Mud Acoustics

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Introduction

Long before kindergarten, many of us experimented with mud. Mud's squishiness, the fact that we could launch airborne blobs with a kick or a stomp and the satisfying "thwuuck" sounds that this made provided hours of delightful exploration, sometimes despite protests from our parents. And although most kids outgrow playing in mud, some of us who study sound propagation in the ocean continue to be fascinated by it.

But one might well ask why is mud acoustics interesting and important? The answers are that (1) we live on a muddy planet because oceans cover 70% of the earth and mud covers the vast majority of the seabed; (2) acoustics play a critical role in studying and operating in the oceans because light and radio waves are poorly transmitted in seawater, whereas sound propagates effectively; and (3) acoustic waves in the ocean often interact with and are strongly affected by the seabed. Hence, measuring and understanding the acoustically relevant geophysical properties (referred to as geoacoustic properties) of muds are necessary to apply and predict acoustics in marine environments.

In this article, we provide an overview of mud acoustics by briefly addressing the following questions. What is mud? Which mud properties are important? How are those properties measured, inferred, and modeled? And finally, what is it we still don't know?

What Is Mud?

Marine sediments can generally be divided into two broad categories: (1) granular or coarse-grained sediments (e.g., sand, gravel) in which the individual grains are held together by gravitational forces and (2) fine-grained sediments (muds) in which the grains are held together primarily by electrochemical forces. More specifically, mud is an unconsolidated sediment that must have two components: some amount of microscopic material, be it clay-sized (<4 µm diameter) and/or silt-sized (4-63 µm diameter) grains, and water. Beyond these two requirements, mud may contain almost anything else of any size, such as sand and gravel, organic matter, and microplastics, often making it difficult to determine exactly what is meant when "mud" is used in scientific or engineering applications.

So perhaps it is easier to describe what mud is not because other sediments are well defined. Sediment that is either predominantly (nominally >50% by weight) composed of sand-sized (63 µm to 2 mm) or gravel-sized (>2 mm) material is not mud. Although sand- or gravel-dominated sediments may be described as "muddy" if they have clay- or silt-sized grains incorporated into them, they are not considered to be mud.

Figure 1a shows an optical image of mud. The larger green, brown, and clear grains are minerals worn away from preexisting rocks through weathering and erosion. There is also abundant biogenic (particles produced by living organisms) silt including diatoms (e.g., **Figure 1a**, *large circle*), fragmented plankton shells (fragments with many closely spaced holes), spicules (long needlelike features), clay, and possibly organic matter (disseminated brown material, e.g., **Figure 1a**, above the 50-µm scale bar).

The composition of the materials comprising a mud is vitally important to its geoacoustic properties. Beyond the requirement for water, the composition of mud is primarily a function of the environment in which it occurs. Muds in land-based and marine settings contain a mix of inorganic and organic components derived from local or distant sources. Inorganic components are further divided into minerals from the weathering of nearby rocks; transported phases (e.g., volcanic ash); biogenic materials (e.g., skeletal remains of plankton); and other minerals formed in place by chemical processes. These mineral and biogenic grains have a stunning range of shapes and sizes, from platy clays (layered or sheet crystals) to exotic chambered

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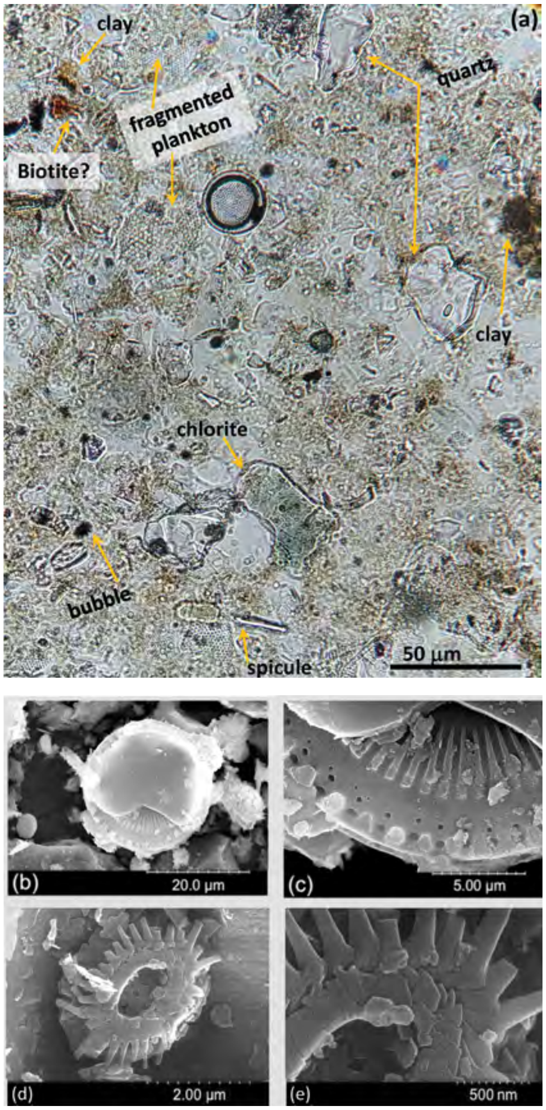


Figure 1. *Images of mud from the New England Mud Patch (NEMP).* ***a:*** *From an optical microscope.* ***b-c:*** *Scanning electron micrograph (SEM) of the remains of a diatom (algae made of silica).* ***d-e:*** *SEM images of a coccolithophore (plankton made of calcium carbonate).* ***Figure 1, b-e,*** *adapted from Dubin et al., 2017, with permission of Acoustical Society of America.*

and ornamented remains of microscopic marine organisms (see **Figure 1, b-e**).

In general, inorganic components tend to dominate the composition of mud. This is the case for a biogenic ooze off the coast of Italy that is almost entirely composed of the fossil remains of single-celled marine algae (85% clay sized). A very different mud composed primarily of land-based grains (15% clay sized) is found in an area known as the New England Mud Patch (NEMP), another site of extensive field studies (Wilson et al., 2020). Both the Italian and NEMP muds are considered further in **Mud Geoacoustics**.

Organic components found in mud come from land-based plant and animal sources and marine organisms (e.g., bacteria, plankton, and larger mobile fauna) that undergo various levels of degradation. The degraded organic matter may suspend silt and clay particles in the sediment fabric or, in other words, restrict the silt and clay particles from touching each other. The organic matter can also adsorb onto mineral surfaces and reside between mineral contacts. All these interactions alter mud properties, decreasing stiffness, increasing viscosity, and decreasing density (Venegas et al., 2022). Biological processes further alter the mud geoacoustic properties through events such as burrowing and tube building of benthic organisms (Dorgan, 2020).

Mud Geoacoustics

The geoacoustic properties of marine sediments that are generally most important in influencing ocean-acoustic propagation are the compressional-wave (sound) speed, attenuation, and bulk density. The shear-wave speed and attenuation in mud can be important in some cases; however, mud shear-wave speeds near the water-sediment interface are typically about two orders of magnitude smaller than the sound speed in mud or water, and, hence, there is little coupling between acoustic and shear waves. Thus, in many cases, modeling mud as a lossy fluid is a reasonable approximation for acoustics.

Sound speed and attenuation in muds and other sediments vary with the frequency of the acoustic waves passing through them. Measuring and understanding these frequency dependencies are challenging but important because they provide clues to the underlying physics that control acoustic-wave propagation in sediments. Geoacoustic properties also depend on the depth below the water-sediment interface. This dependence is important because if the sound speed increases with depth, acoustic waves can be refracted and/or reflected upward back into the water column. Alternatively, if the sound speed decreases with or is independent of the depth, the acoustic energy transmitted into the sediment does not return to the water column.

Measurement and Inference Methods

Geoacoustic properties of muds and other seabed sediments can be determined using two broad approaches:

(1) *Measured directly* using invasive procedures (such as inserting a probe into the sediments or extracting a sediment sample, referred to as a core, for subsequent laboratory measurements), or

(2) Inferred remotely using water-column measurements of acoustic fields that interact with the seabed.

In a previous *Acoustics Today* article, Ballard and Lee (2017) termed these approaches *direct* and *indirect*, whereas we use *direct* and *remote*. Although Ballard and Lee focused on direct methods, we discuss remote methods in more detail to fill out the picture. Direct and remote approaches are both important in developing our understanding of mud, and each has its own advantages and limitations.

For direct methods, sound speed and density are routinely measured in cores, whereas attenuation measurements are less common. Probes normally measure sound speed. Although useful information about mud is obtained with direct measurements, limitations on such methods include (1) the unavoidable disturbance and modification of sediment properties from their natural state, especially for muds that are often structurally fragile; (2) restricted sampling depth, with most cores for acoustic purposes penetrating less than 10 m and commonly about 1 m, whereas probes penetrate up to about 3 m; and (3) restricted range of (high) measurement frequencies, with probes operating at kilohertz to hundreds of kilohertz and core measurements at hundreds of kilohertz. Despite these limitations, an important advantage of coring is that the sediment sample is retrieved and can be studied minutely, including the underlying physical properties such as the mineralogy, chemistry, grain-size distribution, and organic-matter content (e.g., Chaytor et al., 2022). These observations can be crucial for developing a fundamental understanding of the relationships between the physical and the geoacoustic properties of sediments.

In contrast to direct methods, remote-sensing methods infer sediment geoacoustic properties from measurements of acoustic fields (data) that have been altered by interactions with the seabed and, hence, carry information on seabed properties. Remote-sensing methods require a theoretical model for these interactions such that acoustic data can be predicted (computed) given a set of geoacoustic properties, with the goal of determining property values for which the predicted data match the measured data (describing methods by which this is done is beyond the scope of this article). This remote-sensing procedure is referred to as geoacoustic inversion.

A variety of at-sea survey methods can be used to obtain different types of acoustic data that can be employed in geoacoustic inversions. Geoacoustic inversions can be based on measurements of either long-range or short-range acoustic propagation. Long-range methods, in which the propagation path is typically 1-10 km long on the continental shelves, involve multiple or continuous acoustic bottom interactions and provide geoacoustic estimates that represent a lateral average of the sediment properties over the propagation path (e.g., Knobles et al., 2020). Such methods are well-suited for estimating sediment properties for regional models and long-range propagation predictions. A limitation, however, is that unknown spatial and temporal fluctuations in the environment (water column and/or seabed) along the path can lead to biases in the inferred properties. Furthermore, detailed sediment-column structure may not be resolved due to this averaging and intrinsic attenuation can be obscured by other cumulative loss mechanisms such as scattering from rough interfaces or volume heterogeneities. Thus, the detailed structure is best obtained using short-range data that interact with the seabed over with a small lateral footprint (10-100 m), such as the single-bounce reflection method considered in this article.

Advantages of remote methods are that they sample undisturbed *in situ* sediments, potentially as deep as a kilometer or more (depending on the acoustic frequency and sediment type), and they can provide information about sound speed, density, attenuation, and, in some cases, shear and other sediment properties. However, remote methods suffer from the fact that acoustic data contain errors (noise) and provide only limited information on the seabed such that the estimated geoacoustic properties always have some degree of uncertainty (dependent on the data type, frequency, and other factors). Also, remote methods are generally limited to the frequency range of tens to thousands of hertz.

One important thing to note is that neither direct nor remote methods provide "ground truth" (definitive knowledge) for geoacoustic properties. Furthermore, as currently applied, the two methods generally cover distinct (nonoverlapping) frequency bands. This means that for the most complete understanding of sediment acoustic properties, both direct and remote methods should be applied. Even then, both modeling (to bridge the frequency gap) and subjective interpretations are required to explain/understand the disparate observations.

Sound Speed

In contrast to coarse-grained sediments, marine muds often exhibit the curious property of having a sound speed less than that of the seawater above. This is a consequence of the weak electrochemical forces that bind the sediment grains together so that muds often behave essentially as a suspension of fine grains within water (unlike sands or other sediments). This suspension has a higher density than seawater but nearly the same bulk modulus (resistance to compression) as seawater because the individual grains form a weak matrix (frame). Thus, because the sound speed depends on the bulk modulus divided by the density, the result is a lower sound speed for mud than for water. This means that the sediment sound speed ratio (SSR), defined as the ratio of the sound speed in the sediment to that of the overlying seawater, is less than one.

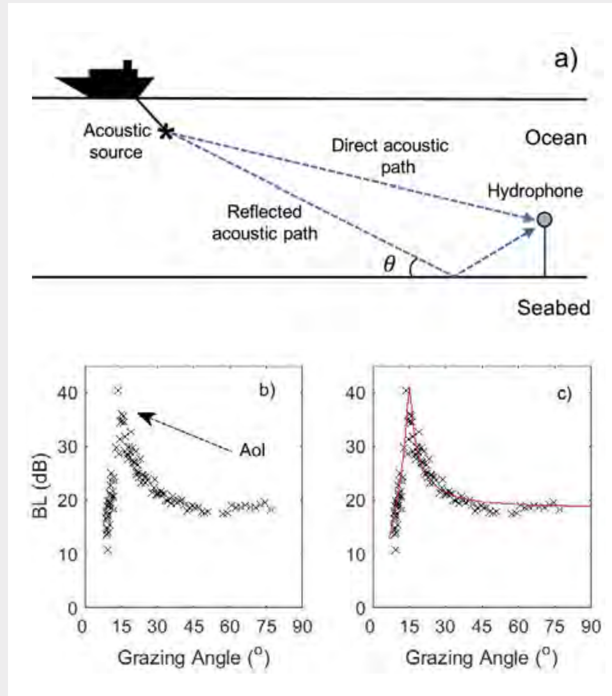


Figure 2. ***a:*** *Reflection coefficient or bottom loss (BL) measurement geometry.* ***b:*** *Measured BL south of Sicily, Italy, as a function of grazing angle θ at 800 Hz, showing a clear angle of intromission (AoI) at 15°.* ***c:*** *Comparison of the measured BL with predicted BL (**red line**) computed using the estimated mud sound speed and density. Adapted from Holland, 2002.*

The SSR is of considerable importance in ocean acoustics. It can be measured directly by cores or probes or inferred by remote (inversion) methods, with the attendant challenges noted in the previous section. Mud SSR measurements can be challenging. This is evidenced, for example, by widely varying measurement results at the NEMP test site where SSRs ranging from 0.94 to 1.02 have been reported within a small geographic area (Wilson et al., 2020).

A useful remote-sensing method for estimating mud sound speeds (and other properties) involves seabed reflection coefficients. The measurement procedure is illustrated in **Figure 2a**. A hydrophone (underwater microphone) is used to record acoustic pulses from an acoustic source that follow direct and bottom-reflected paths through the water column. The reflection coefficient is defined as the ratio of the reflected wave acoustic pressure to that of the direct wave and thus quantifies how the reflection process has altered the wave amplitude. Measuring reflection coefficients for a range of reflection angles using a towed acoustic source provides an acoustic dataset that contains a great deal of information about seabed geoacoustic properties.

A particularly interesting case involves data with an angle of intromission (AoI), that is, an angle at which the reflection coefficient goes to zero (i.e., there is no reflected acoustic wave but rather total transmission into the seabed). The AoI was predicted theoretically by Lord Rayleigh in 1896. Rayleigh showed that the AoI exists for reflection at the interface between two media with sound speed and density ratios less than and greater than unity, respectively.

Because muds often have a SSR less than one and always have a density ratio greater than unity, an AoI should commonly occur in seabed acoustic-reflection measurements. However, there have been only a few successful field measurements of the AoI. One reason for this is that it is challenging to measure the absence of something, in this case, the reflected field. Not only does the signal-to-noise ratio have to be high, but all other "contaminating" paths must be mitigated, including reflected waves from deeper layers in the seabed.

The first clear AoI measurement was published by Winokur and Bohn (1968), who found an AoI of 11° in a deep-ocean setting (water depth 4,500 m). The next observation came more than 3 decades later with a measured AoI of 15° in 100 m of water at several sites in Italian coastal waters (Holland, 2002). One of these datasets is shown in **Figure 2b** in terms of bottom loss (BL) in decibels (with high BL corresponding to low reflection coefficients) clearly showing the AoI.

Using measurements of the AoI and BL at one other angle, the seabed sound speed and density can be calculated from Lord Rayleigh's theoretical work, with values of 1480 ± 4 m/s (SSR = 0.979 ± 0.003) and 1.32 ± 0.04 g/cm^3, respectively, at this site. Using those geoacoustic estimates, the full BL can be calculated theoretically, which compares closely with the measured data (see **Figure 2c**). These data, collected south of Sicily, have the same AoI as data at the same water depth 1,000 km away in the Tyrrhenian Sea, north of Elba Island, Italy (Holland, 2002). This suggests that the physical processes that govern the mud microstructure are likely similar at the two sites.

Depth Dependence

The approach above estimated depth-independent mud geoacoustic parameters using the AoI at a single frequency. But what if the AoI is observed to be frequency dependent? It is well-known that the acoustic penetration depth in sediment decreases with frequency (increases with wavelength) such that very high frequencies (short wavelengths) are sensitive only to near-surface geoacoustic properties, whereas low frequencies (long wavelengths) are sensitive to deeper properties. Thus, depth-dependent sound speed and/or density profiles lead to a frequency-dependent AoI.

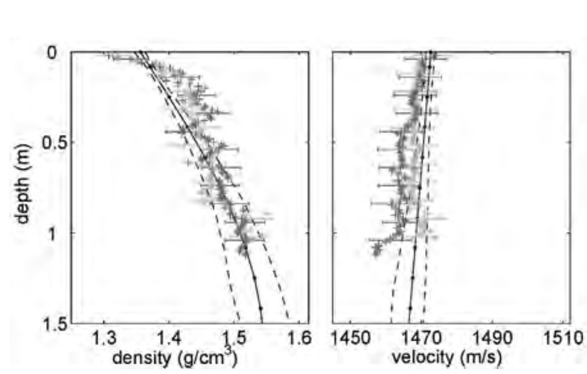
Conversely, frequency-dependent AoI observations provide information about and can be inverted for geoacoustic profiles. This was formulated as a Bayesian (probabilistic) inversion of measured BL data to estimate sound speed and density profiles (Holland et al., 2005). The results show the most probable depth-dependent sound speed and density profiles (**Figure 3**, *solid lines with solid circles*) with uncertainties (**Figure 3**, *dashed lines*).

Figure 3 also shows depth-dependent geoacoustic properties measured from two cores collected at the site, using specially designed corers to minimize sediment disturbance, which revealed the mud to be a nannofossil ooze. The agreement between the geoacoustic properties estimated remotely via AoI inversion and the core measurements is generally quite good, with a SSR = 0.976. It is clear that the AoI frequency dependence *does* contain significant information about the depth dependence of the mud properties.

A simple theory predicts that the minimum possible SSR value for mud is about 0.97. In other words, the minimum sound speed in mud is about 3% lower than that in seawater. Measurements over the last decades confirm this minimum value for muddy sediments with seawater in the interstices (the occasional presence of gas bubbles rather than water in muds can reduce the sound speed much more but is a story for another time).

A few percent variation in sound speed may seem hardly worth noting, but for ocean acoustic propagation, the effect can be considerable. In continental shelf areas, sound can travel long distances due to an acoustic waveguide formed between the sea surface and the seabed, given suitable seabed properties. For example, with sandy sediments, the sound speed is greater than that of water (SSR > 1), and a critical reflection angle exists at which the acoustic wave

Figure 3. *Estimated depth-dependent mud density (**left**) and sound speed (**right**) from an inversion of 300- to 1,600-Hz BL data south of Sicily, Italy, for the most probable geoacoustic profiles (**solid lines with solid circles**) and 95% credibility intervals (**dashed lines**). Properties measured from two cores (**dark and light crosses**) are also shown, with rough uncertainty estimates indicated as error bars. From Holland et al., 2005.*

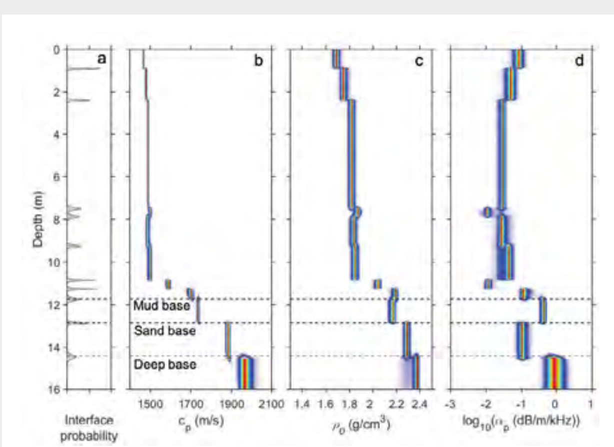


is completely reflected with no acoustic transmission into the seabed (typically at 15-30° grazing angle). In such cases, acoustic energy can propagate at angles below the critical angle with little loss to very long distances equivalent to hundreds of times the depth of the water.

However, for a muddy sediment with a SSR < 1, no critical angle (and therefore no acoustic waveguide) exists. Put another way, for a sediment with a SSR < 1, sound propagation in the ocean is limited to distances equivalent to only a few water depths. However, this rarely happens in practice at frequencies below 10 kHz for two main reasons. First, mud generally has a very low attenuation (compared with sands). Thus even for a mud layer tens of meters thick overlying sand, an acoustic waveguide often exists between the sea surface and the buried sand layer. Second, the mud sound speed can increase with depth such that there is a turning point within the mud where refraction bends the sound waves upward, returning acoustic energy to the water column. This is often the case in deep-water environments where muddy sediments can be many kilometers thick. Both reasons underscore the importance of understanding the depth dependence of sediment geoacoustic properties.

At the NEMP, 95 km south of Martha's Vineyard, Massachusetts, depth-dependent mud properties were inferred using reflection-coefficient data and Bayesian geoacoustic inversion (Jiang et al., 2023). The results are shown in **Figure 4**, plotted in terms of probability profiles for geoacoustic parameters. At this site, the mud thickness is found to be about 11.7 m. As is the case across the NEMP experimental area, a sand layer exists below the mud. The mud geoacoustic properties appear to fall into three depth intervals, upper 0-3 m, middle 3-10.8 m, and lower 10.8-11.7 m. The sound speed (**Figure 4b**) increases with depth in the upper interval, is nearly uniform in the middle, and exhibits an extremely large gradient in the lower.

Figure 4. *Depth dependence of geoacoustic properties at the NEMP from inversion of reflection-coefficient data. Probability profiles are shown for interface depth (**a**), sound speed (**b**), density (**c**), and attenuation (**d**). In these, the warm colors (e.g., **red**) indicate high probabilities and the cool colors (**blue**) low probabilities. The focus here is on the mud layer, above 11.7 m depth. From Jiang et al., 2023.*



When first observed, the high gradients in the lower mud interval were puzzling but have since been determined to arise from sand particles (from the sand layer below the mud) entrained in the mud by biologic (Nittrouer et al., 1986) and geologic (Goff et al., 2019) processes at the time the mud began to be deposited at the end of the last glaciation about 10,000 years ago. The fraction of sand increases with depth in the interval, which leads to the increase in sound speed. We term this lower interval the "transition interval" because it represents a gradual transition from mud to sand as opposed to a sudden change in sediment type.

Geoacoustic inversion results at two other sites at the NEMP, at 5 km and 19 km to the northwest with mud thicknesses of 10 m and 3 m, respectively, show remarkable similarity in the transition interval, its thickness, and sound speed gradient. This suggests that the geologic and biologic processes contributing to its formation were fairly uniform across the mud patch during the formation time. The other two sites also show similar depth dependence in the upper and middle intervals.

Attenuation

Attenuation is a challenging property to determine in sediments. Nevertheless, the inferred attenuation (**Figure 4d**) is sufficiently well determined (has small uncertainties) that we can discern its variation with depth. In the upper interval (0-3 m), attenuation decreases exponentially with depth (linearly in the log plot, smoothing through the stairsteps), is roughly constant in the middle interval, and increases rapidly in the lower (transition) interval. The large attenuation increase in the transition interval, nearly two orders of magnitude, is qualitatively understood to be due to the increasing sand content. At the two other sites at the NEMP (5 km and 19 km away), the attenuation exhibits a similar depth dependence. Recent core data at several locations near the site considered in **Figure 4** also show an exponentially decreasing attenuation in the upper layer at frequencies in the low hundreds of kilohertz.

The transition interval is controlled by biologic processes (e.g., mixing by benthic fauna) and geologic processes (sea level oscillations and sediment transport due to storms). Because these processes are virtually ubiquitous across the planet (e.g., Nittrouer et al., 1986), it seems likely that the transition interval may exist at all or, at least, at many muddy continental shelves. The characteristics of the transition interval are expected to vary depending on the regional processes. However, transition-interval characteristics may be approximately spatially uniform for a given shelf region. The transition interval and its similarity in a given region have been observed for the two continental shelf regions studied thus far in the North Atlantic and Mediterranean. Thus, if the sediment mixing and mud deposition rates are known for a given shelf, it may be possible to predict the transition interval thickness and geoacoustic characteristics and, hence, make better predictions of the depth-averaged attenuation in the mud layer. With improved geoacoustic properties, better predictions of the acoustic field in the ocean can be made, improving our ability to operate in and understand the ocean.

Frequency Dependence

The frequency dependencies of the sound speed and especially attenuation are important in understanding ocean-acoustic propagation in a particular environment. In theory, the attenuation can increase with frequency at rates varying from frequency to the one-half power to frequency squared, but the actual form of the frequency dependence for specific sediments is difficult to measure accurately. Nonetheless, it's quite important to measure because the change in attenuation with frequency over a few octaves can be dramatic.

There is growing evidence at the NEMP and other areas that muds with a modest sand content follow a nearly linear dependence of attenuation on frequency above a few tens of hertz up to at least 10 kHz. Furthermore, several observations (e.g., Yang and Jackson, 2020) have shown that mud sound speed shows little variation with frequency over from a few tens of hertz to hundreds of kilohertz. However, it should be noted that there are numerous other measurements of mud sound speed and attenuation, and there is not yet consensus as to the frequency and depth dependence of mud, even in the well-studied NEMP. **Figure 4** is meant to serve as an example of one set of results from a remote-sensing approach.

Models for Acoustic Propagation in Mud

Sediment-acoustic models are crucial for advancing our understating of mud acoustics. These models predict the wave speeds and attenuations as a function of frequency from a set of physical properties such as porosity. Carrying out geoacoustic measurements can be expensive, and if only a single measurement is available, say a core at 100 kHz, but a specific application requires a sound speed and/or attenuation at 100 Hz, models are required to bridge the spectral gap. More fundamentally, models provide a framework to test hypotheses and provide important constraints, for example, that the frequency dependencies of sound speed and attenuation are linked as a consequence of causality. Geoacoustic measurements and inferences, in turn, guide model development by providing observables that yield clues about the important underlying physics. Three sediment-acoustic models are currently used for muds; two of them have origins in models of wave propagation in granular media, whereas one was developed specifically for mud.

The mCreB model (Chotiros, 2021) is based on the Biot theory (Biot, 1962). Biot's original pioneering work involved modeling wave propagation through consolidated but porous media, such as rocks. This theory was subsequently modified over time to treat unconsolidated sediments. Most of the numerous subsequent Biot theory variants have been aimed at sands and silts, but a few treat mud. The most recent mud variant, mCreB, includes the mechanism of fluid flow ("squirt") at grain-to-grain contacts, developed for granular media, and adds mechanisms believed to be important for mud, including electrochemical forces binding a thin film of pore water to grain surfaces, the presence of tiny grains suspended in the pore water, and creep.

The viscous grain shearing (VGS) model (Buckingham, 2010) is based on a generalized Navier-Stokes equation (describing the motion of viscous fluids), invoking grain-to-grain sliding to introduce rigidity into the medium. The model has developed over several decades, motivated by modeling wave propagation through sandy sediments. However, in the last decade, it has been used for muddy sediments. Is that reasonable? The answer is possibly. VGS is a phenomenological model attempting to capture the complex physics of molecularly thin fluid films between sliding grains in terms of a Hookean spring and a time-dependent (strain-hardening) dashpot and time-independent dashpot (representing classical viscous loss) in series. Given the phenomenological approach, it is possible that the spring-dashpots model is useful for mud as well as for sand, even though the physics at the microscopic level may be quite different.

The silt-suspension theory (SST) (Pierce et al., 2017) considers mud composed of silt grains suspended in an effective fluid consisting of water and a matrix of clay particles. The clay particles are assumed to be arranged in a cardhouse structure (clay particles are electrically charged and can stick together face to edge, forming a so-called cardhouse structure). Although mCreB and GS are phenomenological models, SST attempts to work from first principles, including the electrostatic forces for clay and classical Stokes theory for the suspended silt. More recent work has invoked a continuous smear of relaxation processes that can be associated with diverse types of solid particles nominally in contact but sliding and separating in acoustic wave propagation.

Similarities exist between these models: strain hardening, creep, and relaxation processes are related. Differences also exist, of course, as evidenced by the differences in frequency dependencies predicted by the various models. However, a full discussion of model differences is beyond the scope of this article.

Still Muddy

There is still a lively debate about the properties of marine muds, including their depth and frequency dependencies. Furthermore, challenges remain in reconciling (1) remote measurements with each other, (2) direct measurements with each other, (3) remote and direct measurements, and (4) measurements with models.

Here is a minimal sampling of the outstanding questions being actively pursued in mud acoustics research.

(1) What are the key geologic, biologic, and chemical processes that lead to vertical and lateral variations in the geoacoustic properties of muds?
(2) What generalizations can be made for extrapolating findings for one muddy environment to other locations/mud types around the world?
(3) Do mud properties vary over time, for example, with seasonal changes in the seawater temperature (Wood et al., 2014)?

Acknowledgments

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References

Ballard, M. S., and Lee, K. M. (2017). The acoustics of marine sediments. *Acoustics Today* 13(3), 11-18.
Biot, M. A. (1962). Generalized theory of acoustic propagation in porous dissipative media. *The Journal of the Acoustical Society of America* 34(9A), 1254-1264.
Buckingham, M. J. (2010). Response to "Comments on 'Pore fluid viscosity and the wave properties of saturated granular materials including marine sediments [J. Acoust. Soc. Am. 127, 2095-2098 (2010)]'." *The Journal of the Acoustical Society of America* 127(4), 2099-2102.
Chaytor, J. D., Ballard, M. S., Buczkowski, B. J., Goff, J. A., Lee, K. M., Reed, A. H., and Boggess, A. A. (2022). Measurements of geologic characteristics and geophysical properties of sediments from the New England Mud Patch. *IEEE Journal of Oceanic Engineering* 47(3), 503-530.
Chotiros, N. P. (2021). A porous medium model for mud. *The Journal of the Acoustical Society of America* 149(1), 629-644.
Dubin, J. T., Venegas, G. R., Ballard, M. S., Lee, K. M., and Wilson, P. S. (2017). Physical and acoustical properties of marine sediments containing a wide particle size distribution. *Proceedings of Meetings on Acoustics* 31(1), 070001.
Dorgan, K. M., Ballentine, W., Lockridge G., Kiskaddon E., Ballard, M. S., Lee, K. M., and Wilson, P. S. (2020). Impacts of simulated infaunal activities on acoustic wave propagation in marine sediments. *The Journal of the Acoustical Society of America* 147(2), 812-823.
Goff, J. A., Reed, A. H., Gawarkiewicz, G., Wilson, P. S., and Knobles, D. P. (2019). Stratigraphic analysis of a sediment pond within the New England Mud Patch: New constraints from high-resolution chirp acoustic reflection data. *Marine Geology* 412, 81-94.
Holland, C. W. (2002). Geoacoustic inversion for fine-grained sediments. *The Journal of the Acoustical Society of America* 111(4), 1560-1564.
Holland, C. W., Dettmer, J., and Dosso, S. E. (2005). Remote sensing of sediment density and velocity gradients in the transition layer. *The Journal of the Acoustical Society of America* 118(1), 163-177.
Jiang, Y.-M., Holland, C. W., Dosso, S. E., and Dettmer, J. (2023). Depth and frequency dependence of geoacoustic properties on the New England Mud Patch from reflection coefficient inversion. *The Journal of the Acoustical Society of America* 154(4), 2383-2397.

Knobles, D. P., Wilson, P. S., Goff, J. A, Wan, L., Buckingham, M. J., Chaytor, J. D., and Badiey, M. (2020). Maximum entropy derived statistics of sound-speed structure in a fine-grained sediment inferred from sparse broadband acoustic measurements on the New England continental shelf. *IEEE Journal of Oceanic Engineering* 45(1), 161-173.

Nittrouer, C. A., DeMaster, D. J., Kuehl S. A., and McKee, B. A. (1986). Association of sand with deposits accumulating on continental shelves. In Knight, R. J., and McLean, J. R. (Eds.), *Shelf Sands and Sandstones.* Canadian Society of Petroleum Geologists Memoir 11, 17-25.

Pierce, A. D., Siegmann, W. L., and Brown, E. M. (2017). Characterization of mud sediments using the frequency dependence pf phase velocity and attenuation of compressional waves. *Proceedings of Meetings on Acoustics* 31(1), 070002.

Rayleigh, J. W. S. (1896). *The Theory of Sound, Volume 2,* 2nd ed. MacMillan and Co., New York, NY.

Venegas, G. R., Fey, M. R., Lee, K. M., Ballard, M. S., Clemo, W. C., and Dorgan, K. M. (2022). Relationships between sediment organic content and viscous grain shearing parameters in Mobile Bay, Alabama. *Proceedings of Meetings on Acoustics* 45(1), 070004.

Wilson, P. S., Knobles, D. P., and Nielsen, T. A. (2020). Guest editorial: An overview of the Seabed Characterization Experiment. *IEEE Journal of Oceanic Engineering* 45(1), 1-13.

Winokur, R. S., and Bohn, J. (1968). Sound reflection from a low-velocity bottom. *The Journal of the Acoustical Society of America* 44(4), 1130-1138.

Wood, W. T., Martin, K. M., Jung, W., and Sample, J. (2014). Seismic reflectivity effects from seasonal seafloor temperature variation. *Geophysical Research Letters* 41(19), 6826-6832.

Yang, J., and Jackson, D. (2020). Measurement of sound speed in fine-grained sediments during the Seabed Characterization Experiment. *IEEE Journal of Oceanic Engineering* 45(1), 39-50.

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