

**Seafloor Sediment Environmental Measurements  
(Seafloor Sediment Fabric and Permeability Studies)  
in support of the  
High Frequency Sound Interaction in Ocean Sediments ONR-DRI**

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## **LONG-TERM GOALS**

The study and 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 and quantification of sandy sediment permeability. Part II is a quantitative 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 and related numerical analysis that describe important sediment properties such as fluid flow characteristics, isotropy and anisotropy, and stress-strain behavior (Bennett et al., 1989, Bennett et al., 1996).

## **OBJECTIVES**

SEAPROBE was tasked to contribute to the analysis and quantification of selected sandy sediment properties crucial to the modeling of high frequency sound interaction with ocean sediments (Thorsos et al., 2001). The research objectives focused on two aspects. Part I was the in situ three-dimensional measurement of sediment permeability using in situ measurement techniques and appropriate modeling for data reduction and analysis. Part II is an ongoing study of the sandy sediment fabric, pore fluid pathways, porometry, and bio-organic components. The ultimate objective of the fabric investigations is the development of fabric models that describe important sediment properties such as fluid flow characteristics related to permeability, isotropy and anisotropy, stress-strain behavior, porometry and to understand fundamental relationships among pore space occupied by water, free-gas, and biogenic materials.

## APPROACH

The design and development of the permeameter probe by SEAPROBE was based heavily on earlier proven designs of in situ probes (Bennett et al., 1989b, 1990a, 1990b). State-of-the-art techniques used by other researchers and engineers were incorporated into the design as required and included 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). This design utilizes the constant-head constant-flow technique for measuring permeability. Other techniques 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 fabric studies incorporated refinements in, and extensions of, well-established techniques providing new capabilities that were originally used in the study of fine-grained sediments. The fabric analysis of sand included imaging of “undisturbed” samples that preserve the in situ structure and organic materials. As part of the study of these samples, we reconstructed the two- and three-dimensional fabric and pore fluid pathways, and determined the tortuosity of the sediments. The development of new methods, techniques, laboratory analyses, and digital image analyses was a major aspect of the research.

## WORK COMPLETED

Permeability data were analyzed extensively and a detailed error analysis was performed to assess data quality and permeameter probe performance. Quantitative fabric studies (two-dimensional and three-dimensional) were conducted to analyze the porometry, pore fluid pathways, and related fabric and physical properties of the sandy sediment.

### Permeability Data Evaluation Using Statistical Techniques

The in situ permeability measurements of the sandy sediments were reviewed and tested to gain insight into the statistical error of the field data sets collected offshore Fort Walton Beach, Florida (Figure 1). These analyses provided a quantitative measure of the data reliability and of the permeameter probe performance. This effort in FY-2001 provided a reliable statistical database of the fundamental in situ sediment permeabilities and provided a basis for relating the fabric and porometry characteristics to the hydraulic properties and sediment physical properties following earlier techniques and studies of marine sediments (Baerwald et al., 1991, Bennett et al., 1989a, 1990a, 1999a, 1999b). The probe was built to be rugged and suitable for numerous seabed penetrations to depths of ~50 cm in sand and slightly greater subbottom depths in mud because of greater penetrability in soft sediments. Details of the permeability probe, data collected, and error analysis, are found in Bennett et al., (submitted 2001).

### Fabric, Porometry, and Selected Physical Properties Analyses

The analysis of the fabric and porometry sampled from high-quality diver cores collected during the DRI field exercises was a major effort. Pore fluid pathways and porometry are largely a function of the grain size, mineralogy, fabric, and organic material occluding pores and the time dependent diagenetic processes that drive fabric changes. The sizes and shapes of the solids, the particle

associations, and their three-dimensional orientations determine the various pore sizes and shapes of the pores and the three-dimensional pore fluid pathways. The permeability is thus directly related to the porometry. A modest level of image analysis and three-dimensional reconstruction of the fabric was completed and data were collected on the pore fluid pathways. We reconstructed pores with topographical data collected from serially sequenced, polished sand surfaces. This included determining pore lengths and diameters of pore throats. Photographs of surfaces on horizontal and vertical planes with respect to the seafloor interface were collected. These contrasting sets of photographs are of samples that were in close physical proximity to each other, to compare pore fluid pathways running in two directions. We also measured path lengths in both directions. The analyses provided a measure for assessing the isotropy/anisotropy of the fabric and porometry of the sand. The analyses have provided a representative set of important input data for the acoustic modelers.

Our research team presented a “modified”, high precision, novel laboratory method for determining the sediment porosity of epoxy embedded sediment samples (presented at the DRI High Frequency Acoustics Workshop, January 2001). A suite of samples were analyzed to obtain a statistically representative characterization of the porosity and wet bulk density (calculated from the solid grain density, epoxy density, and volume measurements using embedded samples) for comparison with quantitative data obtained from image analysis (See Bennett, et al. 2001).

Accomplishments and work completed by SEAPROBE and contributors are summarized as follows:

#### **In Situ Permeameter Probe Studies**

- Completed extensive data reduction of the in situ permeabilities for 19 sites at the Fort Walton Beach, FL, DRI site.
- Finalized extensive error analysis of the permeameter probe measurements.
- Developed recommendations for quantitative determination of filter stone permeabilities for future field testing of coastal sediments.
- Presented results on the permeameter and fabric studies at two ONR-DRI-SAX meetings at the Naval Research Laboratory, Stennis Space Center in 2001.
- Submitted (informal) suite of data to Project Leader Dr. Eric Thorsos including reduced permeability data, station location map, set of path length data (tortuosity data), grain size data, sediment geochemistry, uncertainty table of permeability data and selected permeability versus depth plots.
- Completed a major paper on the permeability probe and measurements including a comprehensive error analysis. Paper to be submitted in September 2001.

#### **Fabric and Porometry Studies**

The scales of interest range from millimeters to microns.

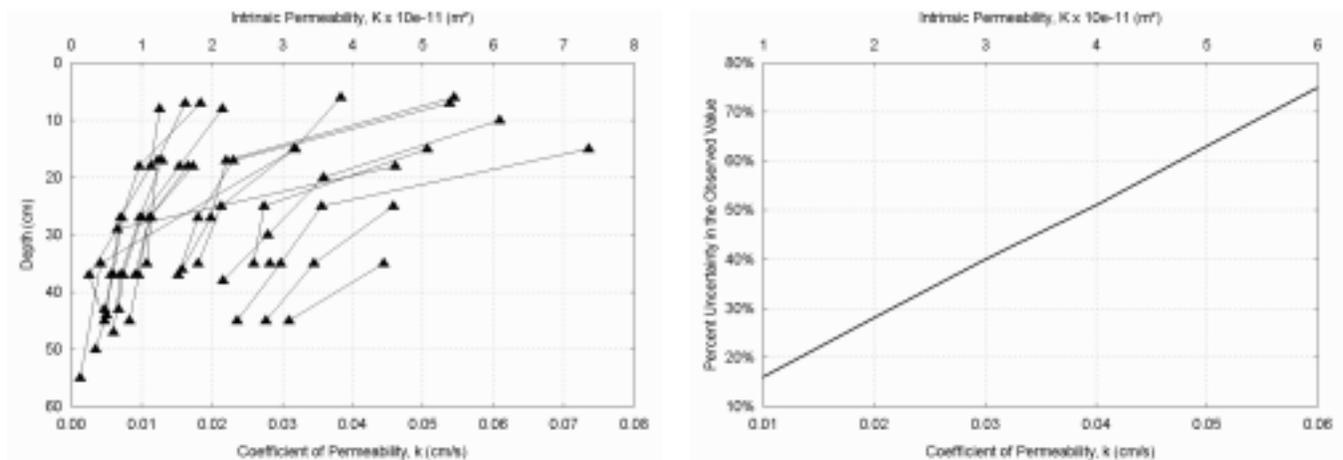
Progress and accomplishments include:

- Continued development and testing of sample preservation and embedding techniques.
- Completed numerous precision surface sample grinding (reproducible to  $\pm 2.5 \mu\text{m}$ ) for imaging.
- Used precision illumination techniques with a half-silvered mirror (beam splitter) to achieve true two-dimensional images of the fabric and continued quantitative image analysis for fabric studies.

- Developed and tested quantitative technique for the determination of sediment porosity and wet bulk density of epoxy embedded samples for comparison and “calibration” of image analysis techniques (volumetric estimates).
- Performed numerous studies to confirm the precision and accuracy of image analysis including gravimetric-volumetric analysis, independent analysis from an outside agency, and analysis of comparable sediment samples supplied from outside agency.
- Collected representative pathlength data for both horizontal and vertical aspects of images collected from 12 different samples.
- Began development of a computer technique for the three-dimensional reconstruction of solids and pores in micron and millimeter scale ranges.

## 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:  $K = 5.5 \times 10^{-11} \text{ m}^2$  to  $0.3 \times 10^{-11} \text{ m}^2$ , Ave:  $K = 1.9 \times 10^{-11} \text{ m}^2$  or Range:  $k = 5.4 \times 10^{-2} \text{ cm/s}$  to  $0.3 \times 10^{-2} \text{ cm/s}$ , Ave:  $1.9 \times 10^{-2} \text{ cm/s}$  (Figure 3). Two values,  $>5.5 \times 10^{-11} \text{ m}^2$  are questionable. The permeabilities are reasonable and compatible with the available sediment porosity and grain size data collected from the site. Permeabilities decreased slightly with depth.



**Figure 1. Permeability versus depth for all stations. A detailed discussion of the permeameter probe, permeability measurements, and error analysis is found in Bennett et al. 2001.**

The sediment fabric 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  $\mu\text{m}$  intervals over a distance of 2.67 mm for each sample. Continuous (linear) pore fluid pathways have been observed to extend  $\sim 7$ -10 median (grain size) particle diameters (2.6 cm long) through the sandy sediment. Subsequent reconstruction includes both

horizontal and vertical aspects of nine additional samples. Numerous additional samples were imaged for fabric studies in previous years.

Initial quantitative image analysis revealed exceptionally high sediment porosities in the upper few millimeters. Stereological techniques allowed us to establish the volume density ( $V_s/V_t$ ) of sand and the porosity ( $1 - V_s$ ) in the images of the fabric samples. This may suggest a “bridging” of sand grains by organic material which has been observed and documented in other studies (Bennett et al., 1999a and Hulbert et al., 2001). Observation of images during high resolution sectioning suggests that particle contact areas in the sands are very small. This was confirmed by sectioning numerous 5-micron intervals that revealed almost no significant, observable particle contacts at this level of observation and sectioning. Particle contact areas are thus demonstrated to be very small. Pore fluid path lengths were determined on numerous sections representing 12 samples that generally show slight differences when measured in perpendicular directions (horizontal vs. vertical on images) in the upper few centimeters of the sediment-water interface. Other analyses of path lengths indicate some slight anisotropy in the sand.

Gravimetric-volumetric analysis of embedded samples from several core sites revealed porosities ranging from 40.5 – 52.1% averaging 45.4 (SEAPROBE samples) and 42.1 – 46.4% averaging 44.7% (NRL samples). The average values vary by less than 1% porosity. Details of the gravimetric-volumetric technique and calibration of the method is described elsewhere (Bennett et al., 2001). This method of porosity determination is used for checking and analyzing measurements of porosity from analysis of fabric images.

## **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 are providing important input parameters for modeling sediment behavior (acoustic and geotechnical) for coastal areas. The studies have direct impact on U.S. Naval activities including application to environmental management activities, mine burial problems, 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 fabric/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, mine detection, pollutant migration in harbor sediments, and environmental impact assessment.

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## **PATENTS**

None.