Seafloor Sediment Environmental Measurements: High Frequency Sound Interaction in Ocean Sediments

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LONG-TERM GOALS

The quantification of selected sediment properties crucial to the modeling of high frequency sound interaction in ocean sediments is the long-term project goal. The research thrust is two fold. Part I is the in situ three-dimensional measurement of sediment permeability. Part II is a study of the sediment microfabric, pore fluid pathways, porometry, and bio-organic components. The ultimate goal of the microfabric investigations is the development of microfabric models that describe important sediment properties such as fluid flow characteristics, isotropy and anisotropy, stress-strain behavior, (porometry, Bennett et al., 1989) and pore space occupied by water, free-gas, and biogenic materials (Bennett et al., 1996).

OBJECTIVE

Scientific and technical objectives for FY-2000 were:

(1) to deploy an in situ permeameter and collect multiple measurements in the full scale DRI field experiment in October 1999 and

(2) to collect sediment samples and study quantitatively the microfabric and porometry.

Objectives included the development of "undisturbed" sediment sampling techniques for sandy deposits and laboratory processing of these samples for microscopy analysis. The samples are being used for the study, reconstruction, and quantification of the two- and three-dimensional microfabric and porometry (Bennett et al., 1989). Interstitial organic material was preserved during sampling that will lead to a better understanding of the interrelationships between the solids (mineral grains) and the microbiota and or organic debris in the sediment pores (Baerwald et al., 1991; Bennett et al., 1999a and b).

APPROACH

The design and development of the permeameter probe by SEAPROBE was based heavily on proven aspects of designs and earlier in situ probes (Bennett et al., 1990, 1989). State-of-the-art techniques used by other researchers and engineers were incorporated into the design as required and include sensor technology, materials, electronics, and computer technology. The permeameter probe design was based on the well-established physical concepts and principles for measurement of fluid flow in porous media using the volume-controlled hydraulic conductivity technique and methods of Olsen et al. (1991) and Gill et al. (1991). The constant-head constant-flow technique for measuring permeability was built into the probe design. Other techniques potentially suitable for field applications were considered during the probe design (Bennett et al., 1990a). The permeameter probe response and behavior for determining sediment permeability was modeled with the assistance of Research Dynamics (Dr. Matthew H. Hulbert). The University of Washington (Dr. Paul Johnson) designed the tripod used to deploy the probe and provided associated instrumentation for the field measurements.

The microfabric studies comprise refinements in, and extensions of, well-established techniques providing new capabilities that were originally used in the study of fine-grained sediments. The microfabric analysis of sand is an effort to collect “undisturbed” samples that preserve in situ structure and organic materials and, from study of these samples, to reconstruct and model the two- and three-dimensional fabric and pore fluid pathways of the sediments. The development of new methods, techniques, laboratory analyses, and digital image analysis has been a major aspect of the research in FY-2000. The microfabric research is carried out at the Biology Department, University of Southern Mississippi, Hattiesburg, MS. Research Dynamics contributed to the permeameter modeling effort and is cooperating with the team on the microfabric modeling. R. Bennett (SEAPROBE, Inc.) is leading the research.

WORK COMPLETED

In Situ Permeameter Probe Studies

The in situ permeameter was designed and built by SEAPROBE, and adapted to a tripod designed and built by the University of Washington under the direction of Dr. Paul Johnson. The probe was built to be rugged and suitable for numerous seabed penetrations to depths of ~50 cm in sand and mud (Figure 1). Progress and contributions by SEAPROBE are summarized as follows:

- Assembly of the permeameter probe at SEAPROBE and shipment to UW.

- Probe testing at UW with Dr. Paul Johnson and staff prior to the field deployment.

- Participation in the DRI-SAX field exercises offshore Panama City and Fort Walton Beach, Florida (collection and shipboard processing of samples for fabric analysis).

- Deployment of the in situ permeameter probe and data collection at 19 sites at the Fort Walton Beach, FL, DRI site.

- Reduction of all raw permeameter field data from the 19 sites and completion of error analysis (a parallel effort with UW, Dr. Paul Johnson and staff).

- Two presentations on the permeameter and microfabric studies at the ONR-DRI SAX-99 meeting in Bangor, Washington in April 2000.

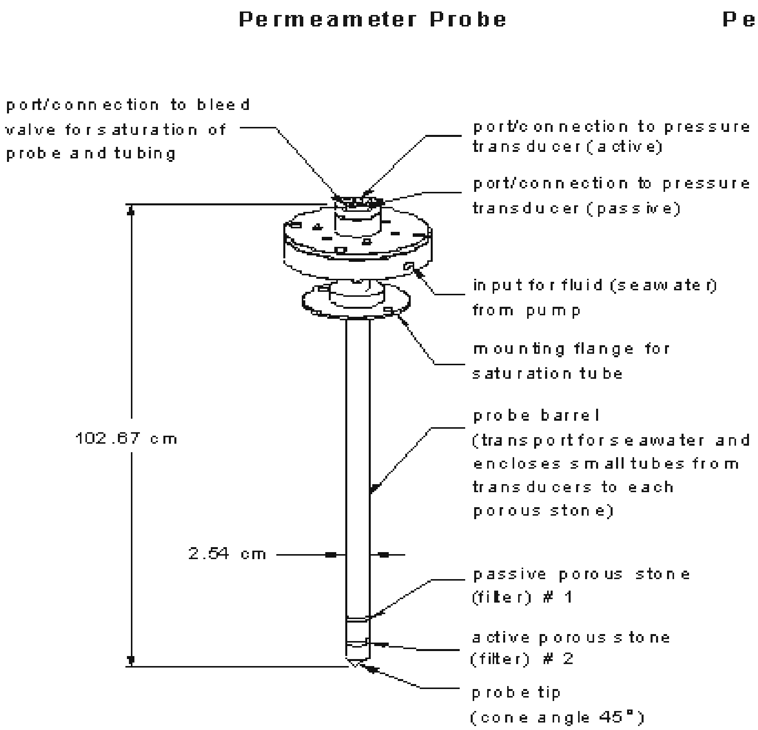

Figure 1A
Drawing of the pereameter probe with dimensions.

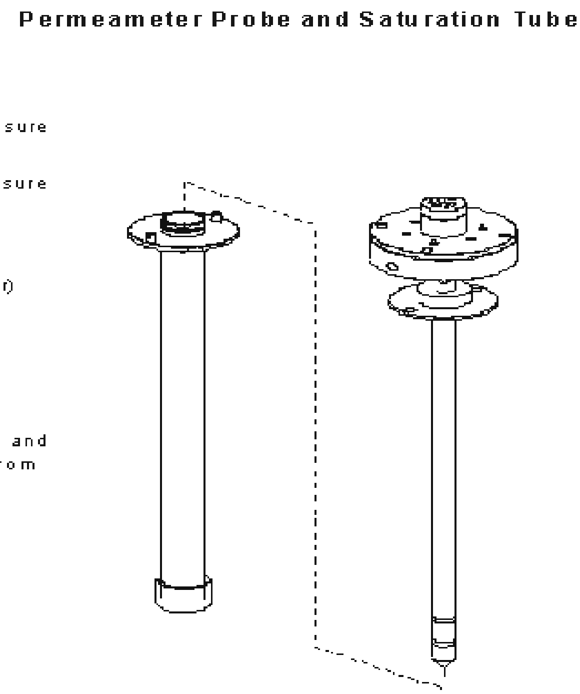

Figure 1B
Probe with saturation tube.

Figure 1A and 1B. ***The probe barrel diameter is 2.5 cm and has two porous stones attached near the probe tip (45^{o} cone) that penetrates the sediment and leads the probe barrel into the sediment. Seawater is pumped into the upper chamber and through the active stone.***

Microfabric and Porometry Studies

Important technical problems were solved for collecting sandy sediment from the seafloor and then transporting samples to the laboratory in an undisturbed condition. Techniques were developed for imaging and reconstructing the three-dimensional microfabric and porometry. The scales of interest range from sand in the millimeter range to microorganisms in the micron range. Progress includes:

- Developed and tested sample preservation and embedding techniques.

- Developed precision grinding techniques reproducible to ± 2.5 μm.

- Developed precision illumination techniques using a half-silvered mirror (beam splitter).

- Implemented quantitative image analysis software for microfabric studies.
- Developed techniques for two- and three-dimensional image analysis.
- Initiated three-dimensional fabric and porometry volume reconstruction.
- Completed grain size analysis from diver cores.
- Completed analysis of TOC, $CaCO_3$, N, and total carbon from diver cores.

RESULTS

In situ permeability data was obtained at 19 offshore stations and at multiple subbottom depths at the DRI site. The permeability data are as follows: (Range: K = 5.5 $x10^{-11}$ m^2 to 0.3 $x10^{-11}$ m^2, Ave: K = 1.9 $x10^{-11}$ m^2 or Range: k = 5.4 x 10^{-2} cm/s to 0.3 x 10^{-2} cm/s, Ave: 1.9 x 10^{-2} cm/s). These permeabilities are reasonable and compatible with the available sediment porosity and grain size data collected from the site. Permeabilities decreased slightly with depth.

The sediment microfabric and porometry studies have revealed significant two- and three-dimensional properties of the sands. The three-dimensional volume reconstruction of the sediment fabric and pore fluid pathways was completed for several sediment samples from different cores within the DRI study area. The first reconstruction included three samples from the top of a core. The reconstruction was done with 41 slices taken at 50 and 100 µm intervals over a distance of 2.67 mm for each sample. Continuous (linear) pore fluid pathways have been observed to extend at least 10 median (grain size) particle diameters 2.6 cm long through the sandy sediment. An example of the fabric and continuous pore fluid pathways are depicted in Figures 2 (color-filled sections) and 3 (wire-frame sections).

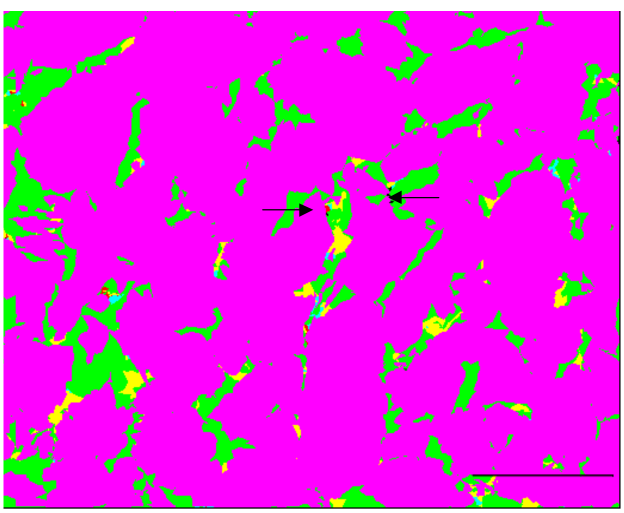

Figure 2
2671 µm thick series of sections with a 20° tilt. Arrows point to four (black) continuous pores. Scale bar 1 mm

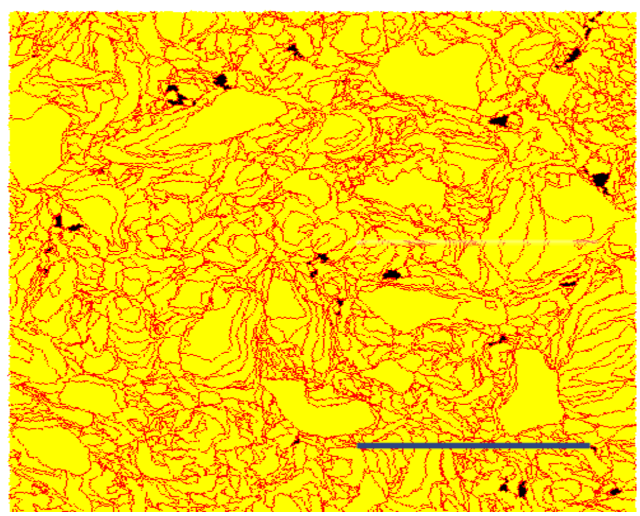

Figure 3
Numerous continuous pores (black) are revealed in the 2671 µm thick section. Scale bar 1 mm

Initial quantitative image analysis revealed exceptionally high sediment porosities in the upper few mm. Stereological techniques allowed us to establish the volume density (V_s/V_t) of sand and the porosity ($1 - V_s$) in the three samples of Figure 4 (upper 3mm of sediment at the sediment–water interface). This suggests a "bridging" of sand grains by organic material which been observed and documented in other studies (Bennett et al., 1999 and Hulbert et al., in preparation). Observation of images during high resolution sectioning suggests that particle contact areas in the sands are very small. This is confirmed by numerous 5-micron sectioning intervals that revealed virtually no significant, observable, particle contacts.

Pore fluid path lengths have been determined on numerous sections, generally showing slight differences when measured in perpendicular directions (horizontal vs. vertical on images). The graph (Figure 5) and other analyses of path lengths indicate some slight anisotropy in the sand. Additional analysis, however, is required to confirm that significant anisotropy is present in the material. Path lengths normalized to the shortest possible distance through the sample reveal that some path lengths are as much as 38% longer than the shortest possible path.

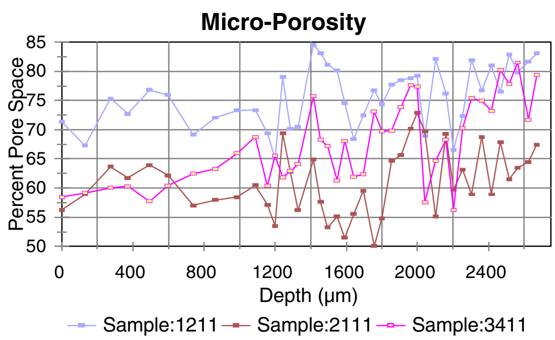

Figure 4
Micro-porosity determined on images with depth in subsamples.

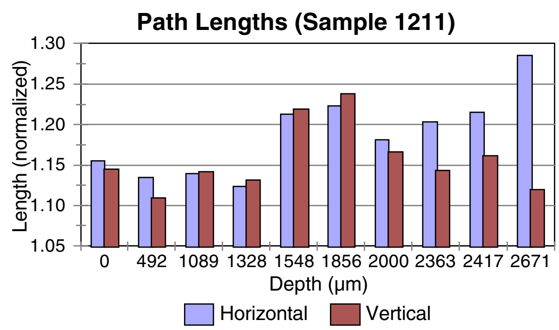

Figure 5
Normalized path lengths through the sediment (relative to the direct path length).

Twenty-five subsamples of the sediments provided by Dr. Rob Wheatcroft (OSU) were analyzed for total carbon, total organic carbon (TOC) and total $CaCO_3$. Values ranged from 0.30 to 0.77% total carbon, 0.04 to 0.19%TOC and 2.0 to 5.1% total $CaCO_3$. As expected for sands, the TOC's are low. This indicates that organic material occludes ~0.05 to ~2.5% of the pore space in the sand having 36 to 37% porosity (Bennett et al., 1999). A few samples with higher TOC revealed pore space filling (occlusion) of ~6 to ~7% in the DRI sand.

IMPACT/APPLICATIONS

Acoustic behavior in sediment is complex. Reliable predictive capabilities (models, numerical formulations, and quantitative estimates) must consider the combined effects of the sediment properties at various scales depending upon the acoustic frequency of interest. Databases of in situ sediment property data are needed for the testing and evaluation of high frequency sound interaction models for shallow water coastal sediment types. These studies will provide important input parameters for sediment in coastal areas and have direct impact on U.S. Naval activities including application to environmental management activities, understanding of hydrologic processes, and engineering and acoustic problems involving objects placed on and in the seafloor.

TRANSITIONS

The project is providing important environmental data on the sediment physical properties and variability and the microscopic characteristics of sandy sedimentary deposits. These data are important to applied problems of interest to the Navy in areas of mine burial, buried mine performance, detection, and environmental assessment.

REFERENCES

Bennett, R.H., K.M. Fischer, D.L. Lavoie, W.R. Bryant and R. Rezak, 1989. Porometry and Fabric of Marine Clay and Carbonate Sediments: Determinants of Permeability. Marine Geology, Vol. 89, p.127-152.

Bennett, R.H., H. Li, J.T. Burns, C.M. Percival and J. Lipkin, 1989. Application of Piezometer Probes to Determine Engineering Properties and Geological Processes in Marine Sediments. Applied Clay Science, Vol. 4, p.337-355.

Bennett, R.H., H. Li, D.N. Lambert, K.M. Fischer, D.J. Walter, C.E. Hickox, M.H. Hulbert, T. Yamamoto and M. Badiey, 1990. In Situ Porosity and Permeability of Selected Carbonate Sediment: Great Bahama Bank Part I: Measurements. Marine Geotechnology, Vol. 9, p.1-28.

Bennett, R.H., J.T. Burns, H. Li, D. Walter, P.J. Valent, C.M. Percival and J. Lipkin, 1990. Subseabed Disposal Project Experiment: Piezometer Probe Measurement Technology. Geotechnical Engineering of Ocean Waste Disposal, ASTM STP 1087, Kenneth R. Demars and Ronald C. Chaney (Eds.), American Society for Testing and Materials, Philadelphia, p.175-189.

Baerwald, R.J., P.J. Burkett and R.H. Bennett, 1991. Techniques for the Preparation of Submarine Sediments for Electron Microscopy. Chapter 35, p.309-320, in: Microstructure of Fine-Grained Sediments: From Mud to Shale, Springer-Verlag, 582p.

Bennett, R.H., M.H. Hulbert, M.M. Meyer, D.M. Lavoie, K.B. Briggs, D.L. Lavoie, R.J. Baerwald and W.A. Chiou, 1996. Fundamental Response of Pore-Water Pressure to Microfabric and Permeability Characteristics: Eckernförde Bay. Geo-Marine Letters, Vol. 16, p.182-188.

Bennett, R.H., B. Ransom, M. Kastner, R.J. Baerwald, M.H. Hulbert, W.B. Sawyer, H. Olsen and M.W. Lambert, 1999. Early Diagenesis: Impact of Organic Matter on Mass Physical Properties and Processes, California Continental Margin. Marine Geology, Vol. 159, p.1-34.

Bennett, R.H. and M.H. Hulbert, 1998. In Situ Mini-Permeameter Probe Design Considerations. SEAPROBE, Inc. Technical Report No. SI-0098-04, 51p. (Not for general distribution).

Bennett, R.H., 1999. Panama City Coastal Sands DRI Sites 10 and GS-172 Sediment Analyses Informal Data Report. SEAPROBE Technical Report No. SI-0099-03, 26p.

Bennett, R.H., H.W. Olsen, M.H. Hulbert, R.J. Baerwald, W.B. Sawyer and B. Ransom, 1999. Organic Matter and Geotechnical Properties Interrelationships: Marine Sediments. In the Proceedings of the 13th ASCE Engineering Mechanics Division Specialty Conference, Johns Hopkins University, Baltimore, June 13-16, (CD-ROM).

Gill, J.D., H.W. Olsen and K.R. Nelson, 1991. Volume-Controlled Approach for Direct Measurements of Compressibility and Hydraulic Conductivity. Geotechnical Engineering Congress 1991, Geotechnical Special Publication Vol. 2, No. 27, ASCE, p.1100-1111.

Hulbert, M.H., R.H. Bennett, R.J. Barawald, D. Lavoie and R. Long, In Preparation. Observations of the Sediment Water Interface. Marine and Fresh Water Environments.

Olsen, H.W., J.D. Gill, A.T. Willden and K.R. Nelson, 1991. Innovations in Hydraulic-Conductivity Measurements. Geotechnical Engineering 1991, Transportation Research Record 1309, Transportation Research Board, National Research Council, p.9-17.