COASTAL BENTHIC BOUNDARY LAYER: A FINAL REVIEW OF THE PROGRAM

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ABSTRACT

The Coastal Benthic Boundary Layer (CBBL) Special Research Program is a 5-year Office of Naval Research study that addressed the physical characterization and modeling of benthic boundary layer processes and the impact these processes have on seafloor structure, properties and behavior. This final report is a summary of the results compiled and published from FY92 through FY98. Quantitative physical models of the benthic boundary layer were tested in a series of experiments at coastal locations where differing environmental processes determine sediment structure. The sites were Eckernförde Bay, Baltic Sea; the West Florida Sand Sheet off Panama City, Florida; the lower Florida Keys; and the shallow continental shelf off Northern California. Predictive models developed through this program should enhance MCM technological capabilities in several important areas including acoustic and magnetic detection, classification, and neutralization of proud and buried mines; shock wave propagation; prediction of mine burial; and sediment classification. This report includes an introduction to the program, a summary of the results of those experiments, a list of publications that have resulted from CBBL research, and final reports from 24 of the 30 groups supported by the CBBL.

COASTAL BENTHIC BOUNDARY LAYER (CBBL)
RESEARCH PROGRAM:

FINAL REVIEW

1.0 INTRODUCTION

The Coastal Benthic Boundary Layer (CBBL) Research Program is a 5-year Office of Naval Research (ONR) program that addressed physical characterization and modeling of benthic boundary layer processes and the impact these processes have on seafloor properties that affect shallow-water naval operations. Four workshops were convened between November 1991 and February 1992 to establish program direction (Richardson, 1992). Based on workshop recommendations, research was focused on modeling the effects benthic boundary layer processes have on sediment structure, properties and behavior (Figure 1).

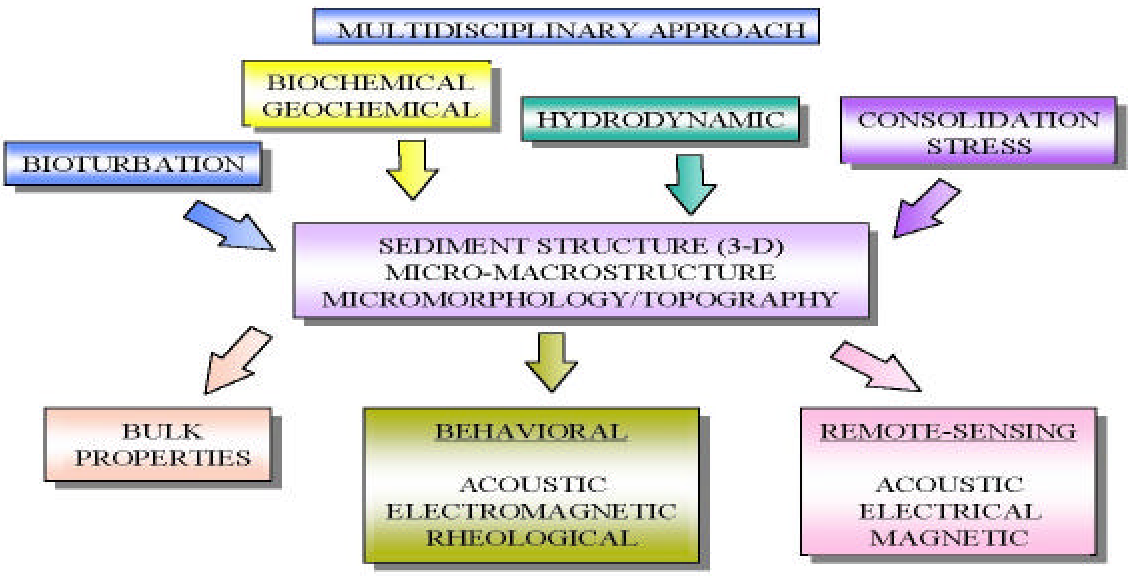

Figure 1. Schematic depiction of the Coastal Benthic Boundary Layer Special Research Program scientific direction.

Sediment physical structure provided the common perspective to: a) quantitatively model relationships among sediment physical, acoustic, electrical, and rheological (mechanical) properties; b) quantify the effects of environmental processes on the spatial and temporal distribution of sediment properties; and c) model sediment behavior (acoustic, electrical, and mechanical) under direct and remote stress.

Basic understanding of the physical relationships among processes and properties will contribute to the development of realistic models of: sediment strength, stability, and transport; sediment stress-strain relationships in cohesive and non cohesive sediments; dynamic seabed-structure interactions; animal-sediment interactions; high-frequency acoustic scattering phenomena; and propagation of high-frequency acoustic energy into and through poro-elastic media. Predictive models developed through this program should enhance MCM technological capabilities in several important areas including acoustic and magnetic detection, classification, and neutralization of proud and buried mines; shock wave propagation; prediction of mine burial; and sediment classification.

Quantitative physical models were tested by a series of field experiments at coastal locations where differing environmental processes determine sediment structure (Richardson, 1994a, 1995; Tooma and Richardson, 1995; Richardson and Bryant, 1997; Lavoie, Richardson and Holmes, 1997; and Richardson and Davis, in press). The first experiment was a joint United States and German study of the gas-rich mud of Eckernförde Bay in the Baltic Sea. At this site biogeochemical processes were responsible for the formation of subsurface methane gas bubbles that significantly affected sediment structure, behavior, and properties. The second experiment was conducted on the West Florida Sand Sheet, southeast of Panama City, Florida. Sediments consisted of a mixture of clastic sands and shells that were reworked by wave-current action (hydrodynamic processes) and biological processes (bioturbation). Experiments were conducted in a carbonate environment in the Florida Keys where biogeochemical diagenetic processes, such as sediment mineralization, dissolution and cementation, as well as sediment mixing by bioturbation control sediment structure. Scientists supported by the CBBL also participated in the STRATAFORM experiments (Nittrouer and Kravitz, 1997) conducted on the shallow continental shelf off northern California. Sediment structure at this site is controlled by combination of sediment deposition from the Eel River, high energy reworking of sediments by waves and bottom current generated by storms, and mixing (bioturbation) by benthic fauna. The goal of the CBBL was to provide physical models that predict sediment structure and behavior from knowledge of environmental processes for each environment. The CBBL program supported 28 projects during its five year duration (Table 1)

The following sections (1.1 through 1.4) describe CBBL results from the four experimental sites. The descriptions of the Eckernförde Bay and West Florida Sand Sheet experiments were edited from introductory articles in special issues of Geo-Marine Letters and Continental Shelf Research (Richardson and Bryant, 1996, Richardson and Davis, in press). The description of the Key West Campaign was edited from an introductory article in GeoMarine Letters (Lavoie and Ricahrdson and Holmes, 1996). References are deleted from this presentation and can be found in the original articles.

1.1 DESCRIPTION OF THE ECKERNFÖRDE BAY EXPERIMENTS

1.1.1 Background and motivation

Most gas in surficial, shallow-water sediments is biogenic and originates from the generation of methane as a by-product of metabolism by methanogenic bacteria. Areas of rapidly accumulating fine-grained muddy sediment rich in organic matter (e.g. Eckernförde Bay) provide ideal environments for the formation of this biogenic methane. Such areas are not uncommon, occurring widely around coastal fringes and in surrounding shallow water seas (Figure 2).

Figure 2. Worldwide distribution of shallow-water sediments that contain free-gas. Most sites were located based on seismo-acoustic survey techniques. The actual distribution of gassy sediments is probably much greater, especially in the poorly surveyed Southern Hemisphere. The numbers correspond to references in Fleischer and are available from the first author.

Once incorporated in the sediment body, methane may exist in various states: as free gas in bubble form (in the pore space), as dissolved gas in solution, or in special circumstances as gas hydrate. Gas concentration, temperature, salinity, and pressure control the state of methane and free bubbles can form when methane concentration exceeds saturation. Methane hydrate forms under specific ranges of temperature (low) and pressure (relatively high). The presence and quantity of methane, together with its state of occurrence, influence the sediment's bulk properties and behavior, and can have such diverse effects as impacting sonar performance, influencing sea floor stability, and even contributing to global climatic change.

Qualitatively, geographical distributions of gassy sediments can be arrived at using conventional seismo-acoustic surveying methodologies. At seismo-acoustic frequencies, typically a few hundred hertz to a few tens of kHz, acoustic propagation in sediments is severely affected by the presence of free gas; bubble layers act as scatterers of acoustic energy, giving rise to clearly recognizable seismic "textures" on sub-bottom profiler records. Traditionally, spatial distribution maps have been produced on the basis of delineating areas of "acoustic turbidity". While this effect provides a useful means of investigating lateral spatial distribution, rapid attenuation combined with scattering prevents analysis of depth distribution of gas, as sub-bottom penetration is severely restricted. Sidescan sonar has also proved useful for routine remote investigations of gassy sediment environments. Surface expressions of gas seeping to the seabed surface are readily recognizable on sidescan records, e.g. pockmarks and domes and these time-lapse phenomena can be monitored on the basis of repeated surveys.

While seismo-acoustics provides an ideal tool for field recognition of gassy sediments, the acousticians goal of providing estimates of gas volume and bubble size distribution on the basis of field seismo-acoustic signature remains. Indirect seismic evidence (large scale) of gas bubbles in sediments has recently been accompanied by finer scale direct evidence of the presence of free gas through headspace analysis of sediment cores, compositional analysis of sediment pore waters by gas chromatography and mass spectroscopy, and observation of bubbles by SEM , x-radiography, and x-ray computer tomographic (CT) techniques. Seismic techniques are primarily restricted to determination of the presence or absence of gas charged sediments; whereas, headspace analysis, chemical analysis, and x-radiographic techniques allow a characterization of percent gas volume.

Laboratory investigations have contributed to significant advances in modeling the frequency dependent behavior (propagation and scattering) of high-frequency energy in gas-rich sediments. For fine-grained sediments, where the bubble size is often considered large compared to the particle size, bubble interactions with the sediment particle frame are known to play an important role in controlling bubble resonance, sound speed, and damping thus greatly influencing sonar performance. In situ validation of these model predictions has suffered from the lack of concurrent in situ measurement of acoustic properties and methane bubble volume, size, shape, and spatial distribution. Models of geotechnical behavior of gassy sediment have been developed based on the relatively few concurrent measurements of sediment structure, physical properties, and strength of sediment retained at in situ pressure in pressurized corers and on sediment created under laboratory conditions. Although not validated by in situ experiments, model predictions are consistent with behavior observed in situ. In soft sediments the presence of gas can either increase or decrease undrained sediment strength, depending on the consolidation history and ambient pore pressure. Gas in sediments also increases sediment compressibility greatly increasing the likelihood of sediment liquefaction, especially in sands. Models of acoustic and geotechnical behavior must account for the relationship of bubbles to sediment pore space. Common bubble-matrix relationships include interstitial bubbles, such as in sands where bubble size is small compared to pore space; sediment displacing bubbles, such as Eckernförde Bay mud where bubble size is large compared to pore space; and gas reservoirs, where gas volume is high and particles are included within the bubble volume.

Gas in marine sediments originates from either bacterial or thermogenic reduction of organic matter. Most gas in surficial, shallow-water sediments is biogenic and originates from the generation of methane as a by-product of metabolism by methanogenic bacteria. Thermogenic methane gas, formed at high temperature and pressure (> 1000-m), can migrate to the sediment surface forming another source of trapped shallow gas accumulations. Carbon and hydrogen isotopic analysis of the gas can be used to determine origin. In mud with high organic content, aerobic respiration is usually restricted to the upper few centimeters of the seafloor. Below that zone, sulfur bacteria produce black, odorous sediment rich in hydrogen sulfide. After all of the sulfate is used as a terminal electron acceptor, methanogenic bacteria further reduce simple organic compounds producing methane. Pore water methane concentrations increase until they exceed saturation levels and free methane bubbles form in the sediment. The kinetics of these biochemical reaction are well known, but the prediction of the volume or even the presence or absence of free methane gas that is needed to determine sediment acoustic and geotechnical properties has not been possible.

The defense and petroleum industries will undoubtedly benefit from an improved understanding and predictability of gassy sediment environments. Interest lies both in the performance of higher frequency naval detection and classification sonars and lower frequency seismo-acoustic systems used to prospect for oil and gas. In addition accurate models of the behavior of gassy sea floor sediments are essential for the prediction of object burial and foundation stability. Gas in sediments also has implications for engineering and environmental studies. Free gas in the sediment void space significantly affects the sediment's engineering properties: it is highly compressible and even small quantities of undissolved gas will increase the sediment's compressibility and reduce its undrained shear strength. Sea floor stability problems associated with trapped or migrating gas have also been reported in the literature.

Methane is one of the most important radiatively active (greenhouse) gases in the atmosphere. Its global warming potential is 3.7 times that of carbon dioxide and up to 12% of greenhouse forcing is the result of atmospheric methane. It is therefore important to have an accurate inventory of sources and sinks of methane and to understand the dynamics of shallow-water methane generation, consumption, transport, and subsequent emission into the atmosphere. Hovland and Judd estimate that 30% of the world's shallow water area produces methane bubbles and that 8 to 65 Tg CH_4 per year is transported into the atmosphere. These emission volume estimates, which account for up to 20% of the total atmospheric contributions of methane, are based on very limited data. Accurate estimates of gas volume, bubble size, and transport dynamics are required to predict the contribution of shallow-water methane to climatic cycles. Also of interest to the environmentalists is the evidence for enhanced biomass of meiofauna and macrofauna at some seep sites as a direct consequence of methane escaping to the seabed.

1.1.2 Eckernförde Bay: early investigations

Some of the earliest evidence for the presence of gassy sediments in Eckernförde Bay was presented by Schüler who noted a reduction of the penetration of acoustic energy into shallow basin sediments in the Baltic Sea. The associated acoustic texture, referred to locally as the "Becken Effekt" and internationally recognized as "acoustic turbidity", was presumed to be the result of gas interacting with acoustic energy. Seabed depressions (later referred to as pockmarks) were also evident in these early acoustic records. By the mid-70's chemical analyses of sediments collected with piston cores and by in situ pore water and gas samplers demonstrated that the acoustic turbidity was the result of free gas in sediments overstaturated with methane. The biochemical origin of methane and delineation of zones of aerobic respiration, sulfate reduction, and methanogenesis were described by Michael Whiticar in a series of papers in the 70's and early 80's. The origin and maintenance of pockmarks in Eckernförde Bay has incited considerable debate. Early explanations include erosion, military or fishing activity, or methane gas ebullition but the current hypothesis primarily attributes pockmarks to submarine freshwater seepage from groundwater aquifers.

Scientists at the University of Kiel championed much of the early research relating to oceanographic conditions, biology and chemistry of the water column and sediments, and geological processes in Eckernförde Bay. Many of these studies were part of two, six-year interdisciplinary programs (1971-1982) designed to develop models of water column - seafloor interaction in the southwestern Baltic Sea. Although the goal of developing quantitative models linking all aspects of water column - seafloor interaction were never met, scientists supported by this program provided much of the early knowledge of conditions and processes in Eckernförde Bay. During this period, the physical and biological processes that control annual cycles of plankton primary and secondary productivity were quantified. Organic flux to the seafloor in the southwestern Baltic was found to be highest in late spring and autumn separated by long periods of low flux to the seafloor. The high input of organic matter that occurs during the spring phytoplankton bloom, and lack of water column mixing can create anoxic conditions that destroy benthic communities in the deeper parts of Eckernförde Bay. Benthic fauna that do exist in central Eckernförde Bay consists of small opportunist species restricted to near surface sediments that do little to mix the sediment. The high organic flux to the seafloor combined with the restricted benthic activity provides an ample source of energy to drive the biochemical processes that eventually produce methane in near surface sediments of central Eckernförde Bay.

Kiel Bay is an area where oceanic waters from the North Sea mix with fresh waters of the eastern Baltic. Horizontal mixing is driven by a Baltic-wide seiche. The stratification of less dense fresh water over the denser higher salinity water of the North Sea is intensified during the formation of a summer (April to October) thermocline. Tidal range is minimal and vertical mixing occurs primarily during winter major storms. Sediment transport is therefore primarily dependent on storm-induced wave action and topography.

Siebold studied the marine geology of Kiel Bay (including Eckernförde Bay) and designated this part of the southern Baltic a large fjord comprising a system of subglacial channels; Eckernförde Bay forms one semi-enclosed basin within this large fjord system. Water depth and oceanographic conditions control sediment distribution in the southwestern Baltic Sea. Coarse-grained sediments (morainal tills, coarse and medium sands) are found on topographic highs at depths shallower than 12 m. Grain size generally decreases with depth and basins, at depths greater than 20 m, are filled with muddy sediments. Eckernförde Bay is partially cut off from the rest of Kiel Bay by a glacial moraine (Mittelgrund) located at the head of the Bay. The central basin, where near bottom energy levels are at a minimum, effectively acts as a sediment sink, i.e., an area of net sediment accumulation. Sediment is derived mainly from cliff erosion, and although accumulation rates show some fluctuation, it has been concluded that the average accumulation rate is high. Milkert attributes some of the fluctuation in sediment accumulation to storm activity. Strong currents generated from easterly winds erode sediments from the shallower regions of Eckernförde Bay and deposit them in the central basin. Preservation of these storm deposits is possible as their thickness often exceeds the depths of biological mixing.

The combination of high organic flux to the seafloor, high rates of sedimentation, slow bottom currents, depositional nature of the environment, occasional anoxic conditions, and the shallow depth of bioturbation, create conditions ideal for methane formation.

1.1.3 Summary of the Eckernförde Bay experiments (1993-1995)

Based on the considerable knowledge base existing on the gas-rich sediments of Eckernförde Bay, a site in the central basin of the Bay was chosen to study the relationships among the environmental processes responsible for methane bubble formation, and the resultant sediment structure, properties, and behavior. A strong emphasis was place on acoustic bubble interactions and the possible use of acoustics to characterize these gassy sediments.

Eckernförde Bay, a semi-enclosed, fjord-like bay located in the southwestern Baltic Sea (Figure 3).

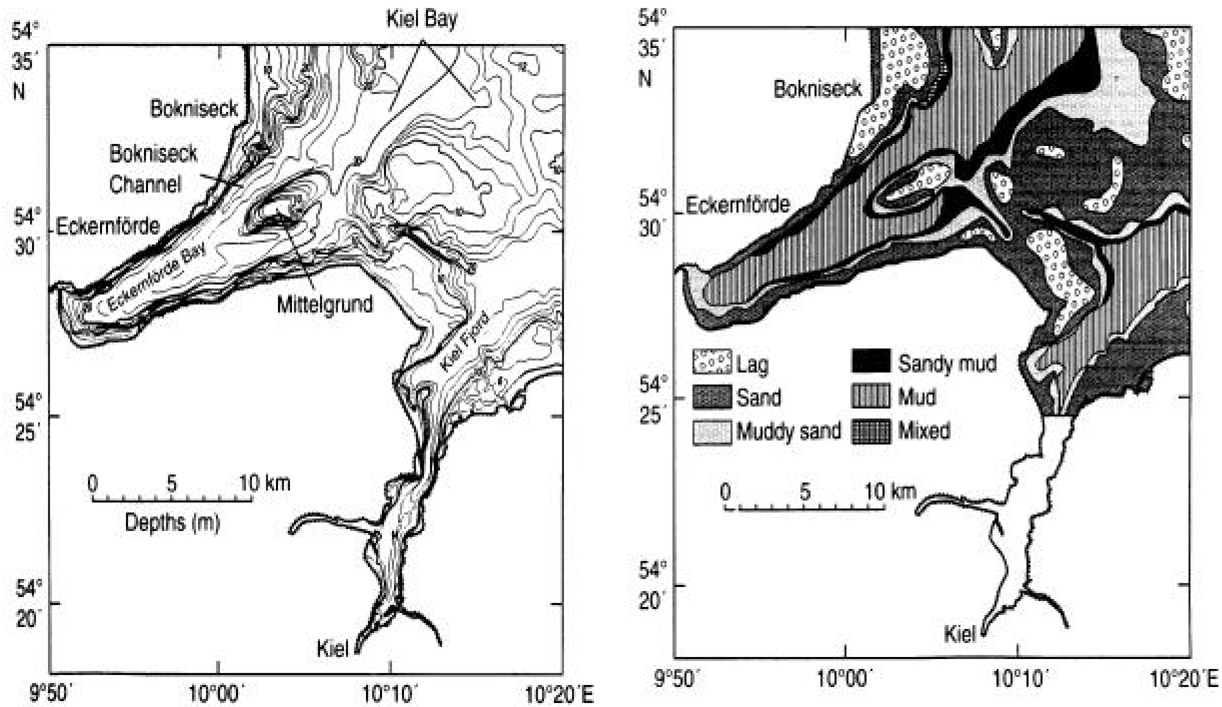

Figure 3. The Morphology of Eckernförde Bay including bathymetry (A) and sediment distribution (B). Hausgarten and NRL (this study) are the location of extensive interdisciplinary research efforts.

is a depression that was formed when glaciers receded during the last ice age (13,000-yr. BP). Sediments accumulating in the central basin formed a relatively flat (~26 m) basin that rises abruptly to the surrounding shorelines. The east entrance to the bay is partially blocked by a morainal sill (Mittelgrund) which divides water flow between a larger northern channel (Bocknis Eck) and a smaller southern channel. The water column is stratified especially during summer and bottom waters of the bay often experience hypoxia with occasional anoxia. Tidal range is slight and wind, storm surges, and baroclinic seiches control fluctuations in sea level. Oscillations in bottom currents correlate in time but not magnitude with the 26-28 hour barotrophic Baltic-wide seiche. This weak barotropic seiche creates near resonance internal waves in the stratified Eckernförde Bay, which in turn generate the stronger baroclinic currents. In the deep central basin, however, bottom currents resulting from these baroclinic currents or from local wind or storm driven currents are insufficient to erode sediments. The central basin therefore acts as a trap for sediment advected into the bay by bottom currents or eroded from nearby shorelines and shallow subtidal areas during storms.

Sediments in the central basin of Eckernförde Bay are soft, organic-rich, silty clays with evidence of considerable near-surface biological activity. During subbottom oxide conditions, the uppermost sediments consist of a 2- to 3-cm layer of brown, oxidized mud, which overlies soft, black sediment with a distinct hydrogen-sulfide odor. These surface sediments are heavily colonized by tube-dwelling, surface deposit-feeding spionid polychaetes (*Polydora ciliata*) and surface deposit-feeding bivalves (*Abra alba*). Radiochemical profiles of excess ^{234}Th and bioturbation experiments with fluorescence tracer particles demonstrate that most biological mixing is restricted to the top 5-10 mm of the sediment. Ventilation of surface sediment with oxygenated bottom water by the small, head-down, deposit-feeding polychaetes (*Heteromastus filiformis* and *Capitella* sp.) and tubificid oligochaetes probably controls the depth of the brown, oxidized layer and affects rates of near-surface biochemical processes. Functional group characteristics, young age, small organism size, low diversity, and shallow particle mixing are all consistent with the hypothesis that this benthic community is controlled by regular disturbance which maintains the community at a low level of complexity (i.e., a pioneering community). In spite of the limited depth of mixing, the benthic community effectively pelletizes most of the sediment reaching the surface. Sediment accumulation rate, determined by ^{210}Pb geochronology, ranges between 3-10 mm y^{-1}. Laminated bedding, preserved in the sedimentary record, results from alternating deposition of thin (< 1 cm) storm-suspended sediments (non-pelletal, often graded bedding) eroded from adjacent shallow-water areas and a fair-weather deposition of thicker (> 10 cm) layers organic-rich suspended material (pelletal, anisotropic fabric). This record is preserved as a result of relatively high sediment accumulation rates in a predominantly depositional environment and the absence of significant physical or biological mixing.

Eckernförde has long been characterized by acoustic turbidity, masking deeper sediments from acoustic characterization. This acoustically turbid zone was evident in acoustic records covering the frequency range of 0.5 to 50 kHz. Although a persistent feature in Eckernförde Bay, the areal extent, intensity, and depth of acoustic turbidity varies with season. These seasonal variations correlate with sediment temperature and are controlled by methane solubility rather than changes in rates of methane production or bubble formation. X-ray Computer aided Tomographic (CT) scans of sediment core samples retained at ambient pressure and temperature revealed only occasional methane gas bubbles from the upper 50 cm depth in the sediment, while below that depth, numerous clusters of small methane bubbles were found. These bubbles occurred in distinct horizons rather than in a continuous distribution. Bubble radii range from 0.4 mm (the smallest radius resolvable by this technique) to as large as 5.0 mm. Larger gas bubbles appear non-spherical and have two long and one short axes (disk-shaped). Gas bubble concentrations ranged from 0 to 2% by volume within the main experimental site and reached as high as 8% in the seafloor within a nearby pockmark. It is apparent that the pockmarks included in these studies are considerably different than the pockmarks near Mittelgrund where acoustic turbidity is absent. These CT techniques represent the first quantitative characterization of bubble size, shape, and distribution in marine sediments and provide a unique opportunity to test models of acoustic propagation and scattering.

Biogeochemical studies demonstrate that methane concentrations in this organic-rich, anoxic sediment reach saturation within less than a meter of the sediment-water interface. Aerobic metabolism is generally restricted to the upper 1-2 cm of sediment with sulfate reducing sediments (50-100 cm thick) found between the zones of aerobic respiration and methane production. Martens, Albert and Alperin developed a kinetic model of the complex biochemical interaction of bacterial methane production, methane consumption at the base of the hydrogen sulfide reduced horizon, advective and diffusive transport processes, organic supply, and sedimentation rates in methane-rich sediments. They demonstrated that predicted methane distribution is most sensitive to the flux and degradation rate of reactive organic matter. Albert and Martens successfully used this model to predict methane and sulfate concentration profiles, rates of biogeochemical reactions, and methane gas volumes in the sediments of Eckernförde Bay. Differences in the depth of methane bubbles at three sites were, in part, controlled by rate of vertical pore water advection from freshwater aquifers. Higher rates of flux of reactive organic matter to local topographic depressions such as pockmarks resulted in a decrease of depth and increase in volume of free methane gas. Bussmann and Suess demonstrate that high ground water flow increases the concentration of methane in bottom waters near the pockmarks of Eckernförde Bay, increasing flux of methane to the atmosphere. Possible ebullition of methane bubbles was also detected acoustically.

High sedimentation rates, high organic contents, near surface anoxic conditions, and restricted biological activity in sediment from the central basin result in surficial sediments with very high water content and low bulk density. These bubble free sediments are easily compressed and have very little strength, therefore exhibiting low values of shear strength, compressional wave speed and attenuation, shear wave speed and shear modulus. Characterization of in situ sediment physical, acoustical and geotechnical properties of the deeper gassy sediments presented a considerable technical challenge. Laboratory measurements on depressurized sediments are suspect, as ebullition of gas when sediments are depressurize tends to disrupt sediment structure. In situ measurements or measurements on cores retained at ambient pressure and temperature are preferred. With the exception of sharp gradients in bulk density and water content in the upper 5-10 cm, sediment physical properties such as water content, bulk density, mean grain size, and organic content varied little within the upper few meters. The high sediment organic content, high sedimentation rate, pelletized nature of the sediment, and presence of free gas may limit consolidation by self-weight. Shear strength although very low, increased with depth in the sediment. A comparison of in situ and laboratory shear strengths suggests a slight reduction in shear strength due to gas bubbles. Shear wave speed, another measure of sediment strength or rigidity, was the lowest ever reported for marine sediments based on in situ measurements. The presence of gas bubbles appeared to have little affect on this frame borne property, which is in agreement with predictions from current propagation models. Values of sediment permeability were higher than expected for silty-clay sediments, as the pellitzed nature of the sediment creates microchannels that allow increased fluid flow.

In addition to standard laboratory methods, sediment macrostructure was measured by x-radiographic and micro-resistivity imaging of sediment cores. Employed together, these techniques elucidate not only spatial correlation lengths but allow determination of sediment tortuosity, a rarely measured parameter for modeling conductivity and fluid flow in porous media. Image-based texture analysis of x-radiographs and resistivity images of near surface sediments indicates that density structure is highly anisotropic with shorter correlation lengths in the vertical (graded or laminated bedding) than the horizontal direction. Graded and laminated bedding, as well as burrows and occasional shells are evident in x-radiographs of the upper 30-cm of surface sediments. These laminae correspond to the well-pelletized layers deposited in quiescent periods and the non-pellitized graded beds deposited as a result of storm events described by Nittrouer and by Milkert. Sediment microstructure, determined using transmission electron micrographs (TEM) of the upper 2 meters of the sediment column, is characterized by dense aggregates of silt and clay-sized particles separated by relatively large, fluid-filled canals. This pattern may reflect the dominant preservation of surficial zones pelletized by deposit-feeding invertebrates. High sediment permeability, for muds, is probably related to the very loose sediment microstructure, lack of consolidation, and existence of channels between remnants of fecal pellets. Weak sediment fabric may also explain high values of sediment compressibility, whereas physico-chemical strengthening of interparticle bonding may account for the high apparent overconsolidation of near-surface Eckernförde mud. Discrete element simulations based on microfabric images appear to have promise in the prediction of acoustic (wave speeds) and finite (compressibility, strength, apparent overconsolidation) behavior in bubble-free fine-grained sediments from Eckernförde Bay.

Analysis of high-frequency (40 kHz) acoustic backscattering data demonstrated that scattering originates from a layer of free methane gas 0.5 to 1.0 meters below the seafloor rather than from the sediment-water interface. Spatial and temporal variability, including migrations and differences in concentrations of free methane gas, probably account for the high spatial variability and temporal decorrelation of backscatter images. Event-like changes in acoustic scattering in the water column were attributed to ebullition of gas bubbles from the seafloor. These events did not correlate with bottom stress due to bottom currents, temperature changes, or refraction due to stratification but were strongly correlated with changes in bottom pressure. These observations are consistent with gas ebullition due to pressure release. The flux of methane to the water column is estimated at between 3 – 20 $mol\ m^{-2}\ d^{-1}$, based on estimated bubble radius and a comparison between measured and predicted scattering strengths. These data support observations of a significant flux of methane from the seafloor to the water column reported by Bussman and Suess, and suggest a direct flux to the atmosphere. Knowledge of bubble volume, size, shape, distribution provided by Anderson and Abegg has allowed quantitative modeling of high-frequency acoustic scattering heretofore impossible. The effects of non-spherical bubbles shapes, multiple scattering, bistatic have been quantified. Volume scattering, based on normal incident acoustic profiles obtained by sediment classifiers (15-30 kHz), has been effectively modeled for the first time given sediment properties and the bubble distribution and characteristics provided by this program.

Initial measurements of the speed and attenuation of compressional and shear waves in Eckernförde Bay sediments were in general agreement with model predictions and laboratory studies. In situ shear wave speeds were the lowest ever reported for marine sediments. These low shear speeds and near surface gradients were, however, in agreement with physical and empirical models developed for gas-free sediments. It is apparent that the small volume of free gas (< 2%) found in most Eckernförde sediments has very little effect of sediment rigidity. On the other hand, the small volume of gas in Eckernförde sediments greatly affected compressional wave speed and attenuation. Attenuation of compressional waves was very high as a result of scattering from individual bubbles at high frequency, damping near bubble resonance and scattering from bubble clouds at low frequency. Sound speeds were greatly reduced below bubble resonance and speeds were near that of bubble-free sediments at higher frequencies. This unique set of data, including bubble size, shape, and distribution; sediment, pore water, and gas physical properties; and in situ acoustic measurements over the frequency range of 5-400 kHz, provided the first opportunity to test propagation models developed for gassy sediments. The agreement between measurement and theory convinced both Richardson and Lyons that measurements of acoustic propagation within and scattering from the seafloor can be used to determine bubble volume, size, and distribution in fine-grained gassy sediments.

1.1.4 Modeling

The primary objectives of the interdisciplinary studies of gassy sediments of Eckernförde Bay were to characterize and model benthic boundary layer processes and the impact these processes have on seafloor structure, properties and behavior. Measurements made during these experiments have considerably increased our knowledge of the characteristics of these gas-rich sediments. CT scans of sediment retained at ambient pressure and temperature have provided the first quantitative characterization of in situ bubble populations including estimates of bubble shape, size, and distribution. Questions still exist as to the possible contributions of bubbles with radii smaller than 0.4 mm and the importance of scales of spatial and temporal heterogeneity found for these bubble populations. Processes controlling bubble formation, size distribution, and migration are still unknown.

The quantitative bubble population data combined with a unique set of in situ acoustic and physical property measurements have allowed us to validate acoustic propagation and scattering models. Accurate predictions of frequency dependent sound speed, attenuation due to bubble damping and scattering, and volume scattering suggest that acoustic techniques can be used for in situ characterization of bubble volume, size and distribution. Acoustic perturbation models that account for surface roughness and volume heterogeneity do not adequately predict high frequency scattering from the seafloor in gassy sediment. New empirical models that treat bubbles (oblate spheroids) as discrete single or multiple scatters were developed to predict acoustic scattering from gas-rich layers.

Detailed biological and oceanographic measurements have allowed models of sediment transport, erosion, deposition, and sediment physical and biological reworking to be developed. Models of strata preservation based on depths and rates of biological and physical mixing, sedimentation rates, frequency of storms, and source of particles are in agreement with the observed stratigraphic record. A kinetic model of the complex biochemical interactions of bacterial methane production and consumption, advective and diffusive transport processes, organic supply, and sedimentation rates has successfully been used to predict methane and sulfate concentration profiles, rates of biogeochemical reactions, and gas volumes. The spatial distribution and strength of acoustic turbidity is accurately predicted by these biochemical models, whereas the seasonal migration of the acoustic turbidity horizon correlates with changes in sediment temperature and is modeled using methane solubility. Accurate prediction of the rate of input of reactive organic matter to the sediment, rates of methane production and consumption, and groundwater advection are generally not available thus restricting the use of these static kinetic biochemical models. Historical changes in rates of sedimentation and organic flux to the seafloor, seasonal changes in sediment temperature and salinity and short-term changes in bottom pressure and the hydraulic flow from subbottom aquifers all dictate the need for time dependent kinetic biochemical and solubility models. Studies that combine acoustic characterization of temporal changes, migration, and ebullition of methane bubble populations with biochemical studies may help in the development and validation of those models.

1.2 DESCRIPTION OF THE WEST FLORIDA SAND SHEET EXPERIMENTS

1.2.1 Geological Background

The West Florida Sand Sheet experimental site is located 23 nm southeast of Panama City, Florida on an otherwise fine-grained, sand-wave field (Cape San Blas Sand Facies) of the inner continental shelf. The shelf of the northeastern Gulf of Mexico is currently sediment-starved with most material deposited by the Apalachicola River during lower sea stands. Hydrodynamic processes, especially major storms, control recent large-scale seafloor morphology. Silt- and clay-sized particles are occasionally deposited over the sand sheet during severe storms. These finer sediments can be either worked into the predominantly sandy surface sediments by biological activity or winnowed out of the sediments by minor storms. Small ripples form at coarse sand sites in response to the passage of winter fronts, and may persist for months. Hurricanes and other major storms also change bottom relief forming 2-10 m megaripples as a result of strong bottom currents. Megaripples formed after the passage of hurricanes Elena (September- October, 1985) and Kate (November, 1985) decayed after two years, presumably a result of active bioturbation during quiescent periods

Acoustic surveys of a 20-km^2-area, using side-scan sonar, chirp sonar and 3.5 kHz echo sounding, allowed experimenters to delineate a 600-by-625 m primary experimental site which had uniformly high acoustic reflectivity (Figure 4).

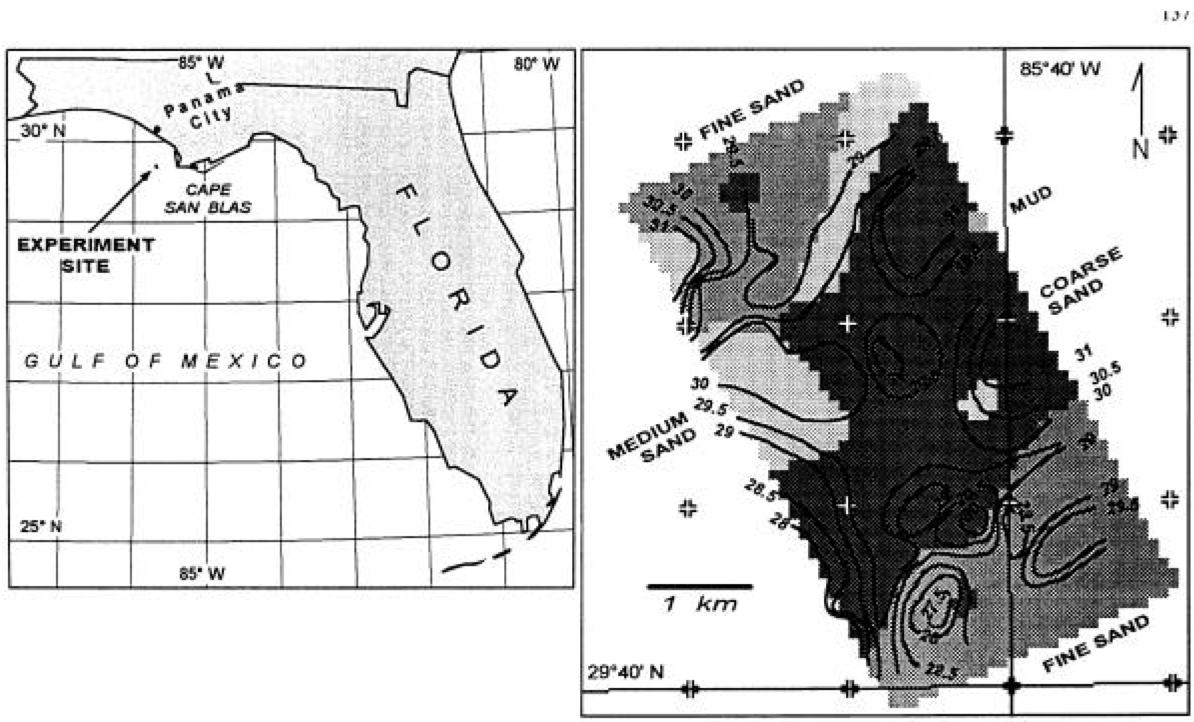

Figure 4. Bathymetry (meter isobaths) and sediment types of the West Florida Sand Sheet experimental site (adapted from K.S. Davis et. al. 1996 and Fleischer et. a;. 1996)

Acoustic backscattering strength in the larger area was highly correlated with sediment mean grain size and carbonate content. Sediments in the highly reflective area were coarse-grained sands (mean phi: 0.84 phi) mixed with shell hash, coralline algae fragments and numerous large mollusk shells. Sediments outside the experimental site were comprised of lower reflective, medium- and fine-grained sands (mean: 2.39 phi) with little shell hash and occasional muddy layers or inclusions. Values of porosity (mean: 40.3 %), density (mean: 2.01 g cm^{-3}), compressional wave velocity (mean: 1711 m s^{-1}), attenuation (mean: 30.4 dB m^{-1} at 58 kHz) and shear wave velocity (mean: 118 m s^{-1}) varied little between sediment types. CT-scans of sediment core samples from the highly reflective area reveal thousands of shell and shell fragments per cubic meter. The suggestion, based on acoustic measurements, that this sediment contains small amounts of free gas was not supported by geochemical evidence or groundwater flow.

1.2.2 Acoustic Modeling and Experiments

Acoustic scattering experiments and time-lapse monitoring of environmental conditions were restricted to the highly reflective sediment. Temporal decorrelation of successive acoustic scans of the seafloor was an order of magnitude greater than at the Eckernförde site. Rapid decorrelation of acoustic scans collected during experimental manipulations of the bottom by divers suggests that the short-term acoustic decorrelation noted in the long-term acoustic record were the result of changes in fine-scale topography. The near-bed hydrodynamic regime was dominated by reversing tidal currents with typical speeds of 10-cm s^{-1} or less. Maximum bed shear stresses remained too low to resuspend or transport the sediments. The high temporal variability in acoustic scattering strengths must, therefore, be related to biologically induced changes in bottom micro-roughness. Therefore hydrodynamic processes, especially major storms, dominate kilometer-scale decadal sediment characteristics of this site, whereas meter-scale, seasonal-to-daily bottom characteristics are controlled by minor storms and biological activity.

Acoustic model simulations by Anderson and Lyons, based on the distribution of shells from CT-scans of core samples, suggests that at 40 kHz acoustic backscattering strength from the sea floor is controlled by seafloor roughness above a grazing angle of about 10 degrees, while sediment volume scattering controls backscattering strength for lower grazing angles. Jackson and Williams, on the other hand, demonstrated that surface roughness accounts for most of the modeled backscattering strength over grazing angles of 5-60 degrees. Their acoustic model predictions based on perturbation theory and the extensive environmental characterization available from this site (sediment physical properties, seafloor roughness, and spatial heterogeneity) is in agreement with measured backscattering strengths over the range of 5 to 20 degrees. In either case roughness and volume heterogeneity are both dominated by the distribution of shells within an otherwise homogeneous sand-sized sediment. Biological and hydrodynamic processes, which control this spatial heterogeneity, must be understood in order to predict the frequency dependent nature of seafloor scattering and its temporal variations. It was also shown, by frequency dependent target strength measurements, that the larger shells alone can provide the same order of magnitude of acoustic backscattering strength as was measured from the sea floor in these field experiments. The importance of discrete scattering from shells at or near the surface should therefore be included in bottom scattering models as well as the aforementioned roughness and volume scattering mechanisms.

Measurements of the penetration of high-frequency acoustic energy into the sediments at Panama City, Florida were inconsistent with sediment modeled as fluid with flat interface where a critical grazing angle is predicted below which there will be no appreciable acoustic penetration. These anomalous results together with other field and laboratory studies have lead to an Office of Naval Research (ONR) Departmental Research Initiative (DRI) to study these phenomena. Experiments are planned for the continental shelf off Panama City during the summer of 1999.

At present, three mechanisms are hypothesized to contribute to this subcritical acoustic penetration. First, the porous nature of the sediment leads to a "slow" wave with a speed less than the speed of sound in water; thus no critical angle for that converted wave exists. Second, seafloor roughness diffracts energy into the sediment. Third, sediment volume heterogeneity scatters the evanescent wave energy that propagates along the seafloor interface into the sediment. Measurement of normal incident reflection loss in these sandy sediments was also found to be inconsistent with models that approximate the sediment as a fluid. Chotiros and Boyle used modifications of the Biot theory to model these data. Their assumptions, including values of grain and skeletal moduli have generated much controversy and will require additional well-controlled experiments.

1.3 DESCRIPTION OF THE KEY WEST CAMPAIGN

1.3.1 Introduction

The third major experimental site was in the vicinity of the Marquesas Keys and the Dry Tortugas in the Lower Florida Keys where bioturbation and biogeochemical processes were believed to control sediment structure (Tooma and Richardson, 1995). The area surrounding the Florida Keys provide the only environment in continental US waters which is analogous to shallow-water tropical carbonate settings that are becoming increasingly important to naval interest. During February 1995, four research vessels (WFS PLANET, R/V SEWARD JOHNSON, R/V PELICAN and R/V SEAWARD EXPLORER) and 115 scientists and technicians from five nations mounted a major cooperative scientific effort that became known as the Key West Campaign. (Figure 5).

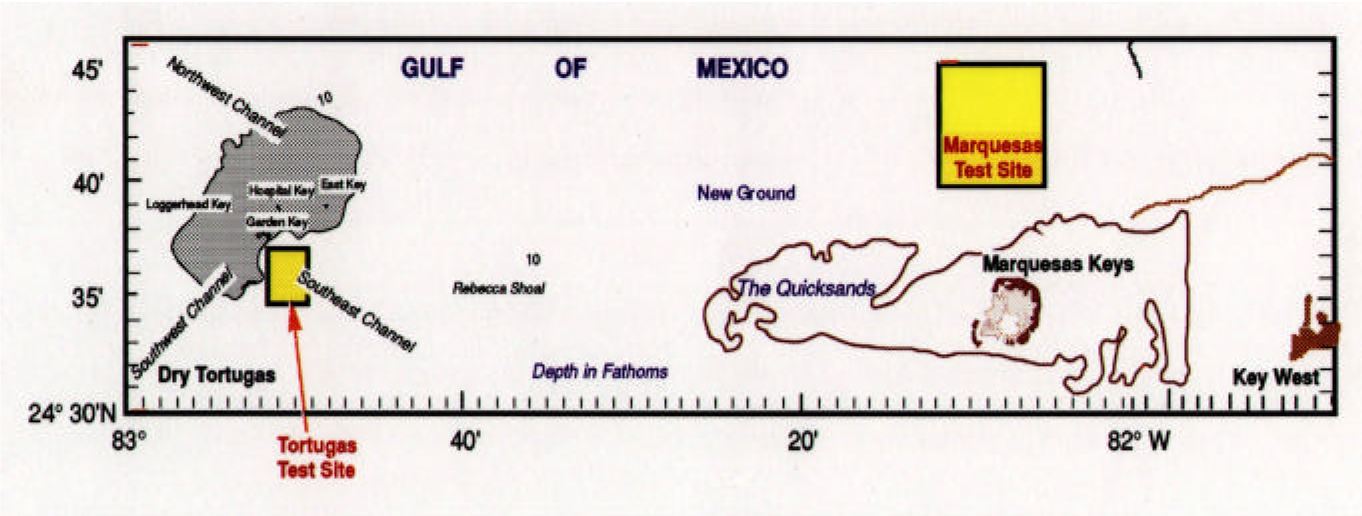

Figure 5. Map of two major experiment sites during the Key West Campaign.

1.3.2 Geological Background

The Florida platform is constructed of approximately 10 km of Cretaceous to Holocene carbonates and evaporates resting on a patchwork basement of Precambrian to Jurassic igneous, metamorphic and sedimentary rocks. Based on the analyses of samples and approximately 2500 km of high-resolution, single channel seismic data, Holmes defined 26 facies on the southern most Florida Platform. These facies were divided into four categories: (1) hardground and outcrops; (2) areas of recent sediment movement; (3) periplatform deposits; and (4) the "inner shelf" deposits. The nature origin, and distribution of the units classed as hardgrounds and outcrops (the Miocene terrace, the shelf-edge reef complexes, the central reef trend, and the southern banks) are keys to the geological history of the area. The second category, areas of recent sediment movement, characterizes the sedimentary processes presently active on the shelf. The third category, the periplatform deposits show evidence of past sedimentary processes responsible for the shelf accretion in their morphology and bedding. The inner shelf deposits are the result of longshore processes and sediment trapping landward of the hardgrounds.

The areas of concentration for the CBBL program encompass two of the categories; category two, an area of present sedimentary activity immediately seaward (facing the Florida Straits) and the fourth category, those sediments deposited in the lee of a hardground. The area selected for the most intense investigation was the region of present sedimentation, adjacent and east of the complex of islands dominated by Garden Key (Fort Jefferson). In this region, the nearly circular Dry Tortugas Platform is indented, possibly due to the fracture pattern in the bedrock. This indentation forms a sediment trap, a region of lower energy, which contains sediment washed by the winds and tides from the adjacent platforms to the west and north. These sediments appear to be coarse attesting to their origin and the high physical energy in the environment of deposition.

The secondary area of study is located on the eastern edge of the sedimentary basin, north of the sands that extend west from the Marquesas Keys. The adjacent platform, known as the quicksands due to the rapidly migrating sand waves, which wash across it, forms a barrier to large physical activity from the south. The basin is also deeper than the shelf to the north. As a result, the basin is a sediment trap, which contains finer components than the other areas. This sedimentary body is characterized by a high organic content attested to by the rich shrimping grounds in this part of the Gulf of Mexico. These two sites, in close proximity, with contrasting sediment types and differing physical and chemical settings, made this location ideal for the CBBL program in a carbonate environment.

1.3.3 Description of the Key West Campaign experiments

Acoustic surveys utilizing the Acoustic Sediment Classification System (ASCS), a chirp subbottom profiler, a sidescan sonar system, and seismic sled (Magic Carpet) towed along the bottom characterized the distribution of sediment properties in the Lower Florida Keys. Based on data from these efforts, a protected area appropriate for the many planned experiments in the Southeast Channel of the Dry Tortugas (Figure. 5) was chosen for intensive study. Within this experimental site, high-frequency acoustic scattering measurements were made from the R/V SEWARD EXPLORER using the Applied Physics Laboratory Benthic Acoustic Measurement System tower and from the R/V SEAWARD JOHNSON using a remotely-operated vehicle designed by Applied Research Laboratory/University of Texas.

Shallow sediments were sampled using box cores, gravity cores, and diver coring for radiological, geotechnical, biological, biogeochemical, physical, and geoacoustic studies. The resultant data provide an understanding of the environmental processes that affect sediment structure, a quantification of sediment structure from the micron to cm scale, and a measure of sediment behavior under various stress-strain conditions. Hydrodynamic data were collected with an instrumented tetrapod fielded by the Virginia Institute of Marine Science and, in conjunction with the sediment data, are being used to improve our understanding of scattering mechanisms and to validate or develop new acoustic scattering models.

The original framework established by the CBBL illustrates how the interrelationship between prevailing processes and sediment properties and behavior operates in the Key West environment (Figure 6).

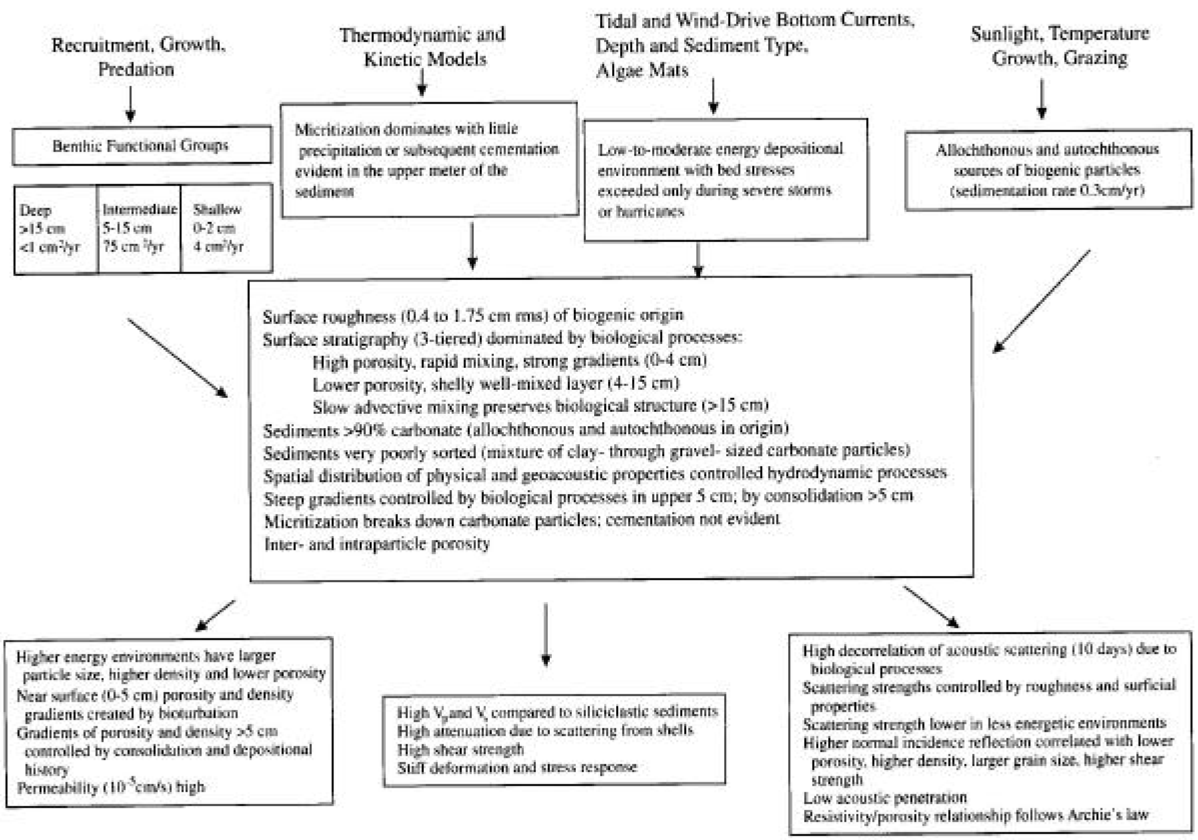

Figure 6. Schematic summary of the major environmental processes and sediment structure, properties and behavior.

Benthic fauna at the Dry Tortugas site are vertically tiered and can be divided into three functional groups: a shallow fauna, surface deposit and suspension feeders, which thoroughly mix the upper 4-5 cm in days to weeks; an intermediate fauna, carnivores/scavengers, deep deposit feeders, and head-down deposit feeders, which intensely mix sediment to depths of 15 cm over time scales of 10-20 years; and a deeper fauna, gallery-creating callianassid shrimp, which only partially mix sediments. Rates and depths of sediment mixing, rates of deposition and the depth and frequency of erosion can be used to model the preservation potential of sediment layers and structure generated by both physical and biogenic processes.

Shallow-water carbonates normally undergo extensive post-depositional biogeochemical diagenesis that includes dissolution, precipitation, and subsequent cementation. Significant changes in surficial carbonate fabric result from subaerial exposure, exposure to fresh-water, micritization, bioturbation, and pore water chemical changes due to the breakdown of organic matter. Although pore waters supersaturated with carbonate, no significant precipitation was noted in the upper meter of sediment at the Dry Tortugas. Current thermodynamic or kinetic models are unable to explain this lack of precipitation or cementation, which is common in other carbonate environments. Advection of water rich in oxygen by bioirrigation to depths as great as 15 cm may explain these model discrepancies. Foraminfera tests show only a slight evidence of the weak reducing conditions found in subsurface sediments. The dissolution features, minor precipitation of calcium carbonate and formation of occasional pyrite framboids may result from the presence of micro-chemical habits within the tests. The dominant processes affecting sediment structure appear to be mechanical and chemical breakdown of carbonate particles, effectively converting sand- and silt-sized carbonate particles to clay-sized matrix material.

Benthic biological processes act in complex concert with physical processes to control sediment transport and seafloor microtopography. The benthic boundary layer at the Dry Tortugas is characterized by low to moderate energy. Bed stresses, primarily due to tidal currents, only occasionally exceed the threshold for sediment transport. Sediment microtopography is biologically dominated, in part a result of surface algal mats that bind sediments increasing sediment critical skin friction. Thus, the Dry Tortugas site is a low-energy sediment sink with most sediment being derived from erosion of the Dry Tortugas Bank just to the north. Severe winter storms and hurricanes can redistribute sediments locally.

Sediments in the Dry Tortugas originate primarily from the breakdown and subsequent transport of biogenic carbonate material from nearby reefs and other hardgrounds (allochthonous) rather than through in situ (autochthonous) production. Sedimentation rates are approximately 0.3 cm/yr. The result is a carbonate sediment (>90%) consisting primarily of aragonite plates and needles derived from the breakdown of plates of aragonitic green algae (*Halimeda*, *Penicillus*, and *Udeota)*, molluscan shells, benthic and planktonic foraminifera, echinoid spines, sponge and coral fragments, diatoms, and less than 5% particles of siliciclastic origin. Microroughness (0.5- to 1.75-cm rms) is primarily biogenic in origin. Sediment is tiered with a thin (0-4 cm) high porosity, homogenous layer covering a more heterogeneous (4-15 cm) shell layer. Bioturbation creates the strong depth gradients in porosity, bulk density and sediment geoacoustic properties. A combination of biogenic mixing and storm-generated stress creates inhomogeneities such as fine laminae and shell lag deposits. Below 15 cm, biogenic heterogeneity dominates the sediment. The vertical gradients and variability of sediment physical, geotechnical, electrical and geoacoustic properties reflect the tiered nature of these sediments. Pore water is distributed as both intra- and inter-particulate porosity.

The distribution of sediment characteristics is primarily controlled by the biological processes that generate carbonate skeletal material and by hydrodynamic processes that erode, fragment and redistribute those particles. Post-depositional biogeochemical processes appear to have little effect on surficial sediment physical and geoacoustic properties in the lower Florida Keys. The distribution of geoacoustic properties correlates with the areal distribution of surficial sediment physical properties including grain size, porosity and sediment bulk density. Higher sound speeds are found in more energetic environments where coarser-sized particles dominate and lower values of sediment porosity and density are found. Empirical relationships between sediment physical and geoacoustic properties for these carbonate sediments are significantly different than for siliciclastic sediments. Higher shear and compressional wave speeds relate to the high percentage of interparticle porosity, the higher grain bulk modulus, and the very poorly sorted nature of these carbonate sediments compared to siliciclastic sediments. High attenuation in carbonate sediments is probably the result of increased scattering from abundant gravel- and sand-size shells rather than differences in intrinsic attenuation. Empirical relationships among porosity, density, resistivity and shear wave speed have also been established for carbonate sediments. The stiff deformation and stress responses of the sediments do not reflect cementation but may be caused by interlocking of angular particles.

Surface backscattering strengths (at 40 kHz) and bistatic scattering strengths can accurately be predicted from bottom roughness and values of surficial sediment density, velocity and attenuation, only if the sediment properties are based on an average of the upper few centimeters. Scattering strengths appear to be dominated by surface roughness scattering. Subsequent acoustic modeling must include the effects of the steep gradients in sediment bulk density and sound speed. High frequency bottom scattering rapidly decorrelates with time probably as a result of near-surface biological activity.

1.4 DESCRIPTION OF THE NORTHERN CALIFORNIA EXPERIMENTS

Several teams of CBBL investigators participated in the STRATA FORmation on Margins (STRATAFORM) experiments on the Northern California continental shelf during the summer of 1996. STRATAFORM is an ONR-sponsored program designed to unravel the effects of past and present shallow-water benthic boundary layer processes on sediment fine-scale stratigraphy (Nittrouer and Kravitz, 1996). The strength of the STRATAFORM program is the interaction of marine geologists who study active benthic processes and relate these processes to strata being created and marine geophysicists who document stratigraphic relationships through seismic records and attempt to interpret the history of formative processes (Nittrouer and Kravitz, 1996).

The (CBBL) objectives were to determine and model the effects of current benthic processes on the spatial variability of physical, geoacoustic and mechanical properties in surficial sediments. We also planned to characterize the sediment structure of the upper 2 meters of the sediment column to determine which benthic processes dominate the recent stratigraphic record. Data on the spatial variability of sediment physical and geoacoustic properties and bottom roughness collected by CBBL scientists will also be used as input to and test of high-frequency acoustic bottom scattering models. Concurrent and long-term measurement of high-frequency (40 kHz) acoustic backscattering and bistatic scattering were obtained as part of the STRATAFORM program at site S-60 by Jackson and Williams (APL-University of Washington). The effects and rates of environmental benthic boundary layers processes (hydrodynamic bottom stress, rates and depths of bioturbation, and rates of sediment deposition) were quantified at S-60 by other STRATAFORM scientists. These data are analogous to the concurrent environmental, sediment property, and high-frequency scattering data collected during CBBL experiments at Eckernförde Bay, Panama City and Key West and will greatly expand our comparative database.

A combination of high-frequency acoustic remote sensing, in-situ measurements, and laboratory sediment analysis techniques were employed to quantify the spatial (horizontal and vertical) variability of sediment strength, stability, geoacoustic properties, sediment reflectivity, and sediment impedance. Sediment distribution at the study site, located in 30-100 meters water depth off the northern California coast, is controlled by complex interactions among benthic boundary layer processes including: sediment deposition from floods from the Eel River, erosion and deposition due to intense winter storms, and sediment mixing by benthic fauna. Measurements were made along two transects; one normal to the coast (S-line) about 30-km north of the mouth of the Eel River, and the second parallel to the coast along the 70-m isobath. The central axis of recent deposition from Eel River floods occurs along the 70-m isobath. An emphasis was placed in determination of vertical and horizontal variability of sediment properties at the S-60.

Sediments at the shallow-most sites (10-40 meters water depth) were low-porosity, high-density sands. Strong bottom currents and wind-wave resuspension apparently winnowed out most fine-grained sediment and transported particles in both northward and offshore directions. Values of in-situ surficial sediment compressional wave speeds (1580-1647 m/s) and shear wave speeds (60-112 m/s) were high and within-station variability of these sediment properties was relatively low. The mid-shelf sediment (80-100 meters water depth) was primarily a fine-grained, high-porosity, low-density mud. Values of in-situ compressional wave speed (1458-1480 m/s) and shear wave speeds(30-42 m/s) were significantly lower than at the shallower sandy sites but also exhibited low horizontal and vertical variability. This region is primarily depositional and sediment mixing is dominated by bioturbation. Sediment at the intermediate location between 45 and 65 meters water depth was a mixture of sand-sized and fine-grained clay particles. The high values of vertical and horizontal variability in sediment grain size were reflected in the high variability in other sediment properties such as compressional and shear wave speeds, porosity, sediment density, and shear strength. The highly variable structure was also evident in x-radiographs from the mid-depth sites.

The surficial in-situ measurements of sediment geoacoustic properties were complemented by direct measurements of low frequency seismic shear wave propagation (Magic Carpet) within the upper meter of sediment. The seismic techniques provided detailed vertical and horizontal gradients of shear wave speeds within water depths of 40 to 70 meters. The agreement between high-frequency in-situ shear wave speeds and shear wave speeds from these lower frequency seismic techniques is remarkable. The good correlation between seismic shear wave speed and sediment porosity and void ratio demonstrate the value of these techniques in estimating gradients and spatial variability of seafloor physical properties.

A dominance of wind-wave-current effects in shallow-water stations is manifested in a low variability in values of geoacoustic and physical properties. Hydrodynamic stress affects the sediment structure by mobilizing the surficial sediment and creating relatively homogeneous, low variability sands. In deeper water (70-100 m), only exceptional waves can effect the movement of water near the sea floor and the lack of significant hydrodynamic stress on the sediment results in little or no resuspension or migration of sediments. Biological activity of benthic infauna at the deeper sites affects the sediment structure by mixing the surficial sediment and creating relatively homogeneous clayey silts and silty clays. Structure (layers) created by changes in sediment deposition is destroyed by active surficial bioturbation. At intermediate water depths (45-60 m), interaction between biological and hydrodynamic processes creates great variability in acoustic and physical properties. Interplay between processes creates a complicated structure reflecting flood deposition, erosion and redeposition by storm events, and mixing by bioturbation. When one process dominates over the other, the tendency is toward uniformity in acoustic and physical properties.

This interplay among benthic process and the variability of seafloor physical properties and sediment mechanical and geoacoustic behavior was evident at deeper depths within the sediment. The record of past benthic boundary layer processes was preserved and observed in sediments collected with gravity corers, direct in-situ low-frequency seismic studies, and also reflected in remote high-frequency (15-30 kHz) seismo-acoustic profiling. Conditions during the experiments were less than ideal for remote acoustic data acquisition, and the resolution of the acoustic records was degraded by heavy seas. In spite of these difficulties it is obvious that similar environmental processes have acted over the last several thousand years, and traces of that record are preserved in the sedimentary record.

Laboratory tests on the contractive/dilative behavior of shallow water sand suggests that sand sediment along the California coast (30 to 40 meters water depth) is too compact to liquefy under seismic or ocean wave stresses. Object burial by liquefaction is therefore unlikely in this high-energy environment.

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TABLE 1. RESEARCH PROJECTS SUPPORTED BY THE COASTAL BENTHIC BOUNDARY LAYER PROGRAM (FY93-97)

Discrete element simulation of the microstructure of marine cohesive sediments (Johns Hopkins) • *Rajah Anandrajah*

Measurement and description of the upper seafloor sub-decimeter heterogeneity for macrostructure geoacoustic modeling (Texas A&M) • *A.L. Anderson*

Sediment properties from grain and macrofabric measurement (NRL, University of New Orleans, and Resource Dynamics) • *R.H. Bennett, Dennis Lavoie, P.J. Burkett, R.J. Baerwald, and M.H. Hulbert*

High-frequency acoustic scattering from sediment roughness and sediment volume inhomogeneities (NRL) • *K.B. Briggs and M.D. Richardson*

Effects of carbonate dissolution and precipitation on sediment physical properties and structure: microfossils component (University of Southern Mississippi) • *C.A. Brunner*

Processes of macro scale volume inhomogeneity in the benthic boundary layer (Texas A&M) • *W.A. Bryant and N.C. Slowey*

Analysis of data from in-situ acoustic scattering experiments (University of Texas) • *N.P. Chotiros*

New geophysical technologies applied to the quantitative evaluation of seabed properties related to mine burial prediction (UCNW) • *A.M. Davis*

Analysis of the rheological properties of nearbed (fluid mud) suspensions occurring in coastal environments (Lafayette College) • *R.W. Faas*

Statistical characterization of the benthic boundary for broadband acoustic scattering (Penn State) • *K.E. Gilbert, T.J. Kulbago*

The chemical dynamics of the South Florida carbonate test site (USGS and Eckerd College) • *C.A. Holmes and G.R. Brooks*

Measurement of high-frequency acoustic scattering from coastal sediments (University of Washington) • *D.R. Jackson and K.L. Williams*

Electrical resistivity imaging of unconsolidated sediments (BGS) • *P.D. Jackson*

Structural analysis of marine sediment microfabric (Quest Integrated, Inc.) • *J.J. Kolle and A.C. Mueller*

Qualification of high frequency acoustic response to seafloor micromorphology in shallow water (NRL) • *D.N. Lambert, D.J. Walter and J.A. Hawkins*

Measurement of shear modulus in-situ and in the laboratory (NRL) • *Dawn Lavoie, Y. Furukawa and A. Pittenger*

Quantification of gas bubbles and dissolved gas sources and concentrations in organic-rich, muddy sediments (University of North Carolina at Chapel Hill) • *C.S. Martens and D. Albert*

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