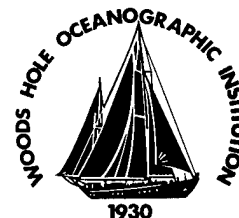


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11 March 1999

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Dear Joe:

On behalf of my Co-Principal Investigator, Rob Wheatcroft, and myself, this letter is submitted to satisfy the final report requirement on our expired grant no. N00014-93-1-1042, entitled "Transfer of Contaminants between the Water Column and Bottom Sediments: The Role of Deposit- and Suspension-Feeding Benthic Invertebrates". The long-term goal of this research was to determine the dominant mechanisms whereby and the rates at which fine particles ( $< 50\mu\text{m}$ ) are incorporated into marine sediments. This project consisted of two successive three-year grants with the specific objective of developing a mechanistic understanding of how deposit- and suspension-feeding benthic invertebrates affect particle deposition and burial relative to the abiotic case. One graduate student, Mr. J. Stephen Fries (WHOI/MIT Joint Program in Ocean Engineering; anticipated graduation in the summer of 2000), was supported from 7/1/95-6/30/98 by an AASERT grant (no. N00014-94-1-0713) to work on this project. In addition, during FY95 we received supplemental instrumentation funds to acquire a Planar Laser Induced Fluorescence/Particle Image Velocimetry (PLIF/PIV) system for quantifying fluid and particle motions in two dimensions.

The approach for this study was to perform laboratory flume and still-water experiments to quantify specific effects of suspension- and deposit-feeding benthic invertebrates on the transport of fine suspended particulates from the water column to the bottom, and the retention of such particulates within the seabed. Major experiments were performed on (1) the effects of biogenic roughness (fecal mounds) on sand transport, (2) the potential effects of worm-tube arrays on fine-particle deposition, (3) fine-particle subduction by a surface deposit-feeding worm, and (4) density-dependent bioturbation by a head-down deposit-feeding worm. We also began studies of particle trapping by the viscous sublayer, a topic which became the main focus of Fries' dissertation research. We briefly describe results for each of these studies below. We also describe the PLIF/PIV system that was built in-house by Drs. Wade McGillis and Erik Bock. This system was used widely both on our project and on other fluid-dynamics projects at the Institution. Some of the papers emanating from the use of the PLIF/PIV system are listed at the end of this letter.

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**Biogenic roughness and sand transport:** Conditions resulting in ripple formation within and downstream of biogenic mounds were studied in a medium sandy ( $d_{50} = 290 \mu\text{m}$ ) sediment under flume flow conditions (Fries et al., in press). The deposit-feeding worm *Cistenides gouldii* (Family Pectinariidae) is a tube-dwelling, head-down, conveyor-belt feeder that ejects excavated sediment into the water column just above the sediment surface, forming a cone-shaped mound. Preliminary flume observations indicated that asymmetric ripples formed within and downstream of worm beds in subcritical flow. Manipulative flume experiments were conducted to determine if ripple bedforms resulted from the mounds produced by the worms, with or without injection of particles into the water column during worm feeding. Results indicated that mounds were required for ripple formation, and that the effect was density-dependent, with ripples forming only at mound densities  $>150/\text{m}^2$ . Experiments were done to determine the effects of mound density and height on ripple formation and a predictive relationship was developed. These results suggest that ripple formation may not be predicted solely from the near-bed flow regime in regions of dense, large biogenic roughness. Moreover, ripples seen in bottom photographs and stratigraphy do not necessarily indicate supercritical flow. Relative to fine-particle transport, ripple height determines the mixing depth for newly deposited fine particles. The presence of biogenic mounds thus may enhance the probability of fine-particle burial within a sandy bed.

**Worm-tube arrays and fine-particle deposition:** Research in the early 1980s explored the effects of animal tubes on sediment erosion and deposition patterns. They documented stress distributions around isolated animal-tube mimics, but due to severe logistical challenges did not extend these measurements to tube patches. Hence, unresolved were wake interaction effects and the question of what density of tube arrays resulted in a shift from stabilizing to destabilizing bed conditions. The goal of our tube experiments was to quantify the bottom stress distribution and vertical velocity field within tube patches of varying density and aspect ratio. Three-dimensional fluid flow measurements were made using the PLIF/PIV system. Methodologies for use of this system were developed as part of the project (Fries et al., 1996). Preliminary analyses indicated horizontal and vertical velocity patterns within tube arrays that build on previous work. For example, at mean flow speeds of  $\sim 20 \text{ cm/s}$ , vertical velocities below tube heights shifted from negative to positive (i.e., up) with increasing tube density. Positive near-bed vertical velocities may indicate that eddy impingement is prevented (i.e., the start of skimming flow). Interestingly, this effect was observed at tube densities substantially lower than the threshold for stabilizing flow (e.g., Eckman et al., 1981). Fries is continuing to explore these phenomena.

**Fine-particle subduction by a surface deposit feeder:** The vertical flux of particles and associated contaminants due to nonlocal subductive mixing is zeroth-order. Therefore, this mixing mode may have a disproportionate effect on the distribution of contaminants within the seabed. The polychaete worm, *Enoplobranchus sanguineus* (Family Terebellidae), lives in sandy intertidal/shallow subtidal sediments and uses its long tentacles to surface deposit feed. A series of laboratory experiments were conducted on the feeding behavior and particle subduction rate of this species (Starczak et al., 1996). In fluorescent-particle-tracer experiments, for example, the worms subducted at least 50% and sometimes greater than 90% of the total tracer inventory. Worms transported fine-grained sediments to depths of several centimeters in the bed. In contrast, no sediment was moved out of the upper centimeter of an abiotic control. A logical consequence of the particle-subduction activities of these worms is that areas supporting large

numbers of terebellids should have a higher inventory of fine-grained sediments than areas without terebellids. The vertical distribution of fine sediments was sampled in an intertidal sand flat with patchily distributed populations of *E. sanguineus*. There was a significant trend in the percentage of fine sediments as a function of worm density at depths 0-6 cm below the sediment surface, but for the 6-10 cm fraction the percentage of fine material increased with increasing worm density. These results indicating biological subduction of fine particles in sandy sediments are important because it is frequently assumed that physical reworking of sandy sediments in shallow water prevents fine-sediment accumulation within the bed.

**Density-dependent bioturbation by a subsurface deposit feeder:** The impact of population abundance on the feeding rate of the head-down, deposit-feeding worm, *Mediomastus ambiseta* (Family Capitellidae), was studied in a series of still-water laboratory experiments (Wheatcroft et al., 1998). Mean individual pellet production rate (mg/worm/day) decreased monotonically with increasing worm abundance in the range of  $6.5 \times 10^3$  to  $1.3 \times 10^5$  worms/m<sup>2</sup>. Worms fed roughly an order-of-magnitude slower in the high- versus low-density treatments. The vertical distribution of pellets and individuals, however, were insensitive to changes in worm abundance. The likely reason for the decrease in ingestion rate with increasing abundance is that a greater fraction of the sediment is bound in fecal pellets too large to ingest. These results suggest that studies which seek to transfer laboratory-based measures of deposit-feeding rate to the field must be careful to match abundances in the two domains.

**Fine-particle trapping by the viscous sublayer.** In a series of flume experiments, the fallout of fine suspended material was observed over boundaries of fixed sand roughness. The three-dimensional flow field was measured using the PLIF/PIV. During these runs, particles collected in streaks usually associated with viscous sublayer flow structures over hydraulically smooth boundaries. The loss of material from suspension violated the anticipated balance between resuspension induced by bed shear stress and gravitational settling. This effective trapping of particles within the viscous sublayer was the inspiration for Fries' ongoing dissertation research.

**The PLIF/PIV system:** Quantifying fluid and particle motions in the water column just above the seabed is critical for understanding and quantifying biological and physical effects on fine-particle deposition, resuspension and transport. The PLIF/PIV system quantifies fluid and particle motions in two dimensions. It consists of a 20W diode-laser-pumped Nd:YLF laser; a scanning mirror, lenses and filters for creating a very thin continuous sheet of light; a real-time, high-resolution CCD camera; a high-speed RAM card for writing the image directly to the computer; a frame-grabber card to recall the image; and image-processing software. An attractive feature of our system is its portability: the complete system is powered by standard 110 VAC, is self-cooling and can be conveniently transported. Thus, our mobile PLIF/PIV system can be used to track fluid motions in any one of the three flumes at WHOI's Coastal Research Laboratory. For this project, the PLIF/PIV was used to quantify fluid motions on the lee side of ripples, around isolated worm tube mimics and within tube-mimic arrays as compared to a flat, rough bed. Fries has been making extensive use of the PLIF/PIV system in his dissertation research on particle trapping within the viscous sublayer.

**Summary:** Present models of particle (and contaminant) deposition and reworking are based on the presumption of largely abiotic conditions. It is increasingly clear, however, that physical sediment transport can be affected, sometimes strongly, by benthic biology. Our experiments have quantified specific effects of benthic organisms on sediment deposition and accumulation toward developing predictive relationships that ultimately can be incorporated into models of sediment transport and mixing within the bed.

**Publications acknowledging this award:**

Anderson, E., W.R. McGillis, M.A. Grosenbaugh, and M. Triantafyllou, 1999\*. Visualization and analysis of boundary layer flow in swimming fish. *International Symposium on Turbulence and Shear Flow Phenomena*, pg. 259.

Fries, J.S., C.A. Butman and R.A. Wheatcroft, 1999. Ripple formation induced by biogenic mounds. *Mar. Geol.* (in press).

Fries, J.S., W. McGillis, R.A. Wheatcroft, and C.A. Butman, 1996\*. Velocity field measurements over realistic boundaries: Preliminary results using a DPIV/PLIF system. EOS 77: F423.

McKenna, S.P., W.R. McGillis, and E.J. Bock, 1996\*. The influence of surface films on near-surface vortical flows. *Colloids and Surfaces* 18: V118 N3: 263-272.

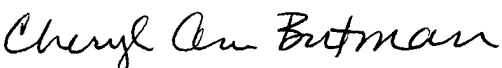
McKenna, S.P., W.R. McGillis, and E.J. Bock, 1999\*. On the relationship between surface divergence and air-water gas transfer: The effects of mechanically generated turbulence. *International Symposium on Turbulence and Shear Flow Phenomena*, pg.16.

Wheatcroft, R.A., V.R. Starczak and C.A. Butman, 1998. The impact of population abundance on the deposit-feeding rate of a cosmopolitan worm. *Limnol. Oceanogr.* 43: 1944-1947.

Starczak, V.R., R. A. Wheatcroft and C.A. Butman, 1996. Particle subduction by a surface deposit-feeding polychaete worm. EOS 76(3) Suppl: 05160.

\*studies involving use of the PLIF/PIV system

Sincerely,

  
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