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Introduction to the special issue on assessing sediment heterogeneity on continental shelves and slopes^{a)}

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ABSTRACT:

Over the past decade, an interdisciplinary team of scientists conducted a series of at-sea measurements designed to further our understanding of acoustics in complex ocean environments. Most of these efforts focused on bottom-interacting acoustics in areas characterized by fine-grained sediments. Geographically, the primary experimental sites and data analysis took place in an area of the Western Atlantic Ocean approximately 60 miles south of Martha's Vineyard, MA, known as the New England Mudpatch, and extending south to include the shelf break and upper slope characterized by larger-grained sediments. This introductory paper provides a summary of the various experimental techniques and analysis approaches detailed in the collection of 23 papers that make up this special issue focused on Assessing Sediment Heterogeneity on Continental Shelves and Slopes. © 2025 Acoustical Society of America.

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I. INTRODUCTION

This special issue was motivated by the Seabed Characterization Experiment (SBCEX) 2015–present, conducted in and around the New England Mud Patch (NEMP), shown in Fig. 1, and by some of the work conducted in the related New England Shelf Break Acoustics Experiment (NESBA). Two previous guest editorials on the characterization of the seabed on the New England continental shelf appeared in 2020¹ and 2022,² and numerous other articles on this topic have been published. The collection of papers in this special issue report on the seabed characterization and acoustic properties of the New England continental shelf, the shelf break, and the slope, focusing on sediment variability, measurement and analysis techniques, and advancements in geoaoustic modeling. The series of interdisciplinary experiments comprising the SBCEX was novel in placing a high priority on occupying, or visiting, sites repeatedly under different oceanic conditions over the course of almost 10 years. A motivation for revisiting sites was to understand the impact, if any, of oceanographic conditions on measurements and/or inferences of seabed characteristics. The heterogeneity of sediments in the region

could then be considered in the context of accounting for the water column, biologic, or other phenomenological effects.

Additional objectives of SBCEX were to investigate variability in sediment content and assess our ability to characterize the surface sediment layer in the presence of variability at all sites shown in Fig. 1, which included various grain sizes from sand to clay, in various proportions and in various water depths, and under various oceanographic conditions. Mud sediments were observed in the central depocenter α and in the two smaller depocenters, δ to the north in about 50 m of water and χ to the south in about 100 m of water. Sands were observed at the shelf break site β along the 200 m depth contour and on parts of the slope to a water depth of about 400 m. The spatial variation in porosity was another marker of heterogeneity observed in the region, with relatively softer sediment (higher porosity) to the west and relatively harder sediment (lower porosity) to the east. Within the site β , the sediments in the shelf break (200 m contour) were inferred to be sand, but farther down the slope (water depths greater than 500 m), the sediments tended to contain an increasing amount of mud. Variability was also found in the inferred acoustic properties of the deep bottom layers below the surface mud layer. Finally, temporal variability was examined by comparing results obtained during the 2016 and 2022 campaigns, which occurred under different oceanographic conditions.

In the context of the variability and heterogeneity in the NEMP discussed previously, and since the publication of

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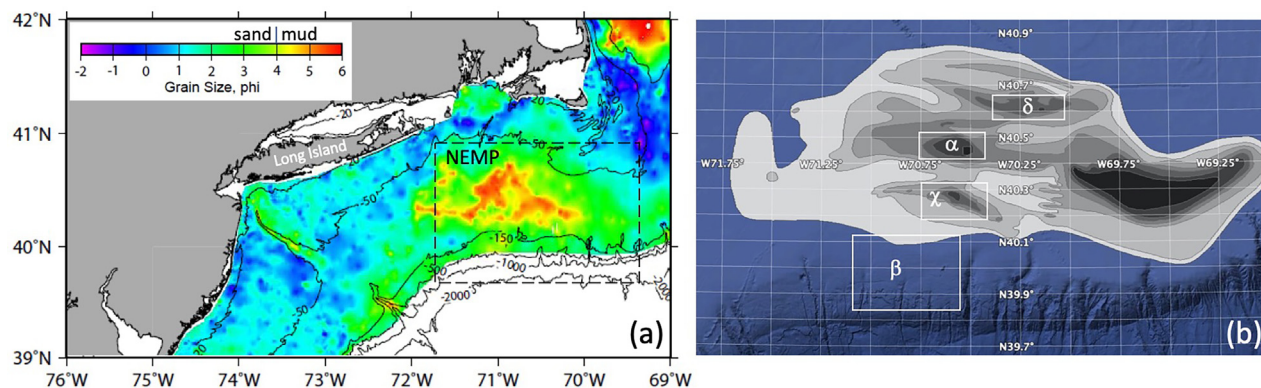


FIG. 1. The general location of the NEMP and SBCEX is shown in (a), outlined by the black dashed box. Seafloor grain size is shown with the color scale (Refs. 3 and 4). Mud thickness contours (gray < black) (Refs. 5 and 6) are shown in (b), with darker colors associated with depocenters. The central site α was the location of the 2015–2017 and 2022 campaigns. The northern δ , southern γ and the shelf break β sites were investigated in 2021 and 2022. NESBA was conducted at site β in 2021 (Ref. 7).

the previous two special issues, additional science objectives have been defined. The original goals of SBCEX were (1) to discover the physical mechanisms that control sound propagation in fine-grained sediments, (2) to evaluate geoacoustic models of sound propagation in such environments, (3) to assess inversion and statistical inference techniques for acoustic remote sensing of seabed acoustic parameters, and (4) to quantify uncertainties in inferred seabed acoustic parameters. One new goal was to expand the area of measurements beyond the central NEMP site to include different types of sediment. The idea of expanding the geographical area was, in part, motivated by the idea of repeating the original acoustic measurements. A second new goal arose to evaluate techniques that, instead of matching modeled and measured acoustic fields, features or attributes of the fields were matched. Examples of feature matching include analysis of reduced dimensional representations of the field, such as interference phenomena or properties relating to modal group velocities. A third new goal to expand the definition of sediment characterization arose from observations made by direct measurements, such as sediment cores, that quantify benthos content and chemical properties.

II. TOPICS

In this special issue, the seabed variability/heterogeneity is explored using a variety of measurement and analysis techniques including (1) direct measurements made by acoustic probes, collecting of sediment cores, and laboratory analysis of sediment samples (see Ballard *et al.*,⁸ Lee *et al.*,⁹ and Venegas *et al.*¹⁰); (2) subbottom layering inversions from ambient noise, platform self-noise, and active low-frequency sound transmissions (see Dahl and Dall'Osto,¹¹ Dall'Osto and Dahl,¹² Lipor *et al.*,¹³ Hopps-McDaniel *et al.*,¹⁴ and Siderius *et al.*¹⁵); (3) inferences from solutions to inverse problems: (a) spectral ratio of particle motion (see Potty *et al.*¹⁶), (b) modal dispersion mechanisms in both water column and sediment (see Bonnel *et al.*¹⁷) and

statistical inference methods for lower frequencies (see Dosso *et al.*,^{18,19} Dosso and Bonnel,²⁰ and Hopps-McDaniel *et al.*¹⁴) and mid frequencies (see Knobles *et al.*²¹), and (c) analyses of reflection data and seabed models (see Buckingham,²² Chotiros,²³ Holland,²⁴ Jiang *et al.*,²⁵ and Knobles *et al.*²¹), analysis of ambient noise (see Siderius *et al.*¹⁵), feature-based inversions (see Knobles *et al.*²¹ and Hopps-McDaniel *et al.*¹⁴), and inversion/inference from autonomous underwater vehicle (AUV) data (see Sabra *et al.*²⁶ and Pfenninger and Lin²⁷); (4) seabed parameterization: (a) shear (see Dosso *et al.*¹⁹ and Potty *et al.*¹⁶) and (b) poro-elastic (see Chotiros²³); (5) inversion with virtual arrays for source localization (see Michalopoulou *et al.*²⁸); and (6) ensemble learning (see Lau *et al.*²⁹) and distributed simultaneous data and automated deep learning (see Vardi *et al.*³⁰)

III. SUMMARIES

A summary of each manuscript in this special issue is presented in alphabetical order according to the last name of the first author.

Ballard *et al.*⁸ present directly-acquired *in situ* sound speed measurements from the NEMP and adjacent shelf break, obtained using an acoustic coring system. Measured values of sound speed and attenuation in the region exhibited spatial variability, with generally lower values for each found on the western side. Sound speed values within the shelf-break region were found to be highest between the 200–350 m isobaths. Vertical profiling in the NEMP reveals a surficial layer with a negative sound speed gradient, transitioning to a positive gradient over an isovelocity zone.

Bonnel *et al.*¹⁷ present trans-dimensional Bayesian inversion results from the three spatially distinct depocenters α , γ , and δ sampled during SBCEX 2022. Using modal time-frequency dispersion data from a single hydrophone, the inversion jointly estimates water column and seabed properties with quantified uncertainties. Comparative

analysis reveals no significant temporal variability at α (2017, 2021, and 2022) and minimal spatial variability between depocenters α and χ ; however, the third δ exhibits distinct geoacoustic characteristics.

Buckingham²² presents a closed-form expression for the plane wave reflection coefficient for a sediment consisting of a homogeneous mud layer overlying an upward-refracting inverse-square sound speed profile representative of sediments in the NEMP. In the absence of attenuation, the plane wave solution exhibits total reflection up to a critical grazing angle; however, by including attenuation within the sediment, the region of total reflection has a sequence of contiguous peaks.

Chotiros²³ compares poro-elastic and visco-elastic models of the acoustic behavior of sandy and muddy marine sediments. The poro-elastic model that includes force chain approximations and a creep mechanism is called the mCREB model, which is shown to fit measured data of wave speeds and attenuation at frequencies from a few hertz to almost a megahertz. One result of this study is evidence that salinity is essential to the poro-elastic behavior of mud.

Dall'Osto and Dahl¹² use the Doppler shift of tonal sound waves as an acoustic source radiating at different angles. In shallow water, a single generating tone may be received at multiple frequencies, each corresponding to sound propagating at an angle corresponding to the discrete normal modes. The mode angle predictions in the NEMP correlate with the observed mode angles at 57 Hz. For lower frequencies, harmonic tones were analyzed from a container ship that traversed the continental shelf from west to east over a 150-km range.

Dahl and Dall'Osto¹¹ continue the work of Dall'Osto and Dahl¹² by examining a slightly lower frequency range (9.5 to 36 Hz) of received acoustic signals from a transiting ship. The deep seabed profile obtained from Dall'Osto and Dahl¹² is further optimized, and the resulting frequency-dependent estimates of the deep layer properties show a correlation between the elastic properties and the compressional wave attenuation.

Dosso and Bonnel²⁰ apply joint inversion for the sound speed profile (SSP) of the water column and the geoacoustic models of the seabed, employing separate trans-D partition models. The approach was applied to modal-dispersion data collected with a hand-deployable source and receiver on the NEMP. Results include an estimated SSP in reasonable agreement with the measured SSP and geoacoustic profiles comparable to those obtained using the measured SSP, although with greater uncertainties.

Dosso *et al.*¹⁸ estimate elastic and fluid seabed models with a trans-dimensional Bayesian inversion applied to wideband (20 to 2000 Hz) data from the NEMP where the data are complex acoustic pressure (frequency domain) over the spatial extent of a vertical hydrophone array. The results for density and sound speed and attenuation are in good agreement with previous inversions and direct measurements. Low shear-wave speeds (≈ 35 m/s) are indicated for the mud layer.

Dosso *et al.*¹⁹ utilize the trans-dimensional technique for geoacoustic inversion of recorded acoustic waveforms processed as modal-dispersion (MD) data (mode arrival times as a function of frequency) and matched-field (MF) data (multifrequency complex acoustic fields across a sensor array) from the same acoustic recordings collected on the NEMP. The results of these comparisons indicate that MD and MF inversions produce similar marginal probability profiles for sound speed and density. MF inversion, however, resolves more detailed geoacoustic structure with smaller uncertainties.

Holland²⁴ introduces frequency-domain reflection coefficient phase measurements collected during SBCEX 2017 from the central mud region in the NEMP, highlighting the underutilized potential of phase data in geoacoustic inversion. A modeling framework is presented alongside the results, demonstrating that the phase can carry significant geoacoustic information in layered or refracting seabeds.

Jiang *et al.*²⁵ refine sediment column modeling in the central depocenter α using trans-dimensional Bayesian inversion of wide-angle broadband reflection coefficient data collected during SBCEX 2017. A generalized model emerges, comprising (1) a surface mud layer with slight depth-dependent variability due to near-surface processes, (2) a homogeneous intermediate mud layer, and (3) a transition zone marked by rapid increases in sound speed, density, and attenuation attributed to increasing sand content above a basal sand layer.

Knobles *et al.*²¹ demonstrate how a feature-based inversion, using ray-interferometer analysis, can be used to infer geoacoustic properties at the shelf break site β . A two-layer seabed model is proposed with the viscous grain shearing model used to parameterize each sediment layer. A statistical inversion method yields the frequency-dependent sound speed at the top of the sediment layer and a compressional attenuation over the 500 Hz to 4500 Hz band, indicating the presence of a thin surficial layer over a deeper hard sand layer.

Lau *et al.*²⁹ present an application of deep learning to seabed classification using vertical line array (VLA) data from shipping noise. Instead of combining the 16 VLA channels into a single input, unique combinations of channels are used to train a base learning ensemble with the ResNet-18 architecture. The models are trained on synthetic spectrograms from transiting ships using different numbers of hydrophone channels as input. The ensembles of trained models are then applied to ship noise spectrograms measured during SBCEX 2017.

Lee *et al.*⁹ investigate the influence of benthic biological activity on the geoacoustic variability of the seabed within fine-grained sediments in the NEMP. Using an acoustic multicorer, *in situ* compressional wave speed and attenuation (30 to 100 kHz) were measured during SBCEX 2022, followed by laboratory analysis of core samples for sediment physical properties, organic carbon content, infaunal composition, and *ex situ* acoustics (10 to 1000 kHz). A correlation between compressional wave modulus and total organic carbon suggests that organic matter significantly influences bulk acoustic properties.

Lipor *et al.*¹³ investigate the impact of low-rank interference on the problem of distinguishing between two types of seabed using ambient noise as an acoustic source. Detecting changes in the seabed type across distinct spatial locations can be formulated as a two-sample hypothesis test for equality of covariance, for which Box's M -test is the classical solution. This method was applied to data from the New England Shelf Break Acoustics experiment (sites α and δ), and the approach was shown to successfully mitigate interference.

Hopps-McDaniel *et al.*¹⁴ employ very low-frequency noise from ships of opportunity to study the properties of the deeper seabed layers using a feature-based inversion. The features that are selected from measured ship noise spectrograms are the frequencies at which the waveguide invariant becomes infinite. A comparison of the sound speed and thickness of the first deep layer obtained for ships traversing different regions of the central depocenter α provides insight into the spatial heterogeneity of the deep layer.

Michalopoulou *et al.*²⁸ use tonal data collected from a vertical line array during SBCEX 2022 for source localization and inversion with traditional matched-field inversion (MFI) and a Gaussian process (GP)-based MFI. The GP approach interpolates virtual array sensors using coherence functions and a Gaussian kernel, enabling inversion with densely spaced synthetic data. A comparative analysis demonstrates that the GP-based technique yields results with lower uncertainty and better agreement with ground truth compared to traditional MFI.

Pfenninger and Lin²⁷ investigate bottom geoacoustic inversions using arrival time measurements of wide-angle seabed reflections from an AUV equipped with a sound source and a towed hydrophone array. Experimental data were collected during SBCEX 2022 at site α . The analysis provides range-dependent geoacoustic parameter estimates in the experimental area with a resolution on the order of 10 m.

Potty *et al.*¹⁶ estimate ocean bottom shear properties and thickness of the sediment layers using the horizontal to vertical spectral ratio (HVSR) of the Scholte wave particle motion measured on two ocean bottom recorders deployed during SBCEX 2022 at site α . The peaks in the HVSR curve depend on the sediment thickness and the shear resonance. Sediment thickness data from seismic surveys and core data from the experimental area constrained the shear speed estimation approach. The bottom model estimated by matching the HVSR and ellipticity angle with the data compares well with two previous inversions from the same location.

Sabra *et al.*²⁶ demonstrate the through-the-sensor sub-bottom profiling using an AUV towed array during NESBA at site β . The towed array recorded the AUV self-noise as it traversed a range-dependent track. Ray-based blind deconvolution is applied to the 100 to 1000 Hz band. The resulting passive sub-bottom imaging results are consistent with those obtained from active sub-array processing methods showing that low-frequency passive sub-bottom imaging is feasible using an AUV.

Siderius *et al.*¹⁵ used wind-generated ocean ambient noise to characterize seabed properties along a 1.7 km drift track at site α during NESBA. A 15 m vertical array with 16 hydrophones recorded ambient sound across 50 to 5000 Hz, with beamforming analysis focused on the 400 to 700 Hz band. Passive fathometer processing identified the water-seabed interface and sub-bottom layering. Inversion results using derived reflection coefficients reveal consistent sound speed, density, and attenuation along the track.

Vardi *et al.*³⁰ present an analysis of impulsive signals generated by explosive charges recorded by a distributed array of bottom moored hydrophones using an inversion method that included deep learning to model a spatially varying sediment layer covering a fixed basement. An application to SBCEX 2022 data in the NEMP suggests an increase in the compressional sound-speed ratio from southwest to northeast in the NEMP, consistent with published sediment core surveys and geoacoustic inversion results.

Venegas *et al.*¹⁰ explore the heterogeneity of the surficial sediment using shear wave elastography in mudflats found in New Hampshire. *In situ* compressional wave speed and attenuation (200 kHz to 1 MHz) were measured using the Core and Resonance Logger. Shear waves (50 to 200 Hz) were generated by the force of acoustic radiation and imaged with high-frame-rate ultrasound. Microscopy revealed millimeter-scale aggregates with shear speeds up to 16 m/s embedded in a lower-speed matrix (≈ 2 m/s). Spectral analysis showed one-dimensional spectral strengths between -42 and -38 dB re 1 m at a length scale of 0.001 m and a spectral slope of 3.5.

IV. SUMMARY

We invite the community to read this collection of papers that cover recent developments in seabed acoustics and the importance of considering heterogeneity.

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