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POLLUTANT TRANSPORT AND SEDIMENT
DISPERSAL IN THE WASHINGTON-OREGON
COASTAL ZONE

Report of Progress, October 1978
through September 1979

Compiled by

Barbara M. Hickey
Coprincipal Investigator

Prepared for

U.S. Department of Energy
under Contract EY-76-S-06-2225 TA25

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DEPARTMENT OF OCEANOGRAPHY
Seattle, Washington 98195

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Research Assistant Professor
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G. C. Anderson
George C. Anderson, Professor
and
Associate Chairman for Research

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30 June 1979

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INTRODUCTION

One of the Department of Energy's primary responsibilities is to evaluate the costs, risks and benefits of future alternative energy development programs. This responsibility necessitates comparing the environmental impact of coal conversion and oil shale processing, offshore oil and gas production and nuclear power production. To evaluate this impact, the distribution of potentially toxic chemicals associated with the use of each energy source must be characterized and the processes affecting their distribution and rates of distribution must be established.

Pollutants are deposited in the coastal zone by rivers and by direct dumping. The fate of a particular pollutant once it reaches the marine environment is a complicated function of water movement, uptake by organisms and/or chemical reactions, dissolution and sediment transport. DOE contractors at the University of Washington have been investigating these relationships for the past two decades. During the early years, when the Columbia River effluent was being studied, the work was primarily descriptive and was performed under one contract. In recent years the work has been supported by separate contracts to chemical, biological, geological and physical oceanographers and has become much more process oriented. Each group has proceeded at the pace allowed by the state of its particular art while maintaining a close relationship with its counterparts in the other disciplines. In particular, from 1971 to 1977 biological and physical oceanographers collaborated in both modeling efforts and field programs. Although several papers have been published on bio-physical modeling, the biological data base has only now become sufficient to allow a meaningful physical interpretation.

During the last contract year, physical and biological oceanographers in the Pacific Northwest (Oregon State University, the University of Washington, and Battelle Northwest) initiated a joint program to investigate the effect

of canyons on circulation, shelf-slope exchange processes, biological productivity and the movement of sediment. Figures 1 and 2 of the report on this study illustrate the importance of such features in the Pacific Northwest. Most of the sediments from the Columbia River (and hence, pollutants adhering to the sediments) are deposited in either Quinault or Astoria Canyon. Canyons are also known to enhance productivity regions near them and are usually excellent fishing grounds. The acquisition of sufficient equipment (transmissometers, current meters and releases), the refinement of biological sampling techniques and the establishment over many years of background physical and biological information in regions of smooth topography permit us to undertake such a study with a reasonable hope of success.

This report summarizes work performed by the physical oceanographic and sediment transport component of the interdisciplinary program (contract # EY-76-S-06-2225-TA-25) during the year of 1 October 1978 - 30 September 1979. The goal of our program is to be able to provide tested predictive models for the transport of dissolved and particulate matter in coastal regions. To this end, we support modeling efforts in coastal circulation, boundary layer mechanics, sediment transport and animal-sediment interactions. Although direct measurements of the turbulent velocity field in the benthic boundary layer have been made in the past, the funding situation of recent years has prevented us from making such measurements, which require intricate and expensive instruments and a large technical support group. Our DOE-supported field program has, therefore, been restricted to flow outside the logarithmic boundary layer. These measurements do, however, provide the information necessary to allow modeling of the flow and the transport of sediment in the benthic boundary layer. Transmissometer and current meter measurements being made this year at several near-bottom locations in the vicinity of Quinault Canyon may permit us to

determine the conditions under which sediment is resuspended and moved into the canyon.

In succeeding sections of the report each component of our work during the past year is presented. With the exception of our ongoing field program, the theoretical sediment transport studies and the animal-sediment interaction study, the work in each area is sufficiently advanced to be presented as a paper. At this time, three of the papers are currently in press and three have been submitted. The report concludes with a list of papers and reports that have been partially or fully supported by this contract during the past eight years.

SUMMARY OF ACCOMPLISHMENTS - FY 1979-1980

The following is a summary of recent accomplishments that relate particularly to DOE's current responsibilities.

1. During FY 1978 we initiated investigations of flow and water properties in the vicinity of canyons. Canyons are important to the transfer of pollutants up the food chain since productivity is enhanced in their vicinity. They are also important to the fate of land-derived pollutants that are bonded to the sediment; for example, Astoria and Quinault canyons are the conduits by which most of the sediment that is injected into the shelf by the Columbia River ultimately reaches the deep ocean. Since a canyon also disturbs the general shelf circulation, knowledge of processes affecting the flow in the vicinity of canyons is important to offshore placement of oil rigs and nuclear power plants and to the establishment of shipping lanes for transport of fuel by oil tankers. During 1978 we studied Astoria Canyon, a narrow feature that cuts into the shelf near the Columbia River. The somewhat surprising conclusion was that the shelf circulation was not substantially perturbed by this extremely narrow feature. During April of this year we deployed eight current meter moorings in the vicinity of Quinault Canyon. The array was designed to be able to detect time dependence in the transport of sediment near the bottom; that is, transmissometers (Zaneveld and Pak, O.S.U.) were attached to current meters near the bottom so that the concentration of suspended matter could be measured simultaneously with currents. We may thus be able to determine under what conditions sediment is moved into the canyon. During 1980 this experiment will be repeated under the more intensive flow conditions of late fall and winter. During the Quinault experiments we will be examining with the biologists whether and how productivity is intensified near the canyon.

2. We have continued processing the data from our 1977 experiment, in which the cross-shelf structure of currents during the winter and spring was investigated. This work is particularly important to the selection of routes for oil tankers, the placement of permanent structures on the shelf and to the transport of sediment, organisms and nutrients. The data show that currents are often stronger in mid-shelf locations than near shore or at the shelf edge. This coastal "jet" is northward when the winds are from the south and southward when the winds are from the north. Both northward and southward jets were observed during the winter. The existence of the southward jet during this period suggests that upwelling was occurring. Currents on the inner shelf are often in the opposite direction to those observed in mid- and outer-shelf areas. This surprising result is of obvious importance for determining the distribution of a pollutant in any real time situation.

3. We have provided local fishermen with information that will enable them to increase their catch on a given run, thus conserving fuel.

4. We have completed a direct comparison between a baroclinic model of shelf circulation and measurements of current and density that were made over a six-week interval in 1975. Results indicate that the model adequately predicts motions of isopycnals for periods as long as two weeks and that fluctuations in currents are well predicted except at longer periods (> 2 weeks) and near the shelf edge. Thus, the model could be used as input for models that predict biological activity or the transport of sediment. The pertinent paper is in press in the *Journal of Physical Oceanography*.

5. Since tidal fluctuations contribute as much as 50% of the variance to observed currents, they are important in their own right with respect to

advection of dissolved and suspended matter. In addition, they can raise the threshold velocity so that sediment (and hence pollutants) can be moved when the wind-driven currents and/or wind waves by themselves are not sufficiently strong to move sediment. During the past year we have completed a study of tidal currents off the Oregon coast. The most important result from an energy-related point of view is that the internal semi-diurnal tide is reasonably consistent with and can therefore be predicted by available tidal models. The pertinent paper is in press in the *Journal of Physical Oceanography*.

6. Since the number of locations at which one would expect to be able to monitor currents and/or wind and/or sea level is limited, it is important to know the area over which a single measurement station is representative. By the end of this contract year we will have completed our investigation of the alongshore similarity of currents, sea level and winds between Vancouver Island and Newport, Oregon. Results indicate that whereas the north-south currents, sea level and winds are similar over distances of 450 km, the east-west currents are usually dissimilar even over tens of kilometers. The pertinent paper has been submitted to the *Journal of Physical Oceanography*.

7. We have expanded a simple model for time-dependent stratified flow in the immediate vicinity of the sea bed. This model differs from other models in that less elegant but cheaper computational methods are employed and in that it incorporates results from empirical data. The importance to energy-related problems is the ability to predict accurately and inexpensively those parameters that are essential to transport of sediment, pollutants bound to the sediments and marine organisms in the benthic boundary layer. The paper has been submitted to the *Journal of Geophysical Research*. Early in the contract year, we were fortunate to locate a unique set of natural boundary layer data pertinent to the stably stratified situation that predominates in the ocean. Although this information was procured in the atmospheric boundary layer of the Antarctic, it is ideally suited for testing the stratification corrections employed in our

bottom mixed layer-bottom boundary layer model; therefore, such a comparison was carried out and the model proved to give favorable results. A manuscript describing the boundary layer model as well as the results of this test is included with this report.

8. The rate of energy transfer in the benthos, the fate of absorbed pollutants and the stability of any mineral or oil drilling structure built in coastal waters are all strongly influenced by the rate of sediment transport. To predict the rate of sediment transport in the marine environment the interactions of functional groups of macrobenthos with the sediment must be understood. Experiments were performed in a recirculating seawater flume using an ampharetid (*Hobsonia selecta*) to examine the relative rates of entrainment of fecal pellets, in apposition to the ambient sediments. These experiments showed that fecal pellets were not preferentially entrained, a highly significant result, and in direct contradiction to the unsupported assertions of several authors. Similar tests were carried out using the bivalve, *Macoma bathica*. An examination of the effect of animal motility on sediment transport, using the bivalve *transenella*, indicated a significant reduction in the critical shear velocity necessary to initiate sediment motion. These results are vital to the development of an accurate marine sediment transport model.

9. Although bedload transport is of only minor importance in regard to the rapid movement of sedimentary materials, this transport component has a major effect on bed topography and is extremely important in regard to the ecology of benthic organisms. On the Washington continental shelf, the size-frequency distributions for the bed material are polymodal and the currents are rarely strong enough to put the coarser modes into suspension. Therefore these materials move as bedload and produce bed forms. Smith and McLean (1977a,b) have outlined a relatively general suspended load transport theory that was

expanded during the past year to include bedload transport as well. The motivation for this work has been to produce a single general equation from which both bedload and suspended load transport rates could be computed (a so-called total load equation) and thereby to provide an expression for the treatment of broad size frequency distributions.

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- Hickey, B.M. and P. Hamilton (in press). "A spin-up model as a diagnostic tool for interpretation of current and density measurements on the continental shelf of the Pacific Northwest." J. Phys. Oceanog.
- Torgrimson, G. and B.M. Hickey (in press). "Barotropic and baroclinic tides on the continental shelf and slope off Oregon." J. Phys. Oceanog.

Hickey, B.M., A. Huyer and R.L. Smith (submitted to J. Phys. Oceanog.). "The alongshore coherence in low-frequency currents on the central continental shelf of the Pacific Northwest."

Long, C.E. and J. Dungan Smith (1979). "A simple model of the time dependent, stably stratified planetary boundary layer." Submitted to J. Geophys. Res.

McLean, S.R. and J.D. Smith (1979). "Turbulence measurements in the boundary layer over a sand wave field." Submitted to J. Geophys. Res.

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QUINULT CANYON STUDY, MAY - AUGUST, 1979

B. Hickey

1. Introduction

The motivation for studying the effects of longshore gradients in topography on coastal circulation and on shelf-slope exchange processes, in particular the effects of canyons, has been discussed in detail in the proposal for the upcoming contract year. It was pointed out that although flow away from top and bottom boundary layers in mid-shelf areas follows the direction of the local isobaths, it is generally unknown to what extent this holds true in regions where isobaths have strong curvature.

Investigation of circulation in such areas is very important on the Washington shelf, since several canyons intrude from the deep ocean well into the shelf (figure 1). Geochemical investigations show that two of these canyons, Astoria and Quinault, provide the primary conduits by which land-derived sediments (and pollutants such as hydrocarbons) reach the deep ocean (figure 2). Since the transport of sediment is driven by mid-depth flow, a determination of the nature of this flow is fundamental to the problem of when and how sediment is moved into the canyon. Canyons are also important for their enhancement of upwelling and, hence, biological productivity over the shelf.

Our field effort during 1978 was directed toward an investigation of mid-water column circulation in the vicinity of Astoria Canyon. The results of this study are contained elsewhere in this report. Astoria Canyon was selected primarily because its sharp structure and east-west direction make it the simplest canyon to model. Results indicate that although the velocity field is relatively unperturbed by the canyon, the density field does have a perturbation in the vicinity of the canyon. During 1979 we are participating in an interdisciplinary study of the Quinault Canyon area. The following is a report of the progress to date in that program.

2. The Quinault field program

An array of eight moorings consisting of 26 current meters and five transmissometers was deployed at the beginning of May in the vicinity of Quinault Canyon. The most southerly line of the array coincides with the historical sampling line of the biologists. The approximate locations of the moorings and wind station are shown in figure 3. Wind speed and direction are being measured continuously at our shore-based station at Ocean Shores. Each mooring consists of several Aanderaa current meters, a subsurface float, an acoustic release and a timer which releases a float to the surface as a backup release mechanism and a radio antenna. A typical mooring is shown in figure 4. Sufficient flotation is used so that each instrument on the mooring is independently buoyant. Each mooring has at least two current meters, one at about 50 m (except 8) and one 5 m from the bottom (except 1 and 9). All near-bottom meters on moorings are equipped with conductivity cells in order to obtain continuous, fixed-depth records of conductivity, temperature and density. This will permit a direct comparison between the upwelling of denser, nutrient-rich water from the canyon and in a region away from the canyon.

The vanes of the near-bottom meters at moorings 2, 6, 7 and 8 have been modified to accommodate the transmissometers of Zaneveld and Pak (OSU). The transmissometers record data on the Aanderaa magnetic tapes simultaneously with the current speed and direction information. The simultaneous recording of light transmission, which can give an estimate of the concentration of suspended matter, and current speed and direction is an innovation. On mooring #6 we are performing a mid-water column intercomparison between Aanderaas with and without modified vanes to determine the effect of the difference in vane area. (Tank tests indicated a negligible change for speeds of interest.) By comparing samples of inorganic suspended matter with the percent transmission, transmission may be converted (by linear regression)

to suspended sediment (Baker, 1976). These data can then be used to determine temporal variations in suspended sediment concentrations and their relationship to longshore current or to wind stress. The boundary layer model of Long and Smith contained in section VI of this report could be used to predict bottom stress from the measured near-bottom velocity field. We might then be able to test models (e.g., Smith, 1977) for the transport of suspended sediment.

A Davis-Weller type current meter will be placed 10 m from the surface in 20 m of water during the interdisciplinary cruise, July 16-August 3 (mooring #3). It will be retrieved in mid-August. This type of current meter is capable of measuring in near-surface and shallow areas where wave activity causes Aanderaa current meter data to be severely aliased. An intercomparison between a Davis-Weller current meter and an Aanderaa is being performed on mooring #8 at a depth of 20 m from the surface. Both Davis-Weller current meters were borrowed from Dr. Russ Davis at Scripps Institution of Oceanography.

The cross-shelf and slope array # 5, 6, 7 and 8 will enable us to investigate fluctuations in the coastal jet and their relationship to wind stress, the cross-shore development of the bottom boundary layer (in terms of the strength of the bottom nepheloid layer), the cross-shore advection of cold nutrient-rich water that is upwelled from the canyon, and flow within the canyon itself. Mooring #4 is monitoring possible shelf-slope exchange of water at the narrow southern head of the canyon. Mooring #2 permits us to estimate shelf-slope exchange and suspended sediment concentration away from the canyon and to monitor disturbances that may be generated by the canyon. Mooring #1 allows comparison of currents over the slope outside the canyon with those inside (#5). The curvature of the 600 m isobath is such that currents over the upper slope may, in fact, not feel the canyon. Lastly, mooring #9 is monitoring disturbances propagating (or standing) to the north of the canyon.

The current meter moorings will be retrieved in late August, thus encompassing the interdisciplinary work of Anderson, Zaneveld, Pak, Small, Nelson and Crecelius. This group will concentrate their efforts during a three-week period beginning July 16, studying nutrient, phytoplankton, bacteria, zooplankton and particulate matter distributions along the historical sampling line of Grays Harbor and along lines perpendicular to and north of the canyon.

A CTD/transmissometer survey consisting of 55 stations was taken during the May cruise with the DOE Neil Brown CTD. Casts were taken to within 5 m of the bottom. Station locations are shown in figure 5. Sections were made in several regions of differing topography, in particular, across the canyon near its head, across the slope north and south of the canyon, across the steep mouth of the canyon, up the main broad axis and up the narrow southern axis. The data have been calibrated and processed. S, T, σ_T and transmissometer sections are shown in figures 6a, b, c and d (down the axis); 7a, b, c and d (across the mouth); and 8a, b, c and d (across the canyon). Geostrophic sections are shown in figures 9a and b. Upon retrieval of the moorings the CTD grid will be repeated to the extent that time permits.

Both of the geostrophic sections show strong poleward flow just seaward of the shelf break. Thus we see that the California Undercurrent does remain geostrophic and follow the curvature of the topography into the canyon. The signature of the Undercurrent is also seen in the S, T and σ_T sections down the canyon axis: S, T and σ_T isolines all slope downward toward the coast below the shelf break (fig. 6a, b and c). Figure 6d suggests that the quantity of suspended matter in the water column is lower near the region of poleward flow. In contrast with the Astoria Canyon results for August (Section II), no enhanced upwelling is observed on either lip of the canyon (figures 7a, b and c and 8a, b and c). The bottom nepheloid layer is thicker in the canyon than on the steep sides of the canyon (figures 7d and 8d).

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Figure 1. Bathymetric map of the Washington coastal zone.

Figure 2. Sediment accumulation rates on the Washington shelf (taken from Nittrouer, 1978).

Figure 3. Locations of current meter moorings and the wind stations in the vicinity of Quinault Canyon, May-August, 1979.

Figure 4. Schematic diagram of a typical shelf mooring.

Figure 5. Locations of current meter moorings in the vicinity of Quinault Canyon, May-August 1979. Locations of CTD/transmissometer stations occupied from April 27 to May 2, 1979 are also shown.

Figure 6b. σ_t section across upper Quinault Canyon, May 1, 1979.

Figure 6c. Salinity section across upper Quinault Canyon, May 1, 1979.

Figure 7a. Temperature section ($^{\circ}\text{C}$) across the steep mouth of Quinault Canyon, April 30, 1979.

Canyon, April 30, 1979.

Figure 7c. Salinity section across the steep mouth of Quinault Canyon, April 30, 1979.

Figure 7d. Transmissivity section across the steep mouth of Quinault Canyon, April 30, 1979.

Figure 8a. Temperature section ($^{\circ}\text{C}$) down the axis of Quinault Canyon, April 29, 1979.

Figure 8b. σ_t section down the axis of Quinault Canyon, April 29, 1979.

Figure 8c. Salinity section down the axis of Quinault Canyon, April 29, 1979.

Figure 8d. Transmissivity section down the axis of Quinault Canyon, April 29, 1979.

Figure 9a. Geostrophic flow across the north slope of Quinault Canyon, April 30, 1979.

Figure 9b. Geostrophic flow down the main axis of Quinault Canyon, May 1, 1979.

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THE EFFECT OF A NARROW SUBMARINE CANYON ON LOW-FREQUENCY SHELF CIRCULATION

Barbara M. Hickey

Introduction

The continental shelf of the Pacific Northwest is intersected at intervals of tens of kilometers by submarine canyons, several of which penetrate over half the shelf width. An experiment was designed to address the following question: over what time scales (if any) does the flow follow the isobaths in the vicinity of large bathymetric curvature; and are propagating or standing disturbances generated by the canyon?

Astoria Canyon was selected for the site of the pilot study because of its simple geometry, its deep penetration into the shelf and its importance as a conduit of land-derived sediment to the deep ocean. Locations of current meter moorings are shown in figure 1. Moorings were of a taut wire configuration with the subsurface float 35 m from the surface. A single Aanderaa current meter was suspended 60 m from the surface and data were recorded at 20 min intervals. Wind speed and direction estimated by coast guard personnel were available on the Columbia River Lightship. Current meter data were low-passed to hourly data (Smith *et al.*, 1976). Both wind and current data were "low-low" passed by a cosine filter with a half-power point of 40 hours to remove tidal and inertial frequencies.

Results

Figure 2 presents the low-low passed wind and current meter vectors as a function of time. The most remarkable result is that the predominant orientation of the response is north-south, even at locations where the local isobaths were oriented in the east-west direction. Figures 3a and 3b,

which detail the response during a strong northward and a strong southward event, show that the east-west components of flow are significantly different from zero and extremely time dependent: fluctuations appear to be of a higher frequency than for north-south components. Moreover, an identifiable spatial pattern emerges: for northward events, the flow south of the canyon is onshore, offshore and then onshore; for southward events, flow south of the canyon is primarily onshore and flow north of the canyon is primarily offshore.

Figure 4 shows that the east-west component of flow is significant at every location and throughout the entire experiment. The smallest fluctuations are observed on the canyon axis. The largest fluctuations are observed on the south rim of the canyon (5), where the isobaths are oriented at 45° from true north. The magnitude of the east-west fluctuations are of the same order as those obtained simultaneously 50 m from the surface at a mooring located in 110 m of water at $45^\circ 20'N$, in a region of smooth topography.

"Event"-scale fluctuations in the north-south component of velocity are generally coherent across the array (figure 2). However, the spectra in Figure 5 show that whereas energy at event frequencies is significantly higher nearer the coast, as predicted by spin-up models of shelf circulation (Hamilton and Rattray, 1978), energy at lower frequencies can be higher away from the coast. The coherence spectra in Figure 5 show that the north-south component of current is not significantly coherent with the north-south component of local wind at frequencies above 0.3 cpd. East-west current is significantly coherent with north-south wind at higher frequencies at moorings 1 and 2, which were located south and north of the canyon, respectively. This suggests that the canyon may generate high frequency (0.3-0.5 cpd) fluctuations in the velocity field in response to wind stress events. The spectra in figure 4 confirm that energy levels in the u component of velocity at these moorings are on the order of or exceed those in the v component at frequencies above 0.2 cpd. This effect is not observed at the canyon head

mooring; nor is it generally true for regions of smooth topography (Smith, Hickey and Beck, 1976). The relatively low coherences between current and wind at low frequencies could be due to non-local effects such as eddies (for the 10 day periods such as that centered on January 30) or interaction with Eastern boundary currents (for monthly periods such as the mean northward flow from 20 January to 20 February and the mean southward flow from 10 March to 20 April).

With the exception of the two outer-shelf moorings, coherences among the north-south components of current are lower than have been found in mid-shelf areas at this time of year over much larger spatial scales (Hickey, *et al.*, 1975). Coherence of east-west components of currents is significant only at very low frequencies. At 0.1 cpd, east-west flow at moorings north and south of the canyon is 180° out of phase.

To further investigate the effect of the canyon on the flow, empirical orthogonal functions were calculated for the period of 19 January - 5 April. The calculation was performed on the series u_i , v_i , $i=1, N$ so that vector eigenfunctions were obtained. The first eigenfunction, which accounts for 45% of the variance, is highly coherent with the north-south component of wind at low frequencies, lagging it by about 45° (figure 8). The spatial distribution of this eigenfunction suggests a response to wind forcing that parallels the isobaths in the mooring vicinity, particularly at mooring #3. Note that fluctuations at moorings 1 and 2 are slightly onshore relative to the mean flow. The spatial distribution of the second eigenfunction, which represents 26% of the variance, shows a strong effect by the canyon: east-west flow is opposite north and south of the canyon, which was the pattern that we identified for southward flow events (figure 36). This eigenfunction is significantly coherent with wind stress at high frequencies (.5 cpd), which is consistent with the coherences between north-south wind and east-west currents that were discussed earlier.

Discussion

In-depth investigation of this data set and accompanying hydrographic information is continuing. The zero order effect of this canyon on the low-frequency current distribution was less than expected. This can be attributed to the narrowness of the canyon; that is, the transit time across the canyon for a particular water parcel is much less than the inertial period. Thus, geostrophic compensation, which must be accomplished through inertial waves, cannot occur rapidly enough so that the flow remains geostrophic and, thus, follows the contours. We are pursuing this idea and are investigating more thoroughly the theory of flow over ridges and valleys such as Johnson (in press) to compare with the eigenfunction and coherence and phase analyses. Hydrographic data (figure 10) have contributed another interesting possibility--that the flow treats the canyon as an obstacle, forming a lee wave such as discussed in Drazin and Moore (1967). This is suggested by the downwarped isopycnals over the canyon and the upwarped isopycnals to its north and south. We expect these investigations to be completed during the present contract year.

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Figure 1. Locations of current meter moorings and CTD stations in the vicinity of Astoria Canyon (January-May, 1978).

ASTORIA CANYON 1978
PLOTING VECTORS EVERY 6 HOURS

Figure 2. Low-passed wind vectors and current vectors at seven moorings in the vicinity of Astoria Canyon.

NORTHWARD EVENT BEGINNING 0000 4 MAR 78

Figure 3a. North-south (v) and east-west (u) components of current at six hour intervals at seven locations in the vicinity of Astoria Canyon, during a northward current event. Depth is in fathoms. Time increases to the right for v and downward for u. Arrows indicate whether flow was onshore or offshore during a given period.

SOUTHWARD EVENT
BEGINNING 0000 11 MAR 78

Figure 3b. North-south (v) and east-west (u) components of current at six hour intervals at six locations in the vicinity of Astoria Canyon, during a northward current event. Depth is in fathoms. Time increases to the right for v and downward for u. Arrows indicate whether flow was onshore or offshore during a given period.

Figure 4. The north-south (v) component of wind and the east-west (u) component of current at seven locations in the vicinity of Astoria Canyon. The east-west component of current at a mid-shelf location in a region of smooth topography 80 km to the south is also shown.

Figure 5. Spectra of north-south (v) and east-west (u) components of low-low passed currents at moorings 1, 2 and 3 in the vicinity of Astoria Canyon for the period 18 January - 5 April, 1978. The v-component of low-low passed Lightship wind is also shown. Each estimate has 14 degrees of freedom.

Figure 6. Coherence estimates between north-south (v) or east-west (u) components of low-low passed currents at moorings 1, 2 and 3 in the vicinity of Astoria Canyon and the north-south component of low-low passed Lightship wind for the period 18 January - 5 April, 1978. Each estimate has 14 degrees of freedom. The 95% significance level is 0.47 (Koopmans, 1974).

Figure 7. Coherence estimates between pairs of north-south (v) and pairs of east-west (u) components of low-low passed currents at moorings 1, 2 and 3 in the vicinity of Astoria Canyon for the period 18 January - 5 April. Each estimate has 14 degrees of freedom. The 95% significance level is 0.47 (Koopmans, 1974).

Figure 8. Coherence estimates between the first and second empirical orthogonal eigenfunctions and the north-south component (v) of low-low passed Lightship wind for the period 18 January - 5 April. Each estimate has 14 degrees of freedom. The 95% significance level is 0.47 (Koopman, 1974).

Figure 9. Mean velocity field and the first two empirical orthogonal eigenvectors for the period 18 January - 5 April, 1978.

Figure 10. σ_t section across Astoria Canyon, August 14, 1978.

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ANIMAL-SEDIMENT INTERACTIONS

by

Arthur R. M. Nowell

Introduction

The detailed mechanism of sediment motion operates within the triptych of flow-animal-sediment interaction. Sediment transport and the dispersion of the adsorbed pollutants will be modeled adequately only when the effects of organisms on the sediment and on the flow are understood. This past year the component parts of this problem have been identified and considerable progress made to determine the influences of biogenic activity on sediment movement.

The approach that has been adopted by the sediment transport group at the University of Washington has been to separate the complex feedback system of animal-flow-sediment interaction into its three primary component parts and then taking each major segment to examine the linkages and the sensitivity of these connections under the simplest of conditions. Once these interactions are predictable and included in a suitable model, the feedback interactions may then be understood. The joint use of deterministic flow models with stochastic models for animal-sediment interaction illustrates the fertility of this intellectual methodology: the results obtained are adequate justification of its utility.

The flow close to a modifiable boundary has been the subject of detailed work under this proposal for several years. Rarely is the flow in the boundary layer on the continental shelf a simple uniform, steady, neutral boundary layer. Rather, there are several important complications that must be included. The influence of boundary topography results in strong flow nonuniformity; a simple model of non-uniform flow over sand dunes, features that embody much of the moving sediment, has already been developed. The time dependent nature of the flow is addressed in an earlier section of this report as is the influence of stratification due to density and the presence

of suspended sediment. A simple parsimonious model for this flow has been developed. The need to model flow over dunes was addressed in earlier years as these features are common on the Washington shelf. The Smith-McLean model (1977) attempted to model the influences of sediment motion on the near wall flow chiefly by varying z_0 , the roughness length of the boundary. Last year we addressed the vexing problem of intermittency in rough wall flows. The results clearly indicate that considerable work remains to be done on this aspect of boundary layer flows, for the mechanisms of momentum transport over rough walls are not yet fully resolved. Bursting and coherent structures found in smooth wall flows are not ubiquitous to all flows, and hence careful laboratory examination of the mechanism of momentum transport under varied boundary conditions including moving sediment is clearly necessary.

In this report we focus on two of the components of the sediment-animal-flow interaction triad. We look at the effects of organisms on sediment characteristics and the effects of the activities of the benthic organisms on the near wall flow characteristics. [It is commonly the activities by the benthic community that control the rate of sediment movement.]

Flow Characteristics

The characteristics of the flow close to the bed on the continental shelf can rarely be characterized into either of the two simple end members of the hydrodynamic classification: that is, the boundary layer is seldom hydrodynamically smooth nor completely hydrodynamically rough. Rarely is the roughness of a type that may be conceptualized as an equivalent sand size. Virtually all the work that has been done on modelling boundary layers on the continental shelf has made the assumption that the controlling length scale z_0 is directly related to particle size. Most frequently, however, as the work of Self and Jumars and Eckman has demonstrated (see Eckman, DOE Progress Report Vol. 1), the boundary is covered by discrete roughness

elements (organisms), the spatial distribution and density of which varies over the continental shelf. The shape of the elements, their geometrical arrangement and spatial distribution are the main characteristics affecting the velocity field. Specifically, the intensity and scale of the turbulence in this near surface layer where frictional drag of the surface is dominant depends considerably upon the properties of this roughness.

The modification of an initially uniform bed by biological activity results in a significant change in the roughness characteristics of the bed; for example, polychaete tubes built of the coarsest fraction of particles in the surface layer dramatically influence the transition to turbulent flow. Such tubes, because they exist in a boundary layer where the flow is unsteady, may alter the Reynolds number of transition by a factor of 2. They act as point sources of momentum extraction and vorticity generation, which significantly affect the resistance to flow and hence enhance the capacity of the flow to maintain fine particles in suspension. The influence of such tubes on the recruitment of other benthos has been documented by Eckman (op. cit.).

Classically, bioturbation is taken to refer to the effects of burrowing by the benthic organisms. It should also include surface crawling, for motile surface deposit feeders and suspension feeders can exert a distinct influence upon the character of the boundary. Many motile creatures leave distinct tracks as they migrate over the sediment. These tracks, whose vertical dimension is often greater than the thickness of the viscous sub-layer, act to increase the roughness of the boundary. This effect is seen as an increase in z_0 , the single length scale used in boundary layer models discussed in an earlier section.

In summary, tube building and surface motility act to alter the surface roughness length scale. The effect of spatially distributed roughness elements on

boundary layer flow characteristics has been investigated by Nowell (Nowell and Church, 1979; Nowell, 1979). These studies have shown that the roughness has a pronounced effect on the lower limit of the logarithmic layer. Traditionally the logarithmic layer is assumed to hold all the way down to the viscous sublayer, the lower matching point being determined from the asymptotic expansion of the law of the wall and the velocity defect region. For the rough wall case, the lower limit has never been investigated. This omission is serious:

laboratory studies of sediment transport use the logarithmic law to estimate the shear velocity that is responsible for entraining sediment. Hence it is important that this lower limit be established, first to allow intelligent review of previous laboratory experiments, and second to permit precise experiments on biologically altered sediments to be carried out.

The evaluation of the local wall shear stress in a two dimensional boundary layer is important in estimating local mass and momentum transport rates. The existence of near wall similarity allows for indirect estimates of the local bed stress from the velocity profile. Such methods make use of the logarithmic law velocity profile. The simplest approach to evaluating the lower limit for this logarithmic law is to look at the similarity laws for turbulent wall flows for both the mean velocity and the turbulence components, and thus to identify the lower bound of the logarithmic region. While a second order theory using matched asymptotic expansions may be used, the simplest approach, using the lowest order of approximation yields a region of overlap between the Prandtl wall layer and the von Karman velocity defect layers. In this region

$$U(z) = u_* \left[A \ln \frac{zu_*}{\nu} + B \right] \quad (1)$$

where A^{-1} is von Karman's constant and B takes the value of 5 from experimental evidence. At large values of $z^+ \equiv (u_* z / \nu)$, well above the viscous sublayer, the velocity gradient for the adiabatic case may be written as

$$\frac{\partial U(z)}{\partial z} = \frac{A u_*}{z} \phi_M(0) \quad (2)$$

where $\phi_n(0)$ is the dimensionless shear stress. Hence if u_* can be evaluated independently then ϕ_n can be computed. It should be unity in the logarithmic layer.

A function similar to equation (1) can be obtained for any turbulence quantity. This equation yields the result that any turbulence quantity when nondimensionalized by a suitable power of u_* should approach a constant in the logarithmic region.

We thus have three criteria for estimating the lower limit of the logarithmic layer:

- 1) a dimensionless shear stress equal to unity
- 2) the goodness of fit to equation (1)
- 3) constant ratios of the turbulence quantities when scaled by u_* .

An analysis of the best measurements for the hydrodynamically smooth wall cases indicates that these conditions are only fulfilled at $zu_*/\nu \approx 100$. This result is significant, for at distances below this we should expect to find departures from statistical horizontal homogeneity, which is the requirement in the derivation of all three criteria (see Figure 1 and Figure 2).

The plethora of recent work on smooth wall boundary layers utilizing flow visualization techniques has shown that the momentum flux is dominated by large scale intermittent events called bursts. These bursts originate in the buffer layer and measurements (Willmarth, 1975) indicate that they contribute the majority of the turbulent momentum flux. These recent studies on Reynolds stress generation and coherent motion have measured one flow feature with considerable accuracy; within the viscous sublayer, parallel to the mean flow there are streaks whose spacing is approximately $y u_*/\nu = 100$, where y is the cross stream distance. These streaks represent lines of low momentum fluid which collect at the boundary between two counter-rotating Taylor vortices. The viscous sublayer is not a laminar region:

rather, it is a complex tangle of structured Taylor vortices that are elliptic in shape having a vertical dimension of $zu_*/\nu = 15$ and a streamwise extent of approximately $xu_*/\nu = 1000$. It is the interaction of these streaks with an inflection point instability in the velocity profile at the top of the buffer layer that is responsible for the bursts. The inflection point instability is likely generated by the intrusion of high momentum fluid from the outer flow region. Strong advective acceleration will then exist in this lower region, such that the assumption of statistical horizontal uniformity is violated. Thus the lower limit for the smooth wall case is controlled by the scales of viscous instability: the interaction of these viscous instabilities with intrusions of high momentum fluid dominates the rate of turbulent stress production.

The relation of the mathematically derived form of the velocity profile to this description of the physics of the flow represents a significant contribution to our understanding of the near wall flow dynamics of smooth wall boundary layers. It is these flows that show the clearest evidence of bursts and coherent motion. Recently, Caldwell (unpublished) has found from detailed velocity profiles that on the outer Oregon shelf in depths of approximately 200 m a continuous viscous sublayer exists at low mean velocities (of order 10 cm/sec), over periods of many hours. During such time, little sediment will be entrained from the bottom boundary, as u_* is too low, but considerable advection may still occur. Fine silts, and pollutants that are adsorbed onto such material from the Columbia River, may thus be transported over 10 km over a hydrodynamically smooth bed. During such times considerable deposition of part of the size fraction will occur: as yet no one has examined the physics of deposition in any field environment or laboratory. But the consideration of the fluid dynamics of the smooth wall case indicates which scales will be important in the process, and such problems may be best addressed in this proposal by undertaking laboratory work.

If we consider the other limiting case, the fully hydrodynamically rough case, there are in general many scales possible for formulating the inner similarity variables. Let us consider the simplest case, and one of practical significance for the continental shelf, notably for the inner shelf, that case concerning dense packed sand. Under these circumstances, the overlap region of the two similarity layers is formulated as

$$U(z) = u_* A \ln \frac{z}{z_0}$$

where $z_0 = \nu \exp \frac{-B}{Au_*} = h \exp \frac{-B'}{A}$ and h is particle diameter.

The scaling length z_0 is also used in the similarity laws for the turbulent fluctuations. The ratios that result from this law should approach the same constant values, namely 5 for the streamwise turbulent kinetic energy, and unity for the turbulent Reynolds stress as in the smooth wall case.

A detailed examination of available data indicates that the lower bound of the logarithmic layer in this case is at $z/z_0 = 100$. Below this level the momentum flux is not totally due to the turbulent Reynolds stresses, indicating that local advective accelerations are having a sizeable effect. This analysis represents the first attempt to justify the assertions made by Townsend (1976) concerning the lower limit of the logarithmic layer. We should note that this height, $z/z_0 = 100$, corresponds (for densely packed sand) to approximately three particle diameters.

As virtually no work has been done on the intermittent generation of Reynolds stresses in rough wall flows, it is impossible to relate this lower limit to any such a concept as sublayer streak spacing. In rough walls, the absence of the continuous viscous sublayer removes one of the vital links in the feedback loop of sweep, local viscous instability, burst and sweep. This feedback loop requires a continuous viscous sublayer to act as the secondary instability which triggers the burst. We thus have fluid mechanical evidence as to why rough walls should not display identical

bursting characteristics as their smooth wall counterparts. As Smith indicated (DOE Report, 1978), bursting does not seem to be universal over sand wave fields: this work represents the first field evidence on the detailed time history of turbulent Reynolds stress production.

One should expect by Townsend's (1976) similarity hypothesis that the gross physics, as it is dominated by the large eddy structures, must be similar between the smooth and rough wall cases. The large eddy structure scales on outer flow layer parameters while the small scale secondary instabilities should depend on wall region scales. This local boundary instability may therefore be related to the vortex shedding by individual particles. The frequency of shedding of vortices from any obstacle is related to the Strouhal number which is given by nh/U , where n is frequency, h is particle diameter, and U the local mean velocity. At low Reynolds number--the particle Reynolds number being the correct scaling parameter--of around 100, the Strouhal number is found to be 0.3. An eddy scale may be uniquely constructed as $L = U/n$, and hence $L = 3h$. Thus, local instabilities of scale 3 particle diameters will be generated by the vortex shedding of the individual particles. A large inrush, due to a sweep of high momentum fluid, would interact with such an eddy, resulting in strong three dimensional motions. Significantly, these local instabilities will be constantly present as each particle will be shedding vortices independently: we would thus not expect to find the strong intermittency in this case, as the local instabilities are always of sufficient magnitude to result in local shear, which will make a constant contribution to the turbulence production. However, it would appear that generation of Reynolds stresses over rough walls must in large part be caused by the interaction of large scale inflows with these local instabilities. As these instabilities scale with local individual roughness elements, one would expect that the length scale of the instabilities, of order 3 times the particle diameter, will set the lower limit for the logarithmic layer in rough wall flows.

This consideration of the near wall physics of rough wall flows has revealed the necessary conditions that laboratory experiments must fulfill in order to use near wall similarity hypotheses to estimate the boundary shear. We have used this information in the laboratory studies detailed in the sediment section of this report. These results are also an indication of the height at which current meters must be set in the field if simple logarithmic profiles are to be used to estimate boundary shear velocities. As Smith and McLean (1977) have shown, when large bed forms are present it is not just the height of the obstacle but also its wavelength that must be considered. A full analysis of this problem for distributed roughness is under development.

The influence of benthic organisms on sediment characteristics has usually been classified in a simple bicameral manner: thus Rhoads (1974) classifies biological activity as either "binding" or "destabilizing". The effect of biogenic activity on flow resistance has never before been considered. The influence of organisms on flow resistance can not be classified in this simple manner. While an individual polychaete tube may act to cause local scour around it, when such tubes become densely packed together they can act to stabilize the bed. The tubes alter the flow resistance and move the effective bed (i.e., the position of maximum energy dissipation, the so-called zero plane displacement height) away from the sediment. This condition is best visualized by an analogy to the wind flow over a forest in the atmospheric boundary layer, where the maximum shear occurs above the forest, not at ground level. Dense packed polychaete tubes may act similarly to significantly affect the resistance to flow. Other organisms are also seen to behave in an analogous manner. Sand dollars, *den- draster excentricus*, alter their spacing among one another: such spacing is found to depend on velocity. In this manner they optimize their feeding

efficiency. Such a strategy is postulated to be common amongst benthic deposit and suspension feeders.

The effect of varied spacing of bed features, such as polychaete tubes, on the resistance to flow has been studied by Nowell and Church (1979). They showed that the flow resistance is a unimodal function of roughness spacing. Roughness spacing is calculated as the ratio of the area of roughness element to the total bed area. For low density spacing the elements act as individual point sources of momentum extraction, the wake behind each element decays and the intervening bed is responsible for a considerable fraction of the overall boundary resistance. This situation occurs for densities below 1 in 50. At an intermediate density of 1 in 50 to approximately 1 in 10, the maximum resistance to flow occurs. Turbulent exchange processes at the bed will be at a maximum and thus the entrainment of sediment, the transport of pollutants and the flux of chemicals across the sediment-water interface should also reach a maximum. At very high densities, greater than 1 in 10, resistance to flow is carried predominantly by the roughness elements, and the overall resistance decreases from its maximum value. This produces a turbulent flow not directly interacting with the bed. This will influence the rate of local deposition and the rate of fluxes across the sediment-water interface.

The spacing and density of polychaetes on the Washington shelf is currently under investigation. Self and Jumars (DOE Report, 1978) identified 31 polychaete families on the shelf from box cores. Cooperative work with Jumars on spacing of organisms must fulfill one goal: the hydrodynamic effects must be unequivocally identified with an optimum feeding strategy. Tentatively we may state that at dense spacing, the reduction in drag on each individual tube may be of primary importance. Winter storms on the shelf may produce shear stresses at the bed sufficiently large to entrain

individual spionid polychaete tubes: if the tubes are densely packed, they may act to stabilize the bed and thus prevent sediment motion.

Lower density spacing may induce optimal feeding conditions, in that tubes locally enhance the deposition of particles. For surface deposit feeders, such as the spionid polychaete, such an environment would exist in the downstream separation zone behind their tubes. This aspect of animal-sediment interaction is of great potential importance in linking together the studies of the benthic biologists and their models of feeding strategy with the work being undertaken on sediment transport.

Sediment Characteristics

The conditions for entrainment and transport of sediment are controlled by the nature of the imposed boundary shear velocity and the characteristics of the boundary sediment. Benthic organisms play a significant role in modifying the conditions of entrainment by (1) altering the individual particle characteristics and their spatial distribution, (2) changing the bulk characteristics of the sediment, such as its permeability or its plasticity, and (3) by varying the boundary properties of the flow as already discussed in the previous section. The nature and scale of microtopography strongly affects the resistance to the flow.

The sediment surface on the Washington shelf is controlled to a great extent by the large input of material from the Columbia River. The movement of sediment along the shelf and across the shelf and down canyons is likely dominated by storm-related events. However, the entrainment of sediment can be dramatically influenced by the activities of benthic organisms. Tube-building polychaetes not only selectively sort sediment to build their tubes and hence lock up the larger particles in their tubes, but also they have been found to select particles on the basis of specific gravity. This will have a strong control over which particles may be transported by any storm event.

Such surface deposit feeders, of which there are many on the Washington shelf, drastically alter the near surface stratigraphy, resulting in a mixed layer. Studies on the Washington shelf from the mid and outer shelf region indicate that in twelve out of eighteen box cores subsurface deposit feeders compose more than 50% of the polychaete community. Such organisms can dramatically influence the surface texture by concentrating certain particle size classes or sediment of a certain specific gravity at the sediment interface.

The motility of organisms also influences the sediment surface. Of the polychaete communities identified on the Washington shelf, over 60% were classified as motile in the sense of Jumars and Fauchald (1977). No studies exist as yet on the influence of flow and turbulence on motility, but it is thought unlikely that the organisms can respond to the frequencies in the turbulence spectrum. Rather, the influence of turbulence is indirect; it determines the nature and rate of deposition of fine particles that deposit feeders require. The influence of motility on the sediment is easily visualized by the traces left by the organisms; the surface roughness is drastically altered and the boundary roughness length scale z_0 is significantly increased.

The most dramatic effect of organisms on sediment is of pelletization. Deposit feeding organisms have been shown by Rhoads (1972) to pelletize the complete surface layer in shallow water regions of high productivity. On the Washington shelf, where the period between storms is highly variable, the rates of pelletization are unknown, but it is likely that over considerable areas the surface sediment is distinctly reworked into fecal pellets. Traditional entrainment criteria, such as Shields criterion, are unlikely to be useful under such conditions, primarily because the entrained pellets are of very low specific gravity, which break up under sediment-transporting flows and change characteristics with the rate of decay of mucal binding. The importance of biogenic activity in controlling the rate of sediment transport

has been emphasized by several authors. Rhoads (1963) made estimates of the reworking rates of the bivalve *Yoldia limatula* and suggested that such organisms produced a fecal-rich, flocculent bottom sediment. He suggested that in Long Island Sound the bottom sediment could be reworked twice in one year. This reworked material could be easily resuspended by bottom currents.

Studies of biogenic activity in the sediment layer, termed bioturbation, have focused upon the direct transport of particles by the organisms. Such effects are manifest in a mixed layer identified by Nittrouer (1978) in the Washington shelf. This layer was identified as being up to 10 cm thick. In this past year, we have focused on the effects of surface motility on particle entrainment and on the effects of pelletization on sediment transport. To study these effects, a series of experiments were conducted in a small recirculating seawater flume.

As few studies exist of the critical erosion velocities for biologically altered sediments, a study of the entrainment of fecal pellets of the ampharetid polychaete (*Hobsonia Selecta*) was carried out. The ampharetid, a tube-building polychaete, is a surface deposit feeder common on the Washington shelf. Areas of high population density of polychaetes may be easily recognized. The tentacles of the polychaete remove material in a circle around the tube, leaving a "moat-like" depression. The fecal pellets are coils of tightly bound mucus-covered sediment. These feces are voided onto the surface into a pile. The mounds of feces coils are usually several tube diameters (5 mm) away from the ampharetid tube and they may reach 1 mm high, sufficient to disrupt the continuous viscous sublayer. The rate of fecal pellet production has not been investigated, for the intent of the study was to look at critical entrainment velocities and not at rates of reworking.

In addition to examining the influence of pelletization, the effect of motility on entrainment was investigated. A small bivalve, which is very motile, was used. It moves around on the sediment surface, leaving behind a "snowplow trail" with steep banks and small levees of sediment approximately 10 grain diameters high. This roughened surface was then subjected to increased boundary stress to measure its critical entrainment velocity.

The experiments we now describe were carried out in a 2.5 m long recirculating seawater flume. The plexiglass flume has a removable box so that sediment cores 30 cm square and 20 cm deep may be placed on the bed of the flume. The flow rate was controlled by a constant head tank and 95% of the water was recirculated through a 10 micron filter. The remainder of the fluid was fresh seawater. Throughout the experiments, which lasted up to 24 hours, the water temperature remained constant to within 0.1°C. The discharge and slope of the flume are adjustable so that the velocity of the flow may be increased and uniform flow maintained.

In such a short flume facility it is unlikely that a totally equilibrium boundary layer can be developed. It is thus important that boundary shear velocity be measured as directly as possible. Using water surface slope and depth will give an estimate of this parameter, but unless the bed and free surface are exactly parallel, such an estimate will represent the integrated value of u_* over the total flume length; in the developing boundary layer, variations of up to 25% may be expected. Instead, the near wall velocity field was measured using a hot film anemometer and the boundary shear velocity calculated from the logarithmic velocity profile. This method will give the local boundary shear stress as precisely as any known.

A DISA 55D5 anemometer with a TSI 1230W conical hot film probe was used. It is the only instrument that will give sufficient frequency response and spatial resolution for near wall velocity measurements. The quartz coated probe was calibrated first by calculating its temperature resistance relationship; this was found to be linear ($r = 0.999$). Thus, the temperature of the probe could always be set, and an overheat temperature of 19°C was used in these measurements. Probe currents were typically of order 5 mW and thus, except at velocities below 1 cm/sec, convective instabilities will not be important. The mean velocity was obtained from a DC volt meter integrating over a period of 30 seconds. The turbulence level was also averaged over a similar period. The signal was continuously monitored on an oscilloscope and the probe itself was visible under a microscope to insure that no contamination due to air bubbles or sediment affected the heat transfer rate. Several of the velocity records were recorded on a HP3960 FM tape recorder for subsequent spectral analysis.

To examine the entrainment of fecal pellets, a box of fine silt was prepared by placing 25 ampharetidae in live positions. They were allowed to acclimatize for 48 hours in a seawater table. The bed surface then had visible doughnut shaped depressions around the tubes and mounds of fecal coils at the edge of some of these depressions. The sediment box was removed from the seawater table and placed into the flume. As there had been no strong directionality to the flow in the seawater table, the fecal pellets were in varied positions in relation to the polychaete tubes.

While the discharge through the flume was gradually increased, an observer would watch the fecal pellets through a microscope. Several piles were looked at to insure that the condition of sediment entrainment was not

totally locally determined. Surface flocculent material was easily entrained at these lower velocities (5 cm/sec), but the ambient sediment and the fecal pellets remained in place. As the shear velocity was increased the coils were observed to rock in situ. The coils on the upstream face of such piles would roll in situ, but would not move from the pile because of the binding by the mucal coating. This rocking motion was of very low frequency and very intermittent: it was not related to the vortex shedding of the obstacle though it is as yet a matter of debate whether this motion resulted from bursts in the viscous sublayer. This feature will be investigated subsequently. The ambient sediment was not moving at this time; even the lightest mica flakes remained on the bed. Velocity profiles at six positions over the bed were made; vertical profiles of 12 points were made in the lowest 1 cm of the flow. The velocity was then increased (15 cm/sec) until the rocking motion of the fecal coils became more pronounced. At this stage some of the fecal coil was losing its identifiable form. The rocking motion resulted in straining of the mucal binding, and the fine particles in the mucus were being removed from the coil by the flow. The whole bed was now just below entrainment. This is defined as when many particles readjust their position. The particles would roll over into a more stable position but would not roll away. The slope of the bed was increased and particle entrainment over the entire bed occurred. The ambient sediment then moved in a series of protracted rolls in contact with the bed. At this stage the fecal coils were still in place. Occasionally, small ends of a coil would break off and such pieces would be rapidly transported at the same velocity as the surface flocculent particles (4 cm/sec). However, fecal coils in general did not move. Instead, the upstream face of the pile decayed from definite coil structures to an amorphous mass of mucal coating, out of which the finer sediment grains had been removed. The lee side of the mounds of fecal coils remained distinct.

If the bed shear stress was further increased the whole bed became "live" with strong transport of all ambient sediment and the mounds of fecal material would be removed, in part by attrition by the transporting sediment.

This result, that fecal material entrained at the same time as the ambient sediment was sufficiently surprising that the experiment was repeated four times. Each time the ampharetid were allowed to acclimatize for up to 24 hours before the velocity was increased. The same results were obtained each time. A similar experiment was then carried out using the bivalve *macoma balthica*. These clams were allowed to burrow into the sediment. Unfortunately many of the specimens did not burrow and so only a limited number of specimens were available but observations of these showed that the pellets of *macoma balthica* also remained stuck to one another until general bed load transport over the whole bed occurred. While an individual pellet was moved at a much lower shear velocity, the shear necessary to remove a single pellet from a mucal-bound pile of the *macoma* pellets was equal to the critical shear velocity for the ambient sediment.

The experiments to investigate the effect of motility on sediment entrainment were also carried out in the seawater flume. A smooth bed of fine sand was placed in the bottom of the flume and the velocity increased until entrainment occurred. Measurements were then made of the mean velocity and turbulence field at five sites over the sediment. The boundary was hydrodynamically smooth just prior to entrainment. The velocity was then reduced to zero and the bivalve *transenellae* were placed on the surface. Fifty were positioned randomly in the 30 cm square box. They were then left for 12 hours. The sediment surface was by then considerably roughened. The tracks of the clams covered less than 10% of the total surface area, but the sides of the tracks, of order 1 mm high were very steep--approximately at the natural angle of repose of the sediment. The discharge in the flume was increased

until sediment entrainment occurred. This happened at the crests of the tracks. Velocity profiles at five positions were then made and averaged to remove the effects of local spatial inhomogeneities. Measurements of the turbulence, of the streamwise kinetic energy and the Reynolds stresses were made and are currently being processed. The shear velocity was found to be 20% less than that which had been necessary to entrain the ambient sediment prior to the transenella being added. Preliminary results indicate that there was no continuous viscous sublayer so that the boundary was hydrodynamically transitional.

These results, on pellet transport and the effect of surface motility, are an exciting start to the laboratory experiments on animal-sediment interaction. They indicate that the conventional wisdom--that pellets are always easily transported and moved much sooner than the ambient sediment--may not always be correct. We investigated one functional group of organisms, namely surface deposit feeders, which are common to the Washington shelf. The results suggest a more detailed look must be taken at other functional groups and that the rates at which some of these processes operate must also be investigated.

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Figure 1. Logarithmic law plot for smooth wall boundary layer. Results from a channel flow using a Pitot tube (■) and a hot wire (●).

Figure 2. Upper: Dimensionless shear stress for a hydrodynamically smooth wall at three Reynolds numbers.
Lower: Logarithmic region for smooth wall.

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BED LOAD TRANSPORT EQUATION

J. Dungan Smith

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J. Dungan Smith

The suspended load calculation technique developed by Smith and McLean (1977a,b) and extended by Smith (1977) is based on an expression for the concentration of sediment in the near bed region of the form

$$\epsilon_o = \frac{\gamma \epsilon_b S}{1 + \gamma S} \quad (1a)$$

or

$$(\epsilon_o)_m = \frac{i_m \gamma \epsilon_b S}{1 + \gamma S} \quad (1b)$$

Here i_m is the fraction of bed material in the size or specific gravity class of interest, ϵ_o is the effective concentration of sediment at z_o , ϵ_b is the concentration of sediment in the bed, γ is a coefficient found experimentally to be 2.4×10^{-3} and S is the excess shear stress $(\tau_b - \tau_c)$ normalized by the critical shear stress τ_c .

In quasi steady, quasi uniform flows the sediment concentration in the neighborhood of the seabed is given by

$$\epsilon_s = \frac{\frac{\epsilon_o}{1 - \epsilon_o} \left(\frac{z_o}{z} \right)^p}{1 + \frac{\epsilon_o}{1 - \epsilon_o} \left(\frac{z_o}{z} \right)^p} \quad (2)$$

where p is the ratio of setting velocity (w_s) to effective sediment diffusion velocity ($\alpha k u_*$), z is the vertical coordinate and z_o is the roughness parameter. If we assume that the vertical component of sediment velocity u_s is $u_w - w_*$ instead of $u_w - w_s$, as is done to obtain the usual form of (2), p becomes $w_*/\alpha k u_*$. Here α is the ratio of mass to momentum diffusion coefficients, k is von Karman's constant, u_* is the shear velocity and w_* is the downward sediment velocity at any point relative to the water. In order to obtain (2) w_* must be constant or nearly

so. In the near bed region w_* is very close to zero, hence $\epsilon_s \approx \epsilon_o$ for particles of all sizes and for all values of z in the layer of concern.

The formal definition for volume discharge of sediment per unit flow width is

$$\vec{Q}_s = \int_{z_o}^{z_\Delta} \vec{u}_s \epsilon_s dz \quad (3)$$

where $z = z_\Delta$ denotes the free surface of the flow. For sediment in a particular size or specific gravity class denoted by the subscript m , this integral can be rewritten as

$$\vec{Q}_m = \int_{z_o}^{\delta_m} \vec{u}_m \epsilon_m dz + \int_{\delta_m}^{z_\Delta} \vec{u}_m \epsilon_m dz \quad (4)$$

where the first term on the right hand side represents the sediment flux per unit flow width in the near bed or sediment momentum defect or bed load layer. Using the approximation that $\epsilon_m \approx (\epsilon_o)_m$ gives the sediment discharge per unit flow width in this layer as

$$(\vec{Q}_m)_b = (\epsilon_o)_m \int_{z_o}^{\delta_m} \vec{u}_m dz = (\epsilon_o)_m \langle \vec{u}_m \rangle \delta_m$$

or using (1b)

$$(\vec{Q}_m)_b = \frac{i_b \gamma \epsilon_b S}{1 + \gamma S} \langle \vec{u}_m \rangle \delta_m \quad (5)$$

In order to proceed we note that Smith and McLean (1977a,b) have provided an expression for δ_m . It is

$$\delta_m = \alpha_1 \frac{3}{2} C_L \left(\frac{1}{k} \ln \frac{z_1}{(z_o)_N} \right)^2 (\tau_*)_{cm} S D_m \quad (6)$$

Here α_1 is a coefficient of proportionality, $(\tau_*)_{cm} = \tau_{cm}/(\rho_s - \rho)gD$ is the critical shields number, ρ_s is the sediment density, ρ is the fluid density, D_m is the nominal grain diameter for size class m , C_L is a lift coefficient, z_1 is a reference level and $(z_o)_N$ is the value of the roughness parameter given by Nikuradse's experiments. Employing the techniques of Einstein (1950) this reduces to

$$\delta_m = \alpha_1 \left[\frac{3}{2}(0.178) \left(\frac{1}{k} \ln \frac{0.35D_m}{(z_o)_N} \right)^2 \right] (\tau_*)_{cm} S D_m \quad (7)$$

$$= \alpha_2 (\tau_*)_{cm} S D_m$$

where $\alpha_2 \cong 260$.

Smith and McLean (1977a,b) also give an expression for the velocity field outside of the sediment transporting layer. It is

$$u = \frac{u_*}{k} \ln \frac{z}{(z_o)_o}$$

where $(z_o)_o$ is proportional to δ_B , which is the concentration weighted average of the δ_m 's. The sediment velocity averaged between z_o and δ_B must be scaled by $u(\delta_B)$ because of the complicated velocity field in the lower part of this zone and the predominant effect of the flow near the top of the particle's trajectory or its mean horizontal speed. Therefore we write

$$\langle u_s \rangle = \beta_1 u(\delta_B) = \beta_1 \frac{u_*}{k} \ln \frac{\delta_B}{(z_o)_o} \quad (8)$$

Here β is a constant with a value that is always less than unity and usually close to 1/2. Because $(z_o)_o \propto \delta_B$, $\ln \delta_B / (z_o)_o$ is also constant and $\langle u_s \rangle = \beta_2 u_*$ where β_2 is approximately 1.2.

Combining (5), (6) and (8) gives a bed load equation of the form

$$(\vec{Q}_m)_b = \alpha_3 (\tau_{*cm}) \frac{i_m \gamma \epsilon_b S \vec{u}_* D_m}{1 + \gamma S} \quad (9)$$

where $\alpha_3 = \alpha_2 \beta_2$ has the approximate constant value of 312. The high boundary shear stress asymptote of (9) is

$$(\vec{Q}_m)_b = \alpha_3 \epsilon_b i_m (\tau_{*cm}) S \vec{u}_* D_m \quad (10)$$

and the low boundary shear stress asymptote is

$$(\vec{Q}_m)_b = \alpha_3 \epsilon_b i_m (\tau_{*cm}) \gamma S^2 \vec{u}_* D_m \quad (11)$$

Here it might be noted that the Yalin bed load equation also goes as $S \vec{u}_* D$ for large S and as $S^2 \vec{u}_* D$ for small S . However, the Yalin equation and (9) do not give quite the same numerical values of $(\vec{Q}_m)_b$ on these asymptotes. Both expressions are empirical so at this point their careful examination in light of the sediment transport data available in the literature is required. This task is proposed for the coming year.

Nevertheless, over the range of present interest the agreement with available data is sufficient to justify use of (9) as part of a total load equation, that is, as the specific expression to be employed as the

first term on the right hand side of (4). When the second term on that side of (4) is calculated as described by Smith and McLean (1977a,b) this equation gives the total sediment flux per unit flow width in a consistent and presumably accurate manner.

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