Real-Time Measurements of Sediment Modification by Large Macrofauna

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LONG-TERM GOALS

Marine sedimentary infauna alter acoustic properties of sediments by creating voids and air bubbles, manipulating grain and shell distributions, moving interstitial fluid and creating surface roughness elements. Our prior results from ONR support suggest that conceptual models of organism modifications of solute flux are grossly inaccurate in both diffusion-dominated and advectively permeable environments. The porewater transients detected by our pressure transducers represent several cm of water pressure in many cases and result in advective flows. The strong, pulsed flows imposed by organisms are radically different from the current models of irrigation-mediated transport or surface-driven porewater advection, a result with significant implications for bacterial transformations and particle movements. Our research addresses fundamental questions in benthic biological oceanography with significant relevance to naval operations: what factors affect infaunal activity patterns and movements and how do these processes affect sediment acoustic properties? Our research has three thrusts: (1) the development of new technologies to measure, in real-time, organism movements and the effects of these movements on the pressures, voids, fluid flows and surface roughness elements of nearshore sediments; (2) the experimental determination of the ecological and geochemical factors, including organism density, resource availability, and the concentration of metabolites in porewater that affect rates of organism movement; and (3) the evaluation of the ecological and geochemical consequences of these interactions. These results will allow us to link the behaviors and dynamics of macrofauna to ecosystem-level processes in coastal habitats and to the predictability of acoustic properties of operational importance to the Navy.

OBJECTIVES

This proposal is centered on expanding (1) our sensor capabilities to allow remote detection of organism activities in sediments utilizing porewater pressure transients, vibrations and optical methods; (2) the number of species, water depths and types of sedimentary environments within our

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database; and (3) the linkages of organisms' activities to alteration of the acoustical, geochemical, and biotic properties of sediments.

The research also fulfills three important goals within ONR's Biological and Chemical Oceanography Program: (1) to enable the prediction of the distribution and abundance of biota and their interactions with biogeochemical processes in shallow water sediments, (2) to understand how biota affect the acoustical properties of operational importance to the Navy, and (3) to explore new instruments to sample and observe biological processes.

APPROACH

Our experimental approach continues to be centered on the supposition that relocation of individuals and biogenic modification of the physical and chemical matrix are driven by interactions among organisms and their biological and geochemical environment. In the past we concentrated our efforts on one species (*Abarenicola*) that is easily manipulated and measured. Our experimental approach, in combination with new technologies, has provided a mechanistic understanding of organism-sediment interactions that highlights the importance of ecological processes in sediments and has broad scale significance for coastal processes. In this award we are expanding both the technologies employed and the array of species examined. We are particularly interested in species that are widely distributed, common and large such as *Arenicola marina* along the European coast, *Amphitrite ornata* and *Diopatra cuprea* on the North American Atlantic coast, and a variety of bivalves both in Europe and North America. We are focusing on related species pairs where we can ask whether similar behaviors by comparable body forms result in predictable signals and associated sediment alterations. We are particularly interested in *Arenicola marina* both as a comparison to *Abarenicola pacifica* and because of the extensive literature on its impacts.

Our initial research confirmed that pressure sensors could detect infaunal activities in unrestrained individuals in the field and that we could differentiate among activities and species (Wethey and Woodin 2005). Our current pressure sensors however use internal atmospheric pressure references, limiting deployment to intertidal or very shallow subtidal depths. We are developing differential pressure transducers to allow deployment in greater water depths and in a greater variety of sedimentary environments. Differential pressure transducers will also increase sensitivity to porewater pressure transients by orders of magnitude thus greatly expanding our capacity to detect activities. Additionally we plan to deploy accelerometers to detect biotic sediment alterations dependent on grain movements, not porewater transients. Pressure sensors detect hydraulic components of activities only. We anticipate that many infaunal activities will cause sediment vibrations detectable using accelerometers. The combination of accelerometers and pressure transducers should allow detection of all major movements and behaviors by large infauna since all involve some combination of grain displacements and porewater pressure transients. Being able to quantify these activities in the field would contribute substantially to models of fluid and particle motion.

Spectrofluorometer fiber optic technology may allow us to detect organism effects on particle motion and organic matter subduction. Our video data indicate that particle motion is highly pulsed and more rapid than traditional mixing measurements suggest. Surface detrital particles that are rich in chlorophyll are moving to depth both by classical subduction mechanisms and via organism-generated feeding cracks. It is rarely possible to quantify these rates however from the video imagery. A fiber optic spectrofluorometer may allow us obtain real-time measures of pigment concentrations associated with organic-rich particles on the sediment surface and at known depths within the sediment column, as a function of infaunal activity and community composition. We plan also to test the application of planar optode technology in collaboration with Dr. Michael Angel, a developer of multilayer optodes.

Our field measurements of advective forces associated with activities of large abundant infauna such as arenicolid polychaetes will be used to confirm the data from the laboratory derived from planar optodes and spectrofluorometric techniques as well as standard geochemical methods. We are using areas from which large infauna have been excluded so that there is a known boundary across which the hydraulic head causing advection can be measured. Nils Volkenborn and Karsten Reise (Alfred Wegener Institute for Polar and Marine Research) have long term exclusion experiments (20 m by 20 m) involving large arenicolid polychaetes at Sylt Germany. They have allowed us to use their experimental plots for our measurements, and we have developed a continuing collaboration. All of these results will have strong implications for physical-chemical biological coupling in the coastal ocean and the degree to which it is pulsile, local and density dependent.

WORK COMPLETED

We now have pressure and video recordings of two arenicolid polychaetes. *Abarenicola pacifica* is a dominant infaunal component from northern California to Japan in the Pacific while *Arenicola marina* is often the infaunal dominant on the coast of Europe.

In *Arenicola marina*, we have measured the advective forces associated with behaviors in the field.

We have carried out laboratory testing of differential pressure sensors but have yet to deploy them in the field. We will deploy the first differential sensors in the field this fall.

We have carried out preliminary measurements with accelerometers. Sediment grain movements are clearly visible on video imagery but to date have not resulted in detectable transients on the accelerometers. We are continuing to explore more sensitive accelerometers.

We have completed two sets of complementary experiments to investigate nonlinearities in the magnitude of sediment-seawater exchange rates as a function of density and activity of infauna.

Five months ago we ordered a field spectrofluorometer with two probes from Ocean Optics to use in determining mixing intensity and subduction of highly productive surface sediments *in situ.* Due to internal problems with the order and problems at Ocean Optics we have yet to receive the instrument.

Our research centers in part on determining what processes promote heterogeneity in sediment dynamics in nearshore systems. To that end, we have discussed benthic fluorescence surface mapping with Charles Mazel and have acquired excitation sources and barrier filters to fit our Nikon camera. Our goal is to examine surface heterogeneity in benthic primary production and to link that variability with feeding behavior and nutrient consumption in sedimentary systems. Our initial attempts to use this instrument have produced some success at identifying chlorophyll hot spots.

RESULTS

A major thrust of this project was to ask whether the pressure transients associated with similar behaviors resulted in similar signals. Recordings of the two arenicolid polychaetes *Arenicola marina* and *Abarenicola pacifica* clearly show a high degree of similarity in terms of activity cycles and feeding mechanisms. Both utilize sediment cracking to open channels to the surface, from which they obtain fresh surface detrital material and both have defecation events characterized by replicable combinations of positive then negative then positive pressure transients. Video of organisms indicated that behaviors during feeding, burrowing and defecation are very similar across species and the recordings of pressure transients look almost identical in form (Fig. 1).

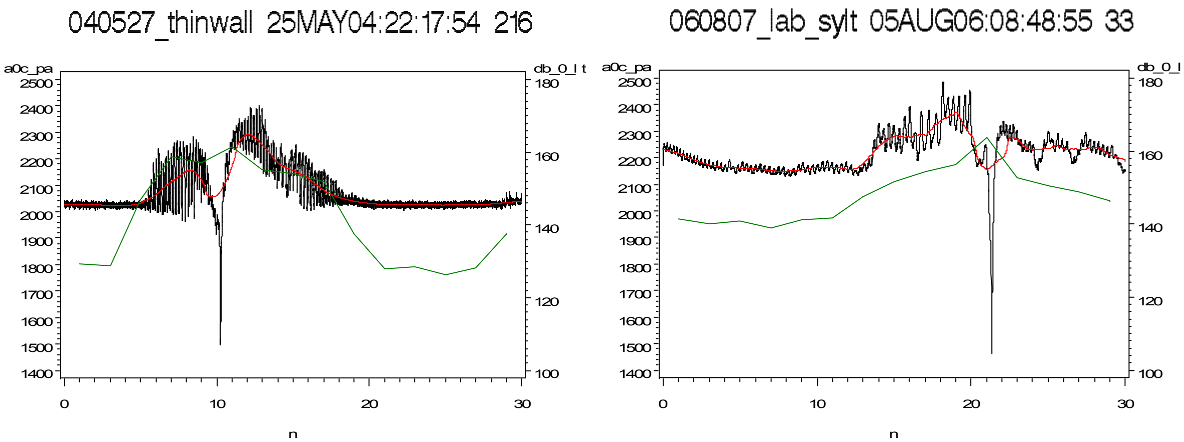

Fig. 1. Defecation signals of Abarenicola pacifica (left) and Arenicola marina (right). Transient porewater pressure (black line, in Pa), running average porewater pressure (red line, in Pa), sound pressure level (green line, in dB). Both species generate large negative porewater transients with sound pressure levels of 160 dB during defecation.

For *Arenicola marina* we used the exclusion experiments at Sylt to measure the advective forces associated with defecation. We arrayed sensors at 10 cm intervals across the boundary of the exclusion experiment and measured the transient hydraulic gradient (Fig. 2), which then allowed us to calculate advection, using Darcy's Law. In one case a defecation event moved over 8% of the porewater at a distance of 10 cm from the animal.

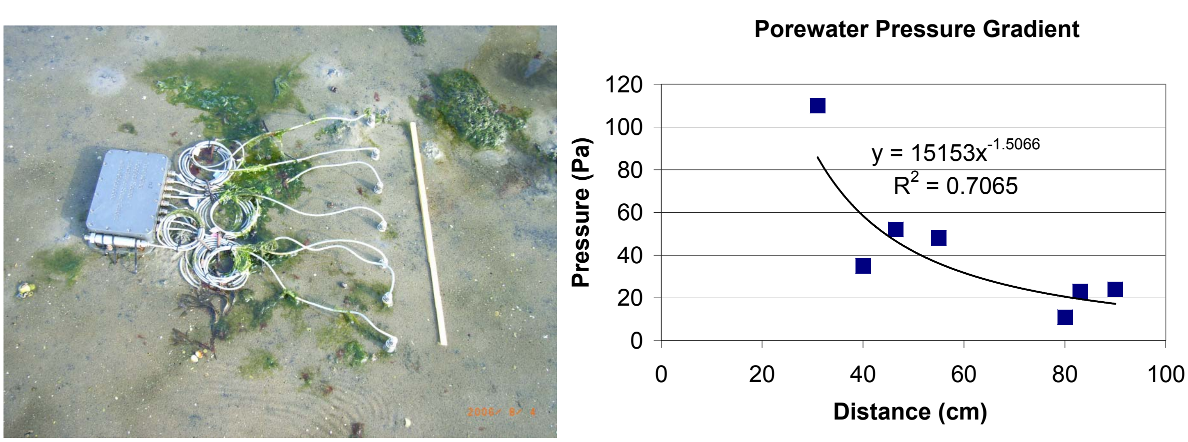

Fig. 2. Sensors across edge of lugworm exclusion at Sylt Germany (left), and porewater pressure gradient during a single defecation event (right) showing the negative exponential decay of signal strength with distance from source.

We obtained independent verification of these porewater movements using temperature sensors arrayed vertically along the burrow. During some periods the water at depth in the sediment is as much as 5º C colder or warmer than surface waters so that when a behavior moves water within the sediments one can see transient fluctuations in the temperature records. We will return to Sylt next spring to further these measurements and deploy more sensitive temperature loggers.

In our experimental manipulations of both density of arenicolid polychaetes and food availability, flux rates were strikingly nonlinear as a function of density and activity. In both experiments we saw significant effects of density and time on elemental fluxes, enforcing our premise that coastal sediment ecological and biogeochemical dynamics are highly transient. These differences are driven in part by the relative magnitude of oxic versus anoxic processes resulting from exchange surfaces created by the density treatments, but are also driven by differences in reaction rates in the cycling of the major inorganic nutrients (nitrate, phosphate, silicate, ammonium). As organisms burrowed, high densities were generally associated with increased fluxes for all the major macronutrients (Fig. 3, May 7 data). However, as the experiment progressed, the interplay of organism activity and reaction rate kinetics changed the pattern of fluxes, with high fluxes often associated with the "medium" density (Fig. 3, May 22 data). We also saw higher growth rates of arenicolids in the higher density treatments, and on a per capita basis, lower rates of defecation with increasing density. Collectively, these findings suggested that (1) infauna can alter nutrient availability in ways that could affect phytoplankton composition and succession and (2) positive density dependent relationships exist within the infauna, i.e. worms benefit collectively by forming patches that facilitate higher rates of surface sediment subduction and microphytobenthic food resources.

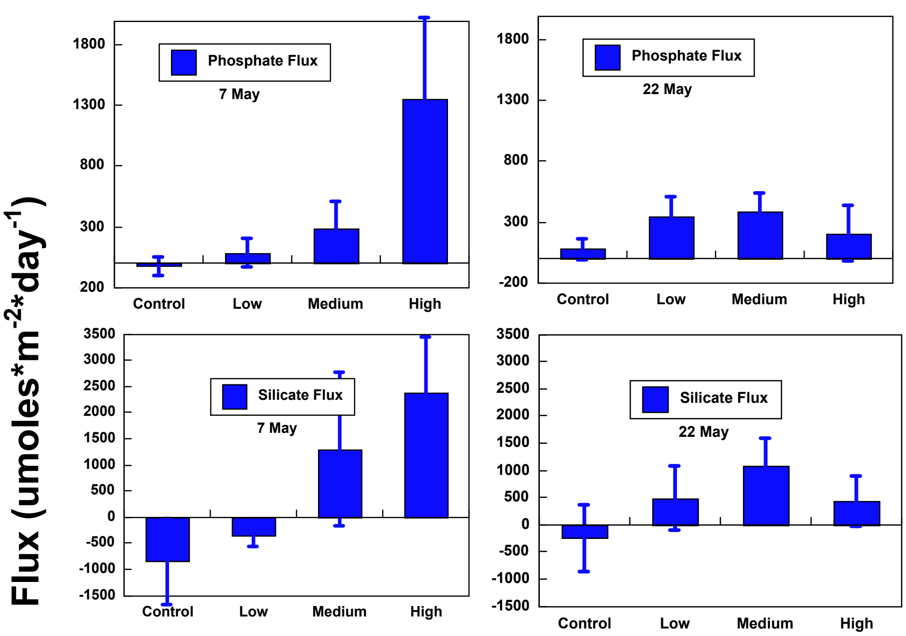

Fig. 3. Flux rates of phosphate and silicate at initiation of the experiment (May 7) and 15 days later (May 22) as a function of density of Abarenicola pacifica. Controls contained no arenicolids. Flux rates are consistently lowest in the absence of arenicolids and highest at the highest densities at initiation when the worms are burrowing and establishing themselves. After 15 days the highest fluxes are at the intermediate density.

IMPACT/APPLICATIONS

Our data consistently demonstrate the pulsile nature of infaunal advective forces in sediments. They also strongly support the idea of positive synergistic interactions (Allee effects) among conveyor-belt feeders such as arenicolid polychaetes. This is consistent with existing data on spatial distributions of organisms such as arenicolids which are often patchy (Krager and Woodin 1993) and implies non-random but predictable differential rates of sediment movement, remineralization, and bacterial activity.

RELATED PROJECTS

The work of Peter Jumars on sediment cracking by infauna and alterations of sediment textures by such activities is clearly related. We have been conversing with one another and we have provided him with video footage of sediment cracking by arenicolid polychaetes. The models of Bernard Boudreau require measurements of grain movements and advective forces by organisms. We will be able to provide him with the latter from measurements such as those at Sylt across a known density boundary of organisms. Some of the lattice automaton model rules may in fact be falsified by our findings plus those of Peter Jumars on the importance of sediment cracking and by our findings on positive density dependent feedbacks.

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