modify the acoustic properties. The potential of biological activity to affect the geoacoustic proprieties of the seabed is discussed below.

Sediment Acoustic Models

Theoretical models describing wave propagation in marine sediment properties can be used to predict the compressional- and shear-wave speed and attenuation of a given sediment from measurements of physical properties. Models of varying complexity (e.g., treating the sediment as a fluid, elastic, or poroelastic medium) have been developed to describe the acoustic behavior of marine sediments. Different models have been applied to predict measured data from various laboratory and field experiments with varying degrees of success; however, there is no general consensus on whether any of the models fully describe the physical mechanisms governing the acoustics in even the most homogeneous granular sediment. The inhomogeneity found in naturally occurring sediments further confounds the predictive capability of the models.

Fluid models are the simplest descriptions of sound propagation in sediment. A well-known example of such a model is the Mallock-Wood equation, which employs mixture rules to predict the sound speed in an effective medium composed of two or more constituent materials (e.g., water/gas, water/mineral, or water/gas/mineral; Mallock, 1910; Wood, 1946). The fluid description of marine sediments inherently includes no rigidity, treating the sediment as a suspension of its various components. According to this formulation, each constituent material contributes to the bulk compressibility and bulk density of the suspension in proportion to its volume concentration. Notably, the resulting sound speed calculated from the Mallock-Wood equation can be lower than that of either of the components.

For sediments possessing rigidity, the Mallock-Wood equation will underpredict the compressional-wave speed. To more accurately model the acoustic properties of marine sediments, more complex models that include the propagation of shear waves in sediment have been developed. Two types of models widely used within the underwater acoustics research community today are viscoelastic models such as Buckingham's grain-shearing (GS) theory (2014) and poroelastic models based on Biot's theory (1956a,b). Both types of models predict the frequency dependence of all four acoustic parameters (compressional- and shear-wave speeds and attenuations) but differ both in their description of the physical mechanisms contributing to the wave dispersion relationships and in their application through the number and type of input parameters.

A recent example of an elastic-sediment model, Buckingham's GS theory (2014), treats unconsolidated marine sediment as a two-phase medium, with internal losses arising at grain-to-grain contacts from shearing and stress relaxation. The wave speeds and the associated attenuations are determined from the compressional- and shear-wave equations, which are developed from a generalized Navier-Stokes equation that takes into account the stresses that are present at the intergranular contacts. It has been shown that the effects of viscosity are important for calculating compressional-wave properties but can be neglected for calculating shear-wave properties. The relative importance of viscosity and its dependence on the type of propagating wave is accounted for in a slightly modified form of the model designated VGS(λ).

An alternative family of sediment acoustic models is based on Biot's theory of wave propagation in poroelastic media, which considers a consolidated elastic frame filled with a viscous pore fluid (Biot, 1956a,b). In the Biot theory, dissipation arises solely from the viscosity of the pore fluid. Stoll (1977) later modified the Biot theory to allow for empirically determined complex frame moduli in an attempt to account for losses in an unconsolidated frame, and he applied the model to wave propagation in marine sediments. Other models seeked to extend the Biot-Stoll formalism by incorporating frequency-dependent losses. In a recent model (Chotiros and Isakson, 2014), these losses arise from the inclusion of grain-contact squirt flow and viscous shear drag into frequency-dependent complex frame moduli, designated as the extended Biot (EB) model.

Fits of the Mallock-Wood equation, VGS(λ) theory, and EB model to the shallow-site data from the Currituck Sound experiment (Lee et al., 2016a) are shown in **Figure 4**. The Mallock-Wood equation, which acts a low-frequency limit to the VGS(λ) model, is frequency independent and hence is not capable of describing the sound-speed dispersion observed at higher frequencies. The VGS(λ) model was fit to the data using measured values of shear-wave speed and attenuation at 500 Hz and compressional-wave speed at 70 kHz.

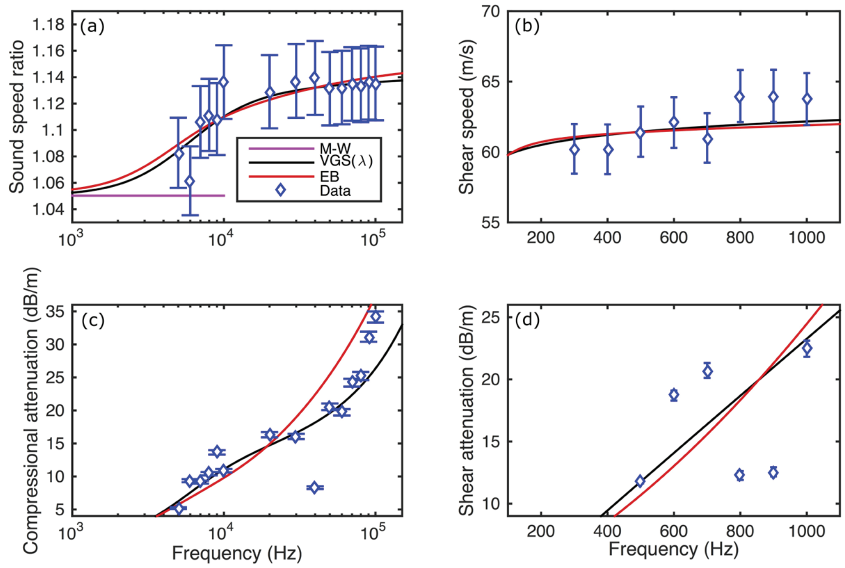

***Figure 4**. Comparison of measured wave data from the deployments at the shallow site with sandy sediment (**open diamonds with error bars**) with the best-fit sediment models. **a**: Compressional sound speed ratio; **b**: shear-wave speed; **c**: compressional-wave attenuation; **d**: shear-wave attenuation. M-W, Mallock-Wood equation; VGS(λ), viscous grain-shearing theory; EB; extended Biot model. The VGS(λ) and EB models were both developed for sandy sediments, and they fit well with the measured data from the sandy sediment site. The M-W is equivalent to the low-frequency limit for sound speed in the VGS(λ) model. Adapted from Lee et al. (2016a).*

For application of the EB model, six additional fit parameters were employed as well as several calculated and tabulated values. It was possible to fit both the VGS(λ) and EB models to the compressional- and shear-wave speed data with comparable model-data agreement. Although there was more scatter in the attenuation data, it was also reasonably fit by the models. To further assess which of the frequency-dependent models more accurately describe the data, comparison with measurements of other acoustic parameters, such as the bottom reflection coefficient, would help reduce ambiguity.

Although models like EB and VGS(λ) have been primarily applied to prediction of the geoacoustic properties in sandy sediments, less attention has been given to muddy sediments or sediments that are mixtures of sand and significant fractions of smaller particles. For example, new models will likely need to be developed that take into account the microscopic physics of the interactions between clay particles. Recent efforts have been undertaken to understand the physics of interparticluate interactions in clay and its impact on shear-wave speed or compressional attenuation (Pierce et al., 2016). However, a unified model capable of predicting all four wave parameters in fine-grained sediments remains to be developed.

Biological Effects on Sediment Acoustic Properties

There have been a number of experimental studies concerned with the effects of benthic biology on seabed acoustic properties. Although some empirical relationships have been established, no predictive theoretical model addresses the acoustic behavior of marine sediment containing organic matter or biological content. In this section, we present two examples of how marine sediment acoustic properties can be affected by the presence of biological organisms by looking at seagrass meadows and benthic infauna.

Seagrass Meadows

Biological processes and physical characteristics associated with seagrass can greatly affect acoustic propagation in coastal regions. An important acoustical effect is due to bubble production by the plants, which can have a significant impact on both object detection and bottom mapping sonars by increasing clutter through reflection, absorption, and scattering of sound (Komatsu et al., 2003). Remote sensing techniques have been demonstrated to monitor biological markers, such as photosynthetic activity from seagrass, as an assessment of marine ecosystem health (Hermand et al., 1998). Additionally, seismo-acoustic survey tools have been investigated to obtain carbon sink estimates for the sediment underneath seagrass beds (Lo Iacono et al., 2008). It has also been shown that gas production by seagrass is temporally variable over both shorter (diurnal) and longer (seasonal and longer) timescales, indicating that the potential acoustic effects are also time dependent (Wilson et al., 2012).

Gas generated by seagrass photosynthetic activity can dissolve directly into the surrounding seawater or form bubbles that cling to the outside of the leaves. In addition to the gas-bearing leaf tissue in the water column, the rhizomes also contain aerenchyma (gas-filled canals), which allow for diffusion of oxygen into the surrounding sediment. The density and elastic moduli of the plants themselves can also potentially affect long-range acoustic propagation by altering the effective material properties at the water-sediment interface and within the seabed when seagrass meadows are ubiquitous in the environment.

In situ measurements of sound speed and attenuation in a bed of *Thalassia testudinum* (turtlegrass) located in east Corpus Christi Bay near Port Aransas, TX, are shown in **Figure 5** (Lee et al., 2017). The acoustic measurements were

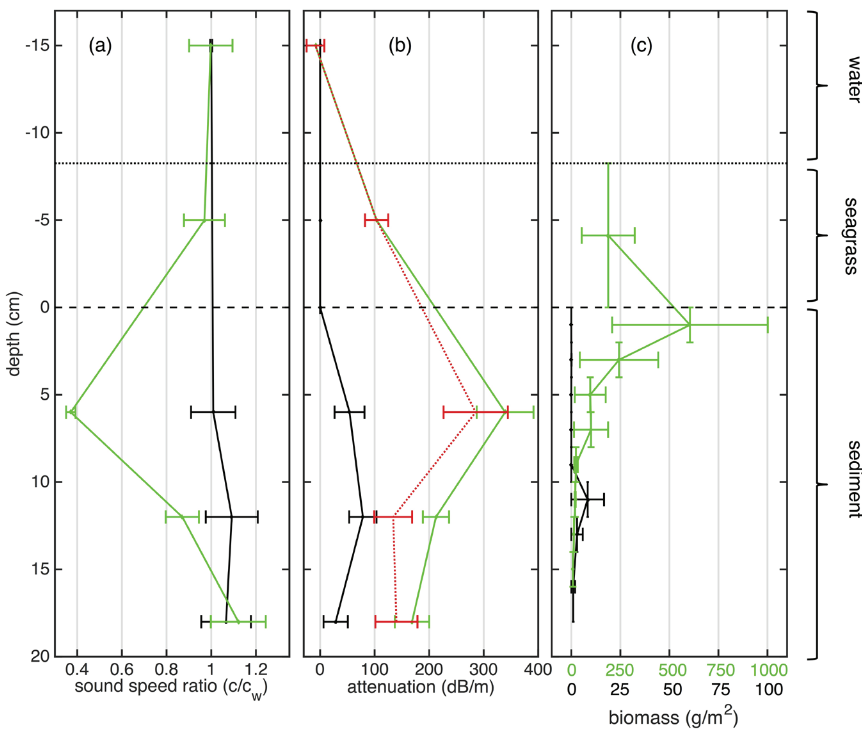

***Figure 5**. **a**: Depth dependence of acoustic and physical properties above and in a* Thalassia testudinum *(turtlegrass) bed (**solid green lines**) compared with the same measurements at a nearby site with no seagrass, only bare sediment (**solid black lines**). **b**: **Red dotted line** indicates the increase in attenuation in the seagrass bed relative to the bare sediment site. Negative values of depth indicate locations in the water column and positive values indicate locations within the sediment. The **dashed horizontal lines** at zero depth in each plot indicate the water-sediment interface. The **dotted horizontal lines** at a depth of −8 cm (above the water-sediment interface) indicate the approximate height of the seagrass canopy. The biomass for the bare-sediment case is multiplied by a factor of 10 so that it can be seen in the same scale as the values for the seagrass bed. **c**: **Green labels** on x-axis correspond to the biomass in the seagrass case and the **black labels** correspond to the bare sediment case. Adapted from Lee et al. (2017).*

acquired using acoustic probes deployed in the water above the seagrass canopy, inside the seagrass canopy, and at several depths in the sediment below the seagrass. For comparison, measurements were also obtained at the same depths at a nearby site with bare sediment. Sediment cores were collected at both sites and analyzed for plant biomass, sediment bulk density, and mean grain size. The depth dependence of the sound-speed and attenuation profiles are markedly different between the two measurement locations. The greatest difference is observed for the shallowest acoustic measurements below the seafloor where the plant rhizome and root systems exist. In the bare sediment patch, the sound-to-speed ratio is greater than unity, consistent for fine-sand sediments. However, in the seagrass-bearing sediment, the sound–to-speed ratio is reduced to a value of 0.37 and the attenuation takes on a maximum value of 340 dB/m. The large change in the acoustic sediment properties was attributed to the seagrass tissue, associated gas volumes within the tissue, and the diffusion of gas into the sediment.

Benthic Infauna and Bioturbation

Bioturbation, which refers to the churning, stirring, mixing, or reworking of sediments by organisms during such activities as feeding, locomotion, or home building, alters sediment physical properties including grain size and sorting, porosity, bulk density, permeability, packing, tortuosity, and consolidation behavior (Jackson and Richardson, 2007). Most infaunal organisms are found in the upper 25 cm of sediment, known as the benthic boundary layer. Changes in the sediment acoustic properties resulting from infaunal activity have been predicted using empirical formulas based on measurements made in both disturbed and nondisturbed sediments (Richardson and Young, 1980). Laboratory and field measurements have demonstrated complicated relationships between infauna, bioturbation, and geoacoustic properties (Richardson et al., 2002; Lee at al., 2016b).

One of the most conclusive studies on this topic relates trends in the measured physical properties of the sediment to the relative abundance of three species of burrowing organisms (Jones and Jago, 1993). The drawings in **Figure 6** show each organism's burrow. Correlations between the number of organisms and the electrical resistivity and shear-wave speed revealed how the organisms' activities affected the geoacoustic properties of the seabed. *Arenicola marina* (lugworm) and *Corophium arenarium* (a type of small crustacean) decreased the sediment's rigidity by creating open burrows, observed as a decrease in shear-wave speed with increasing organism abundance. However, *Lanice conchilega* (sand mason worm) increased rigidity by building shell-lined tubes, indicated by an increase in shear-wave speed when more organisms were present. All three species produced a reduction in the electrical resistivity, indicative of changes in bulk porosity/tortuosity, and hence changes to the sound speed. The process of burrow construction, involving the selection of grains by size and shape, also produced changes in sediment texture and properties between the burrows.

Many infaunal organisms produce a mucus-like material called extracellular polymeric material. In some marine invertebrates, 80% of the animal's total energy expenditure is accounted for by mucus production (Murray et al., 2002). Soft organic cementation (bonding) between particles resulting from infaunal mucus reduces sediment permeability by interstitial pore blockage. Laboratory studies have demonstrated that heterotrophic microorganisms can reduce sediment permeability by an order of magnitude, which can have complicated effects on the sound speed and attenuation due to changes in pore fluid mobility. (Meadows and Tufail, 1986). Field measurements have shown that the wet bulk density of sediments decreases and water content increases with increasing organic content, effects that are associated with a decrease in sound speed (Keller, 1982).

Conclusions

The geoacoustic properties of marine sediments have been studied for almost a century, and much is understood about sound propagation through this medium. A large number of measurements have been acquired, empirical relations have been formed, and sophisticated models have been developed. Nevertheless, the field of sediment acoustics remains an interesting and vibrant area of study. Recent work related to the effects of benthic biology on seabed acoustic properties reveals interactions between sediments and the plants and animals that live in them. It has been shown that biology can change sediment properties as function of space and time in unexpected ways. For biologically active sediments, understanding geoacoustic properties is a multidisciplinary undertaking, involving both the measurement of acoustic properties and the quantification of biological effects. A complete explanation of the results of these measurements will ultimately lead to new sediment acoustic models that account for the presence of flora and infauna and the changes they make to the physical properties of the seabed.

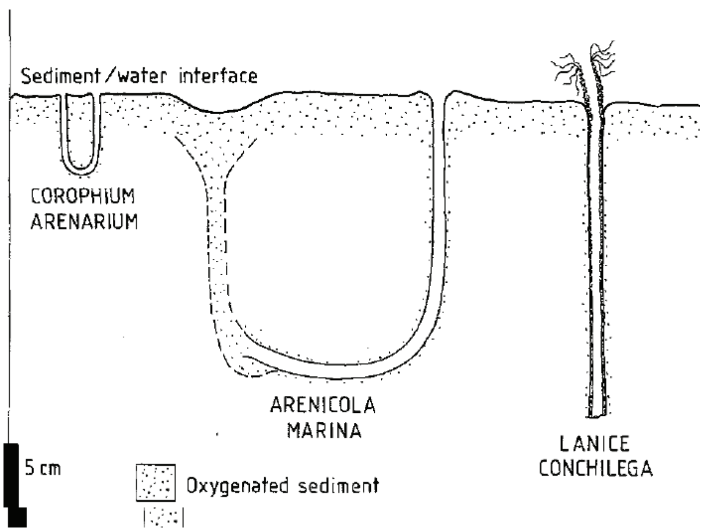

***Figure 6**. Arenicola marina (lugworm) creates large burrows in the upper 100-150 mm of the bed and liquefies and reworks the surface layers, resulting in an increase in bed porosity.* Corophium arenarium *(a type of small crustacean) builds hollow, U-shaped burrows that are open at both ends. They are smaller and occur in much greater densities than those of* Arenicola marina. Lanice conchilega *(sand mason worm) burrows differ from those of* Arenicola marina *and* Corophium arenarium *in their geometry (linear rather than U-shaped) and construction (particle-lined as well as mucus-lined walls). Adapted from Jones and Jago (1993).*

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Biosketches

Megan S. Ballard received a BS in ocean engineering from Florida Atlantic University in 2005 and a PhD in acoustics from Pennsylvania State University in 2009. She is a research scientist at the Applied Research Laboratories, University of Texas at Austin. Dr. Ballard received the R. Bruce Lindsay Award from the Acoustical Society of America in 2016, the Postdoctoral Special Research Award from the Office of Naval Research in 2011, and the National Defense Science and Engineering Graduate Fellowship Award in 2006. She currently serves as the chair of the Underwater Acoustics Technical Committee.

Kevin M. Lee, a plasma physicist by training, has been a physical and underwater acoustician at the Applied Research Laboratories, University of Texas at Austin, since 2009, where his research interests center on seabed acoustics, the acoustics of bubbles and bubbly media (natural and synthetic), underwater acoustics measurements, and acoustic materials characterization. Dr. Lee is also a cofounder of AdBm Technologies, a developer of novel underwater noise abatement systems, and the holder of several related patents. He is a member of the Acoustical Society of America and currently serves on both the Physical and Underwater Acoustics Technical Committees.

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