

BIOSTABILIZATION OF ESTUARINE SUBTIDAL SEDIMENTS

by

Terri-Ann Frances Sutherland

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for the degree of Doctor of Philosophy

at

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ABBREVIATIONS AND SYMBOLS

C_d	drag coefficient	
EPS	extracellular polymeric substances	
MEA	maximum eroded area	mm^2
NER	net erosion rate	$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
PER	peak erosion rate	$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
PN	particulate nitrogen	$\text{mg}\cdot\text{ml}^{-1}$
POC	particulate organic carbon	$\text{mg}\cdot\text{ml}^{-1}$
ρ_s	density of seawater	$\text{kg}\cdot\text{m}^{-3}$
SPM	suspended particulate matter	$\text{mg}\cdot\text{L}^{-1}$
τ	bed shear stress	$\text{N}\cdot\text{m}^{-2}$
U	current velocity (1 m off bottom)	$\text{m}\cdot\text{s}^{-1}$
U_*	shear velocity	$\text{m}\cdot\text{s}^{-1}$
U_{*crit}	critical shear velocity	$\text{m}\cdot\text{s}^{-1}$

ABSTRACT

Laboratory and field studies were carried out to determine the effect of biofilms on sediment erodibility. The effect of growth and carbohydrate production of the diatom, *Nitzschia curvilineata*, on sediment erodibility was explored in the laboratory. Sediment chlorophyll and bulk carbohydrate concentrations were negatively correlated with erosion rate. An increase in bulk carbohydrate content was observed at the end of exponential phase of growth. An increase in eroded aggregate size was observed with age of biofilm, suggesting an alteration of biofilm microfabric through carbohydrate production. The critical shear velocities obtained for the base of the biofilm were greater than those obtained for the surface, suggesting an increase in strength of the biofilm with depth.

An *in situ* flume (Sea Carousel) was deployed at stations along a transect in Upper South Cove, Nova Scotia and in Manitounuk Sound, Quebec, to examine the relationship between the biofilm components and sediment erodibility. In Upper South Cove, erosion thresholds and rates correlated with sediment chlorophyll and colloidal carbohydrate content. Erosion rate may be a more important index of sediment erodibility than erosion threshold, since erosion rates varied by a factor of 7 along the station transect while U_{crit} varied by a factor of 2. In Manitounuk Sound, variations in the physical sediment properties along the station transect were greater than the biological sediment properties, rendering the physical sediment properties more sensitive indicators of sediment erodibility. Erosion rates were correlated with many of the sediment variables influenced by the increase in hydrodynamic energy seaward through the Sound.

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CHAPTER ONE

General introduction

1.1 Introduction

Diatoms play a significant role in the stabilization of marine sediments (Holland *et al.*, 1974; Grant *et al.*, 1986a, 1986b; Paterson *et al.*, 1990; Madsen *et al.*, 1993). Mucopolysaccharides, which are secreted by benthic diatoms for purposes of attachment and locomotion (Harper, 1977; Edgar and Pickett-Heaps, 1984), form connective strands between sediment grains and, therefore, contribute to inter-grain binding (Frankel and Mead, 1973; Grant *et al.*, 1986b; Paterson, 1989). Sediment cohesion increases as mucopolysaccharides, laid down by actively migrating diatoms, eventually fill interstitial voids and form a complex matrix in the diatom-inhabited surficial layer (Paterson, 1989). These extensive mucilage networks or "biofilms" reduce bottom roughness and surface frictional drag (Landahl, 1972), thereby reducing the susceptibility for erosion.

Population explosions of benthic diatoms that occur in both intertidal and subtidal settings of cohesive and non-cohesive sediments (Round, 1971; Cupp, 1977; Baillie and Welsh, 1980; Anderson, 1983; Paterson and Underwood, 1990) will alter erosion thresholds of sediments and reduce both the magnitude and frequency of resuspension events (Neumann *et al.*, 1970; Scoffin, 1970; Holland *et al.*, 1974; Grant *et al.*, 1986b). This reduction in resuspension rates will have a great impact on diatom-related processes at the sediment-water interface, the advection of pore-water nutrients from the sediment to the overlying water column (Grant and Bathmann, 1987; Simon, 1989; Floderus and Hakanson, 1989), the availability of particulates as food for suspension feeders (Baillie

and Welsh, 1980; Grant *et al.*, 1990; Shaffer and Sullivan, 1988; Frechette and Grant, 1991), and the sedimentary processes affecting coastal engineering projects (Amos *et al.*, 1992c).

Mucopolysaccharide secretion has a broader functional significance than that of locomotion. An increase in sediment stability associated with the formation of a mucilage matrix will create a more stable habitat for diatoms and allow certain physiological and obligate reproductive requirements to be met. A stabilized sediment column may be exploited by diatoms as they migrate to the water-sediment interface to capture light for photosynthesis and then to the underlying nutrient-rich sediment to undergo heterotrophy (Lewin and Lewin, 1960). Downward migration will also prevent seaward drift of resuspended cells during ebb tide (Heckman, 1985). Another selective advantage of creating a stabilized sediment layer is the availability of a substratum to allow for locomotion and a greater probability of cell-to-cell contact. Fusion of non-motile gametes during sexual reproduction of pennate diatoms depends on cell-to-cell contact, and it must occur once diatom cell diameters reach one-third of their original size in order to restore a functional cell surface-area-to-volume ratio (Drebes, 1977, Round, 1982; Malone, 1980).

The interaction of growth and behaviour with physico-chemical variations influences sediment stability in complex ways that are difficult to predict (Jumars and Nowell, 1984). Other factors influencing sediment stability include wave and ice loading (Gordon and Desplanque, 1983), sub-aerial exposure (Amos *et al.*, 1988; Paterson *et al.*, 1990), bacteria (Grant and Gust, 1987; Grant and Bathmann, 1987), macrophytes

(Neumann *et al.*, 1970), animal tracking, pelletization, bioturbation, and remoulding (Nowell *et al.*, 1981; Jumars *et al.*, 1981; Grant *et al.*, 1982), worm tubes (Eckman *et al.*, 1981), seagrasses (Fonseca, 1989), and properties of the eroding fluid (Amos *et al.*, 1992b). In order to identify these attributes as stabilizing or destabilizing, they must be delineated and tested.

This thesis focuses on the relationship between the characteristics of diatom biofilms and the erodibility of subtidal sediment. Chapter 1 outlines the general introduction and methods used in the various chapters. Chapter 2 examines the effect of growth and carbohydrate production of the epipellic diatom, *Nitzschia curvilineata*, on the erosion thresholds and erosion rates of sediment in a laboratory system. Factors affecting the erodibility of natural sediment are examined in Chapter 3 (Lunenburg Bay) and Chapter 4 (Hudson Bay). Chapter 5 consists of a general discussion including a comparison of the factors affecting the erodibility of subtidal sediment between a temperate (Lunenburg Bay) and a hemiarctic environment (Hudson Bay).

1.2 Background on the definition of sediment erodibility

Erodibility has been defined in terms of both erosion threshold and erosion rate (Amos *et al.*, 1992c). However, the definition of erosion threshold varies between investigations, since several descriptions of sediment movement/transport/resuspension exist in the literature. The use of these various erosion thresholds depended on the sediment type examined or method employed. For example, the erosion threshold of sediment has been defined as the critical shear velocity when (1) ten or more mineral

grains moved at the same time (Heizelmann and Wallisch, 1991), (2) both attached and organic material and mineral grains were moved (Madsen *et al.*, 1993), and (3) resuspended sediment leads to a substantial reduction (> 30 %) in light transmission (Paterson, 1989). Other investigations described four distinct stages of erosion of (1) the response of a biofilm exposed to stress induced by a flow-through flume (Grant *et al.*, 1986a) or of (2) the response of a "bubble" mat exposed to stress induced by a Cohesive Strength Meter (Yallop *et al.*, 1994).

A standard approach to the determination and expression of erosion thresholds does not exist. For example, Paterson (1994) noted that erosion thresholds have been reported in terms of (1) rpm of a stirring mechanism (Holland *et al.*, 1974), (2) angular velocity (de Jonge and van den Berghs, 1987), (3) bed shear stress (Amos *et al.*, 1992c), (4) shear velocity (Grant *et al.*, 1986a; Madsen *et al.*, 1993), and (5) resuspension of sediments (Manzenrieder, 1983). Also, the application of a single definition or description of sediment movement has been inconsistently applied to a wide variety of sediment types including sand to organic rich mud. Stabilization coefficients (Holland *et al.*, 1974; Grant and Gust, 1987; Paterson, 1994), defined by the ratio of erosion thresholds of biotic sediments to that of abiotic sediments (controls), have been used in order to compare erosion thresholds across investigations involving a wide range of sediment or biofilm types and methodologies (Paterson and Daborn, 1991).

Sediment erosion values reported in the literature varied depending on the methodology employed or on the non-standardized definition of sediment erosion applied. Several methods were employed in this thesis to determine erosion thresholds and are

outlined below. Since biofilms may alter both erosion thresholds and erosion rates of sediment, the quality (erosion type) and quantity (net erosion rate) of erosion rates of sediment were also considered. The following sections (1.3 and 1.4) outline the methods of analysis in determining erosion thresholds and rates that are common to all chapters

1.3 General methods

1.3.1 Determination of erosion thresholds

One way to remove the subjectivity of describing erosion would be to correlate qualitative (observation) and quantitative (extrapolation) approaches to defining critical shear velocity, U_{*crit} ($m \cdot s^{-1}$). Below is an outline of both qualitative and quantitative methods used in this thesis to determine U_{*crit} values of the various stages of sediment erosion. In general, the erosion experiments consisted of step-wise increments in flow velocity over sediment cores (Chapter 2) and natural sediment (Chapter 3 and 4).

Video observations: SuperVHS video records of both the laboratory (Chapter 2) and field (Chapter 3) erosion experiments were used to determine U_{*crit} values for (1) the detachment of a particle, (2) the detachment of 10 particles simultaneously, (3) the detachment of various sized, flake-shaped aggregates, and (4) the onset of ripple migration.

Extrapolation method: Shields (1936) determined U_{*crit} by extrapolating back to the point of zero discharge of SPM on a plot of SPM vs. shear velocity. However, the method of extrapolation was not clear (Lavelle and Mofjeld, 1987). In this thesis, the U_{*crit} values were derived from the SPM vs log U_* plot. The SPM curve was extrapolated

back to the point of zero concentration of SPM. U_{crit} was determined as the x-intercept of a regression analysis of SPM vs $\log U$. The relationship between SPM and U was assumed to be a logarithmic function.

Digitization method: As described in Chapter 2, the diatom, *Nitzschia curvilineata*, was incubated on diatomaceous earth and the biofilm-sediment cores were eroded at successive stages of biofilm growth. Digitization of the exposed area of the underlying white diatomite after the release of the golden-brown diatom-mat aggregates was performed from frozen video frames using the software package OPTIMUS. U_{crit} was determined as the U value at which the smallest visible area of underlying sediment was exposed upon aggregate erosion. This analysis is used in Chapter 2 only and determined U_{crit} for the base of the biofilm.

1.3.2 Determination of erosion rates

Two types of erosion exist, Type I and Type II. Type I erosion is characterized by an initial erosion peak that occurs within 40 seconds after the current speed has increased and is followed, 20 to 40 seconds later, by rapid exponential decay of the erosion rate (Amos *et al.*, 1992c). Type II erosion remains constant with time and occurs along planes of weakness parallel to the sediment surface which are controlled by the microfabric of the sediment. Net erosion rates were also calculated to determine spatial trends along transects impacted by directional gradients that occur in estuaries.

1.4 Sample volume as a reference for sediment measurements

Microbial abundance measurements in sediment have commonly been standardized by sediment dry-weight (Krumbein, 1971, Cadée and Hegemann, 1977, Mayer 1989, Underwood and Paterson, 1993a, Yallop *et al.*, 1994) or by sediment surface area (Hargrave 1972, Dale, 1974). However, microbes may not always have a close association with reference values such as sediment dry weight or surface area. For example, Wachendorfer *et al.*, (1994b) found that the number of microbes inhabiting the pore space in sediment can be greater than those associated with the sediment surface. Similarly, epipellic diatoms could have minimal association with reference values such as sediment dry weight or surface area, since epipellic diatoms exhibit strong rhythmic vertical migrations between sediment grains, relative to their counterparts, the epipsammic diatoms, which usually remain firmly attached to sediment grains. Epipellic diatoms tend to be significantly larger than fine sediments since these diatoms can be up to 500 μ in length, further reducing any association between epipellic diatoms and particle surface area. Madsen *et al.*, (1993) have shown that this motile epipellic fraction of diatoms serves as a better indicator of sediment stability than total biomass of chlorophyll. Therefore, the standardization of this motile diatom fraction by sediment dry weight may dilute this signal and reduce its sensitivity as a predictor of sediment stability.

Figure 1.1 shows profiles of sediment chlorophyll concentration at stations located on a transect across Manitounuk Sound. The chlorophyll concentrations of the subtidal stations standardized to sediment dry weight were greater than those standardized to sample volume, while at the low intertidal station the chlorophyll

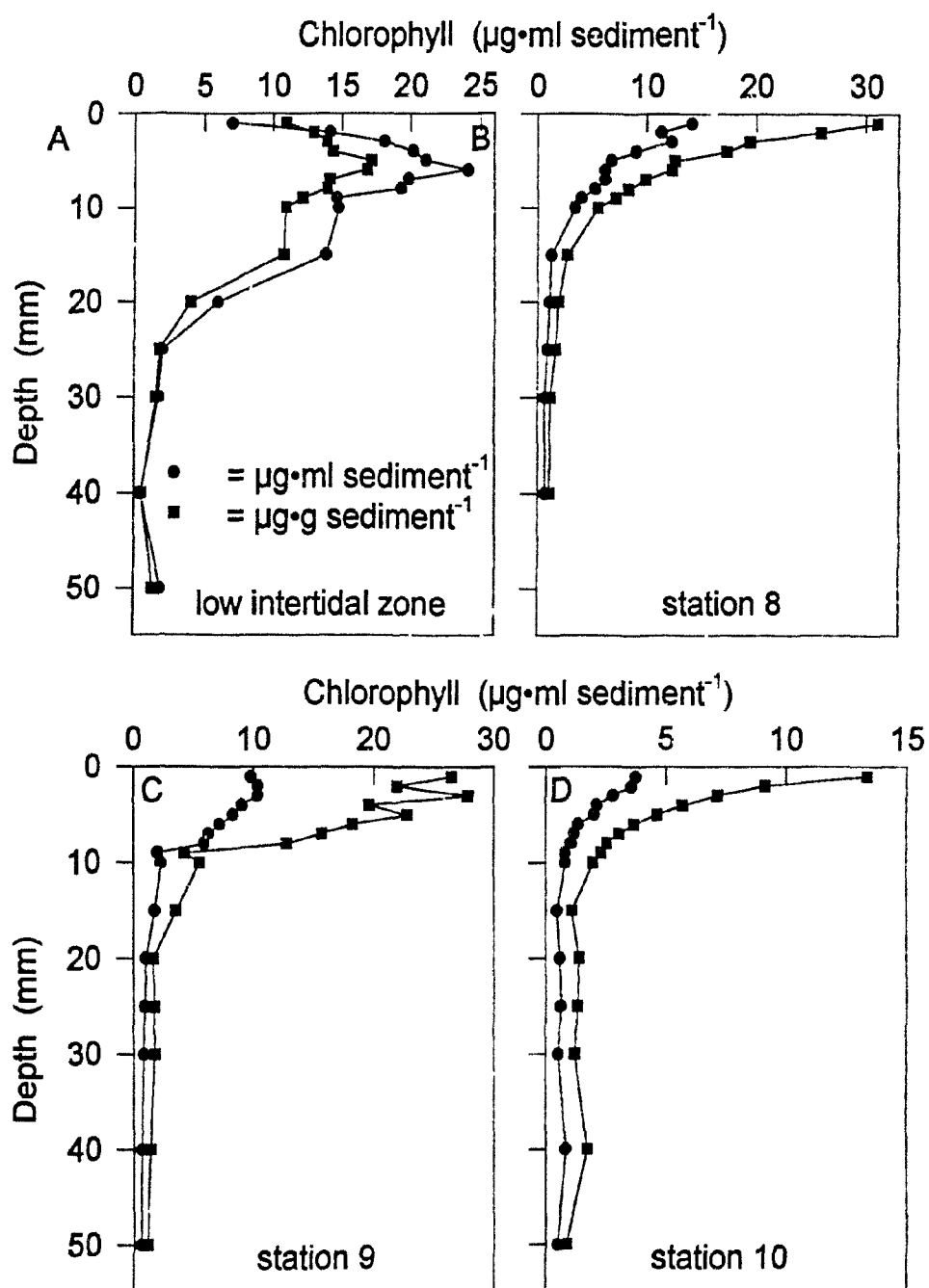


Figure 1.1: Vertical profiles of chlorophyll concentrations at 4 stations located on a transect across the central region of Manitounuk Sound, Hudson Bay. The sediment chlorophyll concentrations were standardized by sediment dry weight and by sample volume.

concentrations standardized to sediment dry weight were lower than those standardized to sample volume. The difference in the physical properties of the sediment, such as, bulk density, porosity, grain size, sediment composition, and extent of consolidation, between the intertidal and subtidal sediment was probably responsible for differences in the chlorophyll concentrations between tidal zones upon the standardization by sediment dry weight. Zobell (1946) demonstrated an increase in microbial abundance, standardized to dry weight of sediment, with decreasing particle size. A higher percentage of sand or larger particles found in the intertidal zone of Manitounuk Sound (Ruz *et al.*, 1994) relative to the subtidal zone may have been responsible for the lower sediment chlorophyll values. Since the physical properties of the sediment of Lunenburg Bay (Chapter 3) and Manitounuk Sound (Chapter 4) varied, the use of sediment dry weight as a reference value may lead to similar discrepancies and cause problems in comparisons between field sites in this thesis. Wachendorfer *et al.*, (1994a) suggested that microbial sediment measurements be standardized to pore-volume using a Fluorescent Sediment Thin Section Technique. However, for ease in sampling procedure, sample volume was considered in this thesis as a reference value for biological parameters measured in the sediment.

The discrepancy in chlorophyll concentrations standardized by sample volume and sediment dry weight was greatest in the uppermost sediment layer where biostabilization of sediment occurs. Of the subtidal stations, the surface chlorophyll concentrations standardized to sediment dry weight are 2.2 (station 8), 2.7 (station 9), and 3.5 (station 10) times greater than those standardized to sample volume. Prediction

of the erodibility of sediment by sediment chlorophyll would be impacted by the reference value chosen to standardize this sediment variable.

CHAPTER TWO

A laboratory flume study examining the effect of growth and carbohydrate production of the benthic diatom, *Nitzschia curvilineata*, on the erodibility of sediment.

2.1 Introduction

The extent to which benthic diatom biofilms significantly alter the stability of sediments depends on the interaction of many physical, chemical, and biological factors (Paterson, 1988). However, the production of extracellular polymeric substances (EPS) by diatoms for locomotion purposes (Edgar and Pickett-Heaps, 1984) appears to be a first-order binding mechanism of biological origin that influences the stabilization of sediment. Scanning electron microscopy (SEM) techniques have shown mucilage bridges formed between diatoms, sediment grains, and associated particles (Grant *et al.*, 1986a; Paterson, 1988).

The measurement of carbohydrate concentration has been suggested to be a direct assay of EPS and, therefore, a more sensitive indicator or predictive tool of biomediated sediment binding (Grant and Gust, 1987). The production and composition ("stickiness") of carbohydrates depends on several factors including nutrient status and growth phase (Decho, 1990). Also, the study of carbohydrate production by diatoms has been largely limited to the planktonic population (Myklestad *et al.*, 1989, Hoagland *et al.*, 1993).

The depletion of pore water nutrients within a stratified oxidized biofilm microzone can potentially lead to enhanced mucopolysaccharide production in sediment, because carbohydrate production can be stimulated during nutrient starvation (Myklestad,

et al., 1972). Nutrient limitation of microphytobenthos in surficial sediment is often not considered, since the sediment pore water is conventionally thought to be a "soup" of nutrients. However, field studies have shown that nutrient loading stimulates microphytobenthos growth (Sundback and Graneli, 1988; Sundback and Jonsson, 1988), and that nitrogen appears to be the limiting nutrient (Flothmann and Werner, 1992). Nitrogen may become quickly depleted in the oxidized microzone of the highly concentrated producing layer through the uptake of nitrogen by diatoms (Sundback, 1994). Microsensor studies have revealed steep concentration gradients of oxygen (Revsbech *et al.*, 1983; Carlton and Wetzel, 1988; Jonsson *et al.*, 1994; Yallop *et al.*, 1994) in the illuminated topmost millimetres of the sediment where diatoms (Paterson, 1986) and cyanobacteria (Jorgensen *et al.*, 1983) concentrate. These gradients are consistent with active growth and the potential for localized nutrient depletion.

The pervasion of extracellular polymeric substances (EPS) into interstitial voids may reduce diffusion rates of pore-water nutrients (Jorgensen, 1994) and contribute to the maintenance of steep nutrient gradients in the sediment column. Furthermore, biofilms containing trapped bubbles, similar to that described later in this study and to previously described "bubble" and "blister" mats, may inhibit diel fluctuations in oxic and anoxic conditions and, therefore, affect nitrification and denitrification processes in the sediment (Wiltshire, 1992). In Texel sediments, oxygenated conditions extended down to a depth of 4 mm in the "bubble" mat, while anoxic conditions were found at a depth of 2.5 mm in the non-bubble mat (Yallop *et al.*, 1994). Carlton and Wetzel (1988) showed that epipelagic algal photosynthesis, or the magnitude of sediment oxygenation, was inversely correlated

with the phosphate efflux rate from lake sediments. The associated production of carbohydrates in response to the nutrient depleted conditions may slow down the diffusion of ions and contribute to the conservation of nutrients in sediment (Decho, 1994a). Primary production in the overlying water may be affected by the formation of "bubble" mats if nutrients become conserved within the sediment.

The objective of this chapter is to determine the effect of growth and carbohydrate production of the benthic diatom, *Nitzschia curvilineata*, on the erodibility of subtidal sediments. An understanding of the effect of growth phase on carbohydrate production and sediment binding by diatoms will aid in the quantitative prediction of biostabilization. The formation of diatom biofilms and the associated changes in microfabric of sediment will have a strong impact on many aspects of sedimentology and benthic ecology (Westall and Rince, 1994).

2.2 Methods

2.2.1 The incubation of *Nitzschia curvilineata* on sediment

A culture of *Nitzschia curvilineata*, was obtained from the Provasoli-Guillard Centre for Culture of Marine Phytoplankton (CCMP555). Stock cultures were maintained in F/2 medium (Guillard, 1972) in 50 ml pyrex screw cap culture tubes at 18 °C and on a 16:8 hour light:dark cycle illuminated by Cool White lamps at $124 \text{ quanta} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, as measured with a quantum scalar irradiance meter from QSL 100 Biospherical Instrument, Inc. To avoid contamination, all glassware used for culturing purposes was soaked in a

10% HCl bath for 24 hours, rinsed 7 times in superQ water and then autoclaved for 20 minutes at 20 psi.

Sediment cores (inner diameter: 11.4 cm) for stabilization measurements were prepared with 200 ml of Celatom diatomite, mixed with 200 ml of 0.45 μm filtered seawater and placed in a core barrel designed to be inserted into the recirculating flume. A description of the flume is presented in the following section (2.2.2). The sediment-laden core barrels (19 replicates) were kept in a sea-table containing a flow-through seawater bath at 15 °C. To prevent mixing of the seawater bath with culture media, the tops of the core barrels were set above the water bath. The sediment cores were incubated on a 16:8 hour light:dark cycle, illuminated by Cool White lamps at $89 \text{ quanta} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

In order to obtain a horizontally uniform distribution of *Nitzschia curvilineata* on the sediment cores, the experimental culture was grown from an inoculum that contained no visible aggregates of diatom cells. Two hundred ml of the experimental culture was placed in each of 17 sediment-laden core barrels, during exponential phase of growth. Fourteen of these diatom-sediment cores were reserved for erosion trials, while the remaining 3 cores were reserved for a time-series record of chlorophyll concentration and carbohydrate concentration. Each day, 2 pasteur pipettes (0.05 ml sample) were used to collect a core from each of the 3 stock diatom-sediment cores. The wide-diameter end of the pipette was used to core the sediment. One pipette-core was analyzed for chlorophyll, while the other was analyzed for carbohydrates.

Chlorophyll analysis was performed by placing each core sample into 10 ml of 90 % acetone:water solution. The samples were extracted for 24 hours in a cold/dark

refrigerator (5 °C), and the fluorescence was measured using a Turner Designs Model 10TM fluorometer. Two drops of 10 percent HCl were added to each sample, and the fluorescence was measured again. The fluorescence readings were converted to chlorophyll following the methods of Parsons et al. (1984). A phenol-sulphuric acid assay (Dubois *et al.*, 1956,) modified for sediments (Lui *et al.*, 1973), was used to determine carbohydrate concentrations. The extraction process was modified for analysis of carbohydrates in marine sediments by using a 30 ppt saline solution, instead of distilled water (Underwood and Paterson, 1995). After an extraction period of 1 hour, the sediment samples were centrifuged at 2000 rpm for ten minutes to separate the sample into colloidal and bulk carbohydrate fractions. Each sample was analyzed on a spectrophotometer at 485 nm and calibrated against a range of glucose concentrations.

The thickness of the biofilm was determined for days 2, 4, 6, 9, 12, 15, 18 of growth. A 5-ml syringe core was collected at these growth intervals, dipped in liquid nitrogen, and frozen over night at - 20 °C. A razor blade was used to split the frozen cores, and the thickness of the biofilm was determined under a dissecting microscope. A sharp boundary between the golden-brown colouration of the biofilm and underlying white sediment was readily evident.

Two hundred ml of 0.45 µm filtered seawater were placed in each of 2 sediment laden core barrels. One of these cores served as a control for the erosion trials, while the other core was subsampled daily for chlorophyll, in order to determine the potential for aerial contamination throughout the incubation period.

2.2.2 Erosion experiment

Erosion thresholds and rates were measured in a recirculating flume, 1.5 m long, 0.2 m wide, and 0.15 m high with a working section located 0.9 m downstream of the inlet. A core sample was inserted into the working section of the flume from below and raised until the upper rim of the core barrel was flush with the flume floor. The flume was slowly filled with 89 l of 2- μ m filtered seawater to give a water depth of 17 centimetres. The core contents were raised with a plunger until the sediment surface was flush with the barrel rim and the flume floor. A Nixon current meter and an Optical Backscatter Sensor (OBS; Downing and Beach, 1989) were located, respectively, 27 cm upstream and 23 cm downstream the midpoint of the diatom-sediment core area, 10 cm above the flume floor. A Sony Handycam 8 mm video-recorder was mounted above the sediment core to record bed erosion. One abiotic core was eroded on the first day of the experiment series. Two diatom-sediment cores were chosen at random every few days and eroded in the recirculating flume.

The calibration of the Dantec stress sensor involved regressing the sensor output to the rate of vertical drop in water height within a 1/4 inch inner diameter pipe. The stress sensor was then placed in the working area of the flume floor and calibrated to the rpm of the propeller motor. Shear velocity values were converted from shear stress values, measured with a Dantec 55R46 stress sensor, using the formula, τ ($\text{N}\cdot\text{m}^{-2}$) = ρ_s ($\text{kg}\cdot\text{m}^{-3}$) $\cdot$ U_*^2 ($\text{m}\cdot\text{s}^{-1}$), where $\rho_s = 1028$ ($\text{kg}\cdot\text{m}^{-3}$), the density of seawater.

The flow in the flume was increased at 500 rpm intervals of the propeller motor and every ten minutes in a stepwise manner. Water samples were collected at time zero

and every speed increment thereafter by siphoning 700 ml of flume seawater at the height of the OBS. Seven hundred ml of 2 μm filtered seawater were then added to maintain a constant volume in the flume. The water samples were filtered with Whatman glass-fibre filters (GF/C) and analyzed for chlorophyll, as above, and for SPM. An isotonic solution of ammonium formate was used to rinse the filters to remove salts from the SPM filters. The weight of the SPM was determined gravimetrically after drying the pre-weighed filters at 55 °C and dessicating the filters for 2 hours. Replicate water samples were collected from only one of the two cores eroded at each stage of growth. These water samples were used to calibrate the OBS employed during each duplicate erosion trial. However, due to the occasional problems in the OBS signal at higher flow velocities, erosion measurements by the extrapolation method were calculated from a single erosion trial. The erosion measurements by means of the digitization method occasionally included duplicates, since both cores of each growth stage were filmed during the later stages of growth. The three methods used to determine U_{crit} are described in Chapter 1 and outlined in Table 2.1.

Table 2.1: Methods used to determine U_{crit} in the laboratory flume experiment.

STAGE OF EROSION	METHOD	DEPTH OF EROSION
OBSERVATION METHOD		
Onset of ripple migration	Video observations	Sediment-water interface
Motion of a particle		
Simultaneous movement of 10 or more particles		
Erosion of aggregates		Sediment-water interface or mat-sediment interface
EXTRAPOLATION METHOD		
Resuspension of SPM from seabed	Extrapolation of SPM curve against U_c to the point of 0 concentration	Sediment-water interface and subsurface
DIGITIZATION METHOD		
Release of diatom mat and exposure of underlying sediment	Digitization of exposed sediment	Mat-sediment interface (diatom-mat base)

2.3 Results

2.3.1 The incubation of *Nitzschia curvilineata* on sediment

The mean growth curve of the replicate stock cultures of *Nitzschia curvilineata* incubated on the sediment cores is shown in Figure 2.1. The chlorophyll concentrations increased exponentially and reached a maximum on day 9 (exponential phase of growth). The chlorophyll concentrations did not increase for the remainder of the incubation period (stationary phase of growth). Contamination of the cultures did not occur since the chlorophyll concentrations of the control core containing 0.45 μm filtered seawater did not increase during the 18 day experimental period. An increase in bulk carbohydrate concentration took place at the end of exponential phase or the onset of stationary phase (Figure 2.2). Since no increase was observed in the colloidal carbohydrate concentrations during the experimental period, it was not used as a correlate of erosion thresholds or rates.

Because it was difficult to obtain a single-celled inoculum of *Nitzschia curvilineata*, growth of the diatom film radiated out from tiny diatom tufts on the sediment surface during the early period of exponential growth, however, the film became more evenly distributed during the early stage of stationary phase. Minute oxygen bubbles, produced through photosynthesis, eventually coalesced up to a size of approximately 1 mm. At first, the oxygen bubbles remained attached to the biofilm surface or trapped within the diatom mat. Fissures formed in the diatom mat when trapped oxygen bubbles gained sufficient buoyancy. These bubbles would occasionally break through the mat, giving it a "flaked" appearance. The diatom mats resembled dense green-brown soft

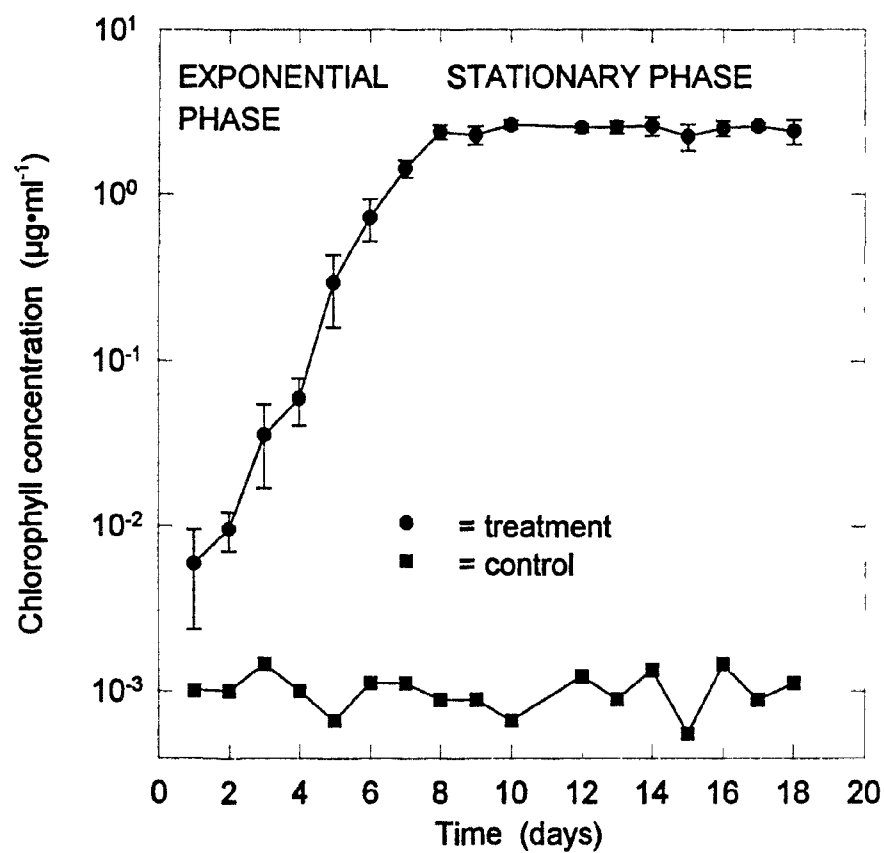


Figure 2.1: The mean growth curve of *Nitzschia curvilineata* incubated on replicate sediment cores. Error bars = 1 standard deviation, $n = 3$. No growth was observed on the control core which contained abiotic sediment.

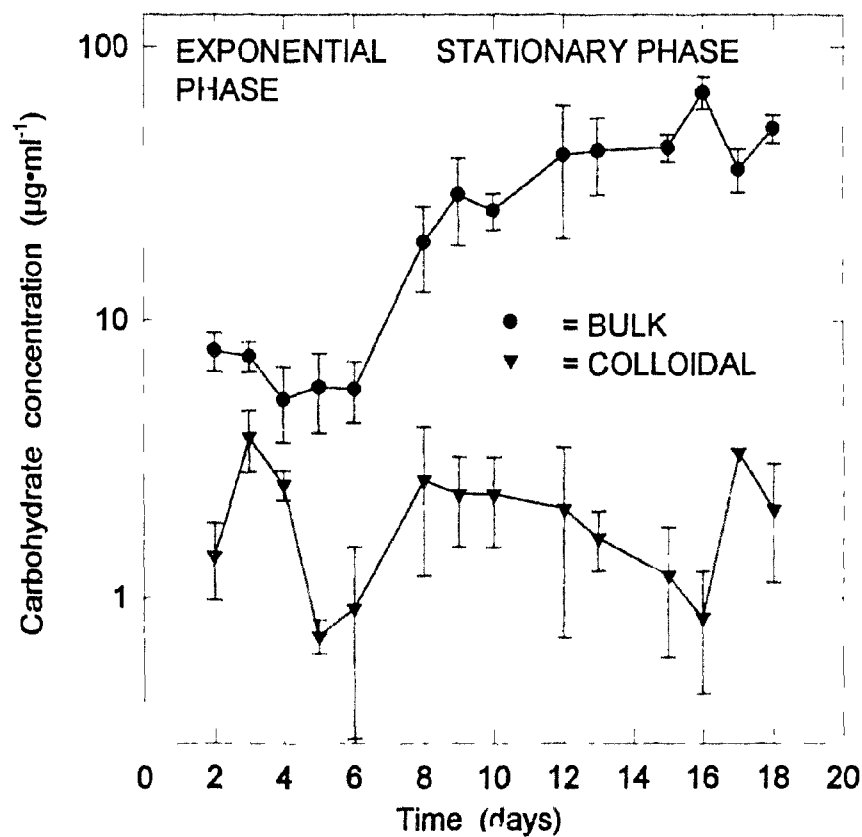


Figure 2.2: The mean colloidal and bulk carbohydrate curves produced by *Nitzschia curvilineata* grown on replicate sediment cores. Error bars = 1 standard deviation, n = 3.

carpets by day 9 of growth. After day 12 of growth the colour of the diatom mat changed from green-brown to a mottled white (diatomite) golden-brown. At this time the diatom mat became more translucent and shrank around the sediment, accentuating the flaked appearance of the mat. The diatom mat at this stage of growth appeared to be more "sticky" than at other stages of growth since any aggregates eroded as bedload would only travel a few centimetres before adhering quickly to the diatom mat. The diatom mat reached a maximum thickness of 2.5 mm on day 12 of the experimental period (Figure 2.3).

2.3.2 U_{crit} determination by the observation method

Figure 2.4 shows the critical shear velocity (U_{crit}) values obtained through video observations (method 1: Table 2.0). The U_{crit} values determined for particle motion (diameter < 1 mm) are shown in Figure 2.4A, while the U_{crit} values determined for the aggregate motion (> 1 mm) are shown in Figure 2.4B. The mean U_{crit} value obtained for particle motion between days 2 and 9 was $0.019 \text{ m}\cdot\text{s}^{-1}$, which was 1.8 times greater than the U_{crit} value obtained for the abiotic control core. The mean U_{crit} value obtained for the simultaneous movement of 10 particles was $0.022 \text{ m}\cdot\text{s}^{-1}$, which was 1.3 times greater than that of the control core (Figure 2.4A). Both the U_{crit} values for particle motion and the sediment chlorophyll concentrations increased between day 0 and 6. No increase in bulk carbohydrate was observed during this period. Ripple migration during erosion ceased after two days of diatom growth, while the movement of particles ceased at the onset of the stationary phase.

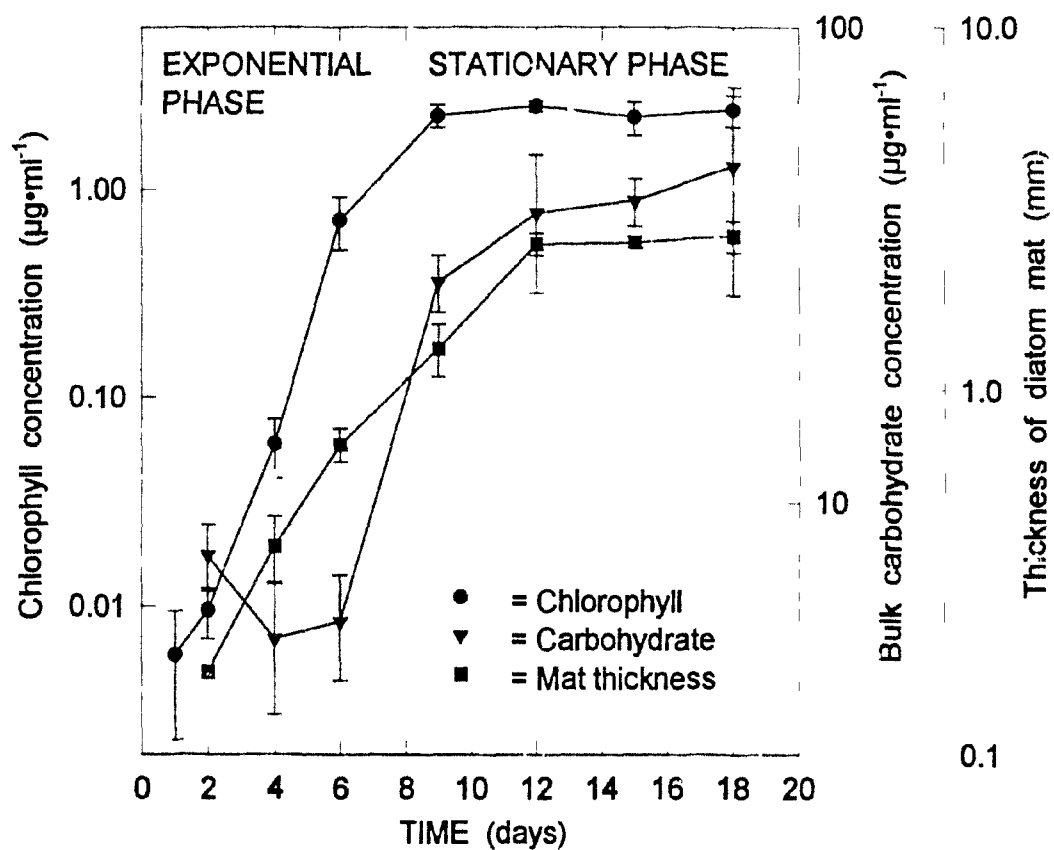


Figure 2.3: The mean growth curve, bulk carbohydrate profile, and mat thickness of *Nitzschia curvilineata* grown on replicate sediment cores. Error bars = 1 standard deviation, n = 3.

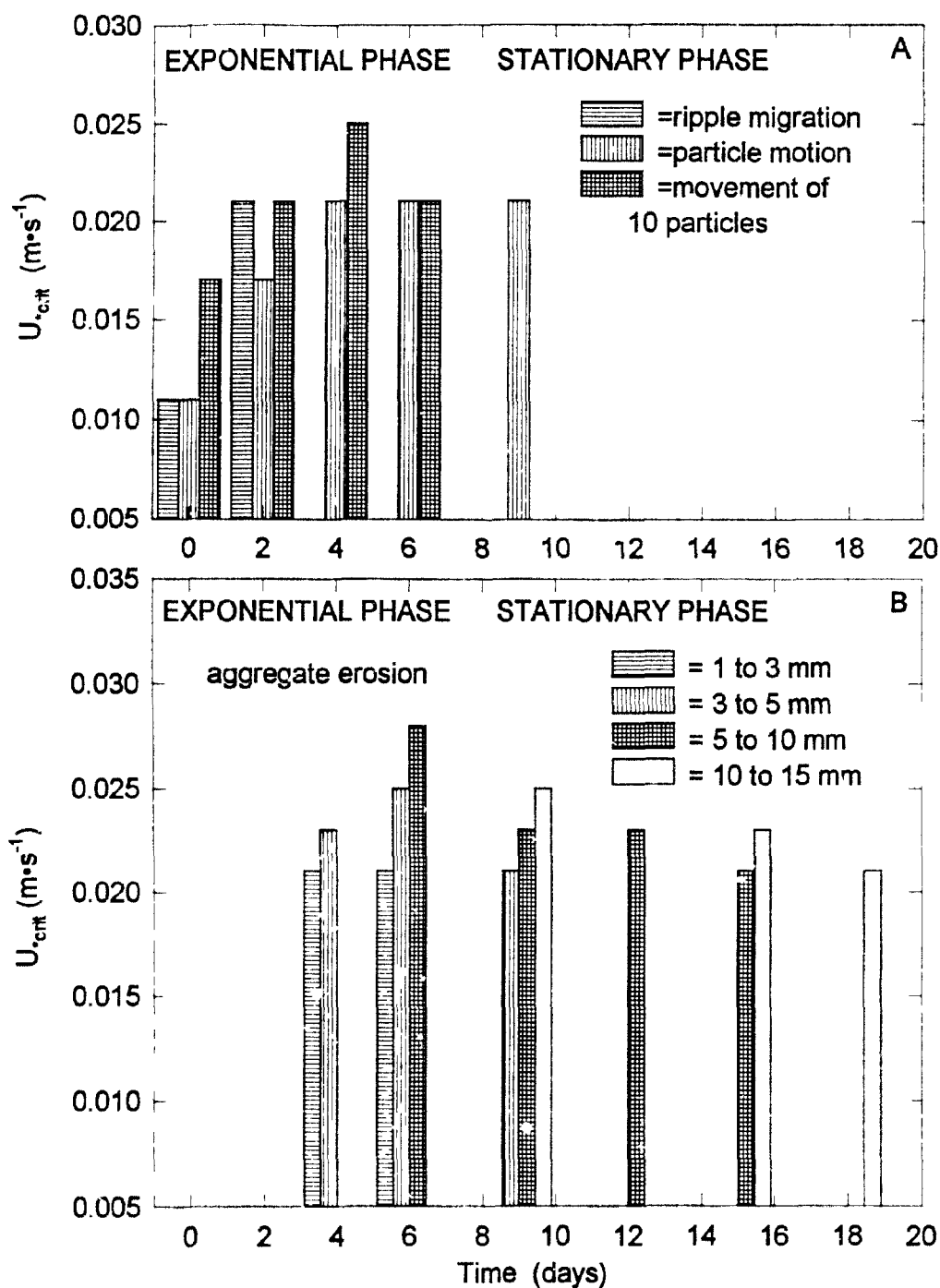


Figure 2.4: U_{cnt} values for (1) particle motion, (2) simultaneous motion of 10 particles, and (3) ripple migration of the *Nitzschia curvilineata* mat at successive stages of growth (A). U_{cnt} values for aggregate erosion (B). An abiotic control core was eroded on day zero.

The movement of aggregates (diameter > 1 mm) occurred only after four days of diatom growth (Figure 2.4B). During the exponential phase of growth, the size of the aggregates eroded increased with increasing U_{crit} within each erosion trial. Fewer number of size categories of aggregates were eroded during stationary phase and erosion of aggregates was limited to the larger size classes of aggregates towards the end of stationary phase. At each erosion trial, the critical threshold for the movement of particles (Figure 2.4A) or aggregates (Figure 2.4B) took place at U_c values of $0.021 \text{ m}\cdot\text{s}^{-1}$ indicating that little change was occurring in the erosion thresholds at the sediment surface. The erosion of smaller-sized aggregates (diameter = 1 to 3 mm) during the exponential phase was gradually replaced with the erosion of larger-sized aggregates (diameter = 10 to 15 mm) during the stationary phase. This change in the behaviour of sediment erosion throughout the experimental period makes it impossible to determine a single erosion criterion.

2.3.3 U_{crit} determination by the extrapolation method

The U_{crit} value obtained on day 2 was 1.8 times greater than the U_{crit} value obtained for the abiotic control core (Figure 2.5A). The U_{crit} values remained fairly constant between day 2 and 18 of growth. The mean U_{crit} value obtained from the biotic cores (days 2 to 18) was 1.76 times greater than the control.

2.3.4 U_{crit} determination by the digitization method

This method measures the exposure of sediment underlying the diatom mat or the release of the diatom mat at the base level, between the mat-sediment interface. The video

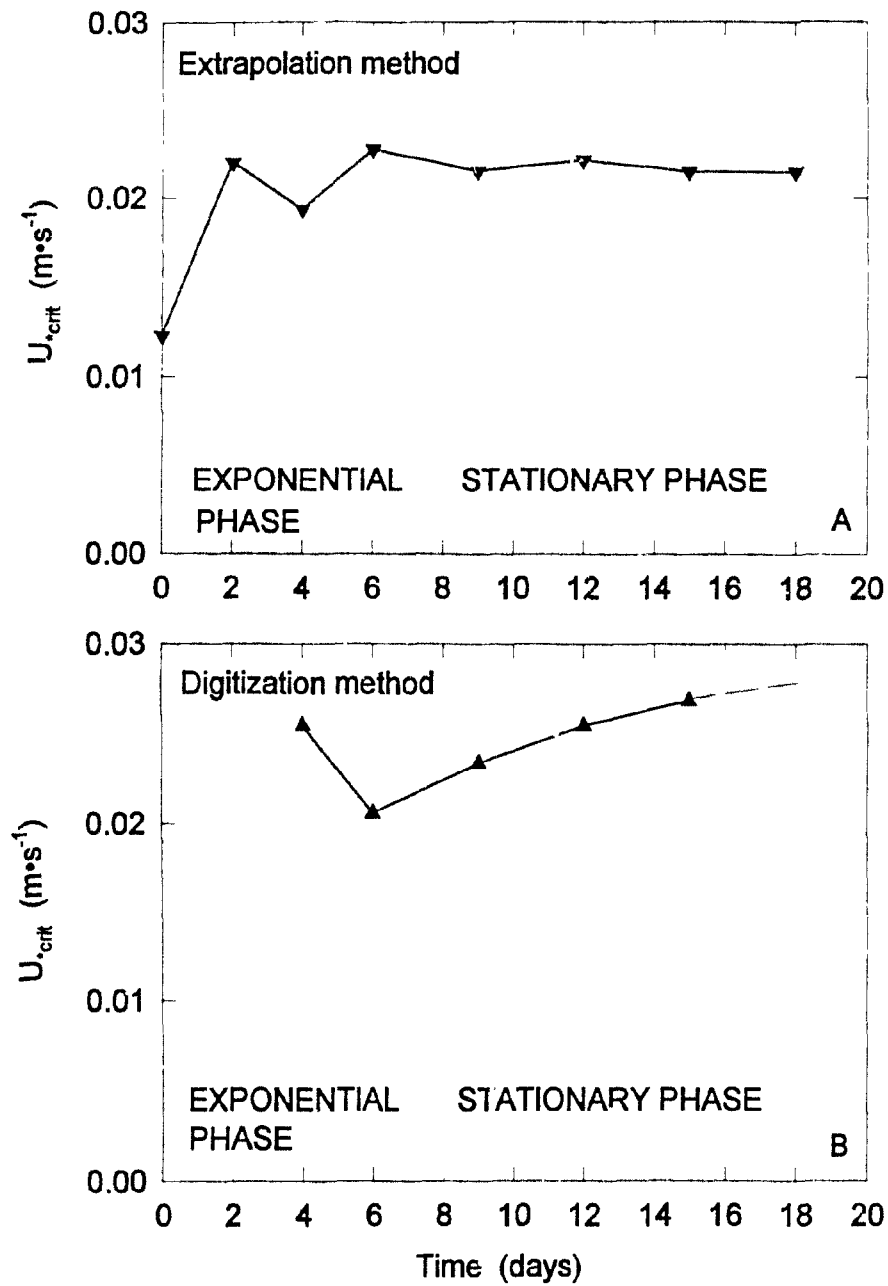


Figure 2.5: U_{crit} values determined by the extrapolation method for the biofilm surface (A), and by the digitization method for the biofilm base (B). Erosion of the biofilm base did not occur on day 18 of growth.

recordings of the eroded cores containing less than 2 days of growth could not be digitized, because the diatom mat (non-eroded area) could not be discerned from the eroded area of the core; therefore, the results for method 3 are limited to the period between day 4 and day 18 of diatom mat growth.

Figure 2.6 shows the relationship between the eroded area of the diatom mat and shear velocity (U_*). U_{*crit} was taken as the point when 0.5 % of the core area of the white underlying sediment was exposed (the smallest observed area exposed after the erosion of a diatom mat aggregate). This threshold determines the critical erosion for the diatom base. Figure 2.5B shows the U_{*crit} values determined for the base of the diatom mat-sediment interface. With the exception of day 4, an increase in U_{*crit} values was observed for the base of the diatom mat at the end of exponential phase and the duration of stationary phase. The observed decrease in erosion on day 6 may be attributed to the extent of reworking of underlying sediment by the diatoms or of "flaking" produced by emerging oxygen bubbles. Before this time the diatom mat existed as a sediment-free layer on the surface. The erosion threshold of the core on the last day of the experiment was greater than the highest U_* value generated by the flume and as a result is represented by a dashed line. An increase in both the U_{*crit} for the base of the biofilm and the sediment bulk carbohydrate concentration between day 6 to 15 are evident (Figure 2.5B).

2.3.5 Increases in U_{*crit} with depth in the sediment

The erosion threshold for the base of the biofilm (digitization method) were generally higher (up to 3 times greater) than those determined for the surface of the

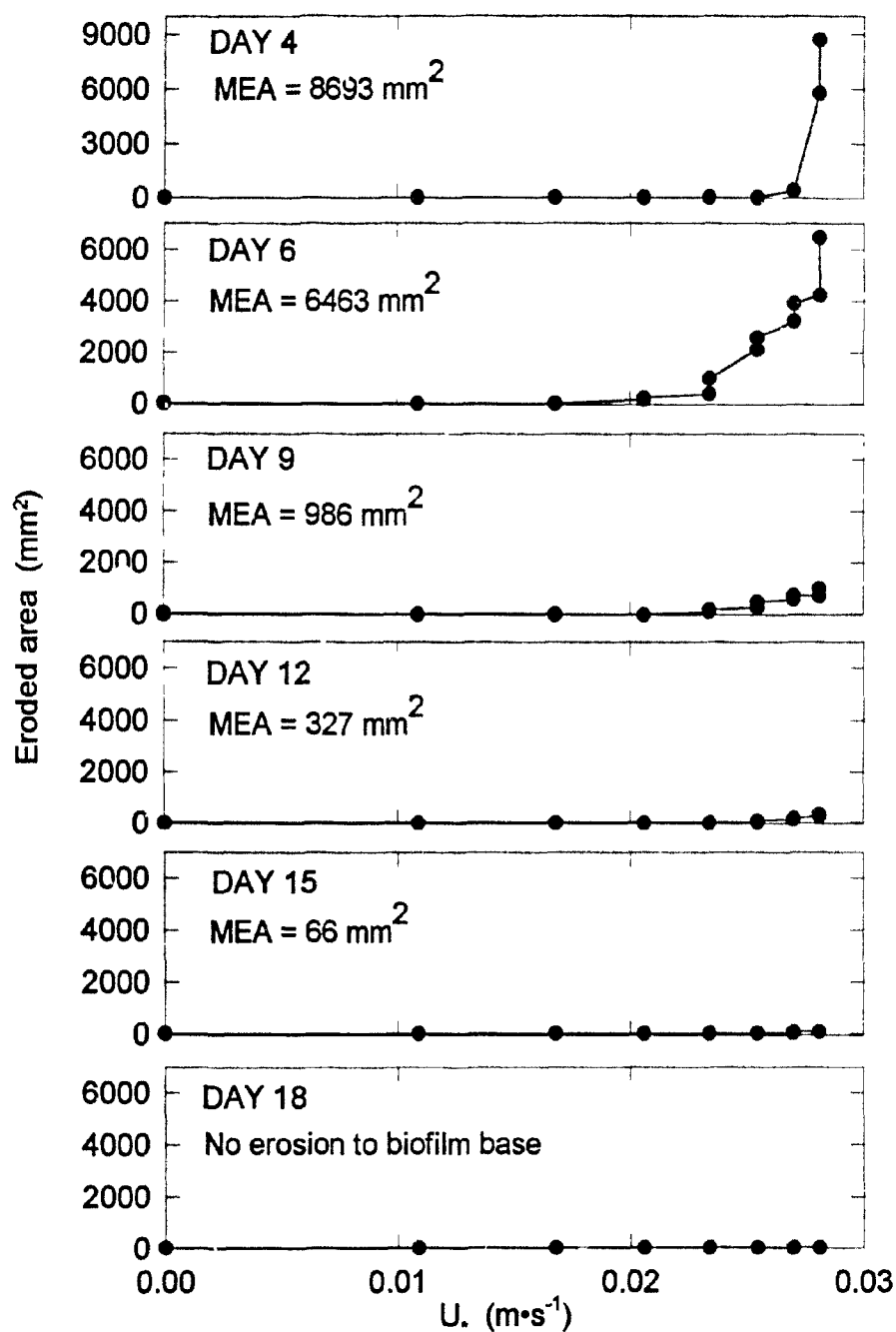


Figure 2.6: The relationship between eroded area of the diatom mat and U , for successive stages of growth of *Nitzschia curvilineata*. Eroded area of the biofilm base was measured using the digitization method. MEA = maximum eroded area.

biofilm (observation and extrapolation method), indicating that the biofilm created a stratified layer of increasing strength with depth. Figure 2.7 shows that the largest changes in erosion threshold occurred at the base of the developing biofilm while the smallest changes in erosion thresholds occurred at the surface of the biofilm.

2.3.6 Erosion rates of chlorophyll (extrapolation method)

Net erosion rates of chlorophyll increased during the exponential phase and decreased during the stationary phase of growth (Figure 2.8A). The erosion rate of a single biofilm component is a function of both the strength of the sediment and the concentration of that component in the sediment available for resuspension. For example, the increase in erosion rate of chlorophyll during exponential phase may reflect the simultaneous increase in sediment chlorophyll concentration available for resuspension. The time-series of chlorophyll flux does not reflect the decrease in erosion rate of biofilm-sediment material measured by extrapolation method. An exponential decrease in the erosion rate of chlorophyll was observed once it was standardized to the concentration of chlorophyll in the sediment. The erosion rate of chlorophyll normalized to the sediment chlorophyll concentration serves as a more reliable measurement of erodibility of the sediment (Figure 2.8B).

The normalized erosion rate of chlorophyll was significantly negatively correlated with the sediment bulk carbohydrate concentration ($r^2 = 0.859$, $p = 0.003$; Figure 2.9). On day 9 of growth, a biofilm core, from which water samples were collected, was inadvertently extruded to a height higher than the flume floor, potentially exposing it to a higher shear stress. As a result the biofilm peeled off and eroded at a faster rate than the

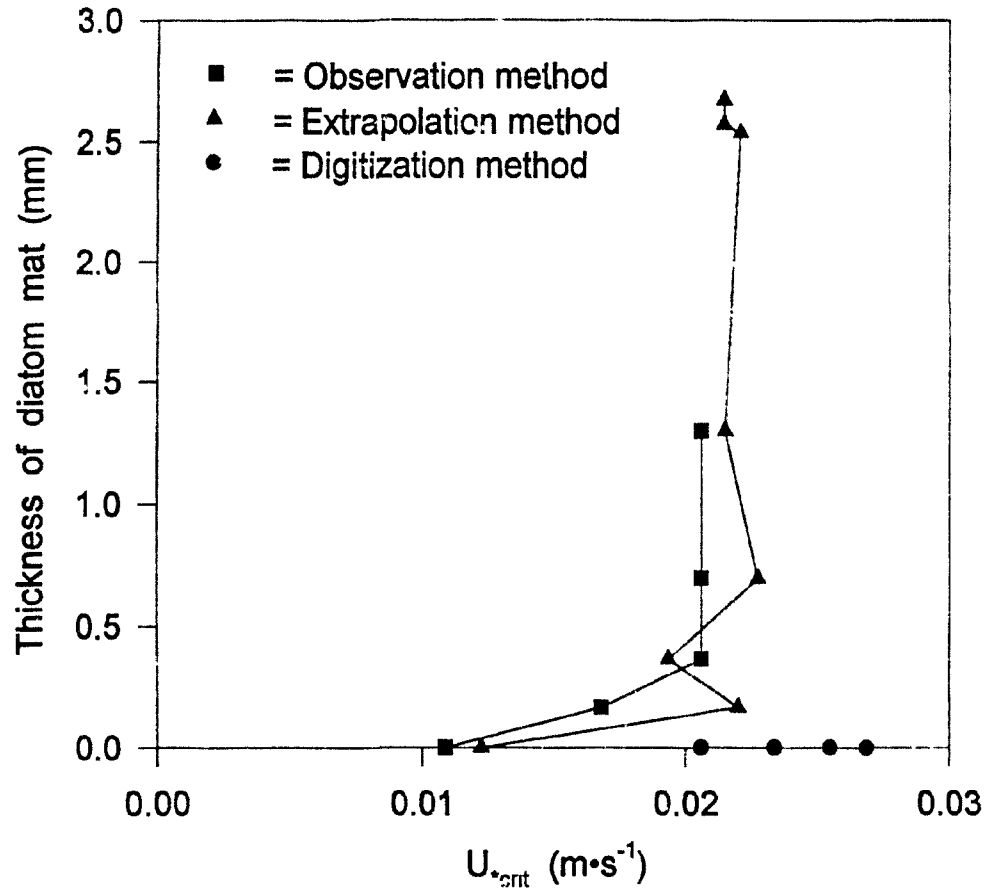


Figure 2.7: U_{*crit} values determined for the surface of the biofilm (observation and extrapolation method) and for the base of the biofilm (digitization method) at successive stages of mat thickness of *Nitzschia curvilineata*.

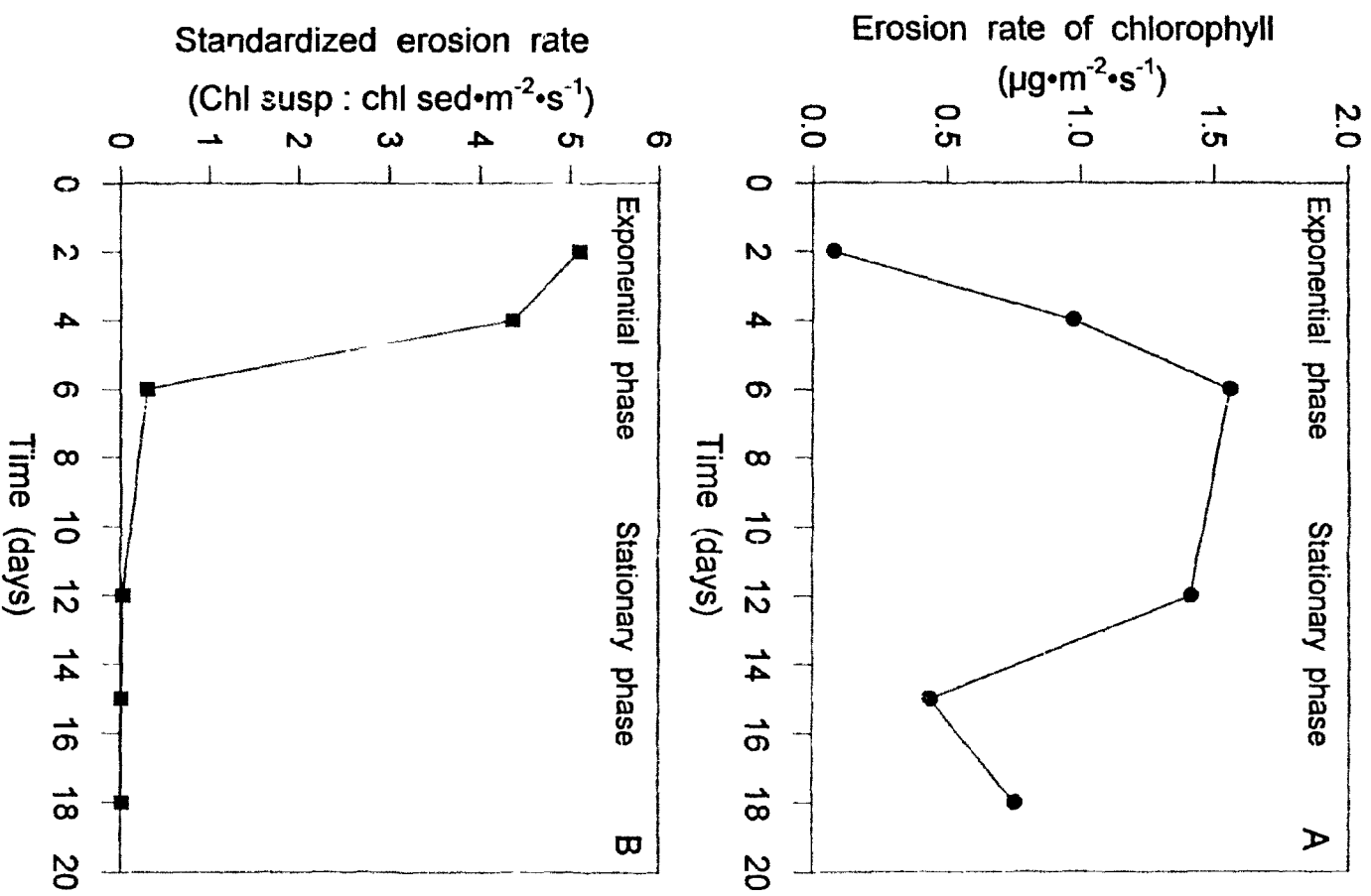


Figure 2.8: Erosion rates of chlorophyll calculated from suspended samples (A) and standardized to sediment chlorophyll (B) at successive stages of growth of *Nitzschia curvilineata*.

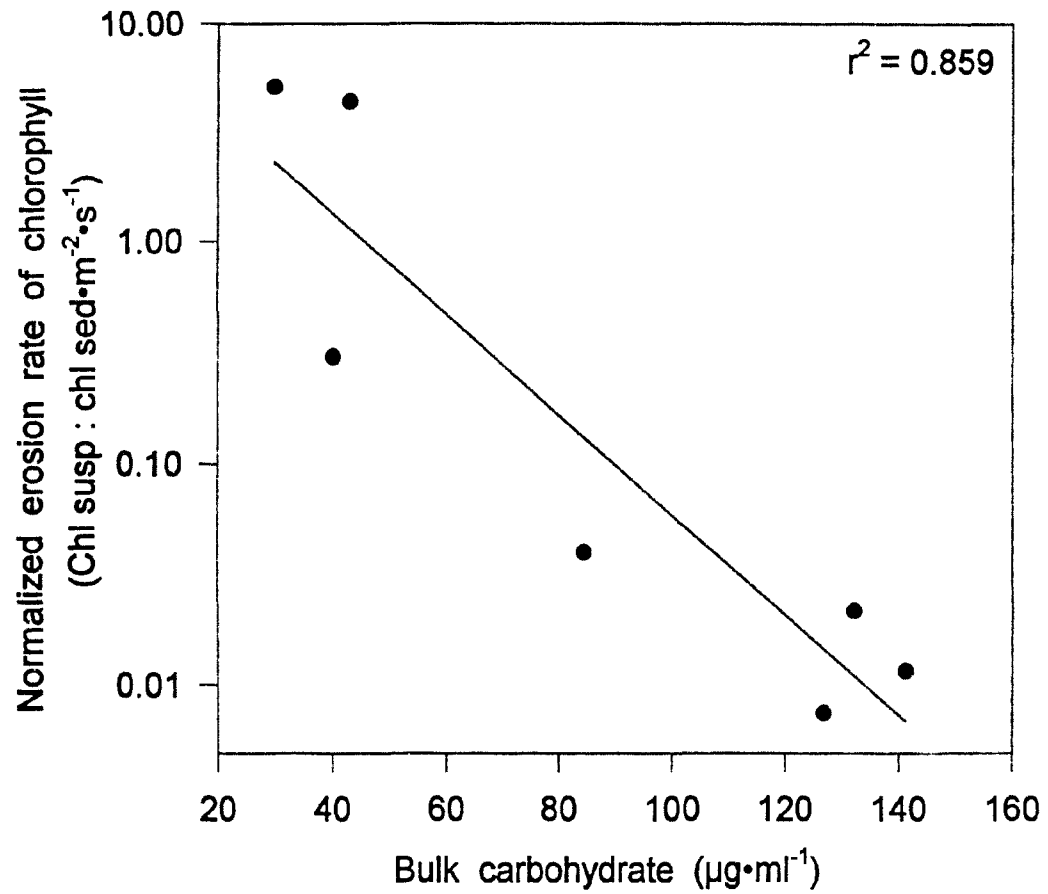


Figure 2.9: Relationship between the erosion rate of chlorophyll standardized to the sediment chlorophyll concentration and the bulk carbohydrate concentration in the sediment.

other two replicate biofilm cores, from which water samples were not collected. Therefore, the erosion rate of chlorophyll was not represented for day 9 of growth of *Nitzschia curvilineata*.

2.3.7 Erosion rates of diatom-sediment mat (digitization method)

A large decrease in the maximum eroded area of the diatom mat took place between day 4 and day 18 of growth (Figure 2.6). An exponential decline was observed for the erosion rates of the total material (biofilm and underlying sediment) eroded with time (Figure 2.10). The volume of sediment eroded was calculated from the eroded area and depth of erosion of sediment material and measurements of diatom-mat thickness. During the stationary phase, the similar rates in total material and diatom mat eroded suggests that the diatom mat was controlling the total rate of erosion of biofilm and underlying sediment. A distinct decrease in the maximum eroded area was observed for successive stages of growth of *Nitzschia curvilineata* (Figure 2.6). Although the maximum eroded area of day 4 and day 6 were very similar, the rate at which the biofilm was eroded differed. Changes in the sediment microfabric due to the extent of bubble formation and "flaking" of the sediment or the extent of diatom migration and reworking of the sediment may contribute to this decrease in erosion threshold and change in erosion rate.

It is interesting to note that the erosion of sediment during stationary phase is tightly controlled by the erosion of the diatom mat (Figure 2.10). The sediment eroded during stationary phase was sediment incorporated into the biofilm during its

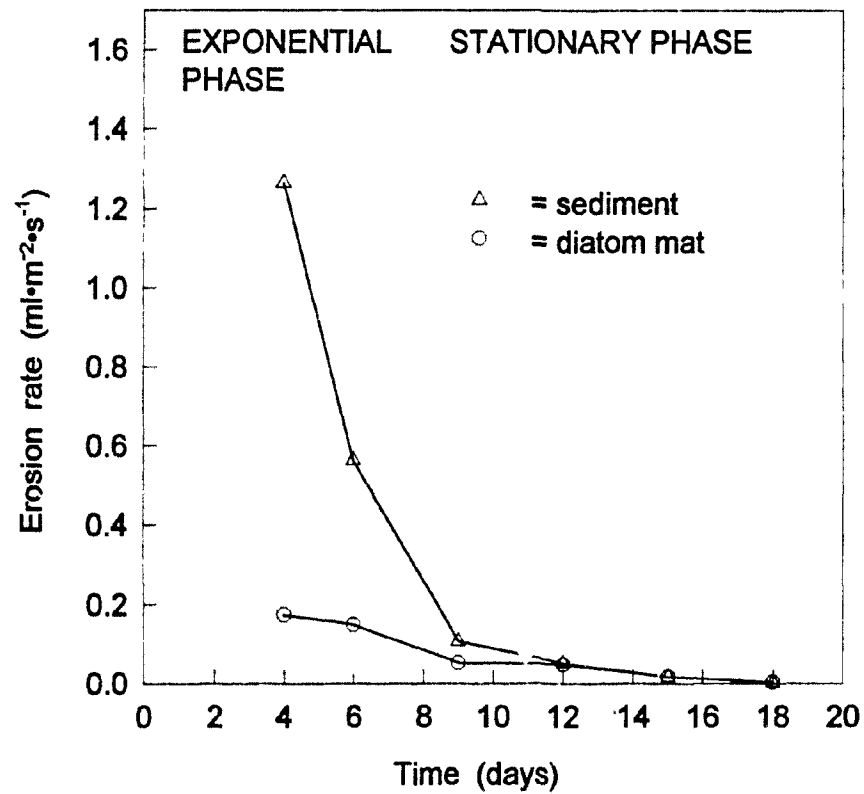


Figure 2.10: Erosion rates of the sediment material and the diatom mat. Erosion rates were determined using the digitization method.

development. The exposed underlying sediment remained under 102 mm² or 1 percent of the total core surface area after day 12. The exposed sediment did not appear to erode, probably due to the fact that the area was too small to allow water to undercut the biofilm since the biofilm-sediment interface was 2.5 mm below the water-biofilm interface. Therefore, thickness of the biofilm may play an important role in the stabilisation of sediment as well as the glueing effect of carbohydrate production.

Negative correlations existed between the erosion rate of the base of the biofilm and sediment chlorophyll concentration ($r^2 = 0.759$, $p = 0.024$; Figure 2.11A) and sediment bulk carbohydrate concentration ($r^2 = 0.958$, $p = 0.001$; Figure 2.11B). The relationship between chlorophyll concentration and erosion rate was not as strong as the latter relationship. A stronger correlation between the chlorophyll concentration and the erosion rate may have been found if more measurements had been made during the exponential growth phase. The erosion rate of sediment was negatively correlated with the bulk carbohydrate to chlorophyll ratio ($r^2 = 0.996$, $p < 0.001$; Figure 2.12). Erosion rates specific for chlorophyll and bulk carbohydrate were calculated and presented in Figure 2.13.

2.4 Discussion

2.4.1 The incubation of *Nitzschia curvilineata* on sediment

The growth of the oxygen bubbles in size and along with the growth, migration, and carbohydrate production of *Nitzschia curvilineata* contributed to the increasing thickness of the biofilm, which reached a maximum of 2.5 mm at the onset of stationary

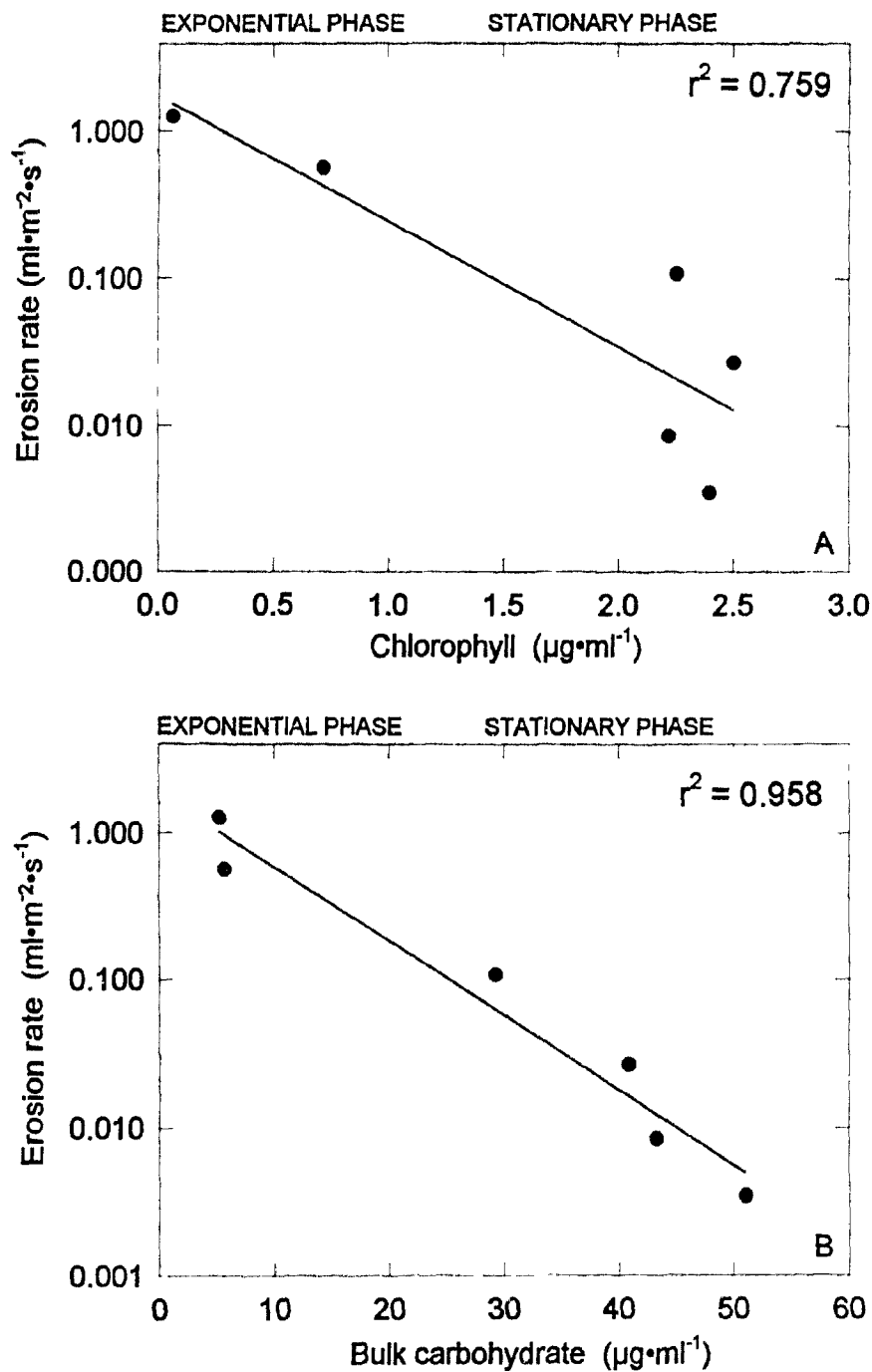


Figure 2.11: The relationship between erosion rate and sediment chlorophyll (A) and bulk carbohydrate (B) content. Erosion rates were determined using the digitization method.

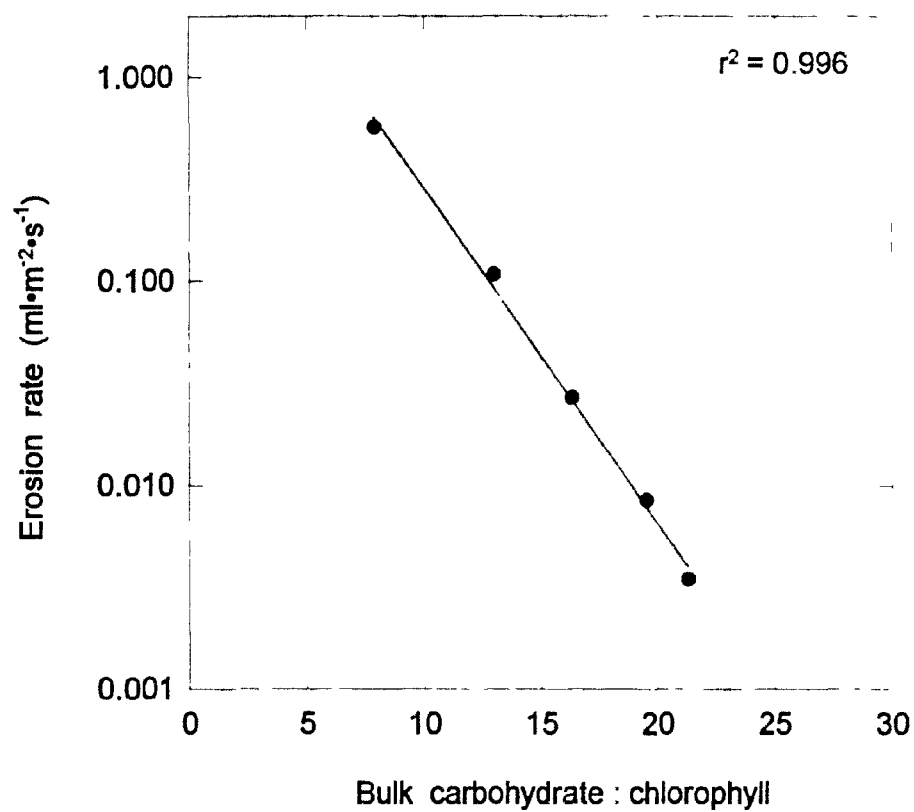


Figure 2.12: The relationship between erosion rate and the ratio of bulk carbohydrate to chlorophyll. Erosion rates were determined using the digitization method.

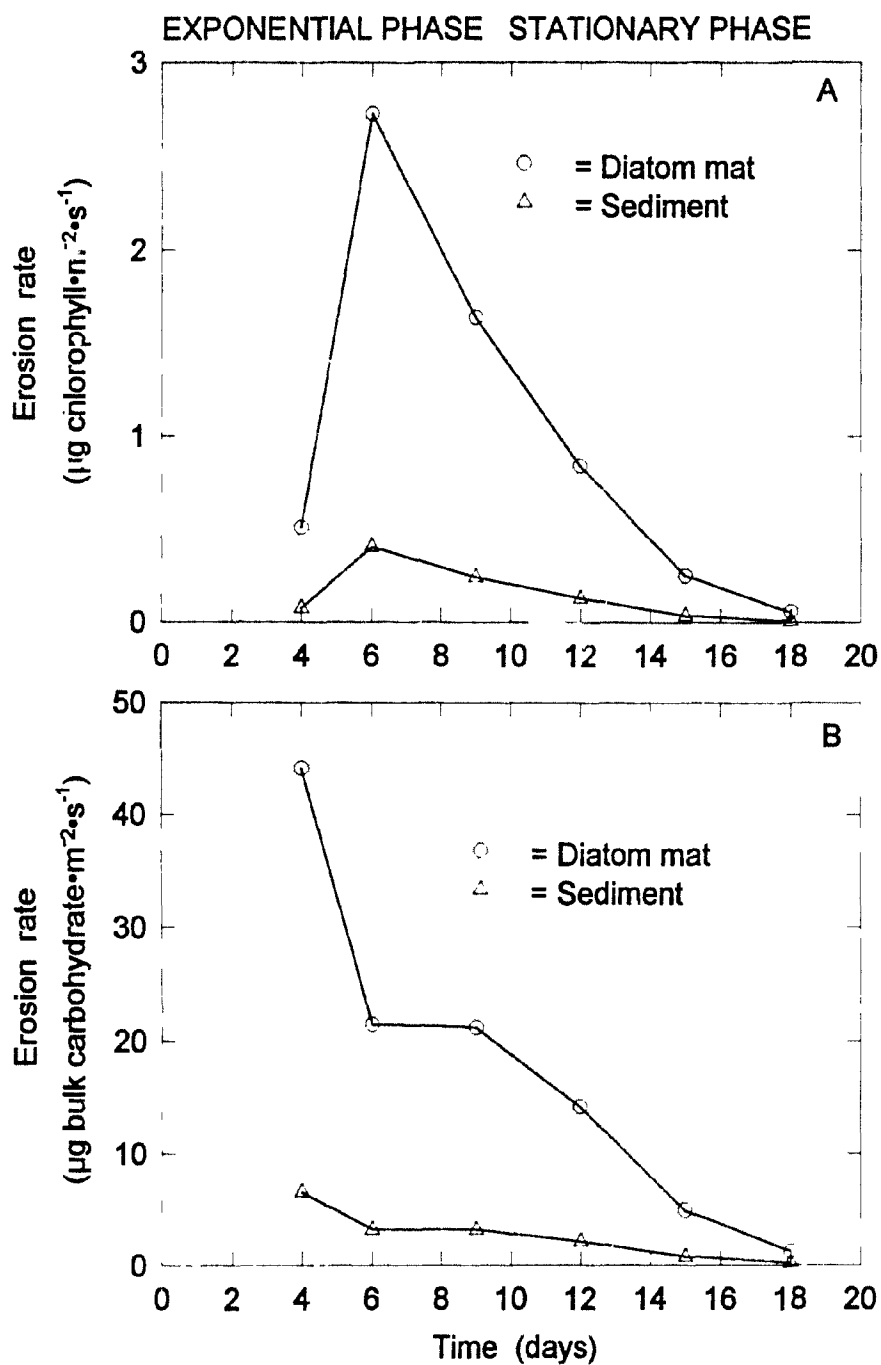


Figure 2.13: Erosion rates of sediment chlorophyll (A) and bulk carbohydrates (B) at successive stages of growth of *Nitzschia curvilineata*. Erosion rates were determined using the digitization method.

phase (Figure 2.3). The interaction of these factors would also contribute to changes in the microfabric of the developing biofilm. Oxygen bubbles formed, coalesced and reached a diameter of up to 1 mm. The coalesced oxygen bubbles gained buoyancy and finally broke through the biofilm, giving the torn biofilm a flaked or cracked appearance. Sundback (1994) suggested that flaking of a productive sediment layer was formed due to a combination of high photosynthetic activity and stagnant conditions. "Blister" or "bubble" mats containing oxygen bubbles trapped by a thin film of microalgal mucilage have been described by Jorgensen *et al.* (1983) and Yallop *et al.* (1994), respectively, and *in situ* flaking has been observed on cohesive mats by Jonsson *et al.* (1994).

2.4.2 Carbohydrate production by *Nitzschia curvilineata*

Colloidal carbohydrate and bulk carbohydrate were the two types of carbohydrate fractions considered in this study. Colloidal carbohydrate is the supernatant fraction, obtained during extraction, and is referred to as the soluble, colloidal, labile or liquid phase (Grant *et al.*, 1986a, Underwood and Paterson, 1993b, Madsen *et al.*, 1993). Bulk carbohydrate is the sediment fraction and is referred to as the bulk, bound, capsular or solid phase. These two general carbohydrate fractions are operational classifications that depend on aqueous extraction and centrifugation. Discrete fractions or physical states of extracellular polymeric substances (EPS) do not exist in nature (Decho, 1994a). Instead, a continuum exists of tertiary states ranging from highly condensed gels, loosely conformed slimes, to colloidal solutions. The capsular form is thought to be produced by microbial cells for attachment purposes, while the slime form is thought to be produced for purposes of locomotion (Decho, 1990).

In this study, the colloidal carbohydrate concentration remained low with no discernible trends throughout the growout period of the diatom biofilm (Figure 2.2). The low colloidal carbohydrate concentrations may be a result of set laboratory incubation conditions, since the exudation of extracellular polymeric substances depends on various environmental factors such as light, temperature, and turbulence (Decho, 1990). The low concentrations of the colloidal fraction may also be due to the use of an isotonic saline solution during the extraction process to reduce cell leakage and, thus, contamination. Previous field studies may have artificially enhanced colloidal carbohydrate concentrations as a result of cell leakage because they followed the method of Lui *et al.* (1971), who used distilled water for the extraction of carbohydrates from lake sediments. The large variability that exists in the colloidal carbohydrate concentrations may be due to the occasional contamination with particulate (bulk) carbohydrate or due to the fact that the concentrations were near the detection limit of the spectrophotometer. Large coefficients of variation of colloidal carbohydrate values have also been found by Grant *et al.* (1986a).

An increase in bulk carbohydrate was observed at the end of exponential phase or the onset of stationary phase. This increase may be due to either an increase in the intracellular carbohydrates and/or an increase in the non-extracted extracellular carbohydrates (capsule or slime). The majority of studies that investigate the physiological factors controlling extracellular carbohydrate production have been performed on planktonic diatoms (Allan *et al.*, 1972; Myklestad and Haug, 1972; Brockman *et al.*, 1979; Myklestad, 1974; Myklestad *et al.*, 1989; Obernosterer and Herndl, 1995). In pelagic forms, extracellular carbohydrate production increases during stationary phase when

nitrogen or phosphate is limiting. During this stage of growth extracellular carbohydrate production has been observed to be 1.25 times greater than the manufacture of intracellular carbohydrates (Myklestad, 1974). The increased production of extracellular carbohydrate in stationary phase also occurs in benthic diatoms *Amphora coffeaeformis* and *Navicula subinflata* showed higher rates of carbohydrate production in the stationary phase (Bhosle *et al.*, 1995), and the cells of *Navicula pelliculosa* showed an accumulation of capsular material during stationary phase (Lewin, 1955). The increase in bulk carbohydrate in this study was probably due to the exhaustion of nutrients from the F/2 growth medium (Guillard, 1972), leading one to think that the increase in bulk carbohydrate was due to the formation of capsular material.

It has been disputed whether the enhanced carbohydrate concentration observed in stationary phase is due to active secretion or is an overflow reaction and, hence, an accumulation of liberated storage products (Allan *et al.*, 1972). It appears that the extracellular polymeric substances are actively produced and transported in Golgi vesicles to secretion sites at the plasmalemma (Hoagland *et al.*, 1993). The composition of extracellular polysaccharides has been observed to be different than that of the intracellular reserve (Allan *et al.*, 1972; Myklestad *et al.*, 1972) and more similar to that of the mucilaginous sheath surrounding the diatom (Allan *et al.*, 1972).

Little is known about the ecological significance of the increased production of extracellular capsular carbohydrates for the enhancement of the growth and survival of the producing microbe. The production of capsular material appears to be a response to a shift in growth phase or the cessation of growth and not to the limitation of a single nutrient

(Kroen and Rayburn, 1984). Both nitrogen and phosphate limitation have been shown to increase carbohydrate production in microbes (Myklestad, 1977; Kroen and Rayburn, 1984; de Philippis *et al.*, 1993; Obernosterer and Herndl, 1995). Capsular EPS may aid in the 1) adsorption of essential nutrients and trace metals, 2) protection against desiccation, grazing, and toxic metals, and 3) adhesion to substrate (Decho, 1990).

2.4.3 Relationship between U_{crit} of the biofilm surface and chlorophyll and carbohydrate production by *Nitzschia curvilineata*

The initial increase in erosion threshold and cessation of ripple migration, relative to the control, indicated that the diatom, *Nitzschia curvilineata*, influenced the erosion characteristics of the sediment (Figure 2.4). The age of the diatom biofilm appeared to affect the size and shape of the aggregates eroded, since larger sizes and flake-shaped aggregates were eroded at later stages of growth (Figure 2.4A and 2.4B). The microfabric of the sediment may be influenced by (1) the amount of biofilm coverage around sediment particles and associated changes in porosity, (2) the extent of diatom migration and reworking of sediment, (3) the increase in the thickness of the biofilm, (4) the extent of bubble formation and "flaking" of sediment, (5) the increase in the production of bulk carbohydrates, or (6) the speculated changes in the carbohydrate composition or "stickiness".

The erosion threshold or onset of particle/aggregate motion determined through the observation method remained at a shear velocity of approximately $0.02 \text{ m}\cdot\text{s}^{-1}$ throughout the exponential growth phase of the biofilm (excluding day 12). This time-invariant threshold may be due to (1) a vertically accreting diatom matrix that

maintained constant physical properties or (2) the sensitivity of the method involved. For example, the accretion of surface mucilage matrices or the formation of diatom forests overlying the sediment layer may maintain constant density properties and promote consistent behaviour in particle/aggregate movement or erosion. Paterson (1988) observed the development of a surface matrix layer made up solely of diatoms and mucilage that extended 22 μm above a diatom inhabited-artificial substrate. *Gyrosigma balticum* cells, 400 μm in length, were observed to form a "forest" by orientating their long axes to the sediment surface using mucilage tubes (Jonsson *et al.*, 1994).

Secondly, the observation method is sensitive to the early stages of erosion or the incipient movement of the topmost biofilm material which will be influenced largely by the accretion of the surface of the biofilm. Changes in the number, size, and shape of the eroded particles/aggregates with age of the culture causes difficulties with the use of a single particle erosion criterion.

The extrapolation method involved the extrapolation of the suspended particulate matter (SPM) back to the point of zero concentration on the U_c axis (U_{c0}). Again, the erosion threshold values of the biotic sediment cores, determined by the extrapolation method, were higher than their respective values for the abiotic control cores, reconfirming that the diatom, *Nitzschia curvilineata*, influenced the erosion characteristics of subtidal sediment (Figure 2.5A). However, the increases in erosion threshold determined by the observation and the extrapolation methods took place initially over a short period and did not follow the increases in chlorophyll and carbohydrate concentrations that took place over a longer time period.

2.4.4 Relationship between U_{crit} of the biofilm base and chlorophyll and carbohydrate production by *Nitzschia curvilineata*

The digitization method determined the critical shear velocity of bed failure that occurred at the base of the biofilm. A decrease in the erosion threshold measured on day 6 was followed by a steady increase in erosion thresholds for the remainder of the experiment (Figure 2.5B). The subsequent increase after day six may be attributed to the increase in bulk carbohydrates during this time (Figure 2.2). However, the bulk carbohydrate concentration stabilized after day 12 of the experiment.

A change in EPS composition may be responsible for the increase in U_{crit} after day 12 (Figure 2.2). The composition of EPS is influenced by nutrient status and growth phase (Decho, 1990). A change in monosaccharide composition, from C-5 sugars to C-6 sugars, was observed during growth of a culture of *Navicula* sp (Stal *et al.*, 1994). This change was related to an increase in hydrogen bridges and the potential for the formation of ion bridges with multi-valent cations. The difference in nutrient dynamics between a "pioneering" vs "established" microbial community (Villbrandt *et al.*, 1990) and the associated change in EPS composition may influence the "stickiness" or inter-grain binding capacity of the EPS matrix. The effect of the quantity and quality of carbohydrate production must be greatest at the base of the biofilm since the largest increases in the erosion threshold are observed at this level (Figure 2.7). The surface of the vertically accreting biofilm represents the "pioneering" diatom community, while the base of the biofilm represents the "established" diatom community.

2.4.5 Increases in U_{crit} with depth in the sediment

In situ measurements of erosion thresholds made on natural biomediated sediment from the Bay of Fundy (Amos *et al.*, 1992c) showed an increase in critical bed shear stress with depth in the sediment, as was observed in the present study (Figure 2.7). Stratification of the thickening biofilm layer could occur due to (1) the maintenance of a diatom-mucilage matrix layer (Paterson, 1988) or "diatom-forest" layer (Jonsson *et al.*, 1994) at the biofilm surface, (2) the extent of diatom migration, (3) a porosity gradient, and (4) changes in the hydration state of the mucilage with depth, and (5) bubble formation. As discussed earlier, the development of a permanent diatom-mucilage, sediment-free layer at the topmost layer of the biofilm would maintain constant properties such as, bulk density, water content, microstructure, and thus, maintain constant erosion threshold values with time. A porosity gradient may be formed due to the concentration and migration of diatoms nearer to the illuminated surface of the biofilm. An enlarged pore structure of a recently deposited sediment was observed to be related to the migration of diatoms within this layer (Hay *et al.*, 1993). If the porosity or water content is less at the base of the biofilm, a lower hydration state of the mucilage may influence the binding capacity of the mucilage. Paterson (1988) found that a lower concentration of carbohydrate in dewatered sediment was more efficient at binding the sediment. The increase in erosion threshold observed at the base of the biofilm with time may be due to changes in composition or "stickiness" of the aging mucilage.

2.4.6 Relationship between erosion rate and chlorophyll and carbohydrate production by *Nitzschia curvilineata*

A strong correlation between the ratio of bulk carbohydrate and chlorophyll concentration and the erosion rate of the base of the biofilm was evident (Figure 2.12). The ratio of carbohydrate to chlorophyll may serve as an indicator of the physiological state of the diatoms which may be used as a more reliable predictive tool for quantifying biostabilization. Madsen *et al.* (1993) found that only the biovolume of motile diatoms harvested with the cover-glass technique gave a significant correlation with erosion thresholds. They stressed that the relationship between chlorophyll concentration and carbohydrate concentration is not simple and that other factors such as the ratios of motile vs. non-motile diatoms and the physiological status of the diatoms should be considered. Knowledge of whether the biofilm is in a "pioneering" or "established" state will provide information on the extent to which changes in the binding of sediment will take place.

Grant and Gust (1987) stressed that photopigments of biofilms are not responsible for the actual binding of sediment, but do serve as a quantitative index of an EPS-producing microbial biomass. However, they did find that specific photopigments of purple sulphur bacteria, which formed a concentrated layer in the topmost layer of the sediment, exhibited a significant correlation with erosion thresholds.

2.4.7 Stabilization coefficient

Since a standard approach to the determination of erosion thresholds does not exist, it is difficult to put the results reported in this chapter in context with those of other laboratory and field studies. Stability coefficients have been used to compare the effect of

different diatoms (Holland *et al.*, 1974) or different biofilm types of various investigations (Paterson, 1994) on the erodibility of sediment. Paterson (1994) defined a stabilisation coefficient as the percent ratio of a U_{*crit} value of a biofilm to a U_{*crit} value of an abiotic sediment (control). Stabilization coefficients were determined for the surface of the biofilm and for the base of the biofilm (Table 2.2). These coefficients cover a much narrower range (123 to 258 percent) compared to those across various investigations (25 to 770 percent) reported by Paterson (1994).

In order to make comparisons between investigations, it is important to distinguish between the stage of erosion examined and the depth at which it occurred within the sediment. For example the erosion thresholds determined for the topmost layer of the sediment were not an indication of the maximum erosion thresholds determined below the sediment surface. The change in erosion thresholds determined for the base of the biofilm, along with a constant value of erosion thresholds of the surface of the biofilm with time support this observation (Figure 2.7). The determination of U_{*crit} for a standard depth in the sediment would minimize the amount of variation across investigations.

2.4.8 Chlorophyll and carbohydrate fluxes

Extracellular polymeric substances can serve as a potential food source for benthic animals (Decho and Moriarty, 1990). An exopolymer matrix is a highly labile source of carbon and exhibits highly adsorptive qualities that allow it to sequester dissolved organic

TABLE 2.2: Stabilization coefficients for growth stages of the diatom, *Nitzschia curvilineata*, incubated on sediment. Stabilization coefficients are expressed as the percent increase in U_{crit} values relative to that of the abiotic control.

CRITERION FOR EROSION		METHOD		
		Observation	Extrapolation	Digitization
particle motion	min	154 %		
	max	189 %		
simultaneous movement of 10 particles	min	123 %		
	max	152 %		
erosion of aggregates	min	189 %		
	max	214 %		
onset of ripple migration		189 %		
resuspension	min		158 %	
	max		185 %	
biofilm base	min			189 %
	max			>258 %

matter (Decho and Lopez, 1993). Figure 2.13 shows a time series of the flux or erosion rates specific for chlorophyll concentration and bulk carbohydrate concentration that are standardized by the depth of the total sediment eroded and the depth of the diatom mat eroded. The flux of this material to the overlying water column can serve as a measure of food availability, an important parameter for the development of carrying capacity models for shellfish aquaculture in coastal embayments (Dowd, 1991). The extent to which the flux of the eroded diatom mat particles or aggregates varies is greater during exponential phase. The concentration of chlorophyll and bulk carbohydrate available to suspension-feeding bivalves will depend on the ability of a suspension feeder to sort and select for the highly concentrated biofilm particles or aggregates.

CHAPTER THREE

Factors affecting the erodibility of subtidal sediment of a temperate embayment, Lunenburg Bay, Nova Scotia.

3.1 Introduction

In the past, estimates of sediment erodibility have been largely based upon erosion coefficients derived from laboratory studies of abiotic sediment. These laboratory results, obtained from artificially settled abiotic sediment, did not include the complexities arising from biochemical and geophysical influences that occur in nature subsequent to sediment deposition (Amos *et al.*, 1992b). The properties of natural sediment are a result of recent and historical events integrating oceanographic, sedimentological, and biological conditions (Paterson and Daborn, 1991). These factors are highly interactive and not easily predicted. Since the application of results based on laboratory studies may not be realistic (Nowell and Jumars, 1987), it is important to carry out sediment stability measurements *in situ* or on sediment that retain their properties during laboratory measurements.

Erosion of undisturbed subtidal sediments and subsequent sampling of resuspended matter was carried out with the use of an *in situ* benthic annular flume (Sea Carousel; Amos *et al.*, 1992b). Several studies have assessed the effect of diatom biofilms on the stabilization of intertidal sediments (Grant *et al.*, 1986a, 1986b; Paterson, 1989, Paterson, *et al.*, 1990); however, little is known of the effect of diatom biofilms on the erosion thresholds of permanently submerged sediments. Diatoms concentrate in the upper 2 mm of sediment and form mucilage biofilms that alter the biochemical and geophysical properties of sediment and may stabilize the seabed (Paterson, 1989).

Population explosions of diatoms at the sediment-water interface may regulate the dynamics of both dissolved and particulate organic matter in surficial sediment. A highly adhesive matrix, formed through the production of extracellular polymeric substances (EPS) by the developing biofilm, will also regulate resuspension rates and further impact the quality and quantity of sediment organic matter. Once the erosion threshold has been surpassed, resuspension of biofilms will influence phytoplankton ecology by enhancing water column concentrations of nitrogen-limiting nutrients (Floderus and Hakanson, 1989) or reducing light attenuation (Arfi and Bouvy, 1995). Therefore, biomediated sediment processes and consequent sediment stability will have an impact on primary production and benthic-pelagic coupling in shallow estuaries.

Resuspension of biofilms may provide a high-quality food source for suspension feeders (Baillie and Welsh, 1980, Shaffer and Sullivan, 1988, Grant *et al.*, 1990, Frechette and Grant, 1991, Emerson *et al.*, 1994). Since both natural and cultured bivalve populations have been observed to deplete the water column of seston (Wildish and Kristmanson, 1984, Frechette and Bourget, 1985), resuspension of microphytobenthos may provide a buffer against a fluctuating planktonic food supply. Alternately, prolonged resuspension events may result in the erosion of increasing concentrations of inorganic matter that may dilute seston quality. Resuspension of material containing a high inorganic content has been shown to have adverse effects on the feeding rates (Bricelj and Malouf, 1984), absorption efficiencies (Conford, 1995) and growth (Wallace and Reinsnes, 1985) of bivalves.

Erosion type is important in defining whether resuspension is beneficial or detrimental to estuarine food webs. Since Type I erosion is associated with the resuspension of the biologically active surface layer, the material suspended will likely contain high quality (low inorganic) seston, important in estuarine food webs. Because the lifetime of Type I erosion is extremely short, this peak in erosion may be missed during the routine sampling of typical monitoring programs. As Type II erosion proceeds the seston quality may become diluted with inorganic matter underlying the biologically productive layer. The objectives of this chapter are (1) to correlate the presence of biofilms with the erosion thresholds, erosion rates, and erosion type of subtidal sediment in Upper South Cove, Lunenburg Bay, Nova Scotia and (2) to examine the relationship between the supply and quality of the eroded seston composition with shear velocity. The Sea Carousel was used to determine the erosion measurements

3.1.1 Study site

Upper South Cove is a shallow coastal embayment situated within Lunenburg Bay, Nova Scotia, located 63 km southwest of Halifax (Figure 3.1). It is a region of particular interest since it contains a commercial mussel farm and is presently being assessed as a site for suspended and bottom scallop culture. Upper South Cove has a length of 3.5 km, an average width of 0.5 km, an average depth of 1 to 2 m and a maximum depth of 8.5 m. The inner termination of Upper South Cove was created in 1968 due to the construction of a causeway between Corkum's Island and the mainland. The narrow constriction located at the mouth of Upper South Cove causes water to enter and leave this region as a

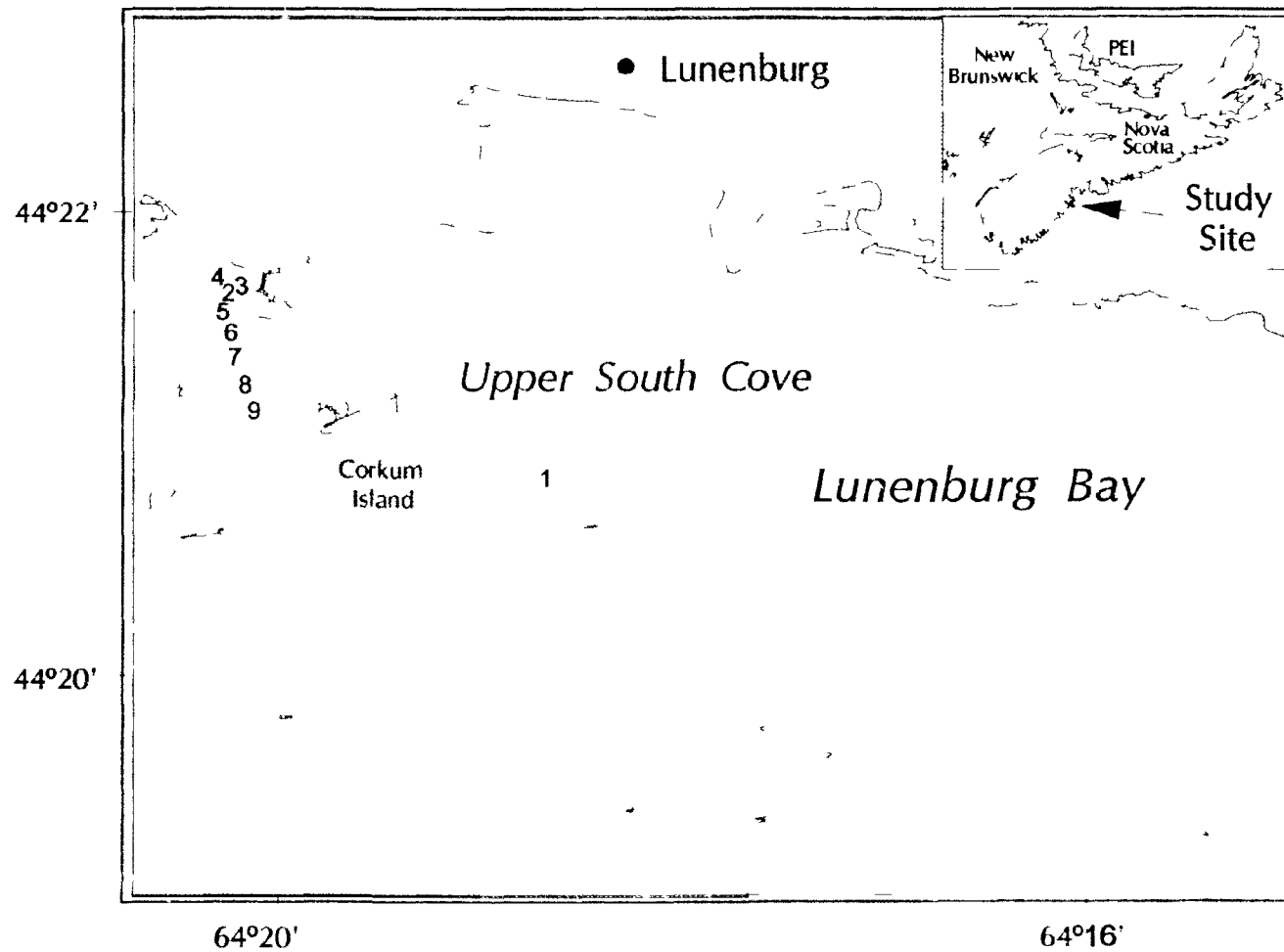


Figure 3.1: Location of stations in Upper South Cove and Lunenburg Bay, Nova Scotia.

tidal jet. A long ebb tide and a short flood tide results in marked differences in tides between Upper South Cove and Lunenburg Bay (Dowd, 1991).

Upper South Cove can be divided into two regions based on tidal excursion (Dowd, 1991). Water in the inner half of the Cove will not be flushed from the Cove on a single tidal cycle; however, water in the outer Cove region, defined by a midpoint approximately 1.4 km from the Cove mouth, will be renewed each tide. Silt deposition in the inner Cove is likely controlled by the velocity distribution and by the asymmetry of the tide, which together cause a headward residual motion of sediment. As a result the inner Cove is a region of silt deposition, while sediment near the tidally scoured entrance contains higher proportions of sand.

In situ testing of sediment stability may result in realistic measures of the erodibility of sediment, however; difficulties arise in the establishment of dominant factors involved. In order to delineate the effect of biofilms on the erodibility of sediment, the inner half of Upper South Cove was chosen since little variation in physical properties, such as sediment grain size and porosity, exist in the sediment. Sediment chlorophyll is generally high in this shallow region as light penetrates to the sediment-water interface (Grant *et al.*, 1995).

Sediment in the inner Cove is characterized by unconsolidated muds of 20 to 30 % silt-clay by weight (Grant *et al.*, 1995). The sediment is highly pellitized with an organic content of approximately 22 % and surface porosities of up to 87 %. The average current in the Cove is $0.12 \text{ m}\cdot\text{s}^{-1}$ with resuspension of fine material occurring at peak flows of 0.3 to $0.6 \text{ m}\cdot\text{s}^{-1}$ during flood tide (Emerson *et al.*, 1994).

3.2 Methods

Seven stations were chosen along a transect extending over the inner half of Upper South Cove, as well as an additional station located outside Upper South Cove in Lunenburg Bay, Nova Scotia (Figure 3.1). The erodibility of the sediment at these stations was determined by use of the Sea Carousel, an *in situ* benthic annular flume (Amos *et al.*, 1992b), from October 16th to 19th, 1993. Duplicate deployments were carried out at one station located at the inner termination of Upper South Cove to assess spatial variability. A core was collected at each station in Upper South Cove by SCUBA on October 20, 1993. Cores were used to conduct laboratory erosion experiments in a recirculating flume, similar to those described in Chapter 2.

3.2.1 The Sea Carousel

The Sea Carousel has a radius of 1.0 m, an annulus width of 0.15 m and a height of 0.30 m (Figure 3.2). A 0.35 hp motor, powered from the surface, drives a movable lid. Eight small paddles, attached below the movable lid, induce flow in the annulus at the onset of lid rotation. A skirt is situated on the outer wall of the annulus and standardizes penetration of the flume into the seabed.

Optical backscatter sensors (OBS, Downing and Beach, 1989) are located inside (0.03 and 0.18 m above the skirt) and outside the annulus to measure ambient and resuspended solids. A window is situated in the inner flume wall, through which an underwater video camera records erosion of the seabed. Azimuthal and vertical components of flow within the annulus are recorded with an electromagnetic

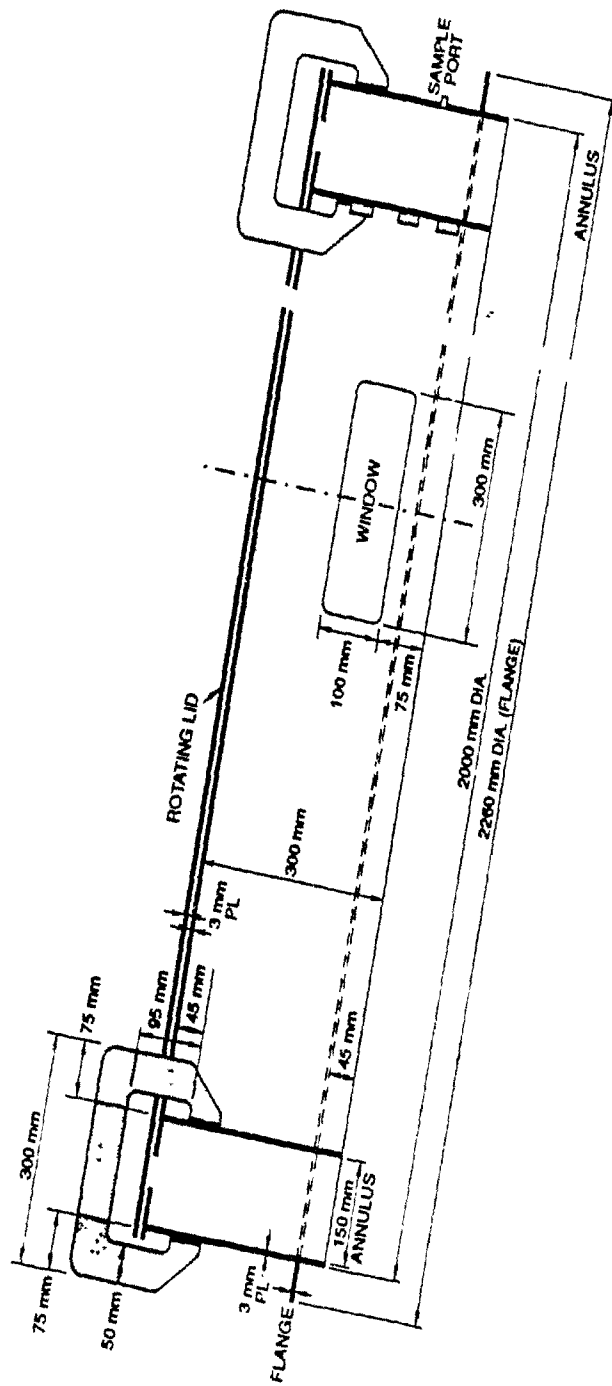


Figure 3 2: A schematic diagram in cross-section of the Sea Carousel, a benthic annular flume

Marsh-McBirney current meter. Data is stored on an underwater storage module and intermittently downloaded to a surface computer. The speed of the rotating lid is increased stepwise at 10 minute intervals to increase near bed flow and, thus, shear velocities. Shear velocity values were derived from lid speed as outlined in Amos *et al.*, (1992). These calculations were based on previous measurements made using an omni-directional, flush-mounted, hot-film probe and on particle velocity profiles obtained through video observations.

A sampling port is situated 0.2 m above the flume skirt at a height similar to the upper OBS. During the deployment, water samples were collected from this port with the aid of a foot pump, attached to a 1/4" (inner diameter) tygon hose. The volume of the hose was flushed before each water sample was collected. Sampling occurred one minute after the speed of the rotating lid was increased in a series of regular steps. The analysis of the eroded material is described below.

3.2.2 Suspended particulate matter, carbon, nitrogen, inorganic, and chlorophyll concentrations of the eroded material.

Deployments took place in October, 1993. Water samples containing eroded material were collected at each speed increment, 2 minutes after the flow was increased. The 500 ml water samples were resuspended and split for analysis of SPM, inorganic content, chlorophyll, phaeopigment, and POC and PN concentrations.

SPM was determined gravimetrically through filtration. Whatman glass-fibre filters (GF/C) were dried at 55 °C for 48 hours and subsequently desiccated for 2 hours. An isotonic solution of ammonium formate was used to rinse the filters to remove salts.

Inorganic content was determined as the residual after combustion for 4 hours at 500° C. A separate series of filters were dried at 55 °C for 48 hours, desiccated for 2 hours, weighed, and processed at 950 °C with a Perkin-Elmer CHN 2400 Elemental analyzer for determination of POC and PN. A t-test revealed that the mean POC content of a series of replicate SPM filters was not significantly different from that of another series of replicate SPM filters exposed to HCL fumes, leading one to conclude that the potential contamination by carbonate was insignificant. In addition, exposure to acid would potentially (1) drive off volatile organic material, (2) result in incomplete decomposition of carbonate, and (3) interfere with combustion tube catalysts present in the CHN analyzer (Moriarty and Barclay, 1980).

Chlorophyll analysis was performed by placing Whatman glass-fibre filters (GF/C) into 10 ml of a 90 % acetone:water solution and extracting for 24 hours in a cold and dark refrigerator. Fluorescence was then measured using a Turner Designs Model 10^m fluorometer. Two drops of 10 % HCl were added to each sample, and the fluorescence measured again. Fluorescence values were converted to chlorophyll and pheopigment according to the method advanced by Parsons *et al.* (1984).

3.2.3 Sediment cores

Replicate 60-ml syringe-cores (inner diameter: 2.6 cm; depth: 6 cm) were taken from a Van Veen Grab sample collected at each station located inside Upper South Cove. One core from each station was analyzed for bulk density by X-ray computed tomography using a GE® Hilite Advantage CT scanner (Amos *et al.*, 1996). Tomogram-averaged bulk

density measurements were taken every 1.5 mm (minimum thickness of tomogram slice) in the upper cm of the sediment column. Below this depth 1.5 mm tomograms were taken every 5 mm. Bulk density values were derived by converting Hounsfield Units to CT scanner values (to remove negative numbers) and then transforming the CT values to sediment bulk density values after Amos *et al.* (1996).

The topmost 1 mm and 2 mm of the second set of cores collected from each station were analyzed for both chlorophyll and phaeopigment concentrations, since the chlorophyll maximum was generally above a depth of 2 mm in the sediment. Slices of each sediment layer were cut in 1 mm depth intervals. Each layer was placed in 10 ml of 90 % acetone-water solution, contained in centrifuge tubes, for 24 hours in a cold and dark refrigerator. These samples were centrifuged at 2000 rpm for 5 minutes. Chlorophyll and phaeopigment concentrations of the supernatant were determined fluorometrically according to Parsons *et al.* (1984). The values for the 1 mm and 2 mm sediment slices of each core were averaged. The surface topography of the sediment cores may have influenced the sediment component concentration of the 1 mm surface interval, limiting its use as an indicator of sediment erodibility. The remaining core was sectioned at 1 mm slices up to 15 mm, 1 mm slices every 5 mm, and then 1 mm slices every 10 mm, thereafter.

Each 1 mm slice of the third set of cores collected from each station was split and analyzed for particulate organic matter and carbohydrate concentrations. One half of each slice was dried at 55 °C for 48 hours and processed with a Perkin-Elmer CHN 2400 Elemental analyzer to determine POC and PN. The other half of each sediment layer was

analyzed for colloidal and bulk carbohydrate using a phenol-sulphuric acid method (Dubois *et al.*, 1956) as modified for sediments (Lui *et al.*, 1973). The half-slices were placed in test tubes that had been acid washed with 10 % HCL and rinsed 7 times with SuperQ water. One ml of 30 ppt saline solution was added to each test tube, and each test tube was shaken thoroughly. The samples were centrifuged for 10 minutes at 2000 rpm after an extraction period of one hour. The supernatant (colloidal carbohydrate fraction) from each sample was transferred to a set of clean test tubes. One ml of 5 % phenol and 5 ml of concentrated sulphuric acid were added to each supernatant and sediment pellet (bulk carbohydrate fraction). Each sample was shaken, allowed to stand for 1 hour, read on a spectrophotometer at 485 nm, and standardized against a calibration curve of glucose equivalents. The values for the 1 mm and 2 mm sediment slices of each core were also averaged.

A Siemens Diffractometer 500 was used to determine the mineralogy of the clay fraction ($< 2 \mu\text{m}$) collected from surface bulk samples of the grab cores. Talc was the standard against which kaolinite, chlorite, and mica were determined, and corundum was the standard for quartz and plagioclase (Amos *et al.*, 1996).

3.2.4 Erosion Measurements

Erosion thresholds were determined using the linear regression analysis outlined in Chapter 1. Peak erosion rates were obtained from a plot of a 10-second time-averaged time-series of erosion rates. The OBS data collected at each station was calibrated with the corresponding SPM concentration of the water samples. Instantaneous erosion rates

were calculated by standardizing the SPM concentration by the volume and area of the flume and then dividing by the time difference between OBS readings. This continuous data set was then time-averaged at a 10 second interval using a GWBASIC program verified by the Geological Survey of Canada. The "peaks" of the erosion rates were obtained from the time series plot which occurred at the onset of each speed increment. Net erosion rates were calculated as the differential concentrations of the eroded sediment variables of the water samples divided by the elapsed time.

Single regressions were used to correlate the sediment biofilm components to erosion thresholds, peak erosion rates, and net erosion rates. Partial regressions were considered, but not used due to (1) the high degree of collinearity between the sediment biofilm variables and (2) the lesser number of data points than sediment biofilm variables (violation of an assumption of multiple regression).

3.3 Results

3.3.1 Biological and physical sediment predictors

The sedimentary column of the cores collected from stations in Upper South Cove consisted of an oxidized layer of golden-brown, loosely-bound, silty, clay overlying black, reduced sediment occurring at a depth of approximately 2 mm. Table 3.1 shows the concentrations of chlorophyll, phaeopigment, colloidal carbohydrate, bulk carbohydrate, POC, and PN measured within the topmost 2 mm of stations 2 to 9 located in the inner half of Upper South Cove (Figure 3.1). Sediment characteristics of station 1 located outside Upper South Cove are discussed in section 3.3.10.

Table 3.1: Sediment biofilm measurements of the topmost 2 mm of single cores collected at stations 3, 5, 6, 7, 8, and 9 in Upper South Cove. Station locations indicated by number in Figure 3.1.

SEDIMENT COMPONENT	STATION					
	3	5	6	7	8	9
Station depth (m)	3.5	5.2	6.5	3.3	8.5	6.1
Station distance along Cove (km)	0.13	0.23	0.46	0.67	0.9	1.3
Chlorophyll ($\mu\text{g}\cdot\text{ml}^{-1}$)	5.12	3.64	2.32	4.47	1.97	2.63
Phaeopigment ($\mu\text{g}\cdot\text{ml}^{-1}$)	12.28	12.78	11.52	12.4	11.8	9.94
Chlorophyll : phaeopigment	0.42	0.29	0.21	0.36	0.17	0.27
Colloidal carbohydrate ($\text{mg}\cdot\text{ml}^{-1}$)	0.14	0.07	0.04	0.1	0.06	0.07
Bulk carbohydrate ($\text{mg}\cdot\text{ml}^{-1}$)	1.93	2.45	1.84	1.51	2.01	2.66
POC ($\text{mg}\cdot\text{ml}^{-1}$)	1.8	2.59	1.97	2.14	2.08	2.06
PN ($\text{mg}\cdot\text{ml}^{-1}$)	0.18	0.25	0.21	0.23	0.22	0.21
POC : PN	10	10.2	9.5	9.4	9.7	10
C : CHL	352	711	849	479	1054	783
Bulk density ($\text{kg}\cdot\text{m}^{-3}$)	950	895	812	954	1006	1150
Inorganic content (%)	77.3	73.9	75.7	82.2	77.2	79.3

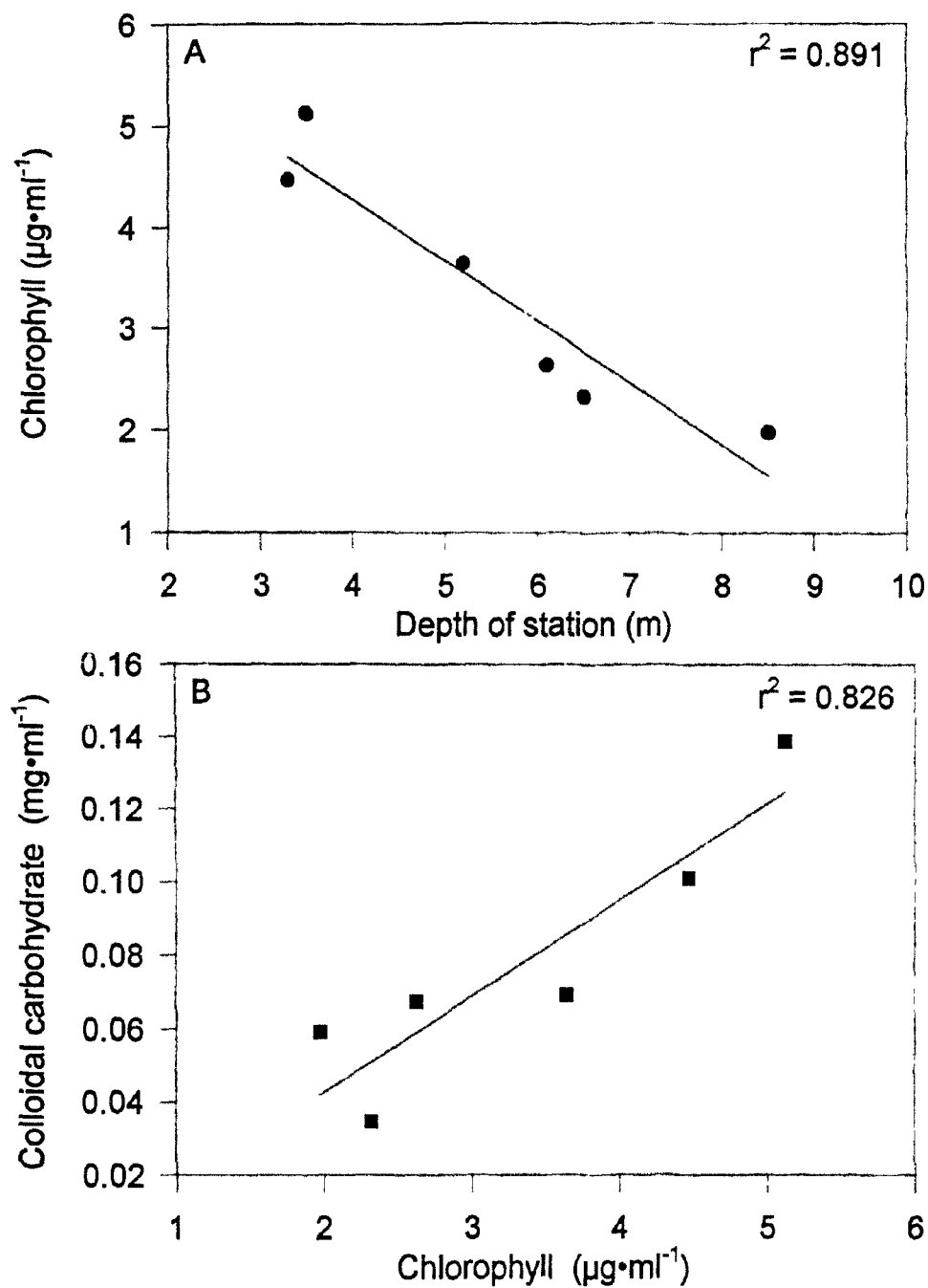


Figure 3.3: Regressions showing the relationship between sediment chlorophyll content and depth of station (A) and between sediment colloidal carbohydrate and chlorophyll content (B).

Sediment chlorophyll concentration was negatively correlated with the depth of station ($r^2 = 0.891$, $p = 0.005$; Figure 3.3A), while sediment colloidal carbohydrate was positively correlated with chlorophyll content ($r^2 = 0.826$, $p = 0.012$; Figure 3.3B). The ratios of colloidal carbohydrate to chlorophyll were higher in the field sediments (17.2 to 30.5) relative to those in the laboratory sediments (Chapter 2) cultured with *Nitzschia curvilineata* (0.2 to 1.3). The ratios of bulk carbohydrate to chlorophyll were also higher in the field sediments (338 to 1011) relative to those in the laboratory sediments (7.9 to 87.2). The higher carbohydrate concentrations observed in the field sediments may be due to (1) ambient nutrient conditions and (2) to the inclusion of carbohydrates from other microbes, macrophyte detritus, invertebrate tubes, pseudofeces, or feces. No significant correlation was found between chlorophyll or colloidal carbohydrate and any other sediment components listed in Table 3.1. Phaeopigment, bulk carbohydrate, POC, and PN showed little variation in concentration in the surface sediment across stations.

3.3.2 Vertical profiles of bulk density and chlorophyll

The vertical gradients in bulk density measurements of stations in Upper South Cove became more structured towards the inner termination of the Cove (Figure 3.4). These profiles could be divided into 3 distinct sediment layers: (1) a biogenic layer, (2) a consolidating layer, and (3) an underlying layer. The biogenic layer consisted of bulk density values below $1000 \text{ kg}\cdot\text{m}^{-3}$ and gradually became thinner seaward through the estuary. The consolidating layer ranged between values of 1000 to $1100 \text{ kg}\cdot\text{m}^{-3}$ and extended to depths of 15 mm at the inner station. The consolidating layer of station 9

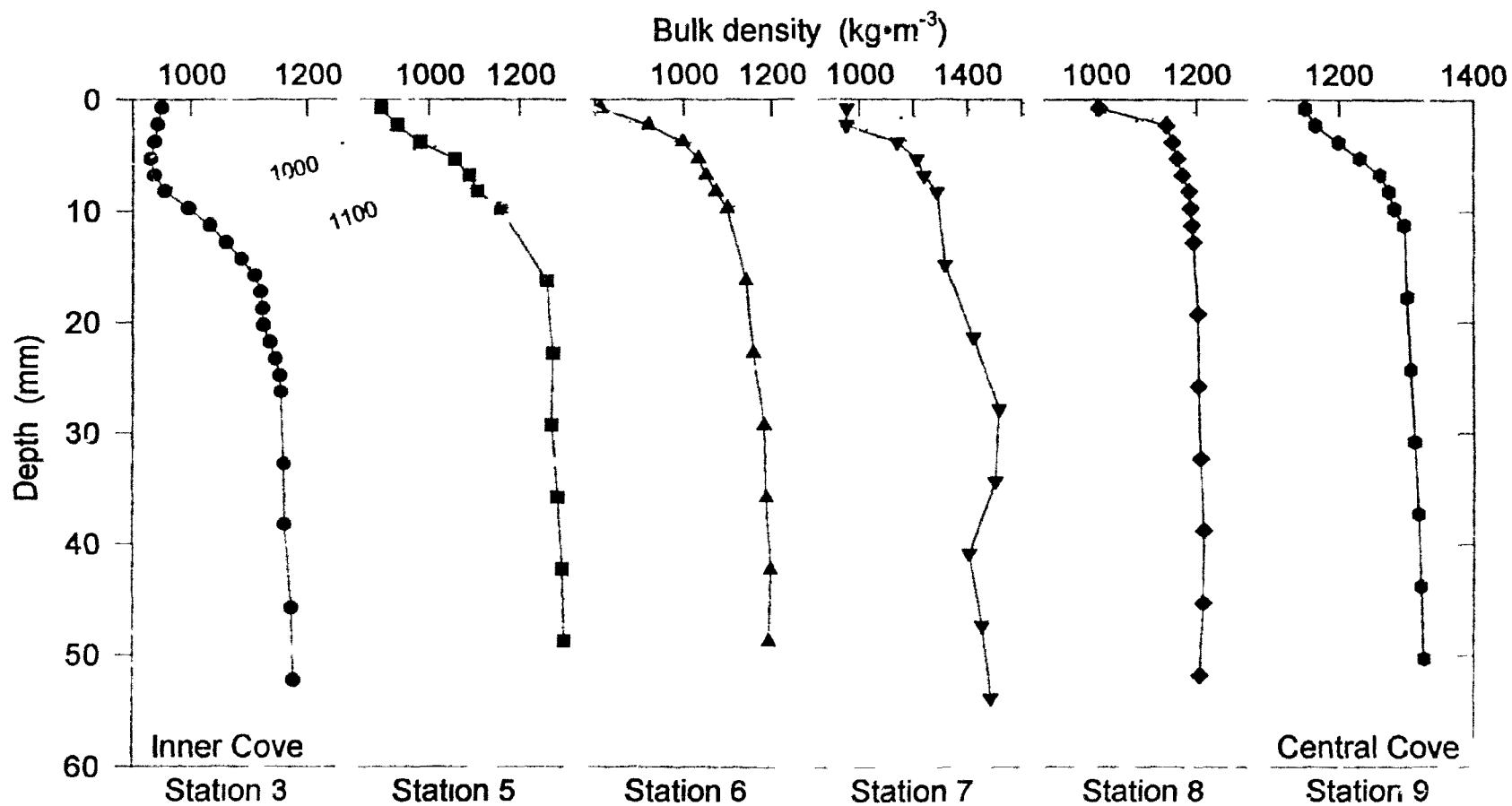


Figure 3.4 Bulk density profiles of stations 3, 5, 6, 7, 8, and 9 located along a transect in Upper South Cove. Dotted lines represent isopycnals. Station locations are indicated in Figure 3.1.

reached a maximum bulk density value of $1300 \text{ kg}\cdot\text{m}^{-3}$ at a shallow depth of 11 mm. This station is located in the Cove centre or the transition zone defined by tidal excursion.

A core of a sediment wedge and air was used to calibrate the CT numbers with bulk density. The histogram of the bulk density distribution of the sediment wedge taken mid core shows two strong peaks representing the air and sediment components (Figure A3.1). Histograms of the bulk density distributions of the surface 15 mm of station 3 shows the replacement of the buoyant material (bulk density values below $1000 \text{ kg}\cdot\text{m}^{-3}$) by a more homogeneous material of higher bulk density (Figure A3.2). The absence of a peak at low densities (gas) in these natural sediment may be due to the integration of gas and biofilm material, since the gas voids were probably smaller than the voxel height (1.5 mm) or Catscan resolution. The dark spheres observed in the tomogram images that may represent gas bubbles were typically less than 1 mm in diameter.

The bulk density profiles show that there is a general increase in surface bulk density from the inner region to the central region of Upper South Cove. Values of bulk density taken every 5 mm were averaged to a depth of 1 mm, 5 mm, 10 mm, 15 mm, and 20 mm. The depth-averaged values of bulk density at 5 mm ($r^2 = 0.345$, $p = 0.010$), 10 mm ($r^2 = 0.808$, $p = 0.015$), and 15 mm ($r^2 = 0.717$, $p = 0.034$) were significantly correlated with distance seaward through the Cove. The bulk density values at 1 mm and the depth-averaged values of bulk density at 20 mm increased with distance seaward through the Cove, although no significant correlations existed. These depth-averaged bulk density values did not correlate with concentrations of chlorophyll and phaeopigment in the topmost 2 mm of sediment. The thickness of the low bulk density surface layer

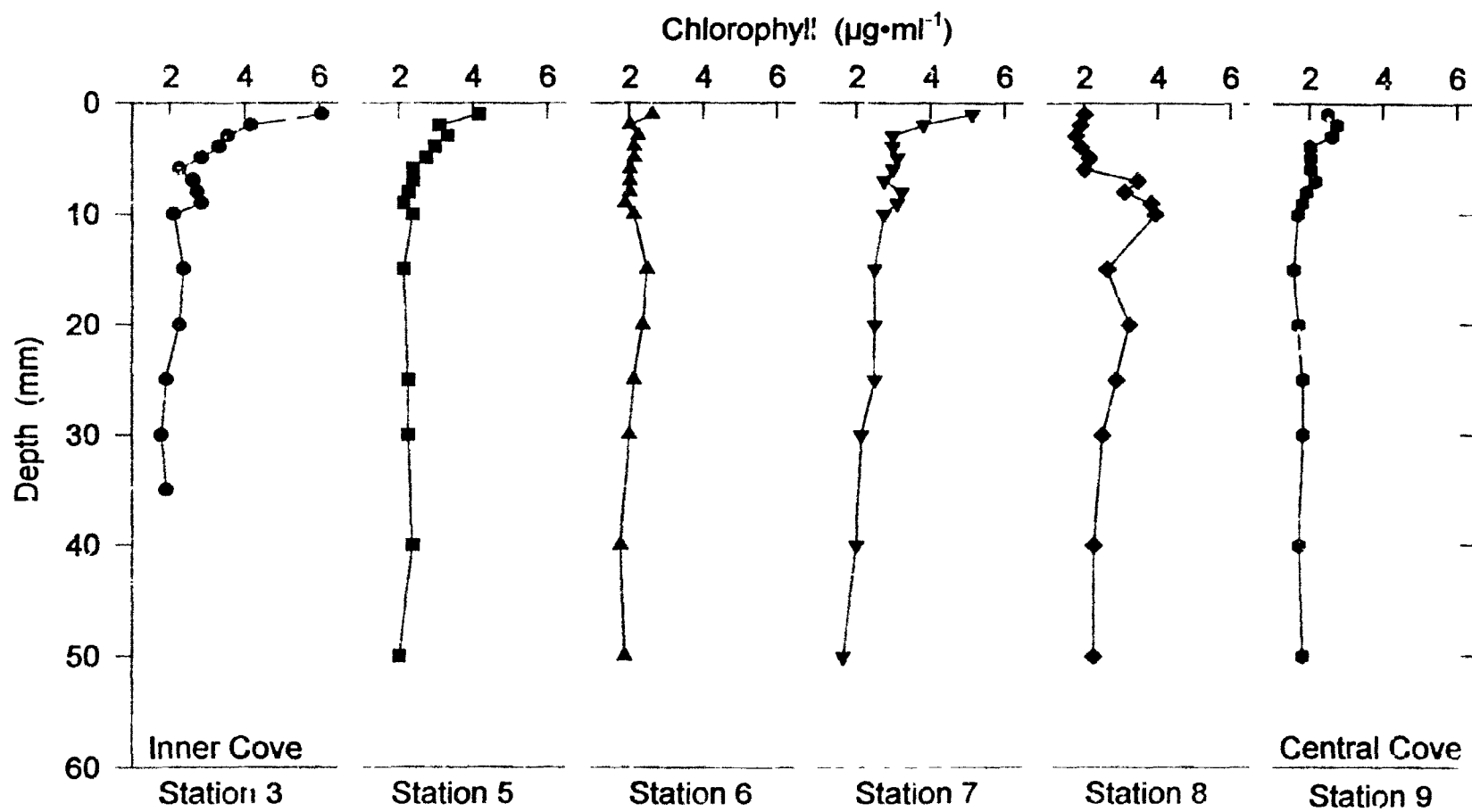


Figure 3.5: Sediment chlorophyll profiles of stations 3, 5, 6, 7, 8, and 9 located along a transect in Upper South Cove. Station locations are indicated in Figure 3.1.

corresponds to the thickness of the chlorophyll gradients in the sediment surface (Figure 3.5). The shallow stations (3 and 7) with higher surface chlorophyll concentrations had higher ratios of chlorophyll to phaeopigment (Table 3.1), suggesting greater growth activity at these stations relative to the remaining stations.

3.3.3 Relationship between U_{crit} and sediment biofilm predictors

The quantity, size, shape, and density of loosely bound organic-mineral aggregates varied across the stations. Well-developed biofilms were evident in the sediment cores of stations 3 and 7 which also contained the highest sediment chlorophyll and colloidal carbohydrate contents. Erosion of these cores in the laboratory flume revealed that once the critical erosion threshold was surpassed, organic-mineral aggregates released ranged in size between 1 to 4 mm. These flake-shaped aggregates became detached and travelled in a rolling motion along the length of the flume floor. The sediment surfaces of the remaining cores (stations 5, 6, 8, 9) became smooth during the erosion trial, suggesting that smaller individual particles were eroded but not detected visually. Eventually, smaller organic-mineral aggregates were eroded from these sediment cores. These aggregates became detached and travelled in suspension forming organic "strings".

Regressions of U_{crit} vs the sediment biofilm components, listed in Table 3.1, revealed that chlorophyll content ($r^2 = 0.948$, $p = 0.001$, Figure 3.6A), colloidal carbohydrate content ($r^2 = 0.854$, $p = 0.008$; Figure 3.6B), and depth of station ($r^2 = 0.843$, $p = 0.01$, Figure 3.6C) were significantly correlated with U_{crit} . Regression equations were listed in Table 3.2.

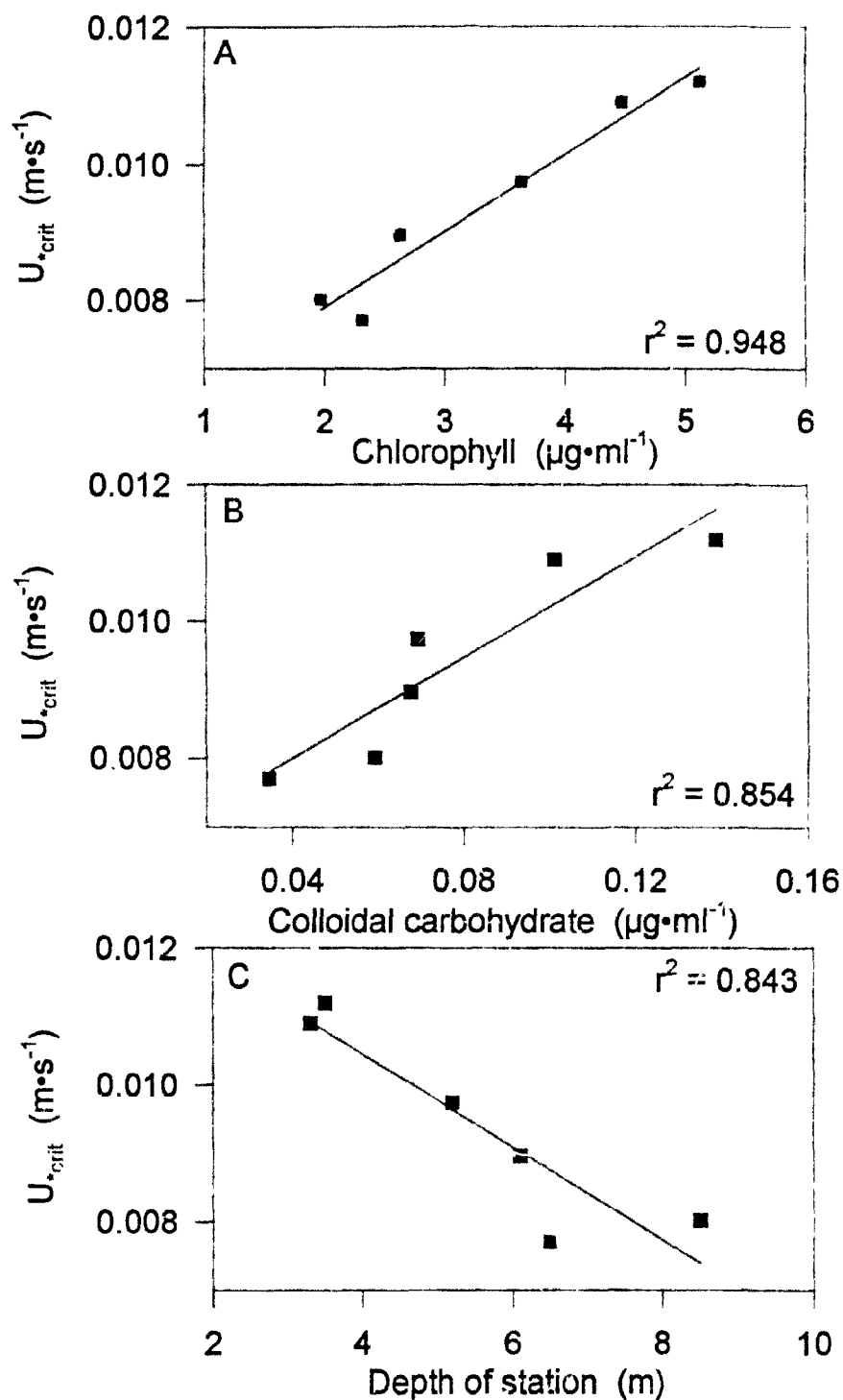


Figure 3.6: Regressions showing the relationship between U_{crit} and sediment chlorophyll concentration (A), sediment colloidal carbohydrate concentration (B), and depth of station (C). Data was collected from Sea Carousel deployments in Upper South Cove.

Table 3.2: Regressions describing the relationships between U_{crit} and sediment: chlorophyll, sediment colloidal carbohydrate, and depth of station. Level of significance = 0.05.

Regression equations	r^2	p
$U_{\text{crit}} (\text{m}\cdot\text{s}^{-1}) = 0.0011 (\text{chlorophyll } (\mu\text{g}\cdot\text{ml}^{-1})) + 0.0056$	0.948	0.001
$U_{\text{crit}} (\text{m}\cdot\text{s}^{-1}) = 0.037 (\text{colloidal carbohydrate } (\mu\text{g}\cdot\text{ml}^{-1})) + 0.007$	0.854	0.008
$U_{\text{crit}} (\text{m}\cdot\text{s}^{-1}) = - 0.0007 (\text{depth of station (m)}) + 0.0131$	0.843	0.01

3.3.4 Reliability of the extrapolation method for U_{crit} determination

Linear regressions of SPM vs $\log U_b$ were used to determine U_{crit} (x-intercept) for each Sea Carousel deployment or station located along the transect in Upper South Cove. The SPM vs U_b curve was assumed to be a semi-logarithmic relationship. When considering each deployment, the entire time-series data of SPM was generally included in the SPM vs $\log U_b$ regression to maintain consistency and avoid any subjectivity. However, insight into the "layering" of the sediment column or the premature erosion of material not associated with the seabed would aid in decisions pertaining to 1) the formation of multi-curves representing distinct sediment layers, 2) the forcing of the regression through the first suspended data point, or 3) the rejection of outlier data points.

The reliability of U_{crit} determination by this extrapolation method depends on the log-linearity of this relationship. The regression plots of SPM vs $\log U_b$ for all stations in Upper South Cove showed log-linear relationships (Figure 3.7B and 3.7C), with the exception of station 3 (Figure 3.7A). The relationship between SPM vs U_b for station 3 is made up of two log-linear parts with an inflection point between 0.04 to 0.05 $m \cdot s^{-1}$. A similar relationship was observed by de Jonge and van den Bergs (1987) during erosion experiments dealing with estuarine sediment. The individual sections that make up this curve represent distinct layers of sediment with different erosion characteristics (Figure 3.7A). The initial shallow slope of the regression plot reflects the erosion of the biogenic layer, while the second steeper slope reflects the erosion of the underlying sediment. Regressions of SPM and U_b for station 3 including the entire data set (multi-log-linear,) and the subset of data (shallow slope only) are shown in Figure 3.8A and 3.8C,

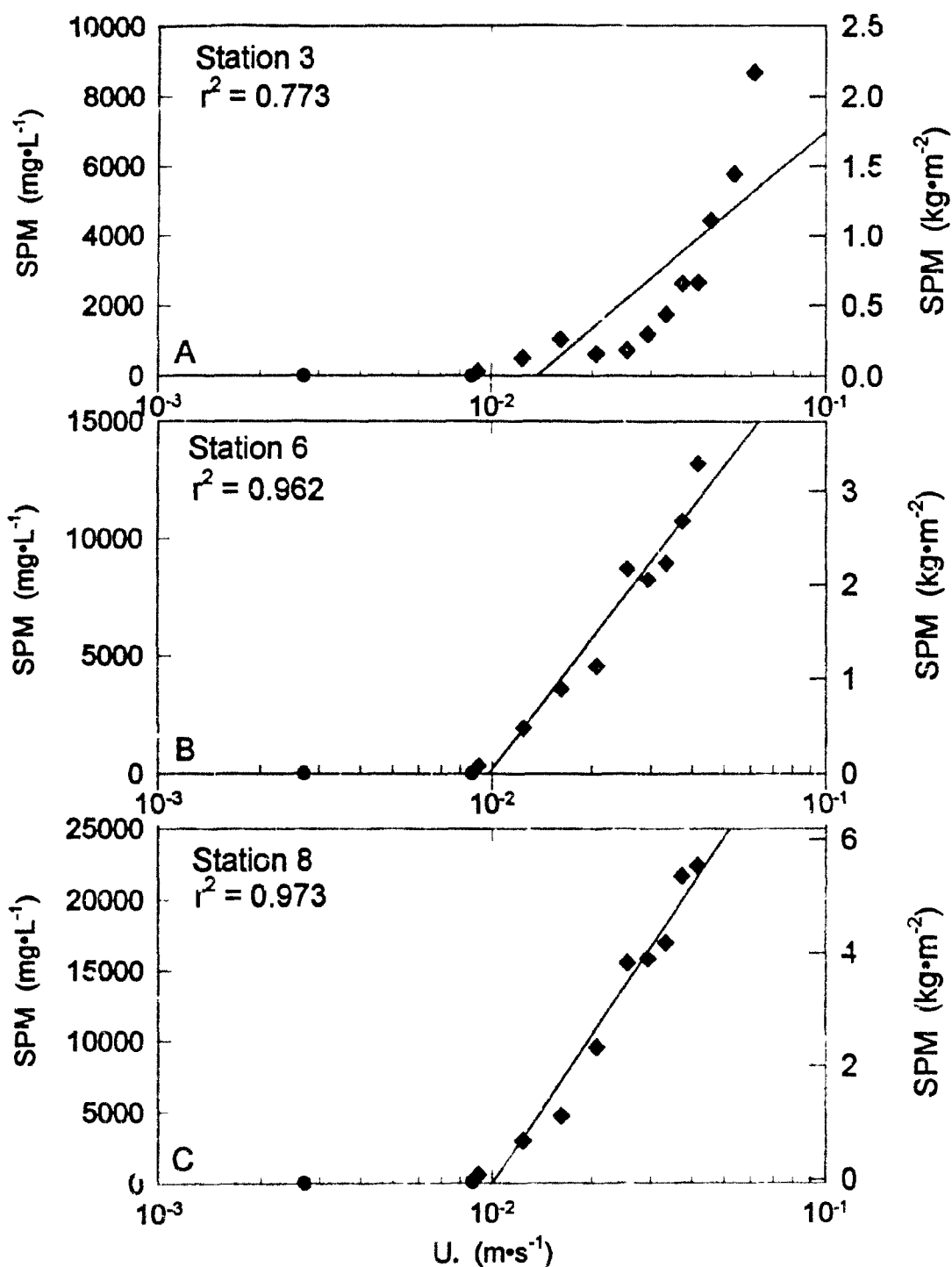


Figure 3.7: Regressions showing relationships between SPM and log U_* for station 3 (A), station 6 (B), and station 8 (C). Diamond symbols represent data points used in regression.

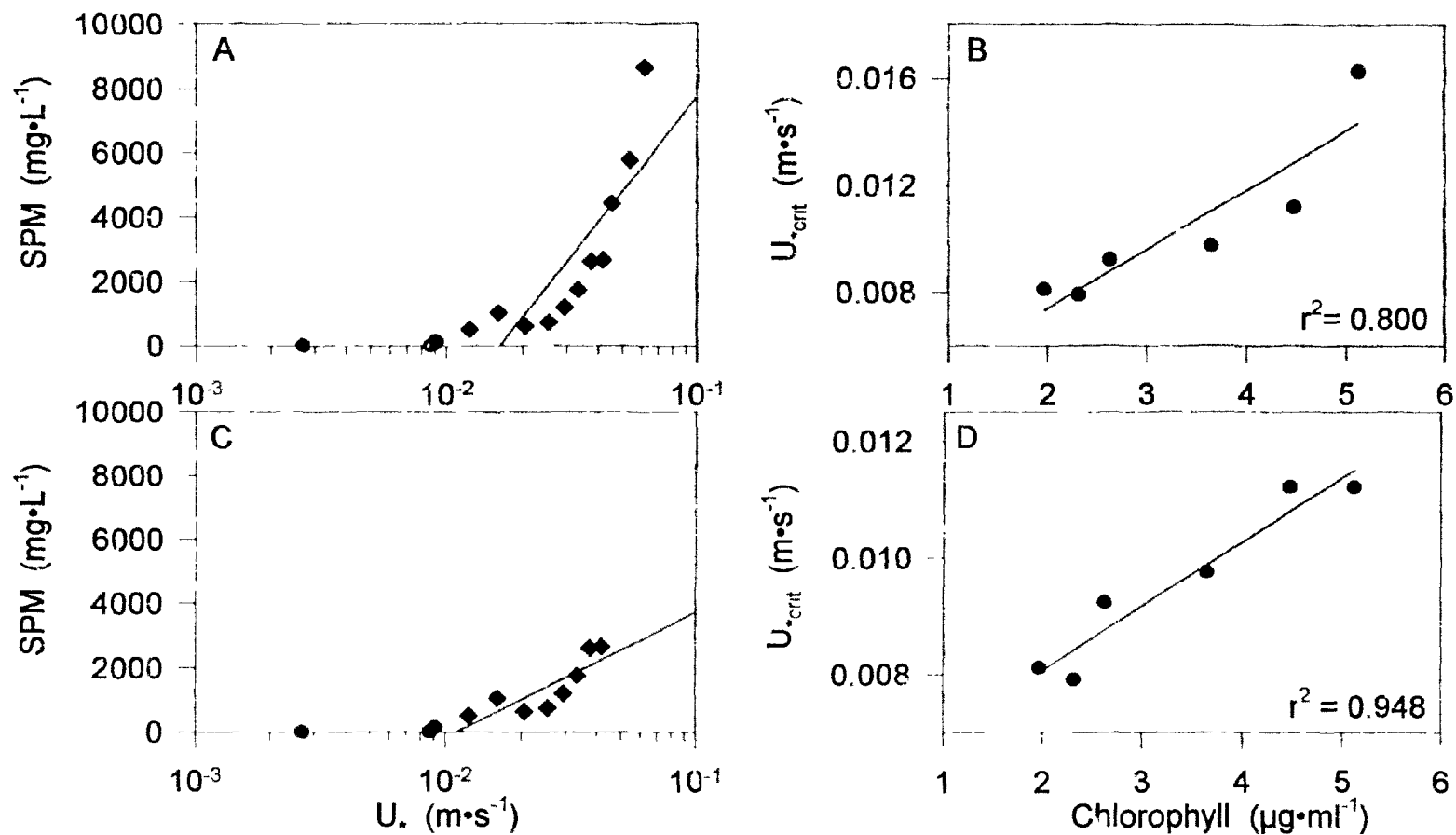


Figure 3.8: Regressions showing the relationship between SPM and $\log U_*$ for the entire data set (A) and for the data subset (C) for station 3. Corresponding regressions between $U_{*,\text{crit}}$ vs sediment chlorophyll content influenced by the use of the entire data set (B) and the data subset (D). Diamond symbols represent the data points used in the regressions for (A) and (C).

respectively. The corresponding plots predicting U_{*crit} from sediment chlorophyll would be influenced by the number of points used in the extrapolation method to determine U_{*crit} and are shown in Figures 3.8B and 3.8D. In order to avoid the potential weighting of the regression by the high values of SPM observed at maximum shear velocities at station 3, the regression determining the U_{*crit} value was limited to the points making up the shallow slope.

The x-intercept, taken as the U_{*crit} value, fell on occasion beyond the data point on the U_* axis that reflected the initial increase in SPM above the baseline ambient concentrations (Figure 3.7A, B, and C). These initial data points may potentially weight or bias the regression analysis, since they have a high noise to signal ratio and may not reflect the erosion of seabed material. For example, the increase and decrease, observed during the initial stages of erosion of SPM at station 3, could have been attributed to the erosion of non-seabed material attached to seagrass fragments lodged into the sediment surface. Video observations were important in differentiating between "noise" and "signal" at the initial stages of erosion and providing a basis for or against forcing the regression through the first resuspended data point.

At station 1 the suspended chlorophyll content reached a maximum concentration or a plateau at a U_* of approximately $0.04 \text{ m}\cdot\text{s}^{-1}$ (Figure 3.9). The maximum suspended chlorophyll concentration reflected the depth at which chlorophyll diminished within the sediment. In addition, 3 initial points did not fall on the linear cumulative plot and were interpreted as the suspension of a chlorophyll fluff layer, not associated with the chlorophyll bound to sediment. It is questionable whether the initial and final data points

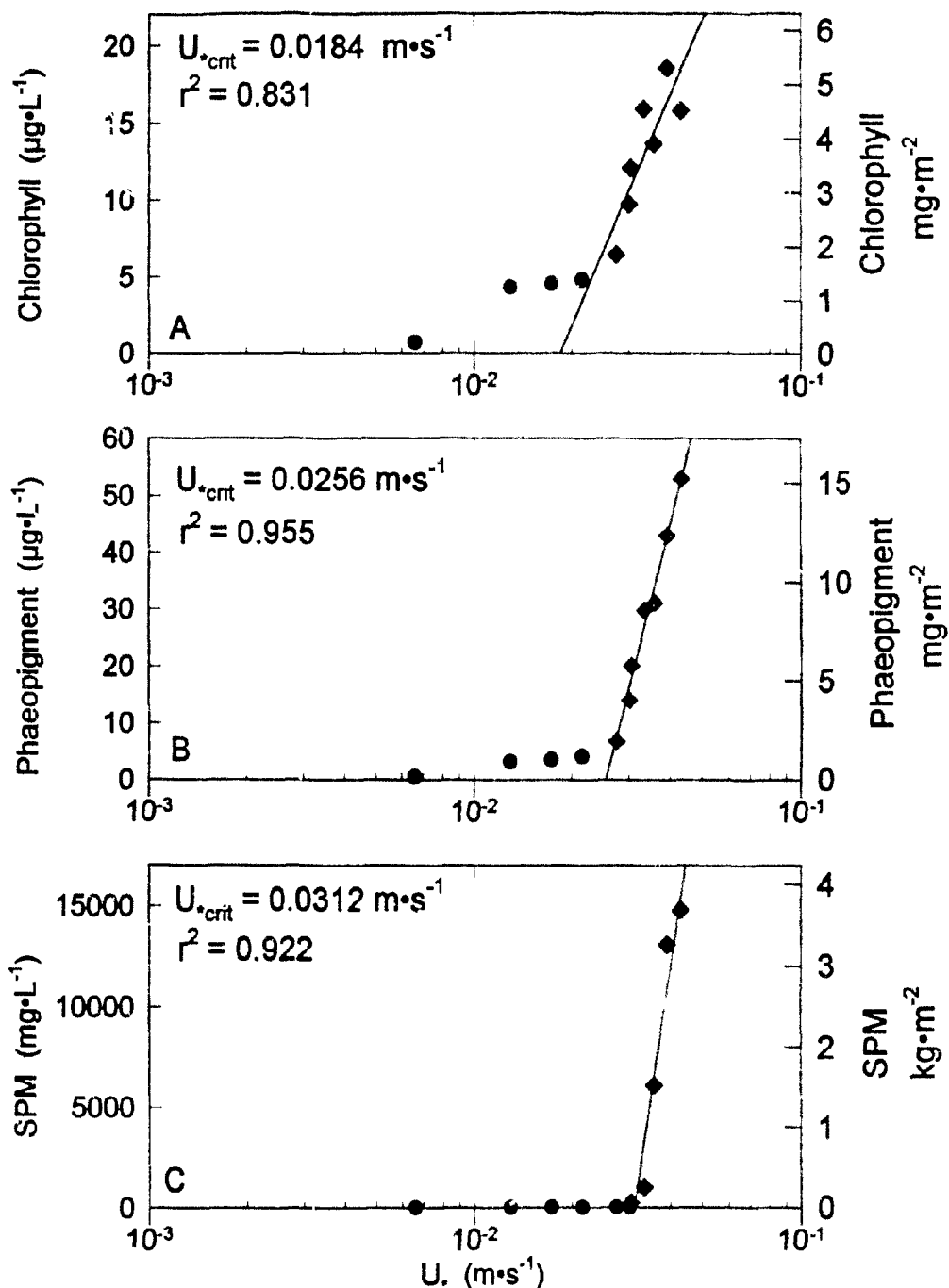


Figure 3.9: Determination of U_{crit} (x-intercept) for chlorophyll (A) phaeopigment (B), and SPM (C) using the extrapolation method (station 1). Diamond symbols represent data points used in the regressions.

on this plot should be used in the regression since these points may bias the analysis. Furthermore, the differential erosion of the various sediment organic components due to a "layering" within the sediment suggests that similar data points need not be used for each component, chlorophyll, phaeopigment, and SPM, at one particular station. For example, chlorophyll was detected on the fifth speed increment, while SPM was not detected until the seventh speed increment at station 1.

3.3.5 Comparison of erosion thresholds of different sediment biofilm components

The largest differences between the U_{crit} values of chlorophyll, phaeopigment, and SPM were observed at station 1 (Figure 3.9). This selective erosion between chlorophyll, phaeopigment, and SPM suggests that a distinct layer of these components exists within the sediment or that there was differential sorting of these biofilm components. During erosion experiments of estuarine sediment, de Jonge and van den Bergs (1987) observed that the size spectrum of suspended material was not in proportion to that of the seabed, with the finer sediment being suspended at lower velocities. Also, a differential suspension of diatom cells was observed, depending on whether the diatoms were associated with the mud fraction or with the sand fraction. These observations are in agreement with those of this study in that the chlorophyll associated with finer particles is suspended before sand grains larger than 200 μm . In addition, there appear to be two increases to the suspended chlorophyll curve. The first increase may reflect the suspension of recently deposited planktonic chlorophyll or fluff layer, not associated with the sediment, or the suspension of benthic chlorophyll associated with a mud fraction that is more easily eroded relative to

the sand fraction. The second increase or linear portion of the chlorophyll curve may reflect the suspension of a chlorophyll layer that is more closely associated with the sand fraction and is limited to the top 2 mm of sediment.

Smaller differences in the erosion thresholds of chlorophyll, phaeopigment, and SPM were observed at stations in Upper South Cove (Figure 3.10). Since the sediments of Upper South Cove are largely made up of fecal pellets and mud aggregates colonized with diatoms, a discriminatory suspension between these 3 sediment biofilm components would not be expected.

3.3.6 Relationship between peak erosion rate and sediment biofilm predictors

Figure 3.11 is a time-series plot of current speed, SPM, and peak erosion rates measured at station 9. The time-series plots of the Sea Carousel deployments of the remaining stations are located in Appendix A1. The continuous data set of SPM and peak erosion rates were derived from the calibrated optical backscatter sensors (OBS). The peak erosion rates of Type I erosion were negatively correlated with sediment chlorophyll ($r^2 = 0.778$, $p = 0.02$, Figure 3.12A), colloidal carbohydrate content ($r^2 = 0.778$, $p = 0.02$, Figure 3.12B), and U_{crit} ($r^2 = 0.691$, $p = 0.04$; Figure 3.12C). The regression equations are listed in Table 3.3.

3.3.7 Relationship between net erosion rate and sediment biofilm predictors

Net erosion rates were negatively correlated with sediment chlorophyll concentrations ($r^2 = 0.875$, $p = 0.006$, Figure 3.13A), sediment colloidal carbohydrate

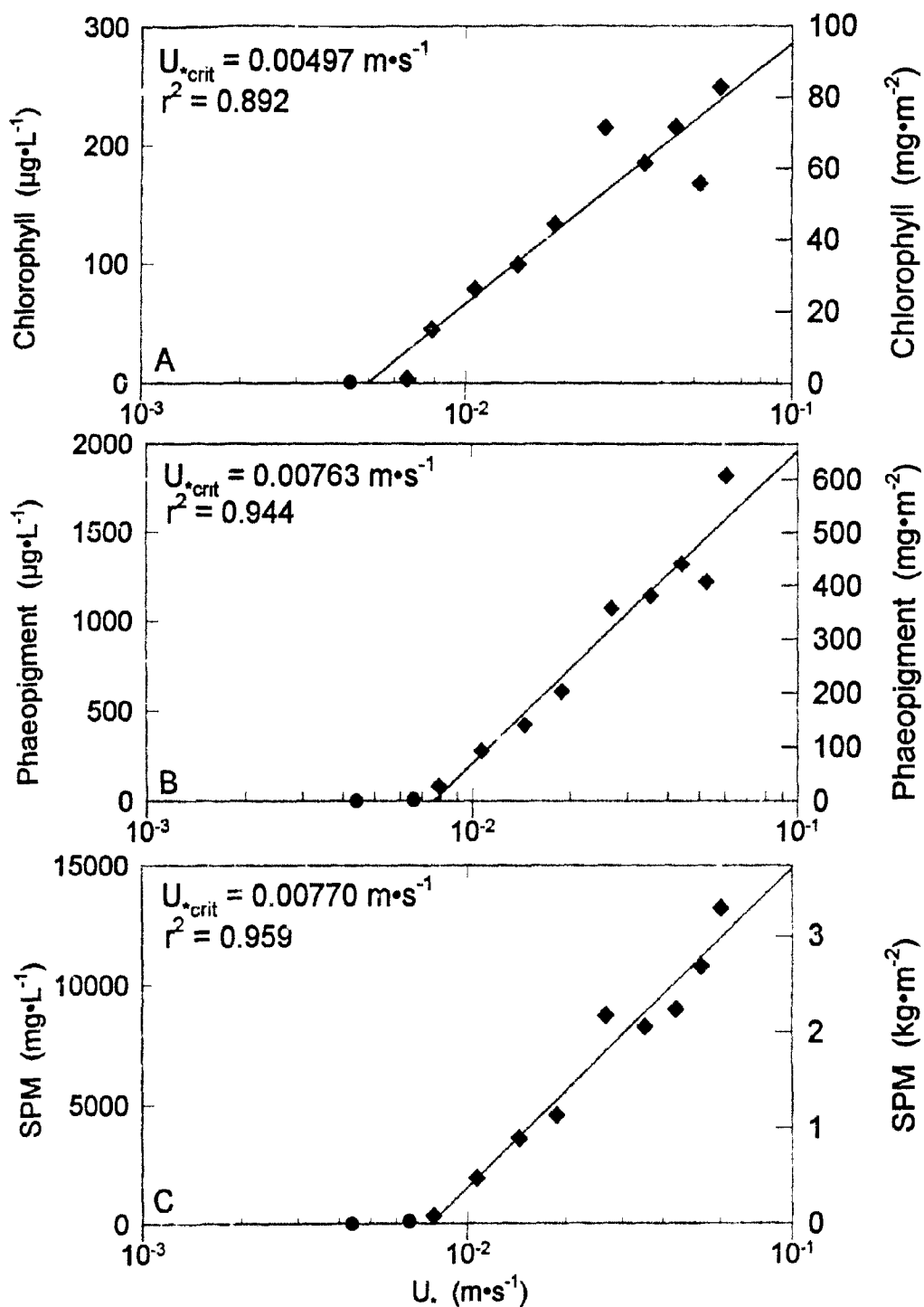


Figure 3.10: Regressions of the sediment biofilm components and $\log U$ of station 6 showing small differences between the respective U_{crit} values.

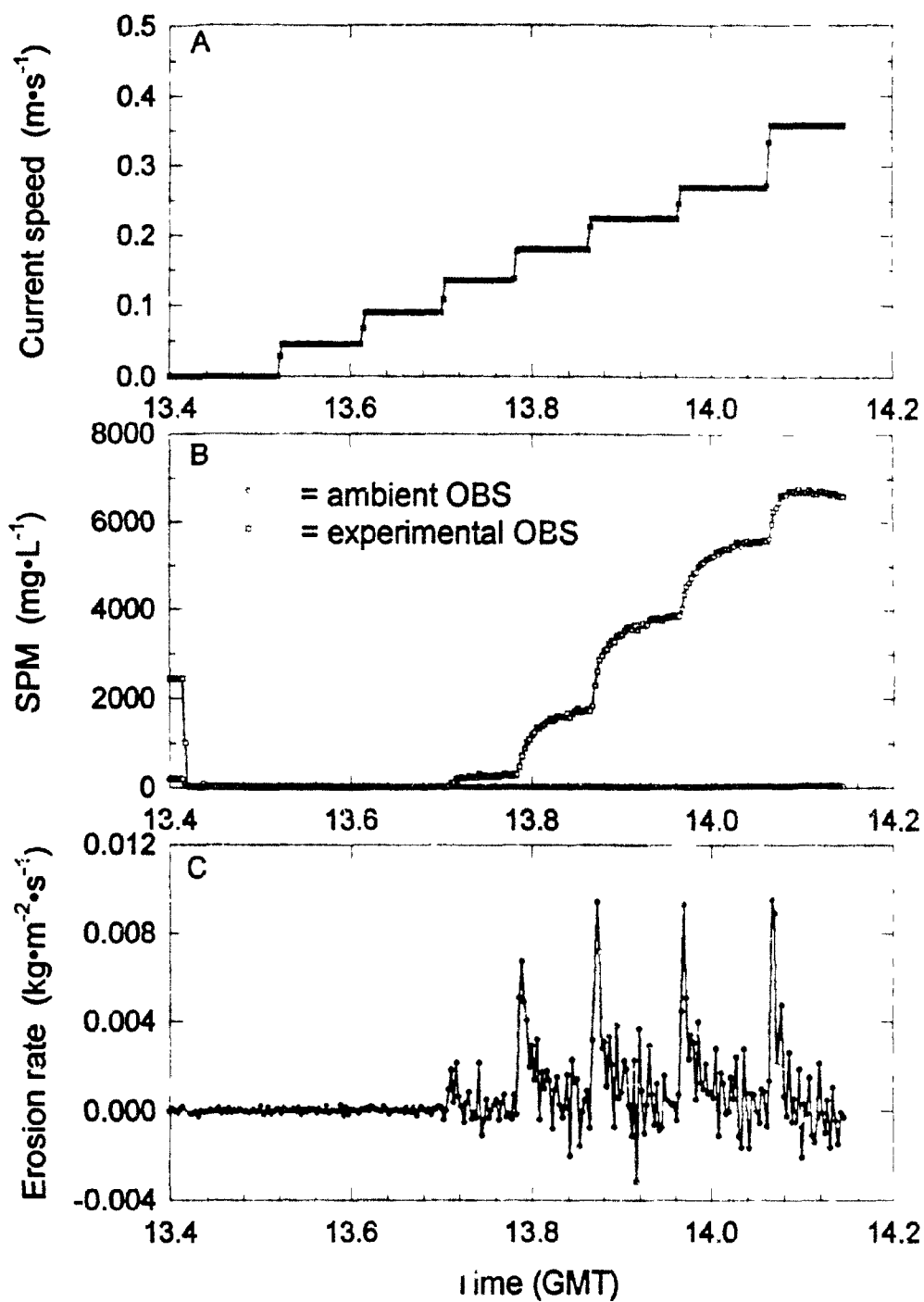


Figure 3.11: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 9 in Upper South Cove. Time-series plots of the remaining Sea Carousel deployments are located in Appendix A1.

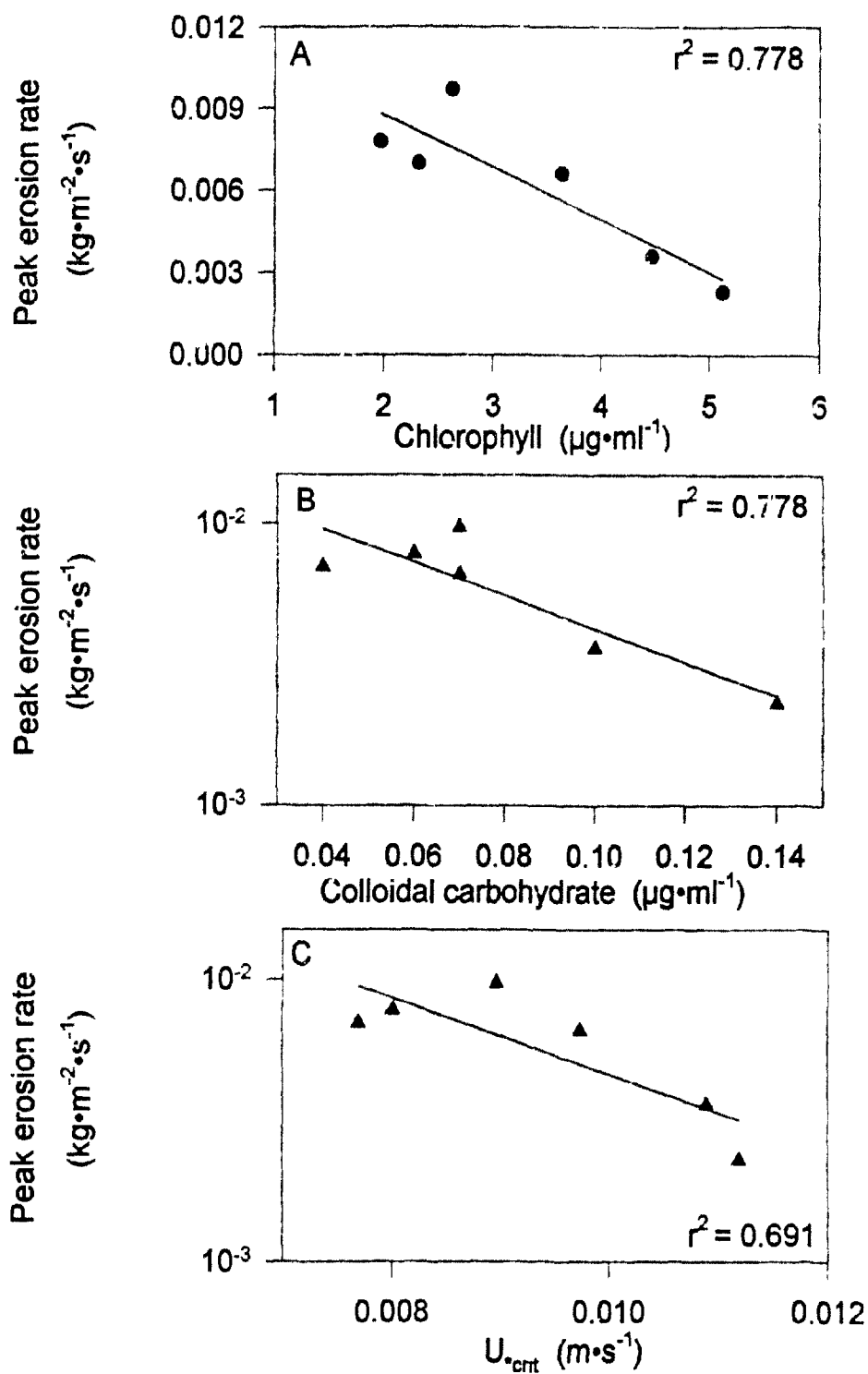


Figure 3.12: Regressions showing the relationships between peak erosion rate and sediment chlorophyll (A), sediment colloidal carbohydrate (B), and U_{crit} (C) for stations 3, 5, 6, 7, 8, and 9 in Upper South Cove.

Table 3.3: Regressions describing the relationships between peak erosion rates (PER) and sediment chlorophyll, sediment colloidal carbohydrate, and U_{crit} . Level of significance = 0.05, n = 6.

Regression equations	r^2	p
$PER (kg \cdot m^{-2} \cdot s^{-1}) = -0.0019 (\text{chlorophyll } (\mu g \cdot ml^{-1})) + 0.013$	0.788	0.02
$\text{Log PER } (kg \cdot m^{-2} \cdot s^{-1}) = -13 (\text{colloidal carbohydrate } (\mu g \cdot ml^{-1})) - 4.2$	0.778	0.02
$\text{Log PER } (kg \cdot m^{-2} \cdot s^{-1}) = -3.10 (\text{log } U_{crit} (m \cdot s^{-1})) - 2.3$	0.691	0.04

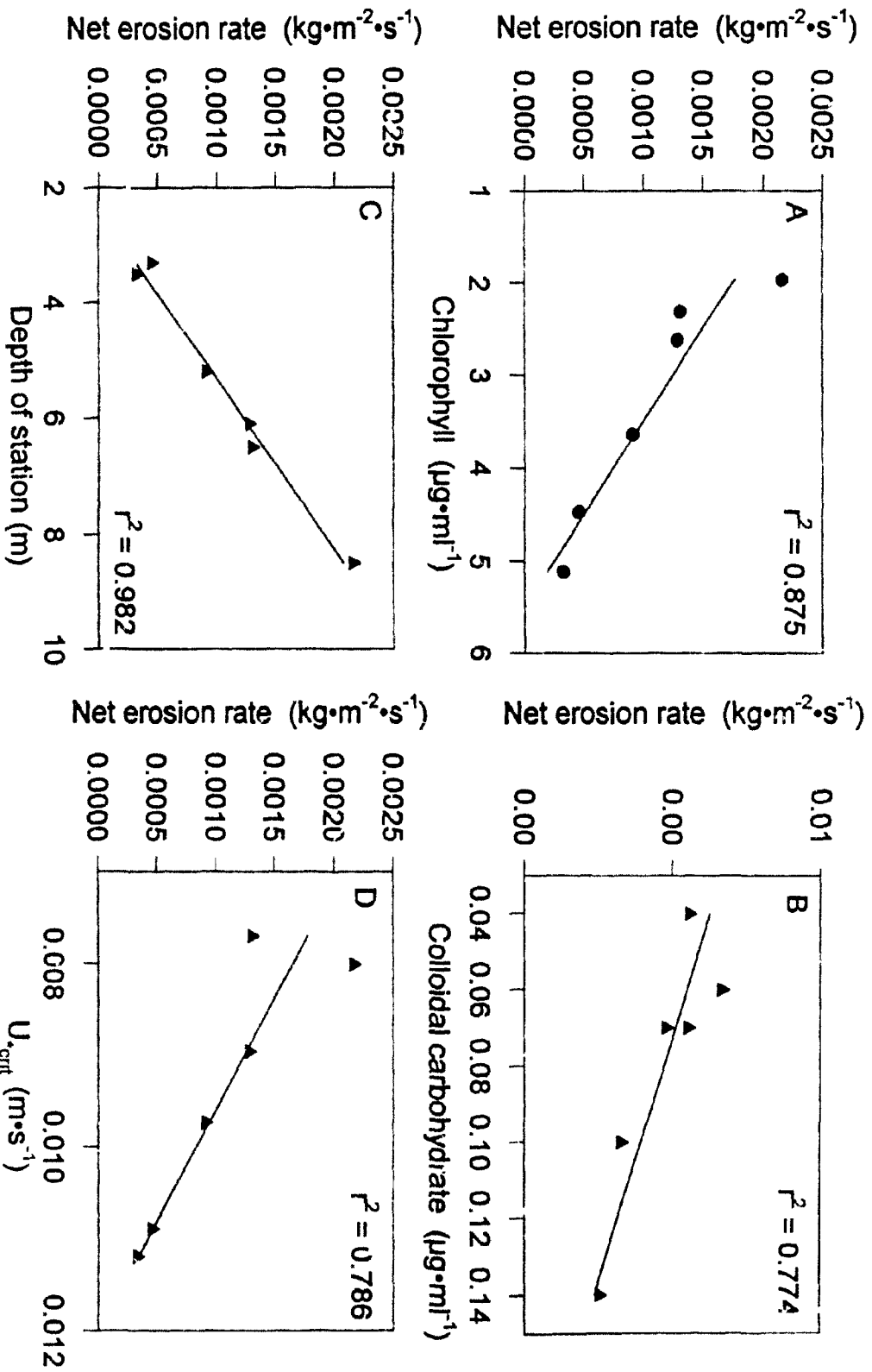


Figure 3.13: Regressions showing the relationships between net erosion rate and sediment chlorophyll (A), sediment colloidal carbohydrate (B), depth of station (C), and U_{crit} (D). Net erosion rates were obtained from Sea Carousel deployments at stations 3, 5, 6, 7, 8, and 9 in Upper South Cove.

Table 3.4. Regressions describing the relationships between net erosion rates (NER) and sediment chlorophyll, sediment colloidal carbohydrate, depth of station, and U_{crit} . Level of significance = 0.05, n = 6.

Regression equations	r^2	p
$NER (kg \cdot m^{-2} \cdot s^{-1}) = -0.00050 (\text{chlorophyll } (\mu g \cdot ml^{-1})) + 0.0027$	0.875	0.006
$\text{Log NER } (kg \cdot m^{-2} \cdot s^{-1}) = -1.7 (\text{colloidal carbohydrate } (\mu g \cdot ml^{-1})) - 5.7$	0.774	0.02
$NER (kg \cdot m^{-2} \cdot s^{-1}) = 0.00034 (\text{depth of station (m)}) - 0.0008$	0.982	< 0.001
$NER (kg \cdot m^{-2} \cdot s^{-1}) = -0.4 (U_{crit} (m \cdot s^{-1})) + 0.005$	0.786	0.02

concentrations ($r^2 = 0.774$, $p = 0.021$; Figure 3.13B), and U_{crit} ($r^2 = 0.786$, $p = 0.019$; Figure 3.13D) and positively correlated with the depth of the station ($r^2 = 0.982$, $p < 0.001$; Figure 3.13C). Regression equations were listed in Table 3.4.

3.3.8 Spatial variation of erosion measurements

Coefficients of variation (CV) were determined to assess the variability in erosion measurements between stations 2 and 3 which were 9 metres apart and between station 4 and the midpoint of stations 2 and 3 which were approximately 59 metres apart. Figure 3.14 shows that the CV determined for U_{crit} and net erosion rate were larger between stations 4 and the midpoint of stations 2 and 3 than those determined between stations 2 and 3. However, the reverse was true for the CV determined for peak erosion rate. The coefficient of variation was determined to assess spatial variation of erosion thresholds and rates. Assuming 100 % reproducibility of the technique employed, the coefficients of variation of erosion thresholds and net erosion rates were lower between duplicate deployments (stations 2 and 3) which were 9 m apart, than those at station 4 which was approximately 59 m away. Therefore, spatial trends in erosion measurements were greater than local variability.

3.3.9 Organic fluxes

Resuspension fluxes were calculated as the differential concentration of the eroded material observed between the maximum U_{crit} and U_{net} , standardized by the eroded area and by time. In general, the resuspension fluxes specific for chlorophyll, phaeopigment, SPM,

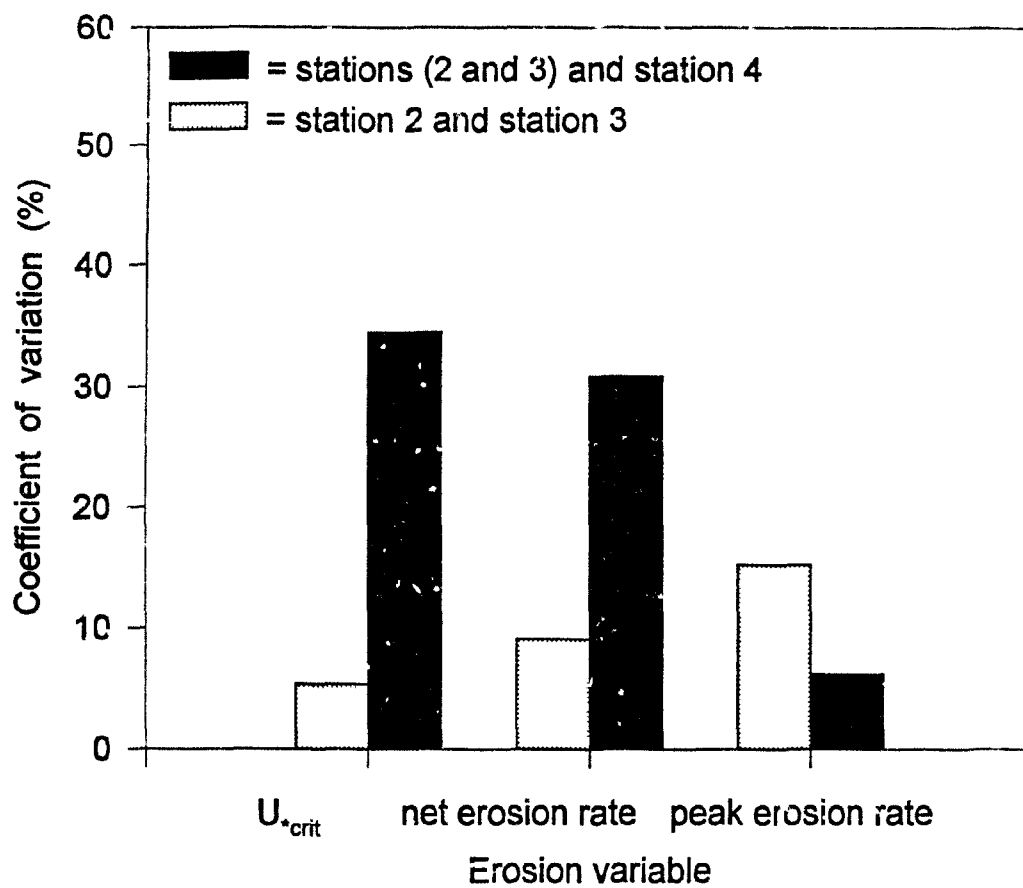


Figure 3.14: Coefficients of variation of erosion measurements of duplicate and replicate deployments of the Sea Carousel ($n = 2$).

POC, and PN in Upper South Cove increased from the inner Cove to the central Cove with the exception of station 7 (Figure 3.15). Station 7 was located on the flank of the depositional basin and does not follow the trend of increasing depth seawards through the Cove. Sedentary suspension feeders (both cultured and wild populations of bivalves) located along this transect would receive significantly different concentrations of suspended particulate matter. However, the POC % and C:N ratio of the suspended matter did not show large variations along this transect (Figure 3.16). The C:N ratios of the suspended matter at all stations were consistent with those measured by Emerson *et al.* (1994), while the C:N ratios of the sediment were consistent with those measured by Grant *et al.* (1995) in Upper South Cove. The C:N ratio and POC % of the suspended matter were lower relative to those of the sediment. Inorganic content of the suspended matter also increased towards the centre of the Cove and was positively correlated with the net erosion rate ($r^2 = 0.710$, $p = 0.035$), peak erosion rate ($r^2 = 0.746$, $p = 0.027$), net chlorophyll erosion rate ($r^2 = 0.950$, $p = 0.005$), net POC erosion rate ($r^2 = 0.929$, $p = 0.002$), and net PN erosion rate ($r^2 = 0.945$, $p = 0.001$).

The inorganic content of the suspended matter ranged between 71 (station 2) to 77 % (station 9), increasing toward the centre of the Cove (Figure 3.17). Within each deployment an increase in the inorganic content occurred at a U_{crit} value of approximately $0.01 \text{ m}\cdot\text{s}^{-1}$ (mean U_{crit} value for all stations) and remained constant thereafter. Sharp peaks in the ratios of suspended chlorophyll and phaeopigment to inorganic sediment generally occurred at this point in the deployment, reflecting chlorophyll and phaeopigment gradients in the sediment column characteristic of strong surface maxima and sharp

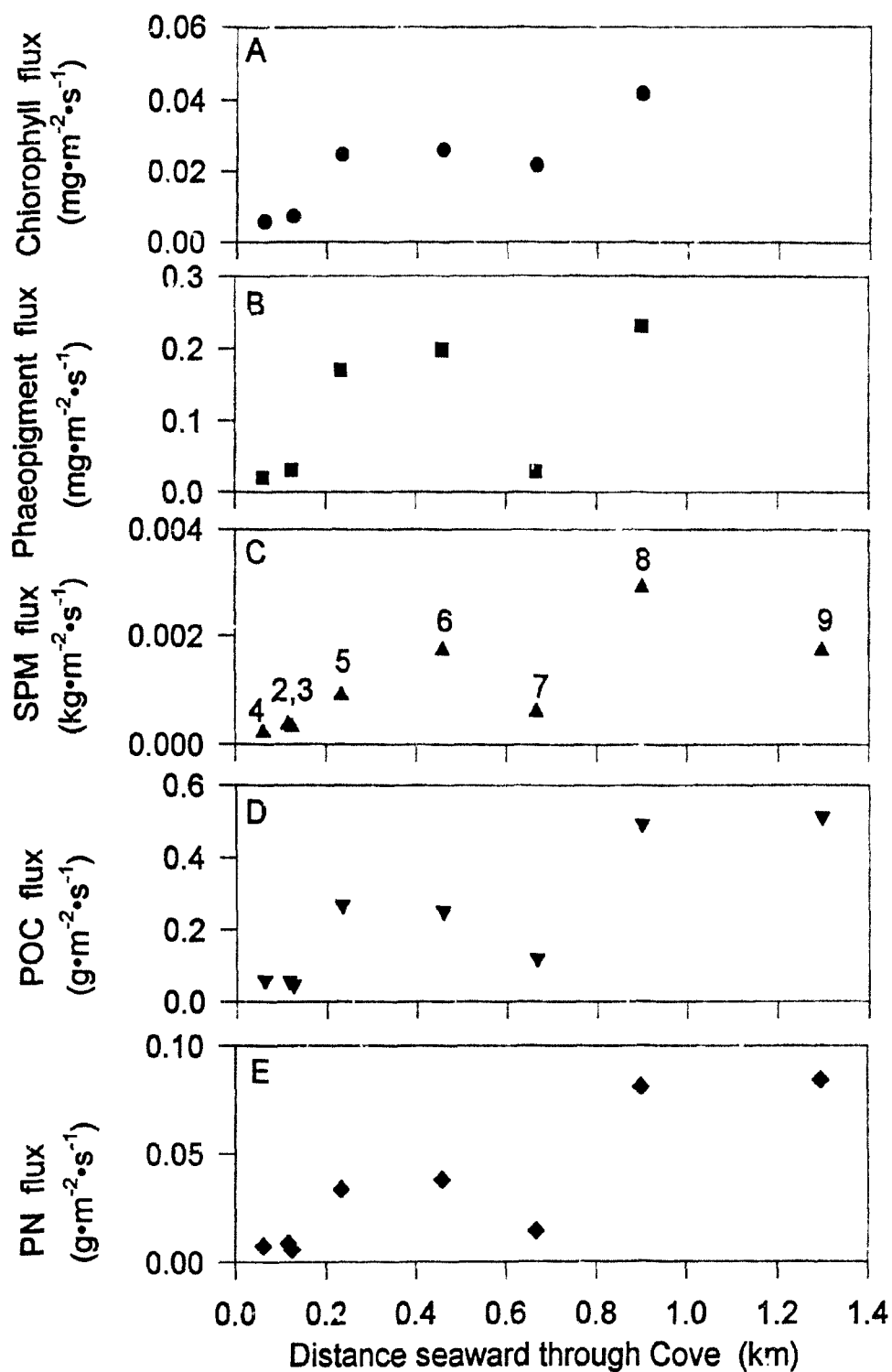


Figure 3.15: Resuspension fluxes of chlorophyll (A), phaeopigment (B), SPM (C), POC (D), and PN (E) for stations 2 to 9 located along a transect in Upper South Cove. Station locations are indicated in Figure 3.1.

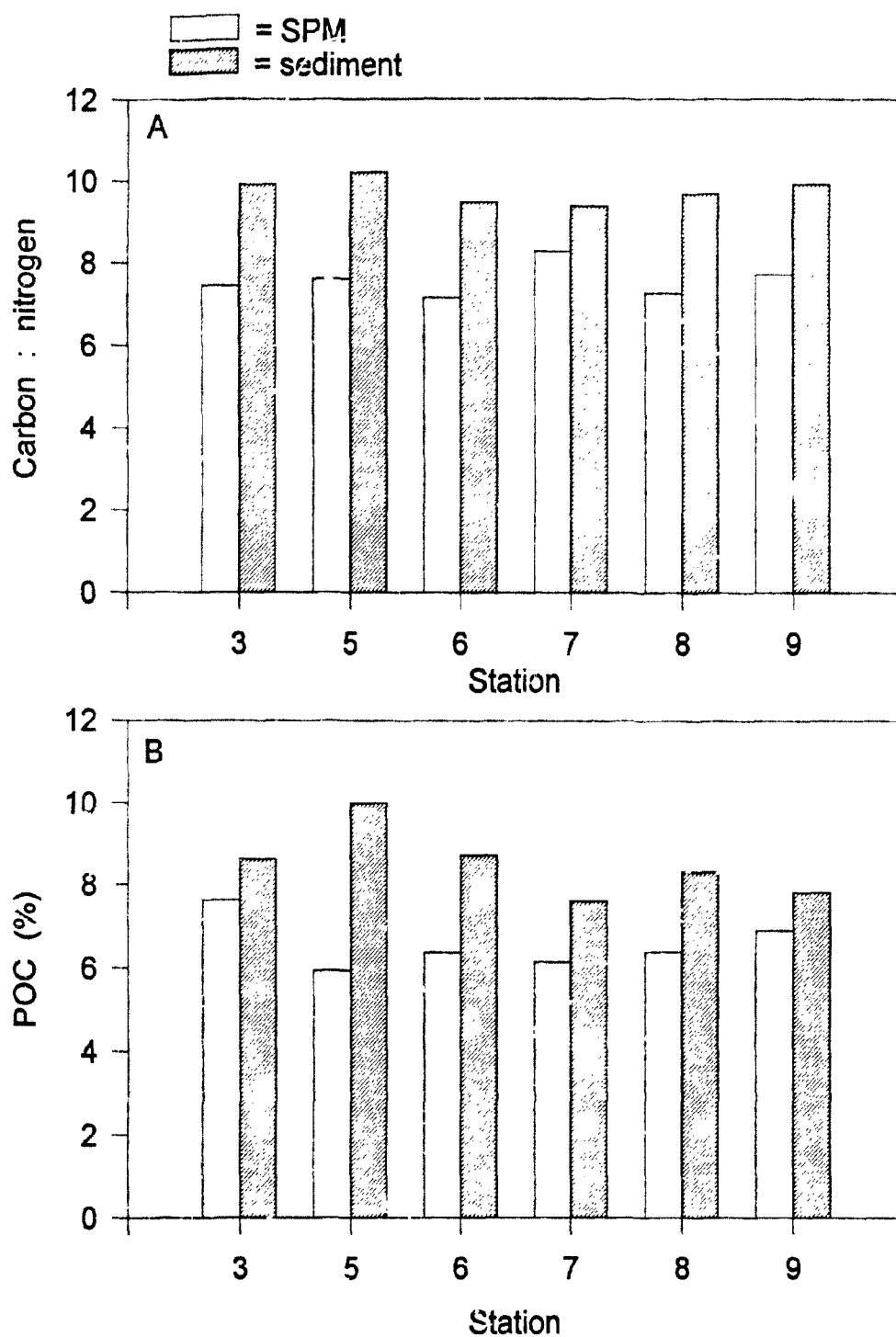


Figure 3.16: Comparisons of C:N ratios (A) and POC content (B) between SPM (Sea Carousel) and sediment cores.

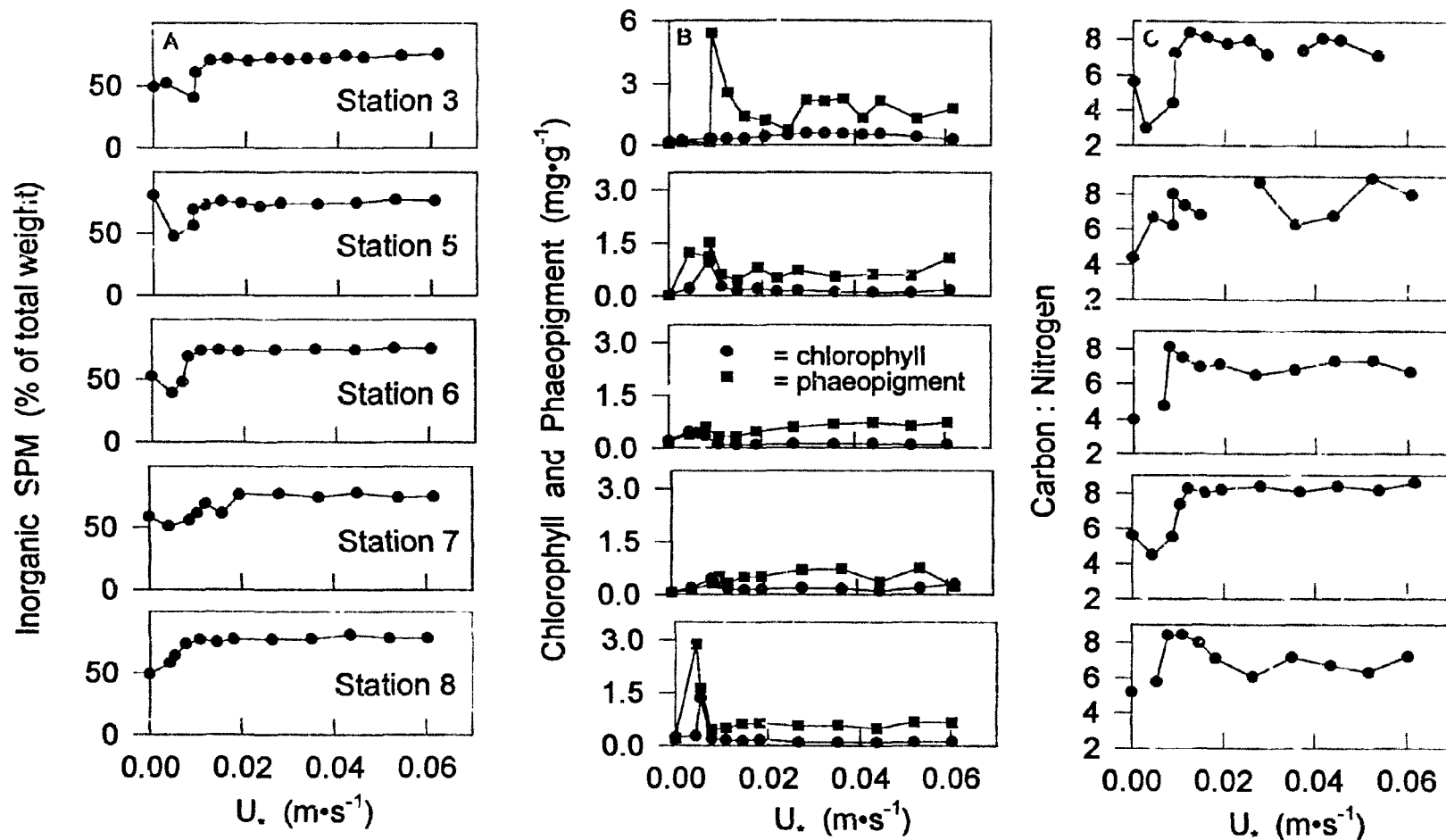


Figure 3.17: Plots of inorganic SPM vs U , (A), chlorophyll standardized to inorganic SPM vs U , (B), and carbon to nitrogen vs U , (C). Station locations in Upper South Cove are indicated in Figure 3.1.

declines with depth in the sediment. The absence of a peak in the ratio of chlorophyll to inorganic sediment at station 3 indicates a tight coupling of chlorophyll and inorganic sediment, probably due to the incorporation of inorganic sediment by the "established" biofilm observed at this site. The occurrence of a phaeopigment peak in the absence of a chlorophyll peak at this station, suggests that differential erosion of phaeopigment (potentially fecal-pellet derived) and chlorophyll occurred. The lag in the occurrence of the phaeopigment peak at this station relative to the other stations was due to the higher erosion threshold determined at this site. Also, a lag in the peak of the ratio of chlorophyll to inorganic sediment occurred relative to the peak of the ratio of phaeopigment to inorganic sediment at both stations 5 and 8.

Erosion thresholds and rates from a Sea Carousel deployment were used to estimate SPM fluxes in the Cove based on current metre records. Figure 3.18 shows time-series plots of U_* (A), SPM flux (B), chlorophyll standardized to inorganic SPM (C), POC content of SPM (D), and inorganic content of SPM (E). U_* was derived from current metre data collected 1 metre off the bottom at a location mid-point in the Cove between October 19 to 22, 1991. The current metre data was converted to U_* using the equations $\tau = \rho_s \cdot C_d \cdot U_*^2$ and $\tau = \rho_s \cdot U_*^2$, where $\rho_s = 1028 \text{ kg} \cdot \text{m}^{-3}$ and $C_d = 0.003$ (Sternberg, 1968). Values for Figure 3.18 B, C, D, and E were derived from corresponding U_* values generated from a Sea Carousel deployment at station 3 on October 17, 1993. An r^2 value of 0.935 was obtained from a regression between the U_* values derived from ambient current metre data and the corresponding U_* values generated from the Sea Carousel.

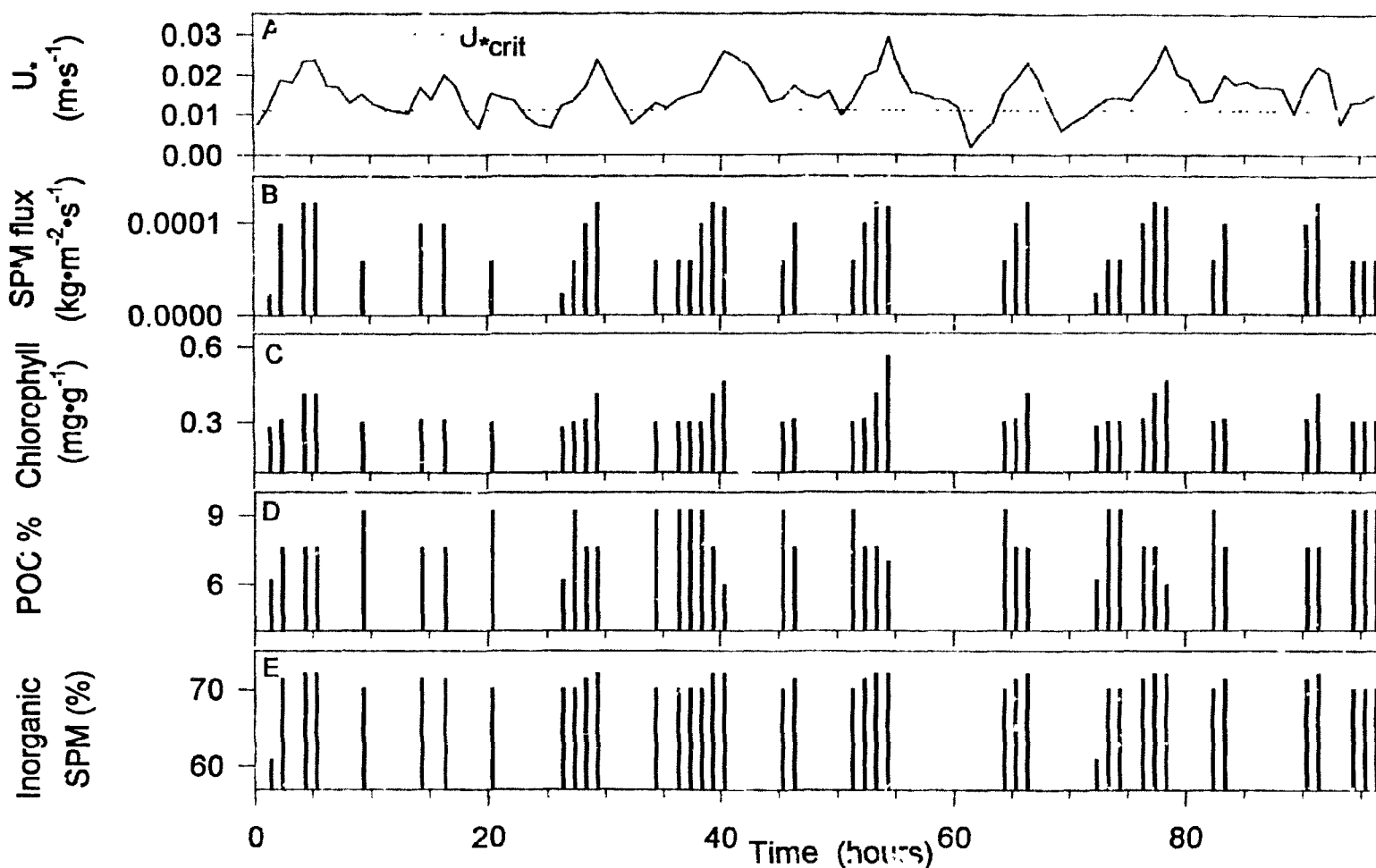


Figure 3.18: Time-series of U_* (A), SPM flux (B), chlorophyll standardized to inorganic SPM (C), POC content (D) and inorganic content of SPM (E). U_* was derived from current metre data collected mid-Cove. B, C, D, and E values were generated from corresponding U_* measured during a Sea Carousel deployment at station 3.

As U_b increased within a single tidal cycle (at 25 hours and 50 hours into the time-series plot; Figure 3.18), the SPM fluxes, the chlorophyll standardized to inorganic SPM, and the inorganic content of SPM increased, while the POC concentrations of SPM decreased. The increase in SPM flux with increasing U_b or with depth in the sediment column may be attributed to (1) the lack of biostabilization at depth or (2) the quality change in eroded material. Since the area and time period of erosion remained constant during Sea Carousel deployments, the transition from the erosion of light organic material at the sediment surface to heavier inorganic material at depth would bias SPM flux measurements within a tidal cycle. The increases in bulk density with sediment depth at station 3 (Figure 3.4) and the increases in the inorganic fraction of SPM with increasing U_b (Figure 3.18C), suggests that the higher SPM flux values observed at higher U_b values may be weighted by the heavier inorganic fraction existing at depth.

The mean erosion rate of SPM during the time-series in Figure 3.18 was calculated to be $3.43 \times 10^{-5} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. This value is much larger than the monthly sedimentation rates measured in Upper South Cove at a reference site ($1.23 \times 10^{-6} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) and under mussel lines ($2.05 \times 10^{-6} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) for the autumn months (Hatcher *et al.*, 1994). The calculation of sedimentation rates from material collected by sediment traps deployed over monthly periods, incorporated the losses of suspended material due to horizontal advection out of the inner Cove and also due to deposition at the accreting inner termination and sides of the Cove. The asymmetry of the tidal cycle in Upper South Cove favours a longer ebb tide relative to flood, supporting the loss of eroded material from the system. For example, a net horizontal flux of $4.89 \times 10^{-4} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ towards the mouth of

the Cove resulted from the calculations of horizontal SPM fluxes of $6.59 \times 10^{-4} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and $1.70 \times 10^{-4} \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in different directions by Hatcher *et al.* (1994). Alternately, the calculation of erosion rates by the collection of eroded material from the overlying water contained by the Sea Carousel during hourly deployments did not incorporate these possible losses of material. These factors must be taken into account before comparisons of erosion vs sedimentation rates can be made.

3.3.10 Sandy site: Lunenburg Bay (Station 1)

The sediment column of station 1 consisted of a well-sorted sand with an oxidized layer extending to 10 mm in depth. Over 90 % of the sediment was 200 μm in size. Bulk density values ranged between $961 \text{ kg} \cdot \text{m}^{-3}$ at the sediment surface to $1675 \text{ kg} \cdot \text{m}^{-3}$ at 6 mm and $1940 \text{ kg} \cdot \text{m}^{-3}$ at 10 mm below the surface, respectively (Figure 3.19). The chlorophyll maximum and the sharp increase in bulk density observed at approximately 7 mm suggests that this depth marks the true sediment-water interface. The low bulk density layer observed between 0 to 7 mm may represent a transient surficial layer. The sequential erosion of these 2 layers is shown in Figure 3.9A. The concentrations of the sediment biofilm components and the erosion measurements are listed in Table .

The U_{crit} values for chlorophyll ($0.0185 \text{ m} \cdot \text{s}^{-1}$) are less than those for phaeopigment ($0.0256 \text{ m} \cdot \text{s}^{-1}$), which are less than those for SPM ($0.0312 \text{ m} \cdot \text{s}^{-1}$) (Figure 3.9). The differences between these U_{crit} values of chlorophyll, phaeopigment, and SPM are higher for this site than the differences observed for each station in Upper South Cove. In general, the fluxes of sediment biofilm components are lower than those in Upper South

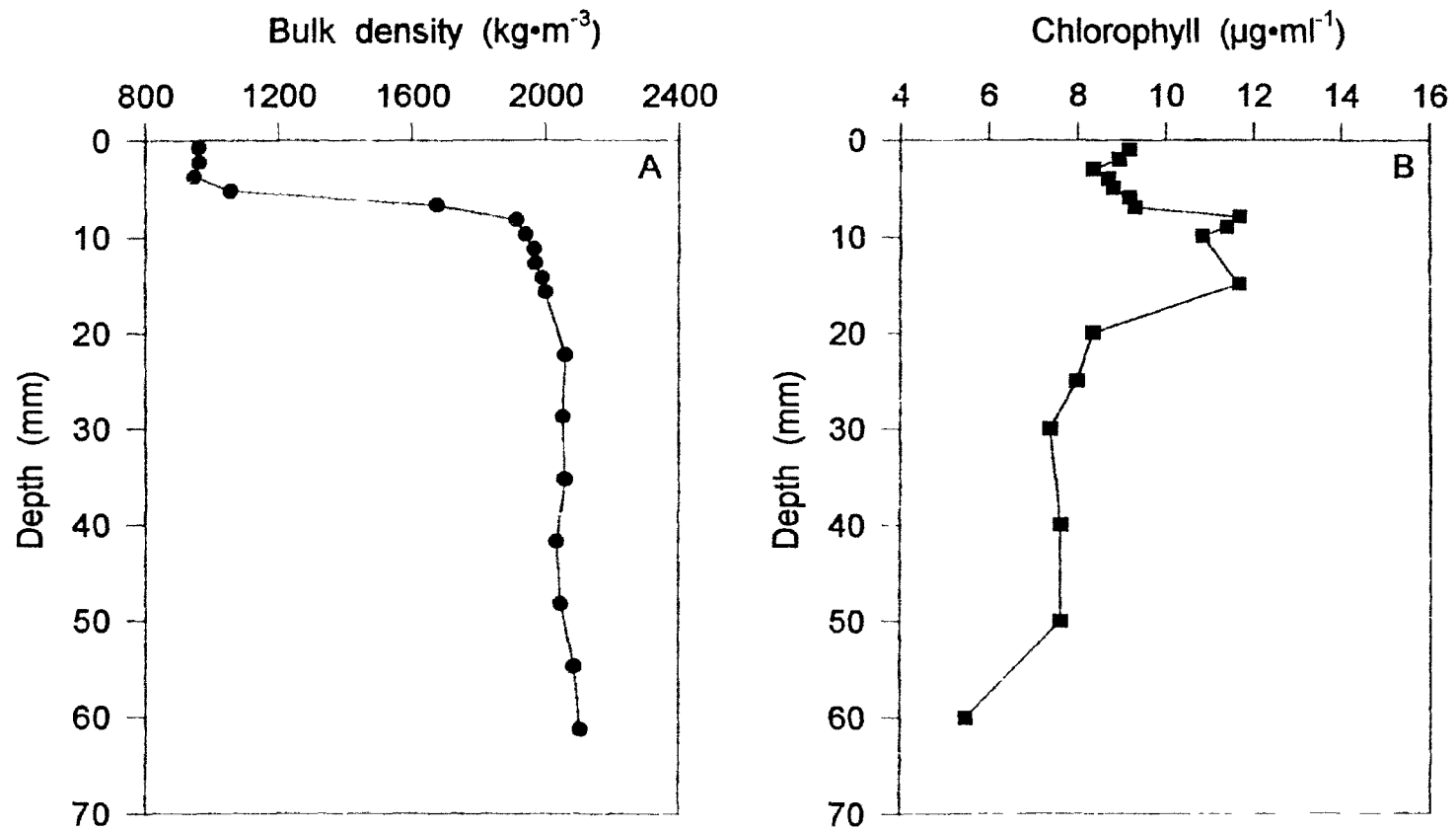


Figure 3.19: Vertical sediment profiles of bulk density and chlorophyll concentration at station 1 in Lunenburg Bay.

Table 3.5: Erosion thresholds and rates and sediment predictors for station 1 located outside Upper South Cove in Lunenburg Bay (n = 1).

SEDIMENT BIOFILM COMPONENTS	
Chlorophyll ($\mu\text{g}\cdot\text{ml}^{-1}$)	9.1
Phaeopigment ($\mu\text{g}\cdot\text{ml}^{-1}$)	6.2
Chlorophyll: phaeopigment	1.5
Colloidal carbohydrate ($\text{mg}\cdot\text{ml}^{-1}$)	0.09
Particulate carbohydrate ($\text{mg}\cdot\text{ml}^{-1}$)	0.04
POC ($\text{mg}\cdot\text{ml}^{-1}$)	0.16
PN ($\text{mg}\cdot\text{ml}^{-1}$)	0.02
Carbon : nitrogen	10.9
Carbon : chlorophyll	18
Bulk density ($\text{kg}\cdot\text{m}^{-3}$)	961
Inorganic content (%)	98
EROSION MEASUREMENTS	
U_{crit} ($\text{m}\cdot\text{s}^{-1}$)	0.031
Peak erosion rate ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	0.0046
Net erosion rate ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	0.0021
Chlorophyll flux ($\text{mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	0.0012
Phaeopigment flux ($\text{mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	0.0058
POC flux ($\text{g}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	0.011
PN flux ($\text{g}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	0.0031

Cove. The ratio of chlorophyll to inorganic sediment in relation to U_* is presented in Figure 3.20. The peak in this ratio was higher in magnitude, occurred at a greater U_* value, and did not decrease as quickly, relative to those in Upper South Cove.

3.3.11 Comparison of erosion thresholds obtained from the recirculating flume and Sea Carousel data

It is difficult to compare the U_{*crit} values (extrapolation method) obtained by the recirculating flume to those of the Sea Carousel since an eroded signal for SPM was detected in the recirculating flume for station 4 only (Figure 3.21). No significant correlation exists between the U_{*crit} values for chlorophyll obtained by the recirculating flume and by the Sea Carousel. The U_{*crit} of values for chlorophyll obtained from recirculating flume are 2 to 5 times higher than those values obtained from the Sea Carousel. However, the U_{*crit} values obtained by the Sea Carousel may be lower since the U_* calculation included a correction factor for SPM, while the U_* values obtained from the recirculating flume were derived from clear water conditions.

A second series of net erosion rates of chlorophyll, obtained from the Sea Carousel data, were calculated up to the eroded depths obtained by the recirculating flume (Figure 3.22). No consistent pattern emerged from this comparison and no significant correlation existed between the erosion rates of chlorophyll obtained by both methods. However, the erosion rates of chlorophyll determined by both flume methods at stations 3, 4, and 8 were in agreement.

Erosion thresholds for the movement of particles were determined by the observation method for cores collected from Upper South Cove stations and eroded in the

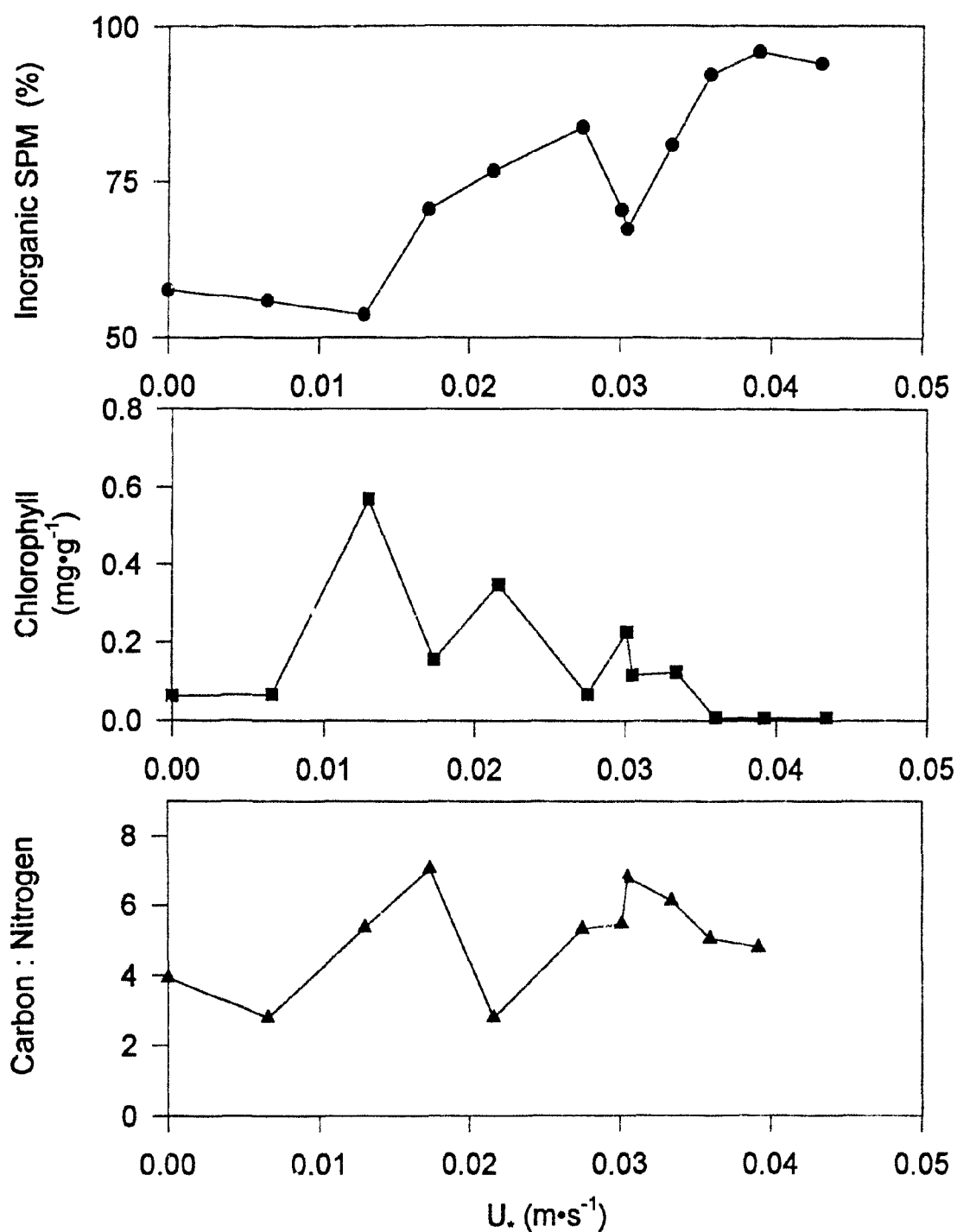


Figure 3.20: Plots of U_* and inorganic SPM (A), the ratio of chlorophyll to inorganic SPM (B), and the carbon : nitrogen ratio of SPM (C) obtained from a Sea Carousel deployment at station 1 in Lunenburg Bay.

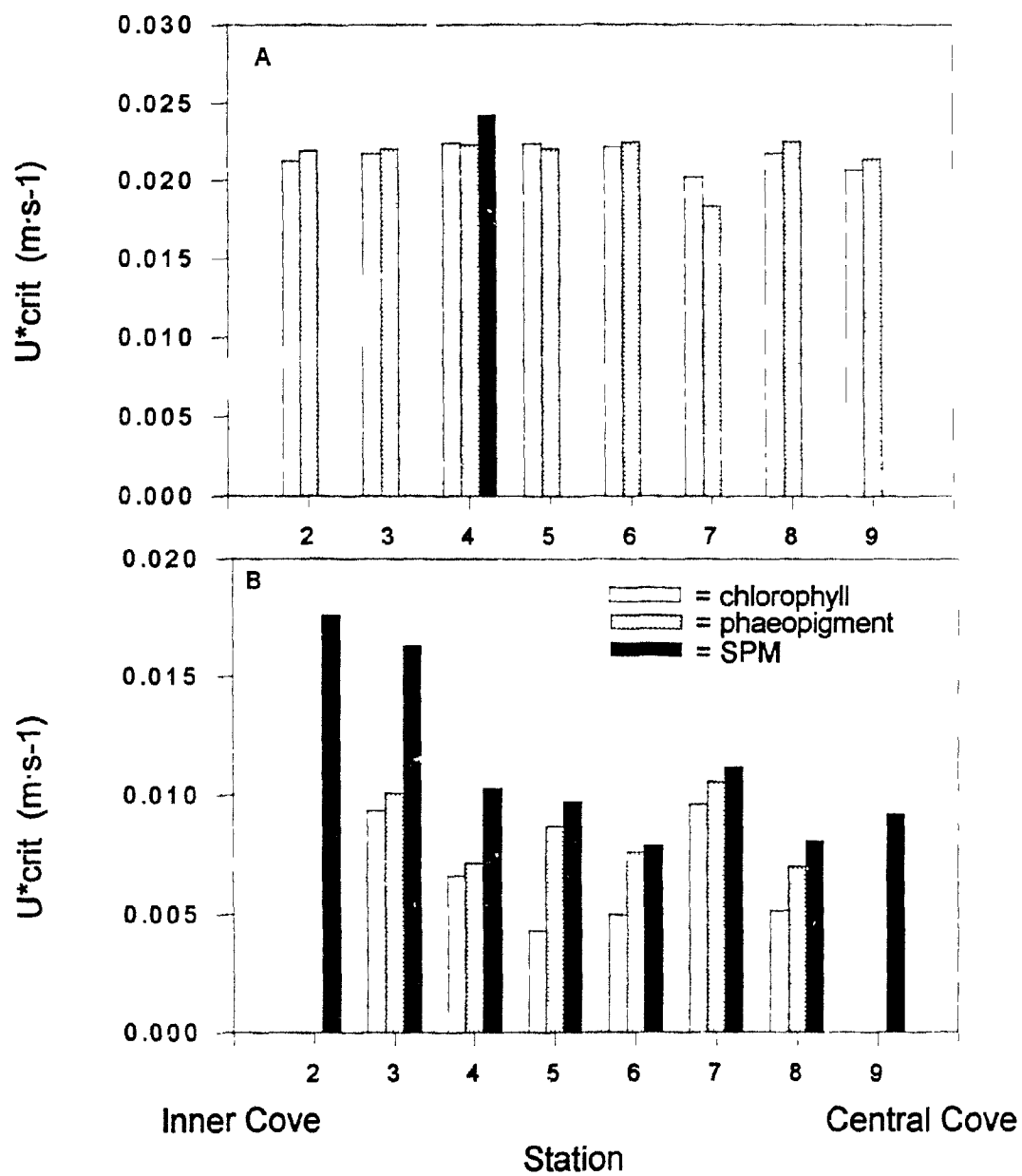


Figure 3.21: A comparison of U^*_{crit} values of chlorophyll, phaeopigment, and SPM obtained by the recirculating flume (A) and the Sea Carousel (B).

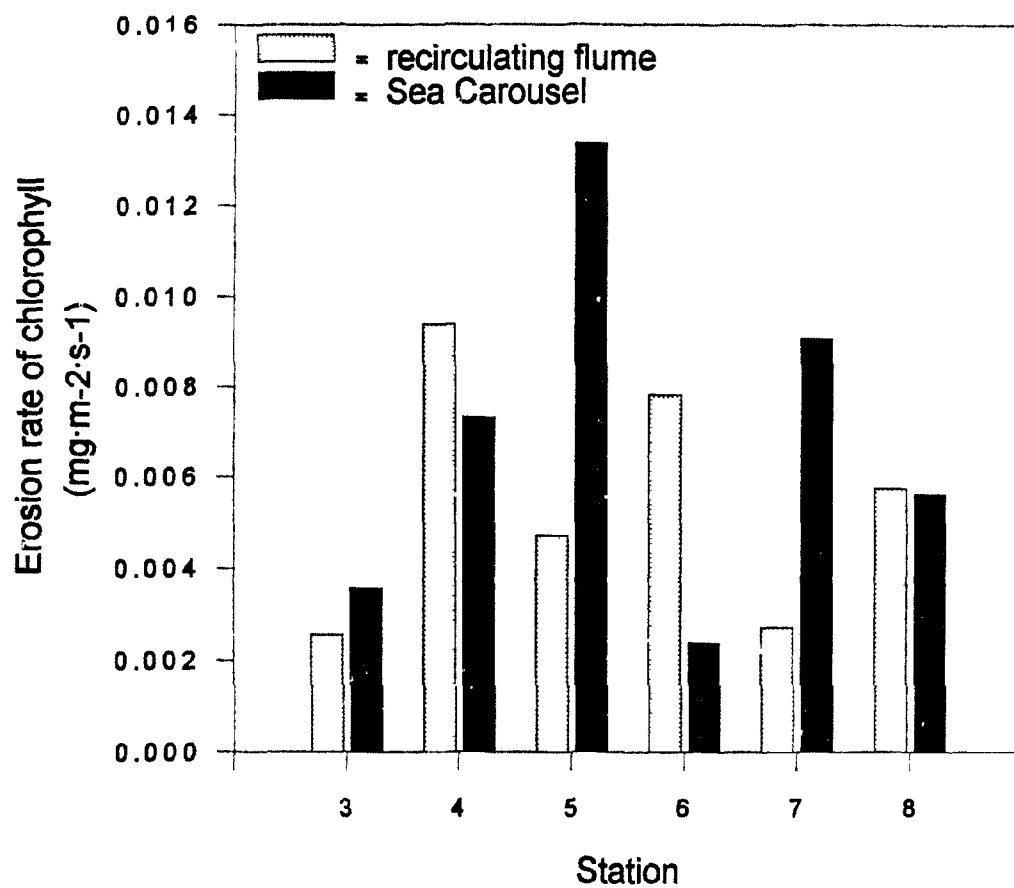


Figure 3.22: A comparison of erosion rates of chlorophyll obtained from the recirculating flume and the Sea Carousel

recirculating flume. The movement of large aggregates was observed for cores collected from stations 2, 3, 4, and 7 that contained well-developed biofilms. The movement of smaller particles was observed at higher U_c values for the remaining cores (stations 5, 6, 8, and 9) that contained lower chlorophyll content. However, the OBS time-series records for the latter stations indicated that material was eroded before the particle movement was detected. Therefore, erosion thresholds of larger particles, associated with "established" biofilms (stations 2, 3, and 4), would be lower than erosion thresholds determined for smaller particles, associated with low-developed biofilms. Neill (1968) also observed that erosion thresholds may be biased by the early detection of large particle movement. The erosion of particle movement should be standardized by particle size to remove any biases. A flume comparison of erosion thresholds for particle movement was not made, since particle motion of the central sediment working area was difficult to determine due to the camera angle on the sediment surface inside the Sea Carousel.

3.4 Discussion

3.4.1 Biological and physical properties of the sediment

Little variation in the physical properties of the surface sediment was observed for the inner half of Upper South Cove. The material that formed a blanket over this region consisted of unconsolidated muds of porosities of 87 % and organic contents of 22 % (Grant *et al.*, 1995). Little variation in the biological properties, such as phaeopigment, bulk carbohydrate, POC, and PN was also observed for the surface sediment in this region, suggesting their limited usefulness as indicators of sediment erodibility (Table 3.1).

The accumulation of fine particles in the sediment of the inner half of Upper South Cove may be influenced by 1) limited tidal excursion (Dowd, 1991), 2) removal and biodeposition of the clay material by bivalves (Haven and Morales-Alamo, 1966; Kausty and Evans, 1987), 3) scavenging of fine particles by a hydrodynamically active fluff layer (Stolzenbach *et al.*, 1992), and 4) subsequent biostabilization of the fine fraction at the sediment-water interface by benthic diatoms (Mayer *et al.*, 1985). Approximately 90 % of the inner half of Upper South Cove is flushed every 2 to 4 days (Dowd, 1991), permitting the retention of fine particles relative to the outer half of Upper South Cove which is flushed tidally with less turbid oceanic water. In addition, the sedimentation of fine particles between the range of 1 to 3 μm has been reported to be enhanced by bivalve suspension feeders (Haven and Morales-Alamo, 1966). This small-sized inorganic fraction would normally settle very slowly in surrounding areas (Simpson, 1982).

The benthic-pelagic cycle of this fluff layer could potentially scavenge and deliver clay or silt particles from the water column to the seabed (Stolzenbach *et al.*, 1992). A large quantity of fluff material, observed during core collection by SCUBA, was resuspended, transported, and redeposited on each tidal cycle. The colonization and stabilization of the organic-mineral aggregates supplied to the sediment-water interface could occur through diatom migration. The sediment colloidal carbohydrate and chlorophyll content exhibited the largest variation of the sediment biological properties measured in Upper South Cove (Table 3.1). The variation in sediment chlorophyll was probably due to light availability at the varying depths (Figure 3.3A). The transect of stations in Upper South Cove ran from the shallow inner termination (3.5 m) to a

depositional basin (8.5 m). The colloidal carbohydrate fraction is a measure of extracellular or secreted mucopolysaccharide of diatoms for locomotion. It is not surprising that the sediment colloidal carbohydrate concentration was positively correlated with sediment chlorophyll concentration (Figure 3.3B), as found in other biostabilization studies (Underwood and Paterson, 1993b).

3.4.2 Vertical profiles of bulk density and chlorophyll in the sediment

The thickening of the "buoyant" surface biogenic layer landward through the Cove could be due to an increase in sedimentation rates in this direction (Figure 3.4). This biogenic layer could be periodically resuspended, recirculated, and deposited differentially along the length of the inner Cove. The station transect along the central axis of the Cove (Figure 3.1) is located in an area of particle retention (Dowd, 1991). However, the classical extinction of chlorophyll with depth in sediment at stations 3, 5, and 7 suggests that this low density surface layer was an established structure and not a recently deposited fluff layer (Figure 3.5). Video observation of the erosion trials confirm that an established biofilm was present at station 3. Biofilm growth may have succeeded the sedimentation rates of fluff material following active migration of diatoms to the illuminated accreting fluff-water interface. In this case, the accreting surficial sediment would then be considered to be a growth structure as opposed to a sedimentary unit (Wachendorfer *et al.*, 1994). The low bulk density layer may persist since the macrostructure or "open card house" arrangement of unconsolidated muds is easily influenced and managed by the larger motile diatoms (Paterson, 1994).

Trapped oxygen bubbles generated by actively photosynthesizing benthic diatoms in the surficial sediment layer could be responsible for the low bulk density values which are below that of water. The colonization of diatoms and associated production of EPS within the aggregates would increase adhesion and prevent this low bulk density fluff layer from floating. The CATSCAN tomograms revealed numerous tiny dark spheres (0.5 to 1 mm in diameter) in the upper cm of station 3 that could represent minute oxygen bubbles. During the incubation of *Nitzschia curvilineata* on sediment (Chapter 2), oxygen bubbles of up to 1 mm in diameter remained trapped within the biofilm. Flat oxygen bubbles of 2 to 10 mm in diameter have also been observed to occur 1 mm below the surface of "blister" mats (Jorgensen *et al.*, 1983). The consumption of oxygen by diatoms during dark periods in these "blister" mats caused a rapid depletion of the oxygen pools. Therefore, the bulk density of biofilms containing trapped oxygen bubbles may fluctuate with the diel photosynthetic cycle of diatoms and with the occasional release of bubbles from the mat. This fluctuation of biological and physical properties of the biofilm would impact the erodibility of sediment. Yallop *et al.* (1994) studying the effect of biofilms on intertidal sediment stability found that non-bubble mat regions eroded more easily than other regions containing bubble mats.

3.4.3 Relationship between U_{crit} and sediment biofilm predictors

Several biofilm components of the sediment were measured in order to determine a suitable quantitative predictor of the erodibility of sediment. Both chlorophyll and colloidal carbohydrate content were positively correlated with U_{crit} at stations in Upper

South Cove (Figure 3.6A and B). Other investigators have found that pigment concentrations are useful predictors of U_{crit} (Grant and Gust, 1987; Madsen *et al.*, 1993). Madsen *et al.* (1993) found that the pigment-derived biovolume of motile diatoms, responsible for laying down mucous trails through active migration, was the only measured variable in their study that correlated significantly with U_{crit} . These authors remarked that the sensitivity of the measures of total chlorophyll and colloidal carbohydrate content may have been diluted by sampling the entire surface 5 mm. In this study, the sediment chlorophyll maximum was often limited to the upper mm of the sediment column. A depth of 2 mm was sampled for chlorophyll and carbohydrate content to avoid the dilution of a near-surface signal by the diatom-free underlying sediment.

The pigment concentrations measured in the present study were correlated with colloidal carbohydrate concentrations (Figure 3.3B). Other groups of chlorophyll containing microphytobenthos or non-motile diatoms may be present in the sediment and alter this relationship between colloidal carbohydrate and chlorophyll (Madsen *et al.*, 1993). If the history of diatom colonization of sediment is unknown, then a conservative approach would be to measure both chlorophyll and colloidal carbohydrates to correlate with U_{crit} .

Low-temperature scanning electron micrographs have qualitatively demonstrated that extracellular mucopolysaccharides, measured as the colloidal carbohydrate fraction, are responsible for the actual binding of sediment grains (Paterson, 1988). Grant and Gust (1987) stressed that photopigments are only an indication of the microbial biomass responsible for increasing inter-grain binding and suggested that extracellular polymeric

substances may serve as a more predictive assay of sediment stability. Underwood and Paterson (1993b) demonstrated that colloidal carbohydrate was the best biochemical predictor for incipient erosion of intertidal sediment. In this chapter, a stronger relationship was observed between U_{crit} of subtidal sediment and chlorophyll relative to that with colloidal carbohydrate.

The erosion of larger flake-shaped organic-mineral aggregates, or laminae associated with well-developed biofilms at the shallower stations suggests a biogenic modification of the effective particle size and shape. Low-temperature SEM (Underwood and Paterson, 1993b) and thin section (Frankel and Meade, 1973; Wachendorfer *et al.*, 1994b) techniques have shown that established biofilms consist of a continuous fabric of mineral particles embedded in EPS. The extent to which EPS pervades the sediment column would influence the degree to which the size, shape, and density of aggregates or physical properties become altered. However, conventional methods of sediment size analysis result in the destruction of these biomediated aggregates and, according to Johnson (1974), create artefacts. Results of standard sedimentological methods do not incorporate the glueing effect of EPS and the associated changes in sediment characteristics and, therefore, may not correlate well with sediment erodibility. In addition, the variation in aggregate size associated with successive stages of biofilm production may cause biased detection of the movement of larger aggregates and introduce subjectivity to the determination of U_{crit} through video observation.

3.4.4 Relationship between peak erosion rate and sediment biofilm predictors

Type I erosion has been previously observed to be a surface phenomenon, characterized by a marked increase in the erosion rate of the sediment surface material and a rapid asymptotical decrease with time (Figure 3.9; Amos *et al.*, 1992c). The magnitude of the peak in Type I erosion was observed to be associated with the quantity, size, shape, and density of loosely-bound organic-mineral aggregates at the sediment-water interface. The well-developed biofilm cores, collected from the shallow stations, contained fewer of the smaller-sized, loosely-bound aggregates than the remaining sediment cores collected from deeper depths. The aggregates eroded during Type I erosion from the established biofilm cores tended to be larger in size and maintain their integrity or shape relative to the aggregates of the remaining cores which were smaller and more malleable, forming organic "strings" upon suspension. Peak erosion rates were negatively correlated with sediment colloidal carbohydrate and chlorophyll content (Figure 3.12), two sediment variables that would influence the size, shape, density, and adhesion of loosely-bound organic-mineral aggregates to the sediment-water interface.

3.4.5 Relationship between net erosion rate and sediment biofilm predictors

Although net erosion rates were correlated with the surface sediment colloidal carbohydrate and chlorophyll content in Upper South Cove (Figure 3.13A and B), the calculation of net erosion rates incorporated the erosion of the sediment column to a depth well below the 2 mm biostabilized surface layer. The initial stages of the erosion process would rely on surface biomediated binding, but the net erosion rate would also rely on the

microfabric of the underlying sediment. This microfabric would depend collectively on the history of bed deposition, preservation of biofilm at depth, and consolidation processes. Deeper stations located in the centre of the Cove, exposed to lower magnitudes of current velocities and light intensities, would experience different degrees of deposition and consolidation, suggesting the other factors besides light-dependence contributed to the high correlation between net erosion rates and depth of station (Figure 3.13C).

A quiescent environment should favour a steep chlorophyll gradient within the sediment column (de Jonge and de Jonge, 1995). In this study, the values of net erosion rates varied across stations by a factor of 13, while the values of U_{crit} and peak erosion rates varied by a factor of 2 and 5, respectively. The large variations in erosion rates may have been influenced more by the sediment properties of the underlying sediment, than by the shallow chlorophyll gradients (Figure 3.5) existing in Upper South Cove. Paterson *et al.* (1994b) found that the sediment underlying the biofilm was more easily eroded than the surficial biostabilized layer. Although erosion threshold is a critical measurement of erodibility, erosion rate may serve as more suitable indicator of biophysical controls on erosion (Grant and Daborn, 1994).

3.4.6 Organic fluxes

Many natural sediments support the growth of biofilms which mediate the quantity and quality of nutrient-rich organic sediment components at the sediment-water interface (Paterson, 1994; Grant and Emerson, 1994). Diffusion rates of inorganic nutrients may be reduced by the infilling of interstitial voids by EPS (Jorgensen, 1994), resulting in changes

in chemical gradients and an accumulation of organic components. Therefore, sediments are not only sinks for organic components, but can be considered also as sources (McCall, 1979). The resuspension and dispersion of fine-grained organic rich sediment is affected by tidal flow (Postma, 1961). Rhoads *et al.* (1984) found that concentrations of POC, PON, and chlorophylls were greater in the near-bottom turbidity zone (BTZ). The thickness of the BTZ varied with magnitude of tide, and the coverage of the BTZ extended over a large portion of the estuary. Therefore, this potentially nutritionally-rich turbid bottom water could be a major food source for natural and cultured sedentary bivalves.

The lower values of POC and C:N ratio of the suspended matter relative to the sediment (Figure 3.16) may have occurred due to 1) hydraulic sorting of the sediment components, or 2) a dilution of the sediment components by the overlying water. Selective erosion results in a qualitative gradient in particle type with height above the seabed (Muschenheim, 1987). Lighter organic-rich material occurred at greater heights relative to the denser fraction which remained closer to the seabed. The results in Figure 3.16 suggest that particles containing a higher percentage of PN are selectively eroded. However, the sediment aggregates may have been broken up upon suspension and diluted with the overlying water that contained greater concentrations of PN relative to the sediment.

The flux of organic sediment components would depend not only on bottom shear stress, but also the supply or concentration of each component in the sediment (Rhoads *et al.*, 1984). Since a greater variation was seen in the POC fluxes across stations than in the POC sediment concentrations across stations, the fluxes were a function of sediment

strength and not only a function of the concentration in the sediment. However, since the sediment chlorophyll concentrations varied across stations, a smoothing of the chlorophyll fluxes may have occurred along this transect.

The material suspended at each speed increment represents a vertical distribution of that component in the sediment column (de Jonge and van den Bergs, 1987). The sharp increase and decrease in the suspended chlorophyll to inorganic fraction observed at stations 3, 5, and 8 in Figure 3.17 reflects a steep vertical gradient of chlorophyll that existed in the sediment column of two of these sites (stations 3 and 5; Figure 3.5). Gradients in sediment chlorophyll are influenced by 1) tidal energy (de Jonge and de Jonge, 1995), 2) limited light penetration (Colijn, 1982), 3) vertical migration (Meadows and Anderson, 1968), and 4) the depth of the H_2S -free oxic zone (Jorgensen, 1989, in Gerdes *et al.*, 1994). High energy environments rework sediment and result in the exportation of chlorophyll at depth. Light penetration in consolidated muds (0.2 mm) is typically less than that of sand (2 mm) due to the difference in the respective packing structures. The chlorophyll maximum in the sediment depends on vertical migration patterns of the diatoms. Finally, high levels of H_2S associated with anoxic muds fully inhibit diatom photosynthesis. H_2S profiles measured during a multidisciplinary study performed in Upper South Cove show an increase in H_2S 6 mm below the surface in sediment affected by the mussel aquaculture site (Grant *et al.*, 1995). A steep gradient in sediment chlorophyll results in a sharp peak in the ratio of suspended chlorophyll to inorganic fraction at flows above U_{crit} . The delayed peak observed at station 3 was probably due to the higher erosion threshold that exists at this site. In general, the peaks

represents a very short-lived time period in which high-quality food would be available to suspension feeders at early stages in the tide.

3.4.7 Sandy site (station 1)

Clear differences between the diatom ecology and sediment type and structure between the sites located inside and outside Upper South Cove render a comparison of sediment erodibility between the two locations difficult. The well-sorted sand present at station 1 is diagnostic of continual reworking typical in high current and wave regimes (Parsieglia *et al.*, 1994). Sediment grain size and turbulent shear stress should largely control the erodibility of the sandy site located outside Upper South Cove, while particle to particle electrostatic charges (Van der Waals forces), bulk density, organic content, and sediment microfabric should control the erodibility of the cohesive sediments found in Upper South Cove (Paterson and Daborn, 1991). In addition, the high energy environment of the exposed station should favour epipsammic diatoms tolerant of sand grain abrasion (Delgado *et al.*, 1991), while the low energy environment of the inside stations should favour epipellic diatoms (Yallop and Paterson, 1994). The larger motile epipellic diatoms, inhabiting cohesive sediments, may represent a small fraction of the total numbers of diatoms, but their large volume may contribute significantly to EPS production and binding of sediment (Paterson *et al.*, 1994b). A comparison of the factors controlling the erodibility of the two locations would not be valid, since striking differences in the nature of the biofilm and sediment structure existed.

Enhanced bivalve growth associated with a sandy substrate relative to a muddy substrate is possibly related to a reduced turbidity over a sandy bottom (Hinch *et al.*, 1986). The differences between the near-bottom particle fluxes at the two locations would depend on 1) the stability of the respective sediment types and 2) the supply of the organic components in the sediment (Rhoads *et al.*, 1984). The higher erosion threshold of the sandy station relative to the muddy stations inside Upper South Cove indicated that the seabed of the outside site was more stable. A comparison of erosion rates between locations to assess stability differences was not considered due to the biased standardization of sediment dry weight. The differences between the supply or concentrations of the organic components of the two locations would be a function of 1) sediment grain size or surface area (Mayer *et al.*, 1985) and 2) biogenic modification or enhancement of organics (Grant and Emerson, 1994). In general, the fluxes of the various organic components of the sediment were greater in Upper South Cove (Figure 3.15), relative to the outside station (Table 3.5) due to greater sediment erodibility and greater supply of organic components present in the unconsolidated muds.

High-quality food particles, such as chlorophyll, are available for a longer duration of a tidal cycle at the sandy site (Figure 3.20). Although the maximum suspended concentration of chlorophyll was lower at the sandy site relative to the muddy site, the maximum ratio of chlorophyll to the inorganic sediment fraction appeared to be sustained for a longer period during the deployment at the sandy site. The depth of the sediment chlorophyll maximum and the steepness of chlorophyll gradient contributed to the rate at which the suspended chlorophyll peak was diluted at both stations.

3.4.8 Comparison of erodibility measurements obtained from the recirculating flume and the Sea Carousel

A SPM signal was not detected during the erosion experiments of sediment cores using the recirculating flume (with the exception of station 4), while a strong signal was detected using the Sea Carousel (Figure 3.21). This lack of SPM detection may be influenced by (1) the differences in the maximum possible U_{*} value achieved in the recirculating flume ($0.03 \text{ m}\cdot\text{s}^{-1}$) and by the Sea Carousel ($0.07 \text{ m}\cdot\text{s}^{-1}$) and (2) the high ratio of the volume of the eroding fluid to eroded area in the recirculating flume (87.3 m) compared to the Sea Carousel (2.5 m). The SPM values obtained by the Sea Carousel were probably a product of heavier material eroded from deeper depths relative to the recirculating flume. A greater ratio of flume volume to eroded area will decrease the detection limit of the eroding signal. However, water samples must be collected in small volumes to prevent overall changes in flow characteristics. As a result the flume methodology comparison was based on U_{*crit} values derived from suspended chlorophyll data.

The greater chlorophyll U_{*crit} values obtained by the recirculating flume relative to those obtained by the Sea Carousel deployments (Figure 3.21) were probably due to 1) consolidation processes that occurred within the sediment core barrels during collection, transportation, and storage, or 2) changes in sediment chlorophyll concentrations during storage of sediment cores (Grant and Daborn, 1994). The maximum number of cores that could be eroded in a day was 3, resulting in a storage time of 1 to 3 days. Growth of diatoms has been shown both to increase or decrease in the dark. However, the consistency in the U_{*crit} values suggests that these values were not dependent on the

varying storage time. It is likely that consolidation occurred during core collection and transportation to the laboratory. Since this flume is portable it would be possible to minimize these disturbance effects by transporting the flume to the site of interest. The trends in erodibility measurements and sediment biofilm components and resulting correlations obtained by the *in situ* method lends confidence that the results of this method are a better reflection of natural conditions.

3.4.9 Summary

In order to assess the erodibility of sediment, it is important to measure collectively erosion threshold, peak erosion rates, and net erosion rates. The erosion thresholds, peak erosion rates and net erosion rates across stations varied by a factor 2, 4 and 7, respectively. The high sediment chlorophyll concentration and low degree of chlorophyll extinction at depth at station 3 was associated with the high erosion threshold and lowest peak erosion and net erosion rates. It appeared that biological control was greater than physical control on sediment stability at these stations. Biological sediment components, such as chlorophyll and colloidal carbohydrate, are useful predictors of surface erosion measurements, such as U_{*crit} , and peak and net erosion rate.

CHAPTER FOUR

Factors affecting the erodibility of subtidal sediment of a hemi-arctic embayment, Manitounuk Sound, Hudson Bay.

4.1 Introduction

The erodibility of estuarine sediments has considerable significance to engineering development, aquaculture, pollutant transport and habitat stability (van de Kreeke, 1986, Smatecek and Walger, 1987). Alternately, anthropogenic influences, such as, construction, dredging, and channel development required for coastal engineering and aquaculture projects, alter processes that govern sediment stability (Paterson and Daborn, 1991). These impacts are not easily predicted and depend on local conditions. The purpose of this field study was to determine trends in the stability of subtidal sediment likely to be impacted by the outflow of a proposed hydro-electric development in a hemi-arctic embayment, Manitounuk Sound, Hudson Bay.

Natural trends in the erodibility of estuarine sediment are poorly known due to the synergistic effects of biochemical and geophysical factors on sediment properties. Laboratory-derived erosion thresholds for abiotic sediments have served as a baseline for field erodibility studies (Paterson *et al*, 1994a). The extent to which natural erosion thresholds vary above this baseline would depend on the physical and biological processes that respond to directional gradients that occur in estuaries. Directional gradients could take place in the form of decreasing sedimentation rates seawards through the estuary or decreasing bottom light availability with increasing depth. These gradients that influence biogeophysical processes in the seabed may be either stabilizing or destabilizing depending on their nature. In order to determine the hierarchy of factors influencing sediment

erodibility, two transects of Sea Carousel deployments were carried out both along the length and across Manitounuk Sound (at the proposed location of the hydro-electric spillway, Figure 4.1).

4.1.1 Study site

Manitounuk Sound is a sheltered subpolar estuary in southeastern Hudson Bay, central Canada, located north of the Grande Baleine river. For an extensive description of Manitounuk Sound see Zevenhuizen *et al.* (1994) and Amos *et al.* (1996). The Manitounuk Islands, consisting of uplifted and tilted stratified bedrock, form the northwestern boundary of the estuary, while extensive mudflats exist on the southeastern boundary. The Sound has an elongated shape with a length of 55 km, an average width of 3 km, and a depth that ranges from 45 m inside the mouth of the sound to 10 m at the inner termination. A sill exists at the mouth of the Sound near Painted Islands (Figure 4.1). A concurrent study monitoring the physiographic characteristics of the sediment divided Manitounuk Sound into 3 distinct regions: the inner Sound, the central Sound, and the outer Sound (Zevenhuizen *et al.*, 1994). The boundaries of these distinct basins are defined by natural restrictions influencing water exchange and consequent variations in depositional style of sediment.

Manitounuk Sound is free of ice for 3 months during the late summer, at which time the water column is stratified due to river runoff from a coastal basin. The Sound is sheltered from waves and experiences semidiurnal tides with a peak range of 2 m. Mean tidal currents reach a maximum of approximately $0.3 \text{ m}\cdot\text{s}^{-1}$.

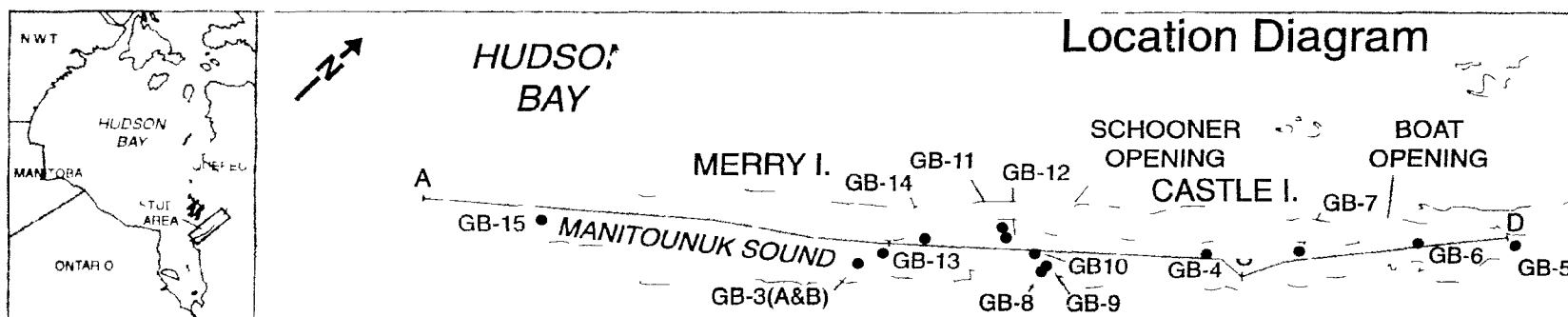


Figure 4 1 Station locations of Sea Carousel deployments in Manitounuk Sound, Hudson Bay

4.2 Methods

Seven stations were chosen along a transect extending over the length of Manitounuk Sound (Figure 4.1). Four additional stations were chosen along another transect perpendicular to the longitudinal transect located in the central sound region. Stations 5, 6, and 7 are located in the inner Sound region, stations 4, 8, 9, 10, 11, 12, and 14 are located in the central Sound region, and station 13 is located in the outer Sound region. Station 15 was not included in this study due to problems during deployment of the Sea Carousel. Sediment erodibility was determined at all stations with the Sea Carousel (Amos *et al.*, 1992b) between August 23 to 26, 1993. A description and diagram of the Sea Carousel is presented in Chapter 3.

During each deployment the speed of the rotating lid of the Sea Carousel was increased in a stepwise manner at 10 minute intervals. Water samples were collected from a sampling port one minute after each increase in lid speed. A foot pump attached to a 1/4" tygon tubing was used to collect the eroded material.

4.2.1 Suspended particulate matter, inorganic, and chlorophyll concentrations of the eroded material.

Water samples containing eroded material were suspended and split for analyses of SPM, inorganic content, chlorophyll and phaeopigment concentrations. Suspended particulate matter was determined gravimetrically after drying the pre-weighed filters at 55 °C for 48 hours and desiccating the filters for 2 hours. An isotonic solution of ammonium formate was used to rinse the filters to remove salts from the SPM samples. Inorganic

content was determined by the weight difference of the SPM filters after they were ashed at 500 °C for 4 hours.

Chlorophyll analysis was performed by placing Whatman glass-fibre filters (GF/C) into 10 ml of 90 % acetone:water solution and allowing extraction to take place for 24 hours in a cold/dark refrigerator. Fluorescence was then measured using a Turner Designs Model 10[™] fluorometer. Two drops of 10 % HCl were added to each sample and the fluorescence measured again. Fluorescence values were converted to chlorophyll and phaeopigment according to the method advanced by Parsons *et al.* (1984).

4.2.2 Biological and physical properties of the sediment

Replicate PVC cores were taken from a Shipek grab sample collected at each station, with the exception of stations 12, 13, 14, and 15. The cores were frozen on the ship and eventually transported on ice to a laboratory freezer. The topmost surface 1 mm and 2 mm of the first set of cores from each station were analyzed for chlorophyll and phaeopigment concentrations. Slices of each sediment layer were cut in 1 mm depth intervals using a razor blade. Each layer was placed in a centrifuge tube and extracted in 10 ml of 90 % acetone: water solution for 24 hours in a cold/dark refrigerator. These samples were centrifuged at 2000 RPM for 5 minutes. Chlorophyll and phaeopigment concentrations of the supernatant were determined according to the fluorometric method advanced by Parsons *et al.* (1984) The values determined for the 1 mm sediment layer and the 2 mm sediment layer of each core were averaged.

The topmost surface 1 mm and 2 mm of the second set of cores from each station were analyzed for organic content. Each sediment slice was dried at 55 °C for 48 hours and ashed at 500 °C for 4 hours. The inorganic content was determined by the weight difference of each sediment layer after ashing. Bulk density was determined by the sediment weight standardized to a volume of 10 cm³. Volume was determined using a Quantachrome Corporation Penta Pycnometer (Gray, 1993). Water content was determined by the percent ratio of the wet and dry weights of each sediment layer, incorporating a salt correction (Gray, 1993). Sediment grain size analysis was carried out on these samples (Buckley *et al.*, 1993).

A Siemens Diffractometer 500 was used to determine the mineralogy of the clay fraction (< 2 µm) collected from surface bulk samples of the grab cores. Talc was the standard against which kaolinite, chlorite, and mica were determined, and corundum was the standard for quartz and plagioclase.

4.2.3 Erosion measurements

Erosion thresholds were determined using the extrapolation method outlined in Chapter 1. Peak erosion rates and net erosion rates were calculated in a similar manner to those described in Chapter 3.

4.3 Results

4.3.1 Sediment properties

Table 4.1 gives a summary of the analysis of the biological and physical properties measured from the surface sediments of Manitounuk Sound. The sedimentary column

Table 4.1: Biological and physical properties of surface sediment samples (uppermost 2 mm) of single cores analyzed at each Sea Carousel station. Station locations are indicated in Figure 4.1

	STATION											
	4	5	6	7	8	9	10	11	12	13	14	
Station distance inner Sound (km)	8.9	2.8	8	14.1	27.4	27.4	28.1	29.6	29.8	33.4	32.9	
Station depth (m)	21	11	24	18	13	13	18	12	43	23	42	
Chlorophyll (µg•ml ⁻¹)	3.5	12.7	3.8	3.9	12.7	10.1	3.7	6				
Phaeopigment (µg•ml ⁻¹)	10.4	8.8	15.7	7.5	10.3	11.6	7.5	3.6				
Mean grain size (µ)	8.9	3.1	8.5	7.1	8.3	6.9	5.5	37.9	2.5	62.1	34.4	
Sand content (%)	27.5	5.3	7.1	25.4	25.5	20.8	20.1	55.3	6.2	62.2	52.7	
Silt content (%)	29.7	40.1	28.1	28.2	32.3	35.3	27.5	15.6	33.1	14.4	17.4	
Clay content (%)	42.8	54.6	64.7	46.3	42.2	43.8	52.4	29.1	60.7	23.4	29.8	
Water content (%)	39.7	54.2	55.6	47.7	51.4	51.4	51.4	65.3	21.4	31	28.9	
Bulk density (kg•m ⁻³)	1820	1680	1710	1720	1790	1790	1790	1590	1650	1970	2010	

consisted of a mottled olive-grey silty clay with an oxidized layer extending to 20 to 30 mm in depth. Bulk density of surface sediments varied between 1650 and 2010 kg·m⁻³ (Table 4.1). This sediment type falls into the category of "soft to stiff organic clays" (Terzaghi and Peck, 1967). The organic carbon content was typically less than 0.6 %.

A general increase in mean grain size of surface sediments seawards occurred to a maxima of coarse silt at stations 11 and 13. The highest clay contents were found in the deep basins (station 12), while the highest sand contents were found on the flanks of the Sound (station 11) or at the sill entrance (station 13). Sediment bulk density increased seawards through the Sound and was the greatest at stations 13 and 14. These stations showed distinct heterolithic laminations and a surface layer of sandy silt, diagnostic of reworking. The clay fraction was dominated by amorphous silica (probably glacial flour). Chlorite was commonly less than 5 %, while kaolinite and smectite were absent. The clays are consequently unreactive and would be expected to possess low cohesive strength. This mineralogy is typical of immature, poorly weathered glacial terrains.

4.3.2 Longitudinal trends

4.3.2.1 Biological and physical sediment predictors

Trends in the biological and physical variables of the surface sediment of stations 4, 5, 6, 7, 10, 14, and 13 (longitudinal transect) are shown in Figure 4.2. Sand content ($r^2 = 0.758$, $p = 0.011$), silt content ($r^2 = 0.757$, $p = 0.011$), clay content ($r^2 = 0.632$, $p = 0.033$), water content ($r^2 = 0.640$, $p = 0.031$) and bulk density ($r^2 = 0.812$, $p = 0.006$) of the sediment were significantly correlated with distance down Manitounuk Sound. Bulk density was significantly correlated with depth of station ($r^2 = 0.599$, $p = 0.041$) along the

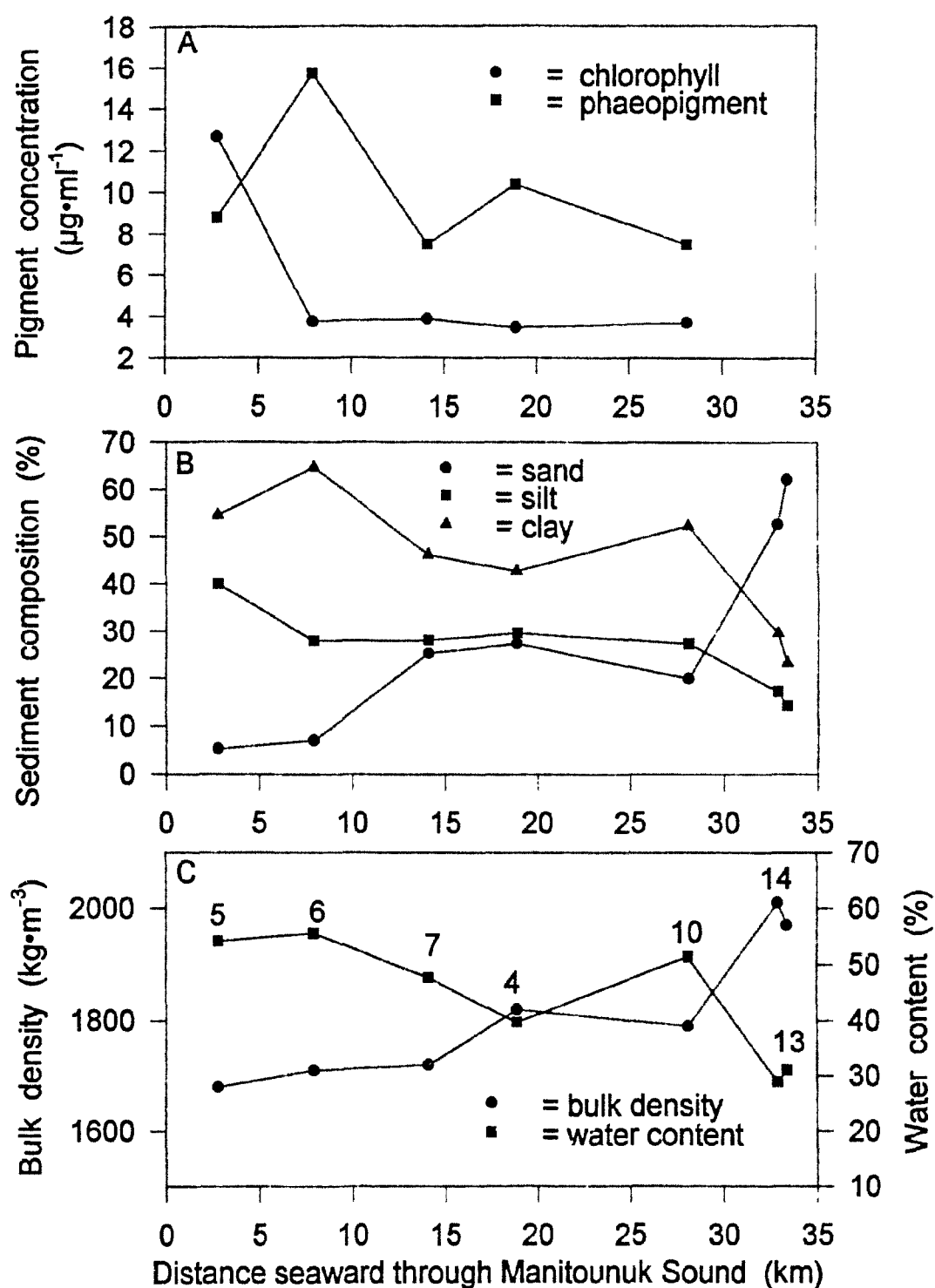


Figure 4.2: Surface biological and physical properties of the sediment: chlorophyll and phaeopigment content (A), percentages of sand, silt, and clay (B), bulk density and water content, with station numbers (C).

longitudinal transect. Of the sediment types, sand content was the best predictor of bulk density ($r^2 = 0.886$, $p = 0.002$).

4.3.2.2 Relationship between U_{crit} and sediment biofilm predictors

Erosion thresholds were determined using the extrapolation method outlined in Chapter 1. The U_{crit} values determined for stations positioned on the longitudinal transect did not correlate with any biological or physical sediment variables. Figure 4.3A shows a slight increase in U_{crit} along the length of the Sound.

4.3.2.3 Peak erosion rate

Peak erosion rates determined for stations positioned on the longitudinal transect did not correlate with any biological sediment variables. Peak erosion rates fluctuated at stations of the inner region and then decreased towards the central and inner regions of the Sound (Figure 4.3B). Peak erosion rates were significantly correlated with mean grain size ($r^2 = 0.739$, $p = 0.013$), sand content ($r^2 = 0.657$, $p = 0.027$), clay content ($r^2 = 0.673$, $p = 0.024$), water content ($r^2 = 0.575$, $p = 0.048$), and net erosion rates ($r^2 = 0.688$, $p = 0.021$; Figure 4.4). Regression equations are presented in Table 4.2.

4.3.2.4 Net erosion rate

Net erosion rates determined for stations positioned on the longitudinal transect were positively correlated with silt content ($r^2 = 0.611$, $p = 0.038$), clay content ($r^2 = 0.841$, $p = 0.004$), water content ($r^2 = 0.832$, $p = 0.004$), and phaeopigment

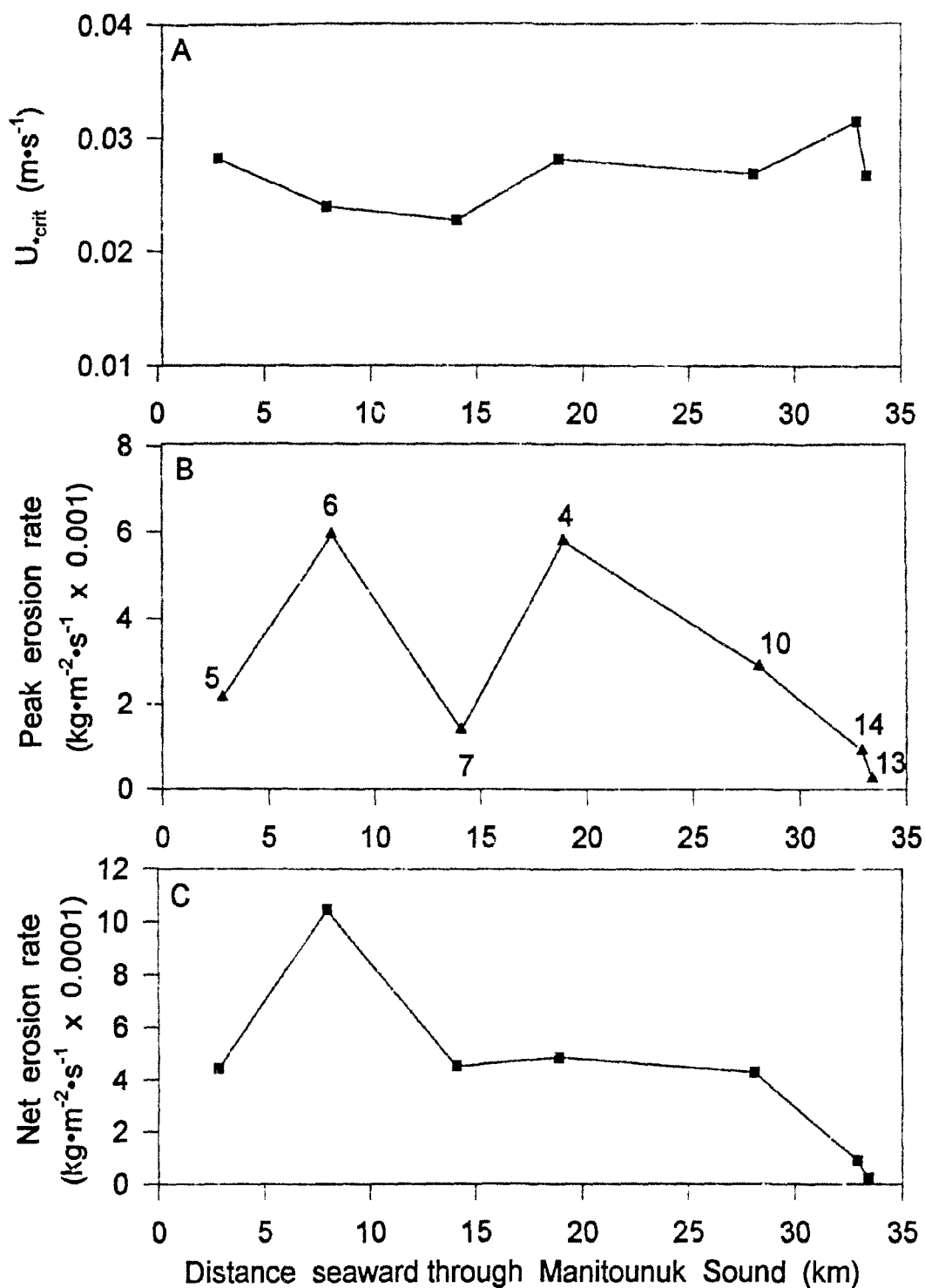


Figure 4.3: U_{crit} (A), peak erosion rate (B), and net erosion rate (C) values obtained from Sea Carousel deployments made on a transect along the length of the Manitounuk Sound.

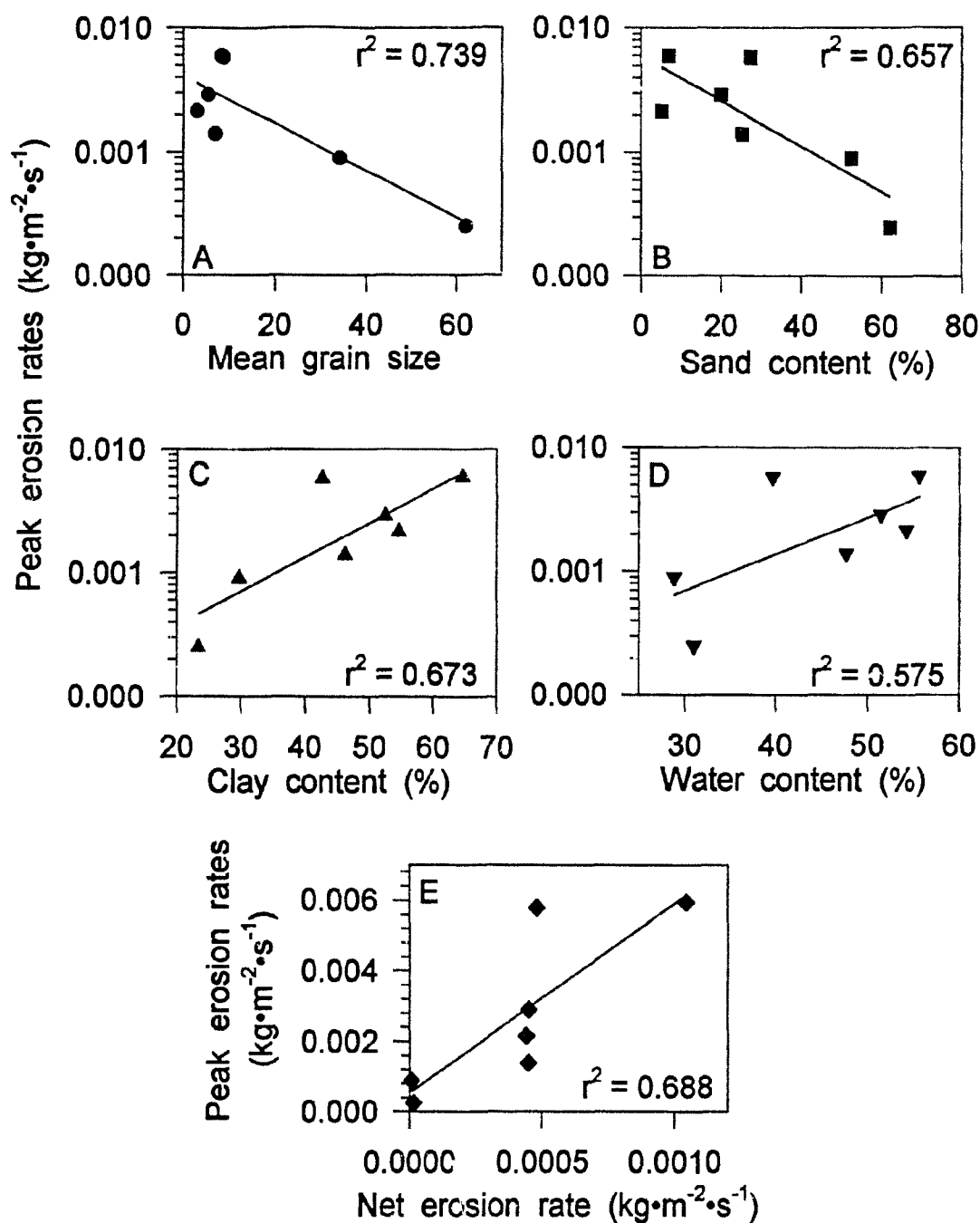


Figure 4.4: Regressions showing the relationships between peak erosion rate and sediment mean grain size (A), sand content (B), clay content (C), water content (D), and net erosion rates (E).

Table 4.2: Regression equations describing the relationships between peak erosion rate (PER) and mean grain size, sand content, clay content, water content, and net erosion rate. Level of significance = 0.05, n = 7).

Regression equations	r^2	p
$\text{Log PER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = -0.04 (\text{mean grain size}) - 5.5$	0.739	0.01
$\text{Log PER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = -0.04 (\text{sand content (\%)}) - 5.1$	0.657	0.03
$\text{Log PER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 0.06 (\text{clay content (\%)}) - 9.2$	0.673	0.02
$\text{Log PER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 0.07 (\text{water content (\%)}) - 9$	0.575	0.048
$\text{Log PER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 2776 (\text{net erosion rate (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1})) - 8$	0.688	0.02

($r^2 = 0.904$, $p = 0.013$) and negatively correlated with mean grain size ($r^2 = 0.926$, $p = 0.001$), sand content ($r^2 = 0.845$, $p = 0.003$), and bulk density ($r^2 = 0.701$, $p = 0.019$; Figure 4.5). Regression equations are presented in Table 4.3. Figure 4.3C shows a decrease in net erosion rate towards the mouth of the Sound. The high sediment chlorophyll value observed at station 5 (Figure 4.2) may have contributed to the low net erosion rate value observed at station 5 (Figure 4.3).

4.3.3 Cross-Sound trends

This transect started on the gradually sloping tidal flats on the eastern border of the Sound, traveled through a deep basin of 43 m, and finished on the flanked slope of the western border of the Sound.

4.3.3.1 Biological and physical sediment predictors

Trends in the biological and physical properties of the surface sediment of stations 8, 9, 10, 11, 12 (cross-Sound transect) are shown in Figure 4.6. Bulk density ($r^2 = 0.906$, $p = 0.013$) and sediment phaeopigment concentrations ($r^2 = 0.943$, $p = 0.029$) were significantly correlated with distance across the central region of Manitounuk Sound. Water content was significantly correlated with depth of station across the Sound ($r^2 = 0.894$, $p = 0.015$).

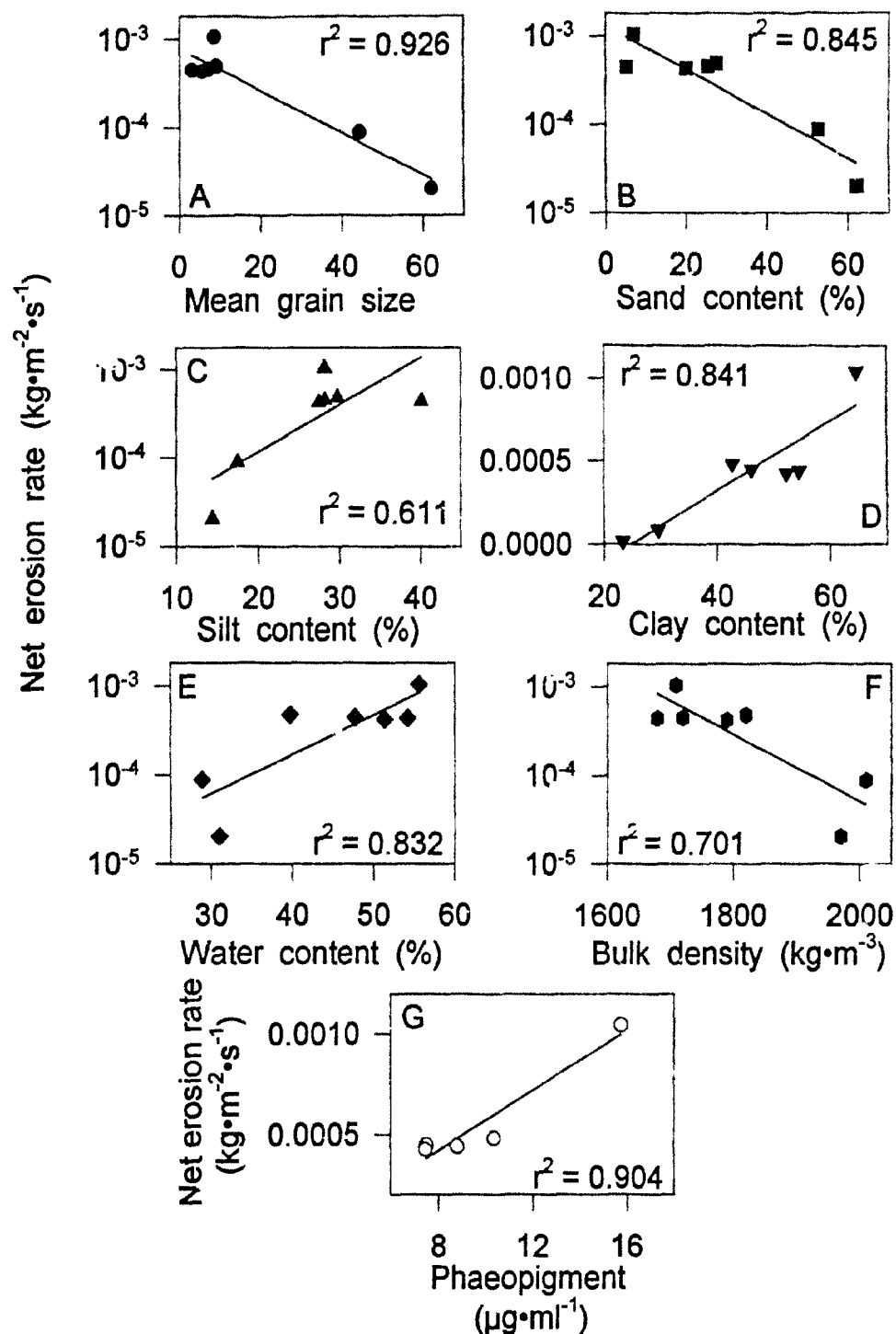


Figure 4.5: Regressions showing the relationships between net erosion rate and mean grain size (A), sand content (B), silt content (C), clay content (D), water content (E), bulk density (F), and phaeopigment content (G) of the sediment surface.

Table 4.3: Regression equations describing the relationships between net erosion rate (NER) and mean grain size, sand content, silt content, clay content, water content, bulk density, and sediment phaeopigment concentration. Level of significance = 0.05, n = 7).

Regression equations	r^2	p
$\text{Log NER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = -0.062 (\text{mean grain size}) - 7.1$	0.926	0.001
$\text{Log NER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = -0.06 (\text{sand content (\%)}) - 6.6$	0.845	0.003
$\text{Log NER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 0.13 (\text{silt content (\%)}) - 12$	0.611	0.04
$\text{NER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 0.000021 (\text{clay content (\%)}) - 0.0005$	0.841	0.004
$\text{Log NER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 0.10 (\text{water content (\%)}) - 12.7$	0.832	0.004
$\text{Log NER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = -0.009 (\text{bulk density (kg}\cdot\text{m}^{-3}) - 8$	0.701	0.02
$\text{NER (kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}) = 0.00007 (\text{phaeopigment (}\mu\text{g}\cdot\text{ml}^{-1}) - 0.2$	0.904	0.01

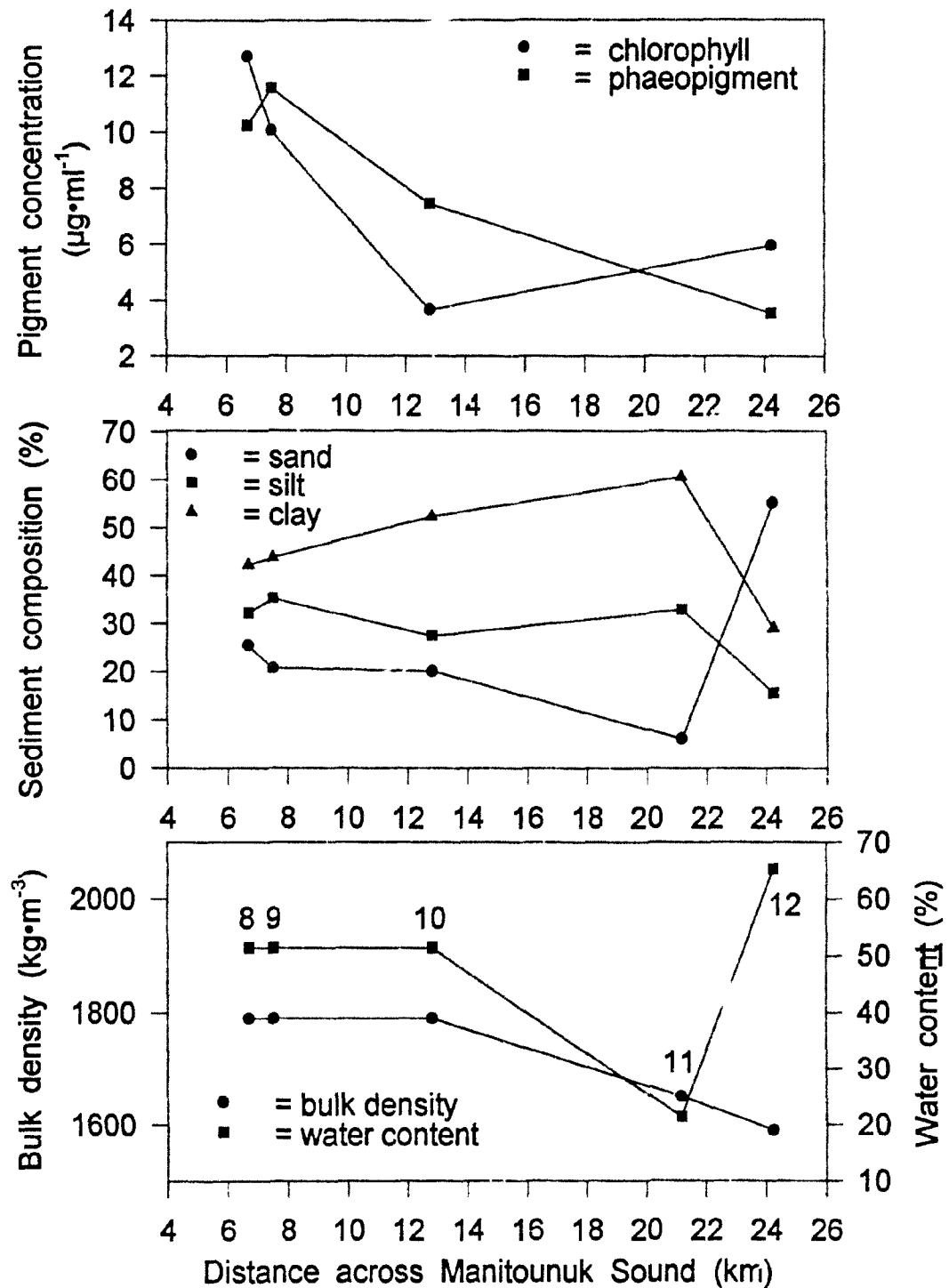


Figure 4.6: Surface biological and physical properties of the sediment: chlorophyll and phaeopigment content (A), percentages of sand, silt, and clay (B), and bulk density and water content, with station numbers (C).

4.3.3.2 Relationship between erosion thresholds and rates and sediment biofilm predictors

Too few data points existed along this transect to run regressions correlating U_{crit} , peak erosion rates, and net erosion rates with the biological or physical sediment properties. The erosion parameters were not calculated for station 11 due to problems during the flume deployment. Although the physical properties of the sediment did not vary between stations 8, 9, and 10, a decrease in chlorophyll away from the tidal flats was observed (Figure 4.6). This decrease may be responsible for higher values of peak erosion rate and net erosion rates observed at stations 8, 9, and 10 (Figure 4.7).

4.3.4 Organic fluxes

The ratios of suspended chlorophyll to inorganic sediment were typically greater than those found in Upper South Cove (Figure 4.8 and 4.9). The increasing slope and decline of the ratio of chlorophyll to inorganic sediment around the peak values were gradual at stations in Manitounuk Sound relative to the sharp "peaks" and pronounced exponential decay in ratios or the dilution of chlorophyll by the inorganic fraction, observed at stations in Upper South Cove. The magnitude of the ratios and the availability "window" of high-quality food particles for suspension feeders appeared to be greater in Manitounuk Sound. The presence of chlorophyll at greater depths in the sediment column (Figure 4.10) may have contributed to the prolonged maintenance of the chlorophyll to inorganic sediment in suspension (Figure 4.8 and 4.9).

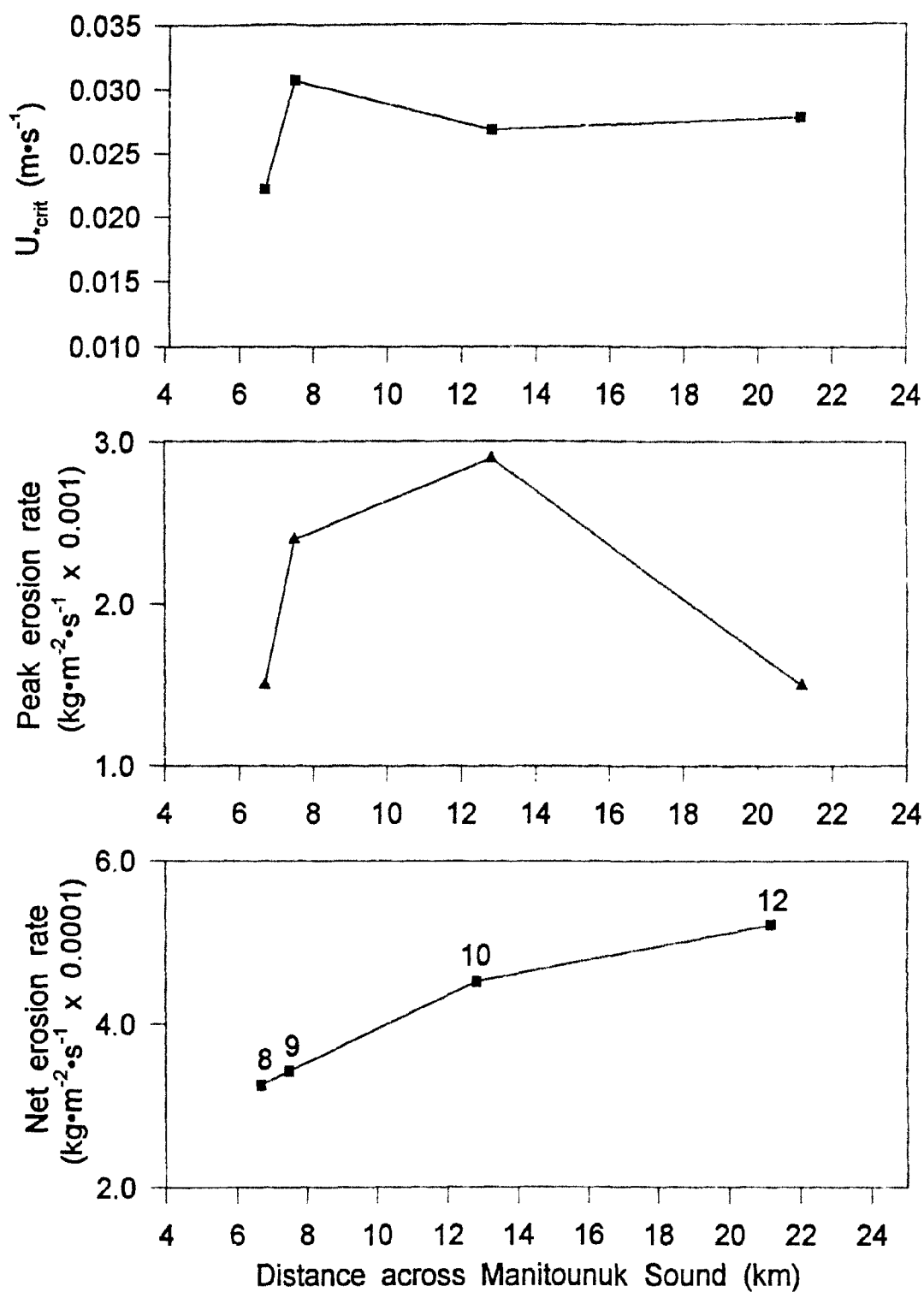


Figure 4.7: U_{crit} (A), peak erosion rate (B), net erosion rate (C) values obtained from Sea Carousel deployments made on a transect across Manitounuk Sound.

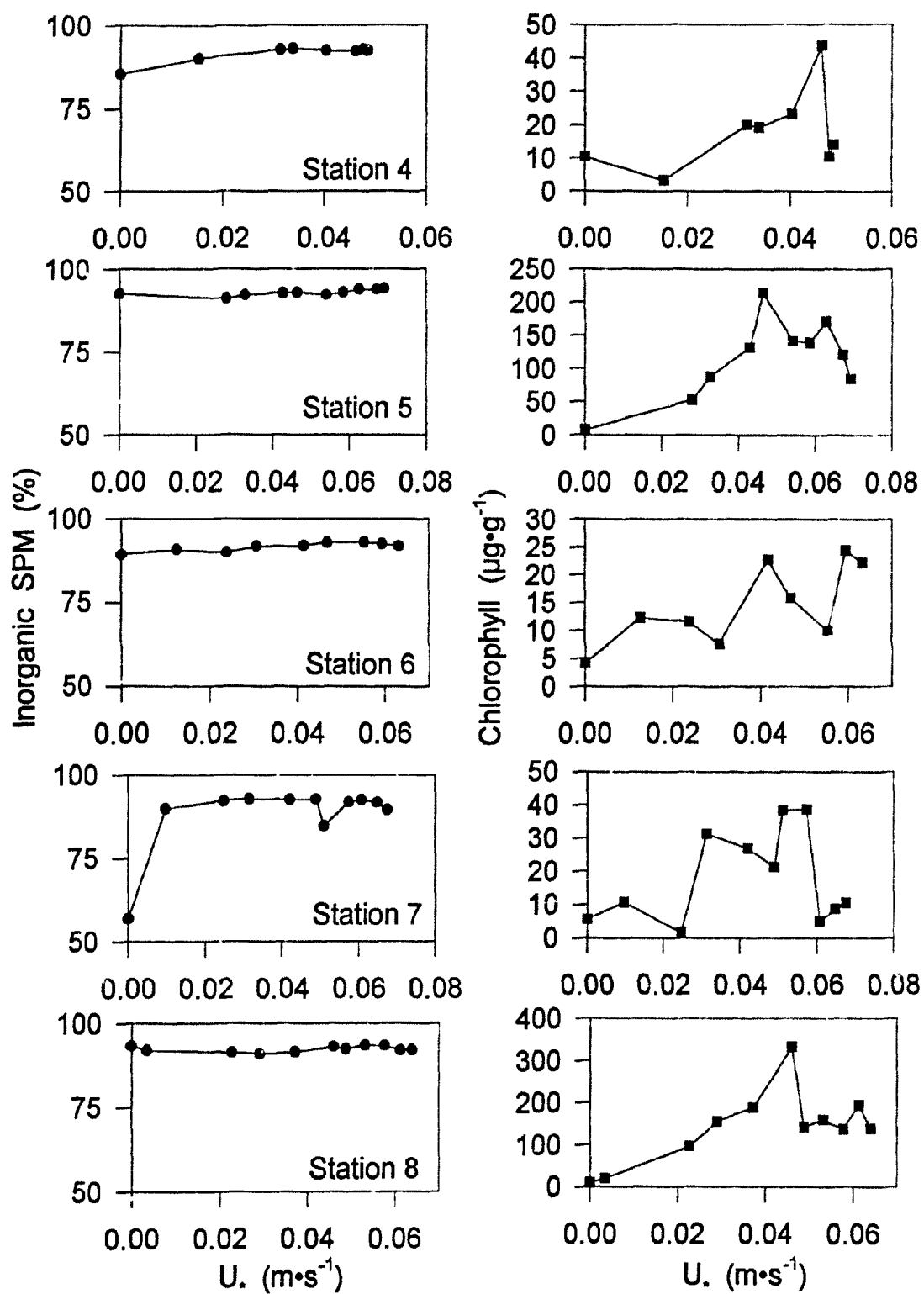


Figure 4.8: Percentage of Inorganic SPM and the ratio of chlorophyll to inorganic SPM in relation to $U.$ at stations 4, 5, 6, 7, and 8.

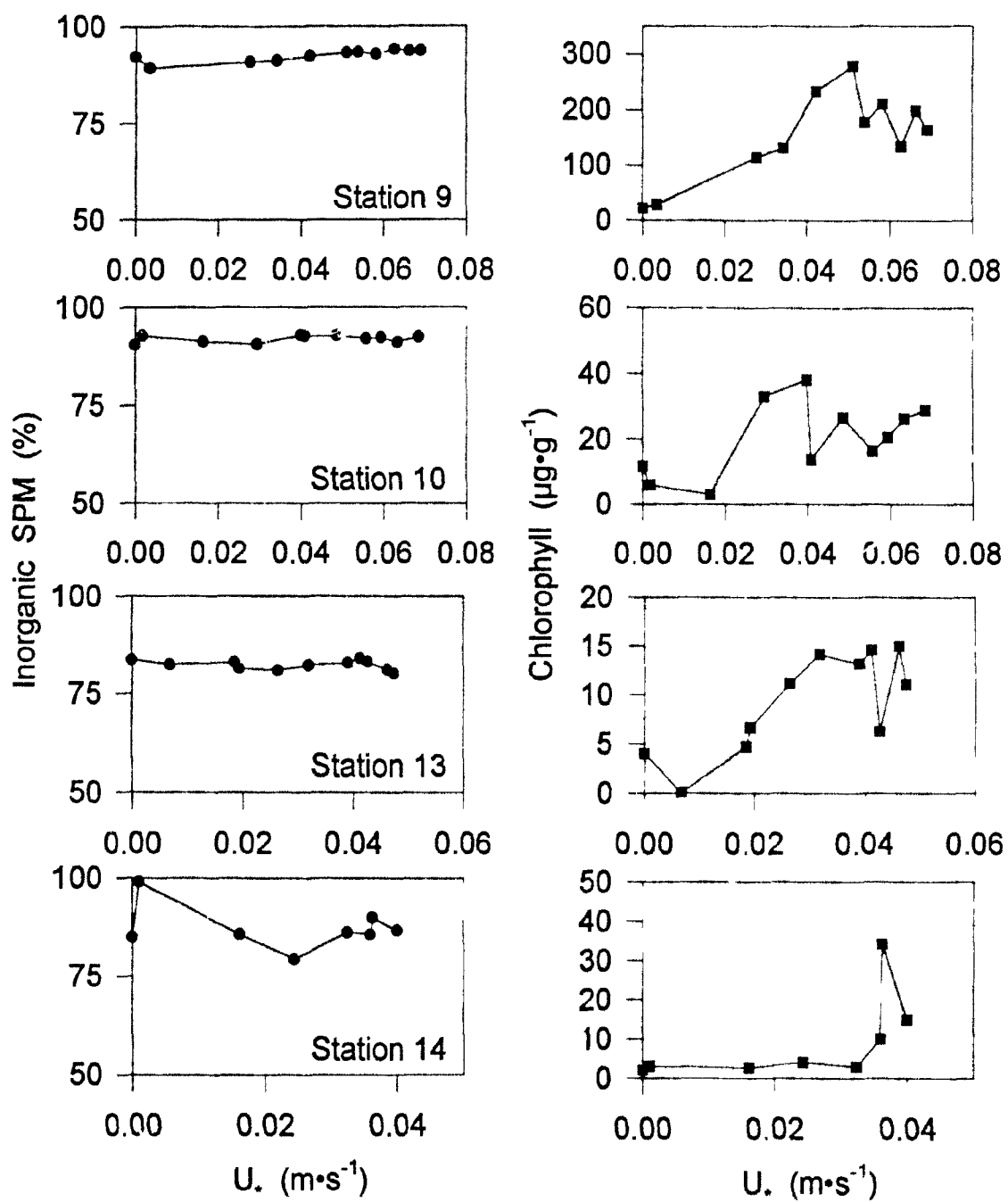


Figure 4.9: Percentage of inorganic SPM and ratio of chlorophyll to inorganic SPM in relation to U_* at stations 9, 10, 13, and 14.

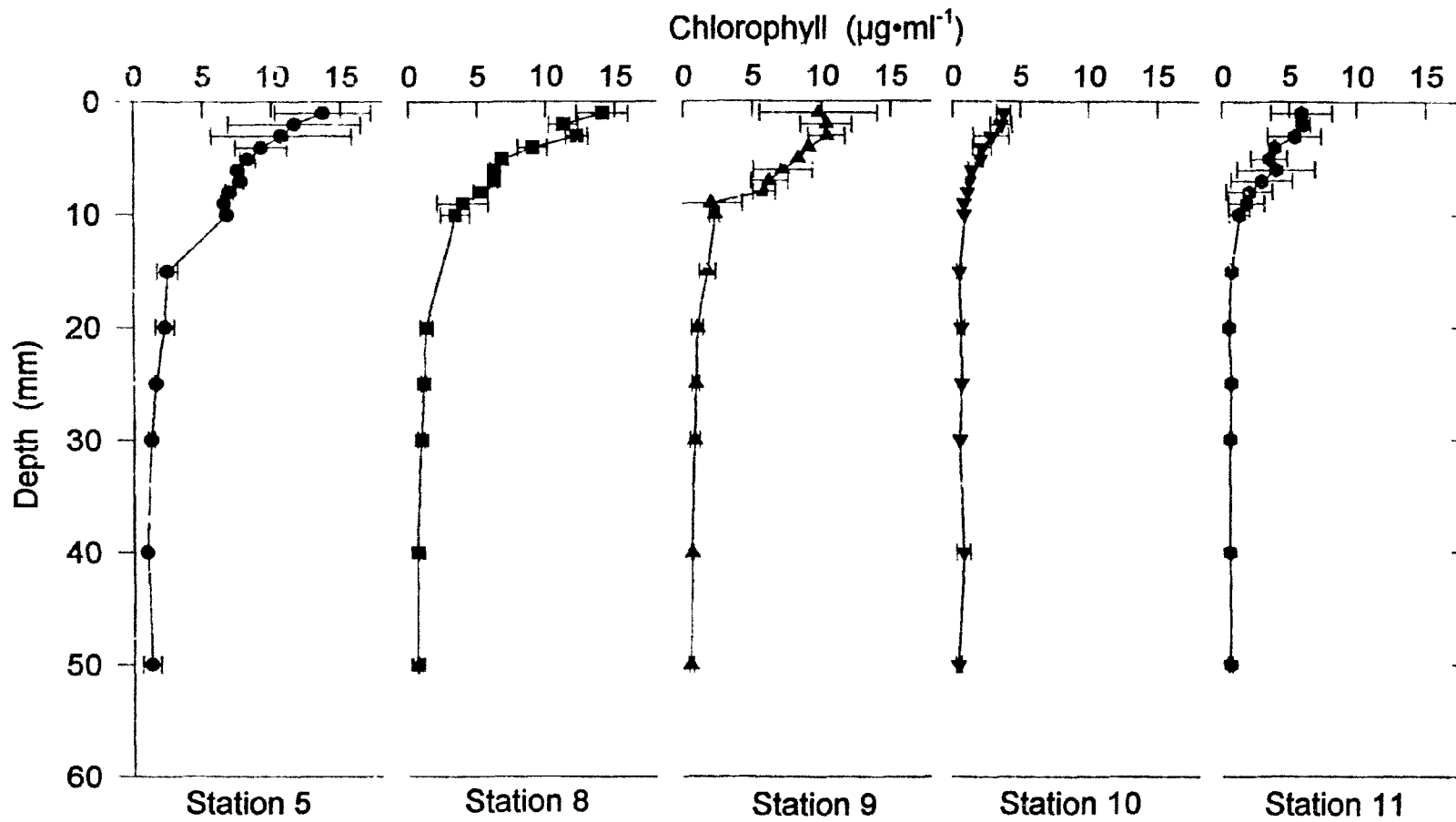


Figure 4.10: Vertical profiles of chlorophyll in the sediment at stations 5, 8, 9, 10, and 11. Station locations are indicated in Figure 4.1. Error bars = 1 standard deviation.

4.4 Discussion

The variations in sediment composition and bulk density along the length of Manitounuk Sound reflected a decreasing trend in sedimentation rates seaward through the Sound (Amos *et al.*, 1996). The inner Sound was characterized by continuous, rapid, post-glacial sedimentation, while seabed reworking and glacial outcrops (sill and flanks) was typical of the outer Sound.

4.4.1 Biological and physical sediment predictors

The extent to which the sediment of Manitounuk Sound was consolidated and varied in sediment size and composition was substantially greater in comparison to variations in sediment characteristics of Upper South Cove. This observation is not surprising considering the station transect lengths of Manitounuk Sound and Upper South Cove spanned 33.4 and 1.3 km, respectively. The large variations in sand content between stations was a product of increasing tidal energy seaward through the Sound. Since sand content varied by a factor of 11 and chlorophyll content varied by a factor of 4, the larger variations in the physical sediment characteristics relative to the biological sediment parameters would be expected to serve as more sensitive indicators of sediment erodibility.

The accompaniment of silt and clay in the surface sediment at stations in Manitounuk Sound indicated that the settlement of fines was not hindered by the presence of continuous or long-lasting hydrodynamic processes at these stations (Parsieglä *et al.*, 1994). The accumulation of silt, clay and organic matter probably occurred during

quiescent periods and formed the interstitial material. Although, the sediment of several stations (11, 13, and 14) in Manitounuk Sound contained a high proportion of sand, these sediments were not as well-sorted as the sediment of the exposed site (station 1) in Upper South Cove.

The development of a complex sediment matrix or fabric would depend on 1) hydrodynamic energy, 2) the cohesive nature of the clay fraction, 3) the aggregation state of the silt-clay and organic fractions (Watling, 1989), and 4) the binding potential of the diatoms present (Paterson *et al.*, 1994b). Sediment mineralogy revealed that the clay fraction had a low chemical effect since it was a product of the surrounding glacial terrain. Although the aggregation state was not measured, it would be influenced by the colonization of diatoms. The fine interstitial material would supply a habitat for epipellic diatoms. High proportions of diatoms (80%) have been shown to occupy the mud coatings relative to the surfaces of sand grains in mixed tidal flats and channels of the Ems estuary (de Jonge, 1985). Correlations between erosion thresholds and the motile epipellic diatom fraction have been found to be significant, while those with total diatom biomass have not (Madsen *et al.*, 1993). Subsequent stabilization of this fine fraction would promote the development of a permanent sediment matrix, the further settlement of fine material and the survival of epipellic diatoms by reducing abrasive effects caused by hydrodynamic sorting (Delgado *et al.*, 1991). EPS has been suggested to act not only as a grain binder, but also as an elastic cushion between sediment grains, inhibiting the disruption of the sediment matrix (Frankel and Mead, 1973). Both biological and physical factors contribute

to the development of sediment microfabric, which in turn influences the erodibility of sediment.

4.4.2 Vertical profiles of sediment chlorophyll

Fine scale vertical-sectioning of sediment cores is necessary to determine the optimum depth of sampling of the sediment predictors required to maintain a strong sediment signal for correlation purposes. The subsurface chlorophyll maximum evident at station 9 would cause problems in obtaining the optimum concentration and maintaining sampling consistency across stations (Figure 4.10). Differences in the rate at which chlorophyll decreased at each mm depth interval across stations, such as 5 and 11, would also influence the depth to which chlorophyll should be sampled.

Although the consolidated nature of the sediments in Manitounuk Sound relative to those of Upper South Cove would presumably result in reduced light penetration due to a greater packing structure (higher bulk density values), higher concentrations of chlorophyll existed at greater depths in the sediment in Manitounuk Sound. In addition, the water depths of the stations in Manitounuk Sound are greater than 10 m, while those in Upper South Cove are less than 10 m. Light availability would also depend on variations in incident irradiance, cloud cover, attenuation in the overlying water column (Pinckney, 1994), however, these conditions were not measured and taken into account. The depth to which chlorophyll extended into the unconsolidated muds of Upper South Cove coincided with the depth to which the sediments became anoxic, suggesting that H_2S production associated with anoxic zones inhibited further penetration of chlorophyll in the

sediment (Jorgensen, 1989) Therefore, the prediction of chlorophyll penetration in sediments based on micro-light sensors would give unreliable estimates of chlorophyll biomass used to predict sediment erodibility. Vertical sectioning of sediment cores is essential in determining the optimum sampling depth to prevent inclusion of chlorophyll-free sediment. A dilution of the chlorophyll signal would reduce its potential as an indicator of sediment stability.

4.4.3 Relationship between erodibility measurements and sediment biofilm predictors (longitudinal transect)

Higher values of erosion thresholds of Manitounuk Sound sediment (Figures 4.3 and 4.7) relative to those of Upper South Cove sediment (Figure 3.6), were probably due to the higher sand content, higher chlorophyll content and greater degree of consolidation of sediment. The lack of correlation between U_{crit} and the physical and biological sediment predictors, may be due to the small degree of variation in U_{crit} values along the longitudinal transect. The U_{crit} values may have represented the erosion of the fine fraction through hydraulic sorting. The erosion characteristics of this fine fraction may not have varied significantly throughout the sound. In addition, the U_{*} values of the initial speed increment of Manitounuk Sound ($0.163 \text{ m}\cdot\text{s}^{-1}$) were much larger than those of Upper South Cove ($0.0044 \text{ m}\cdot\text{s}^{-1}$). It is possible that the erosion threshold of the sediment fell below the U_{*} value associated with the initial speed increment. The high values and consistency of erosion thresholds measured in Manitounuk Sound relative to those measured in Upper South Cove may be controlled by the incipient U_{*} .

The correlation of peak erosion rate and net erosion rate with so many of the sediment variables was due to the collinearity between the sediment predictors that varied together or around a common cause (Figures 4.4 and 4.5). The degree to which these sediment variables vary together would depend on the interaction of hydrodynamic energy (sorting) and biogenic stabilization of sediment. A diminishing sedimentation rate and increasing bulk density seaward through the Sound (Amos *et al.*, 1996) reflected an increase in hydrodynamic energy. These directional gradients were in harmony with the decrease in net erosion rate measured seaward through the Sound. Results from station 5 did not fit this pattern. The low net erosion rate at this station may have been influenced by the high sediment chlorophyll content. Although it is difficult to determine whether biological or physical sediment properties primarily controlled sediment erodibility, it is clear that physical characteristics were important. Conventional sedimentological analyses as correlates of sediment erodibility, may be more useful in regions where strong variations in sediment composition occur.

A stronger relationship between erosion rate and sediment predictor was not always reflected in a high coefficient of determination or low p-value. For example, the correlation between net erosion rate and phaeopigment concentration resulted in a high r^2 value and low p-value relative to the other correlations. However, the data points of this plot could potentially be divided into two populations, with one group "weighting" the relationship of the other. A straight line between two groups of data would result in a high correlation. Therefore, the regressions should be viewed with caution in choosing the best "predictor" of sediment erodibility (Figure 4.4 and 4.5).

4.4.4 Relationship between erodibility measurements and physical and biological sediment predictors (cross-Sound transect)

The increase in peak and net erosion rates observed across Manitounuk Sound (Figure 4.7) may be due to a change in sediment composition or to a decrease in sediment chlorophyll concentration (Figure 4.6). The changes in chlorophyll content are greater than the changes in physical factors, such as bulk density and sediment composition, suggesting that biological factors control erosion rates at stations 8, 9, and 10. These stations are proximal to the chlorophyll-rich tidal flats (Ruz *et al.*, 1994) which could act as a source of benthic diatoms for the subtidal zone.

4.4.5 Relationship between sediment chlorophyll and suspended chlorophyll

The magnitude and shape of the shear velocity profiles of the ratio of chlorophyll to inorganic content would depend on 1) the shear velocity increments, 2) the concentration of sediment chlorophyll, 3) the depth of chlorophyll penetration in the sediment, 4) the steepness of the chlorophyll gradient, and 5) the depth of chlorophyll maximum. The early onset of a sharp peak in the ratio of chlorophyll to inorganic sediment observed in Upper South Cove (Figure 3.17) was a combination of the low sediment strength of the existing unconsolidated muds and the concentration of chlorophyll in the topmost sediment layer (Figure 3.5). The gradual increase in the ratio of the suspended chlorophyll to inorganic sediment observed in Manitounuk Sound (Figure 4.8 and 4.9) was probably due to the presence of the consolidated "soft to stiff organic clays" to a greater degree and the maintenance of chlorophyll at depth to a lesser degree (Figure 4.10). The dilution of chlorophyll by inorganic matter is drastic and occurs at low shear

stress values. Although the inorganic content of SPM was greater in Manitounuk Sound (82 - 93 %) relative to Upper South Cove (71 - 77 %), the peak concentrations of chlorophyll were greater in Manitounuk Sound. In general, higher concentrations of chlorophyll would be available to suspension feeders for a longer duration of the tide in Manitounuk Sound relative to Upper South Cove.

CHAPTER FIVE

General summary

5.1 The impact of biofilms on sediment erodibility

Biofilms influence sediment erodibility. In the laboratory setting, the ratio of sediment bulk carbohydrate to chlorophyll showed a strong relationship with the erosion rate of sediment (Figure 2.12). This ratio indicates the phase of biofilm growth from the "pioneering" to the "established" stages. The growth phase of a biofilm is an important factor controlling the production of EPS. The increase in size of eroded aggregates with age of a diatom biofilm or increased production of carbohydrates indicated a change in the sediment microfabric. This change in sediment microfabric may have been due to a saturation of sediment with EPS or a change in the "stickiness" with the age of the biofilm. The point of EPS saturation of sediment suggests that the erosion rate of individual grains is no longer a function of mineral chemistry or the grain Reynolds number, but a function of the physical and biochemical nature of the biofilm microfabric. The convergence of erosion rates of total sediment and the erosion rates of diatom biofilm supports this (Figure 2.10).

In the field setting, pigment and mucilage components of biofilms, such as chlorophyll and carbohydrate, exhibited strong correlations with *in situ* erodibility measurements (Upper South Cove), such as U_{crit} (Figure 3.6), peak erosion rates (Figure 3.12), and net erosion rates (Figure 3.13). The relationship between the chlorophyll content and peak and net erosion rates of subtidal sediment in both Upper South Cove, Nova Scotia and Manitounuk Sound, Quebec is shown in Figure 5.1B and C. The influence of sediment chlorophyll content on U_{crit} appeared to be restricted to the

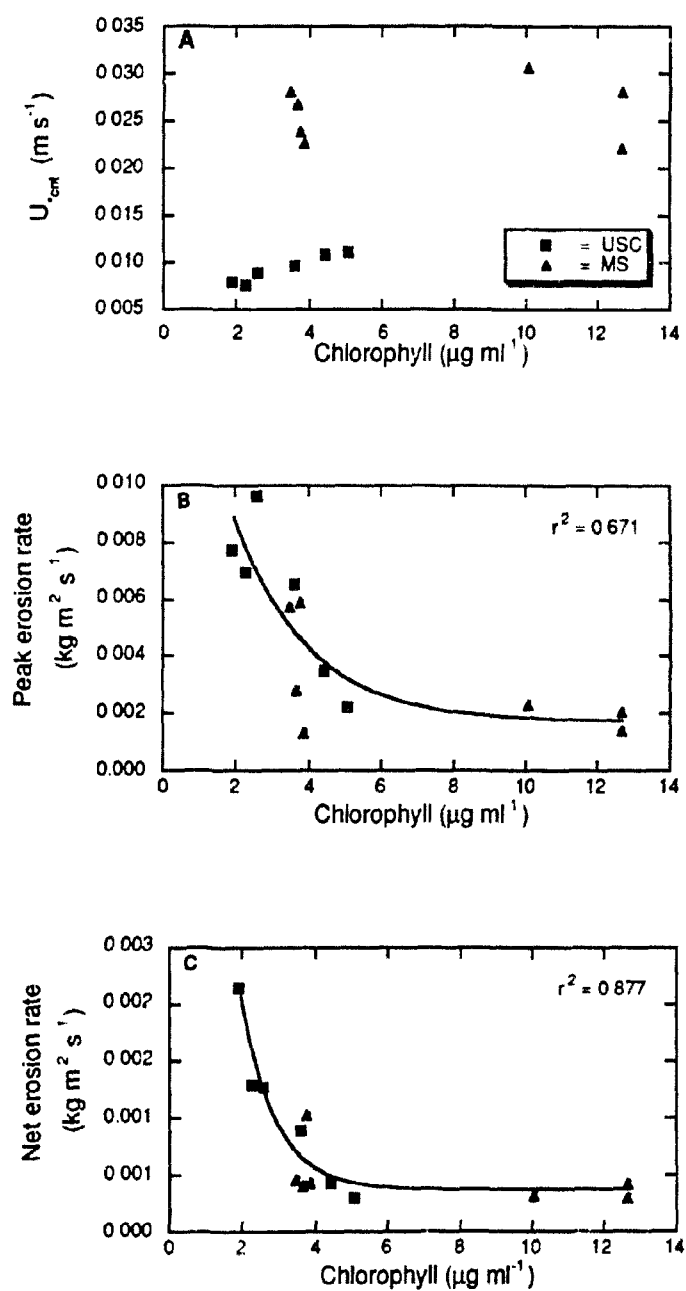


Figure 5.1 The relationship between sediment chlorophyll and U_{crit} (A), peak erosion (B), and net erosion rate (C) for data collected in Upper South Cove (USC) and Manitounuk Sound (MS).

unconsolidated muds of very low bulk density existing in Upper South Cove (Figure 5.1A). Further evidence for biostabilization in this region is the occurrence of a "buoyant" chlorophyll-containing gel mud in the upper centimetre of the sediment column (Figures 3.4, 3.5, and 5.2). In Manitounuk Sound, physical properties of the seabed exerted a stronger control over peak and net erosion rates relative to the influence of biological sediment properties. The relationships between bulk density and U_{crit} and peak and net erosion rate are shown in Figures 5.2 and Figure 5.3A and B, respectively. Although more research is necessary to draw conclusions from the relationship between U_{crit} and bulk density of the two locations, increases in U_{crit} were associated with increases in bulk density (Figure 5.2).

5.2 Definition of sediment erodibility

The entrainment of particles is a critical event as it is used widely in transport formulas and numerical models (Paterson, 1994; Lavelle and Mofjeld, 1987). However, numerous observational definitions of erosion threshold exist in the literature leading to inconsistencies between investigations and, therefore, a variety of quantitative results (Miller *et al.*, 1977). In addition, these investigations have focused predominantly on the erosion thresholds of well-sorted, non-cohesive, abiotic sediment that behave differently than naturally occurring biomediated sediment mixtures. The objective of this section is to outline the various methods of erosion threshold determination in context with Lavelle and Mofjeld's (1987) criticisms of the definition of erosion threshold.

The erosion threshold is the transition point or bed shear stress condition slightly less than that required to initiate bed movement (Miller *et al.*, 1977). Incipient motion is defined as bed movement after the erosion threshold has been surpassed (Lavelle and

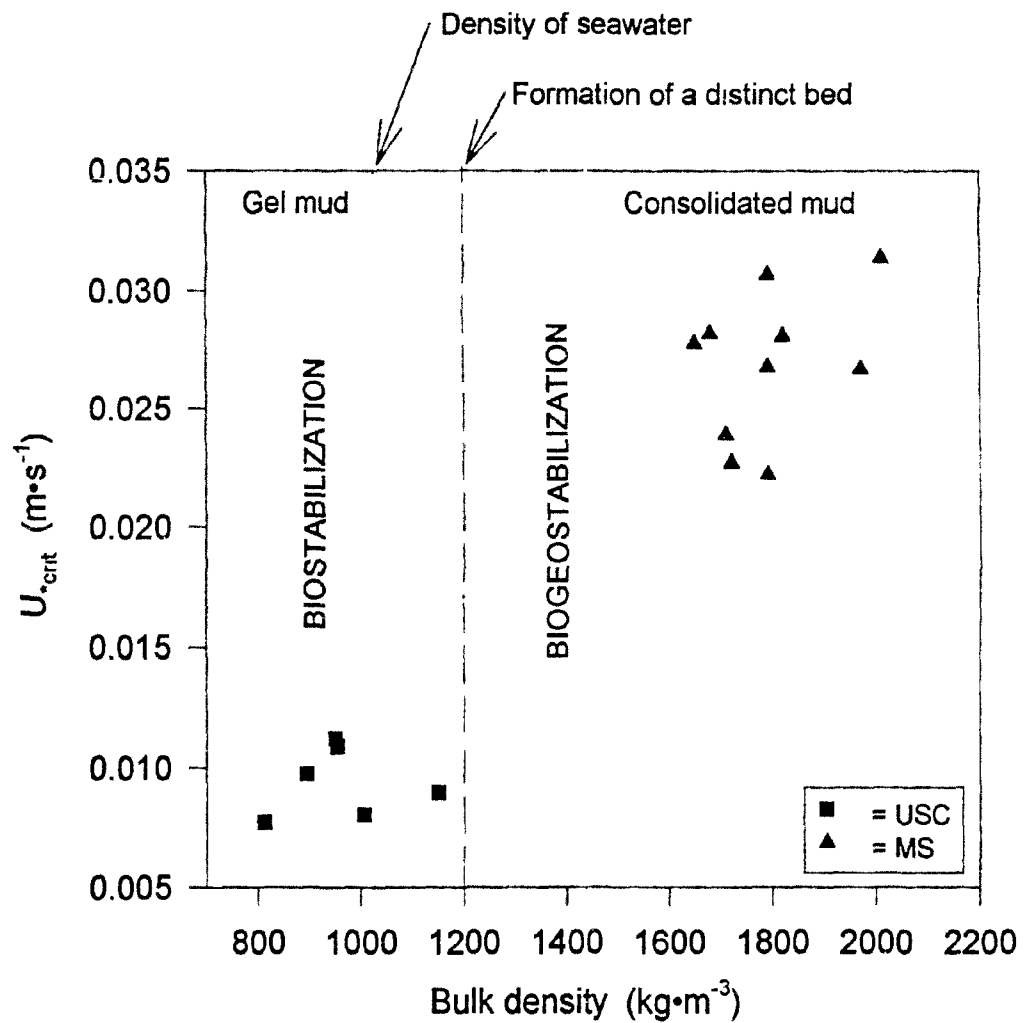


Figure 5.2: Relationship between U_{crit} and bulk density for data collected from Upper South Cove (USC) and Manitounuk Sound (MS).

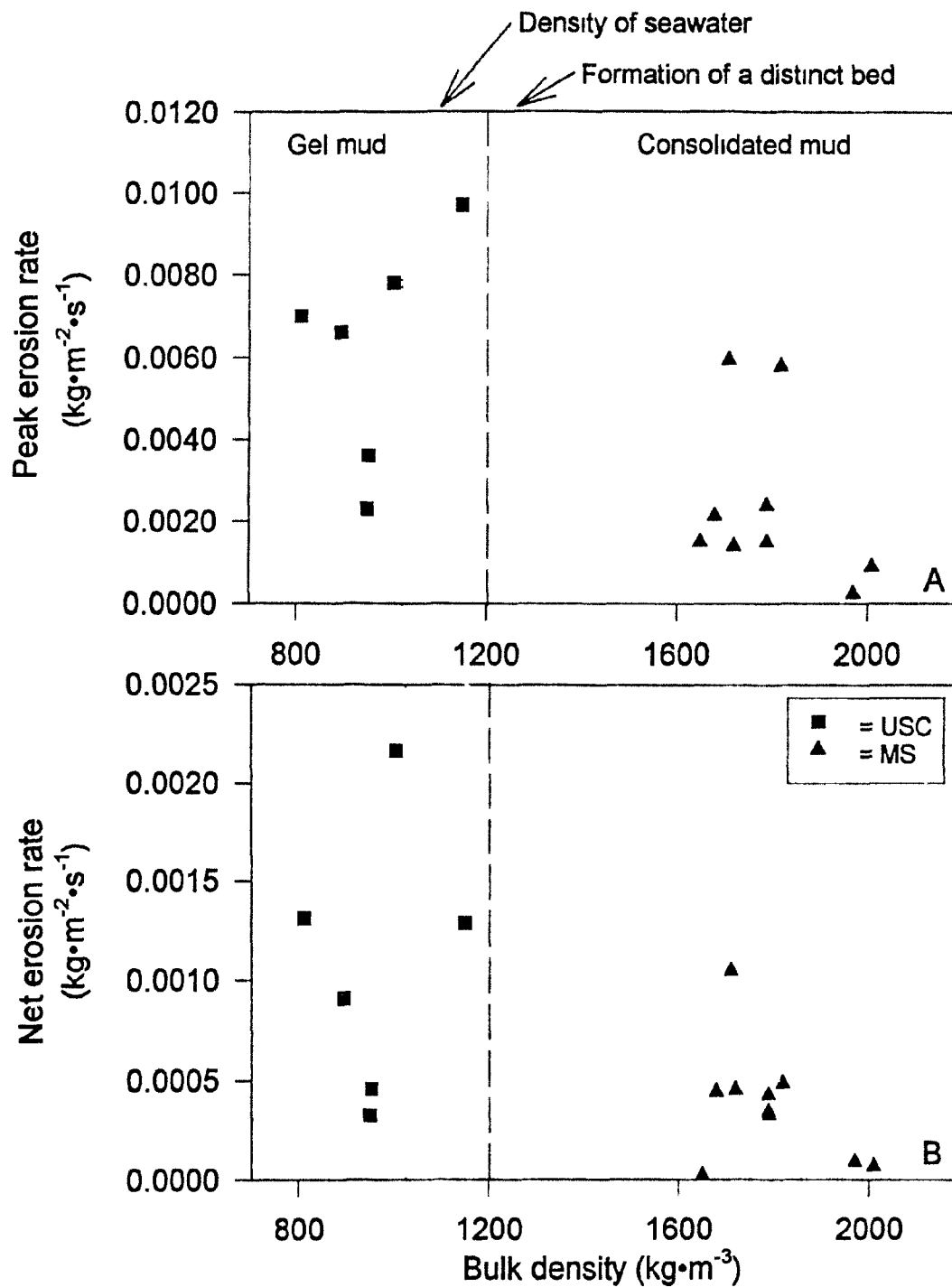


Figure 5.3: Relationship between bulk density and peak erosion rate (A) and between bulk density and net erosion rate (B) for data collected from Upper South Cove (USC) and Manitounuk Sound (MS).

Mofjeld, 1987). How can threshold conditions be measured through observation if it is defined as the critical point before initial motion (Miller *et al* , 1977)?

"Particle threshold" or "bed threshold" is the friction velocity or bed stress required to move or erode single particles or a bed of particles, respectively (Lavelle and Mofjeld, 1987) The preciseness with which erosion threshold can be determined is limited by these numerous and incompatible definitions (Miller *et al* , 1977) Subjectivity arises in these definitions when variations in 1) the area of eroding seabed, 2) the duration of observational period, and 3) the number and size of particles, occur between investigations Also the transition point of particle motion may be different from that of particle discharge In this thesis, definitions such as, particle threshold, bed threshold, and discharge threshold, were used to determine the initiation of sediment movement The following section will outline the application of these definitions

Particle threshold is a function of the duration of the observation period and the area of erosion of a designated experiment A high variation of stresses exists temporally and spatially in the turbulent boundary layer, due to turbulent eddies that can, on occasion, penetrate the viscous sublayer (Lavelle and Mofjeld, 1987) The correlation of sediment resuspension and turbulent bursts has been established in the literature (Sutherland, 1967) Given an extended observation period or working area, the probability of particle movement would increase Such occasional movements may be considered to be irrelevant, but could amount to significant quantities of sediment transport over time Instantaneous bursting could potentially occur below the bed threshold value determined at a time-averaged shear stress Since the time periods of the speed increments or

observational periods did not vary between experiments, the differences in erosion areas between the Sea Carousel (0.873 m²) and the recirculating flume (0.102 m²) may have been partially responsible for the higher erosion thresholds determined by the recirculating flume.

Particle threshold is also a function of the eroding particle or aggregate size, which corresponds to developmental stage or age of a surface biofilm. In Chapter 2, a steady increase in the size of the particles or aggregates eroded was observed during the growout period of the diatom, *Nitzschia curvilineata* (Figure 2.4B). The formation of a biofilm-sediment microfabric through the growth and migration of diatoms and associated pervasion of EPS in the sediment was responsible for the observed increase in eroded aggregate size. In addition, the erosion of larger aggregates from natural sediment cores (Chapter 3) containing the well-established biofilm was easily detected, while the detection of the erosion of individual particles of the remaining sediment cores was very difficult. Although the erosion of individual particles from the latter group of sediment cores was not obvious, erosion was evident from a flattening of the sediment core surface and the detection of the suspended material by the OBS. Problems arise when applying observational definitions of erosion thresholds to different sediment sizes or to biofilms of different developmental stages. Neill (1968) reported that the erosion thresholds of larger particles would be lower than those of smaller particles because the former category will be detected sooner. The erosion thresholds of the detected particles during the early stages of diatom growth (Figure 2.4B) may be too high if they occurred after the erosion of the

undetected surface particle layer. Larger aggregates were eroded at higher shear velocities within the erosion trials of days 6 and 9 (Figure 2.4B)

Bed threshold is a function of the number of particles eroded simultaneously. During exponential phase of growth (exponential phase) of *Nitzschia curvilineata*, the erosion threshold for particle motion was always less than the erosion threshold for the movement of 10 particles simultaneously (Figure 2.4B). The fewer number of particles required to be in motion simultaneously, the lower the bed threshold. However, as the individual particles become incorporated into the biofilm matrix, during stationary phase of growth, the chances of detecting 10 particles moving simultaneously diminishes. Although the motion of individual particles was observed, the simultaneous movement of 10 particles was not detected at the onset of stationary phase. Instead the release of a fewer number of large flake-sized aggregates occurred.

The extrapolation of an eroded sediment signal back to zero transport was performed by Shields, however, the technique used was not explicitly described (Lavelle and Mofjeld, 1987). In this study, a regression was used to extrapolate back to the log U_{*} axis from the SPM curve to determine the threshold of zero concentration (extrapolation method). The "linearity" of the SPM vs log U_{*} regression would depend on the extent of binding, microfabric formation, and lamination within the sediment column. In certain cases, the SPM curve appeared to be made up of two linear parts divided by an inflection point, representing two distinct layers in the sediment. Two intercepts or erosion thresholds were determined to prevent the steeper slope of the SPM curve from influencing the gentler slope occurring at the intercept. Therefore, the extrapolation

method of determining U_{crit} must be used with caution in sediment exhibiting strong vertical gradients in strength.

In some cases when the extrapolation method was applied (Figure 3.7), the first data point for SPM fell below the regression intercept determined as the erosion threshold. Emphasis was not placed on the initial suspended data point due to a larger noise to signal ratio that occurs at very low concentrations. "Noise" may be in the form of 1) resuspension due to instantaneous turbulent bursting, 2) patchiness of large-diameter suspended aggregates, and 3) the erosion of aggregates attached to non-seabed material (seagrass fragments) associated with the sediment-water interface. Since the SPM signal was measured through the collection of water samples, the source of the "noise" required validation through observation.

The term sediment erodibility should include both concepts of erosion thresholds and erosion rate, due to 1) the discrepancies between definitions of erosion thresholds and 2) the greater range of erosion rates measured in this thesis relative to erosion thresholds. If the observation method is used to determine erosion thresholds, the area of the eroding seabed, the duration of the observation period, and the number and size of particles should be standardized. If the extrapolation method is used to determine erosion thresholds, attention should be drawn to 1) the formation of multi-curves representing distinct sediment layers and 2) "noise" arising from the erosion of epiphytic material not associated with the seabed. The larger range in net erosion rate relative to erosion threshold measured in Upper South Cove supports Lavelle and Mofjeld (1987) suggestion that more emphasis should be placed on erosion rate when describing sediment transport. However,

an operational definition of erosion threshold should not be ruled out, since the level of importance of the different definitions varies between investigators (Miller *et al* , 1977)

In summary, biostabilization of subtidal estuarine sediments was greatest in regions of low bulk density (gel muds) characterized by little variation in sediment physical properties. Both sediment chlorophyll and colloidal carbohydrate content exhibited strong correlations with *in situ* erodibility measurements, lending one to conclude that both the pigment and mucilage sediment variables would serve as good indicators of sediment stability. The ratio of sediment bulk carbohydrate to chlorophyll may also be considered an indicator of sediment stability, since this ratio exhibited a strong relationship with the erosion rate of the sediment in the laboratory setting. The growth phase of the biofilm of *Nitzschia curvilineata* controlled the production of bulk carbohydrates and, thus, variations in this ratio. The saturation of sediment with EPS with age of biofilm resulted in an increase in size of eroding particles or aggregates. This shift in eroded particle size was probably due to changes in the "stickiness" of the sediment microfabric with age of biofilm. The results from this study indicate that the phase of diatom biofilm growth is an important factor in the alteration of the behaviour of sediment erosion. Therefore, more knowledge of the physiological status and texture of diatom biofilms is essential for the quantitative prediction of sediment transport.

**Appendix A1 · Time-series plots of current speed, SPM, and erosion rate obtained from Sea
Carousel deployments in Upper South Cove, Nova Scotia**

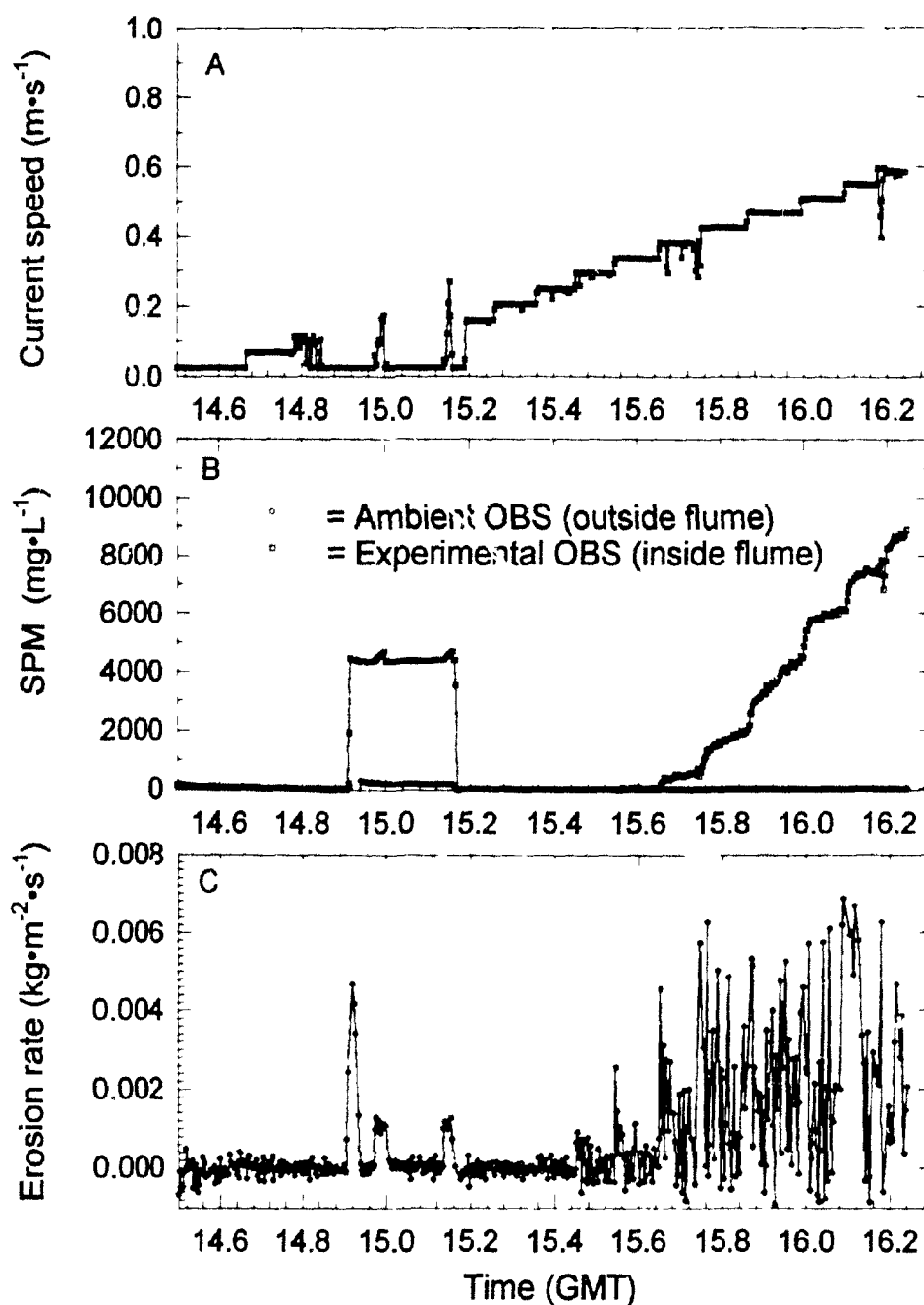


Figure A1.1: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 1 (sandy site) in Lunenburg Bay.

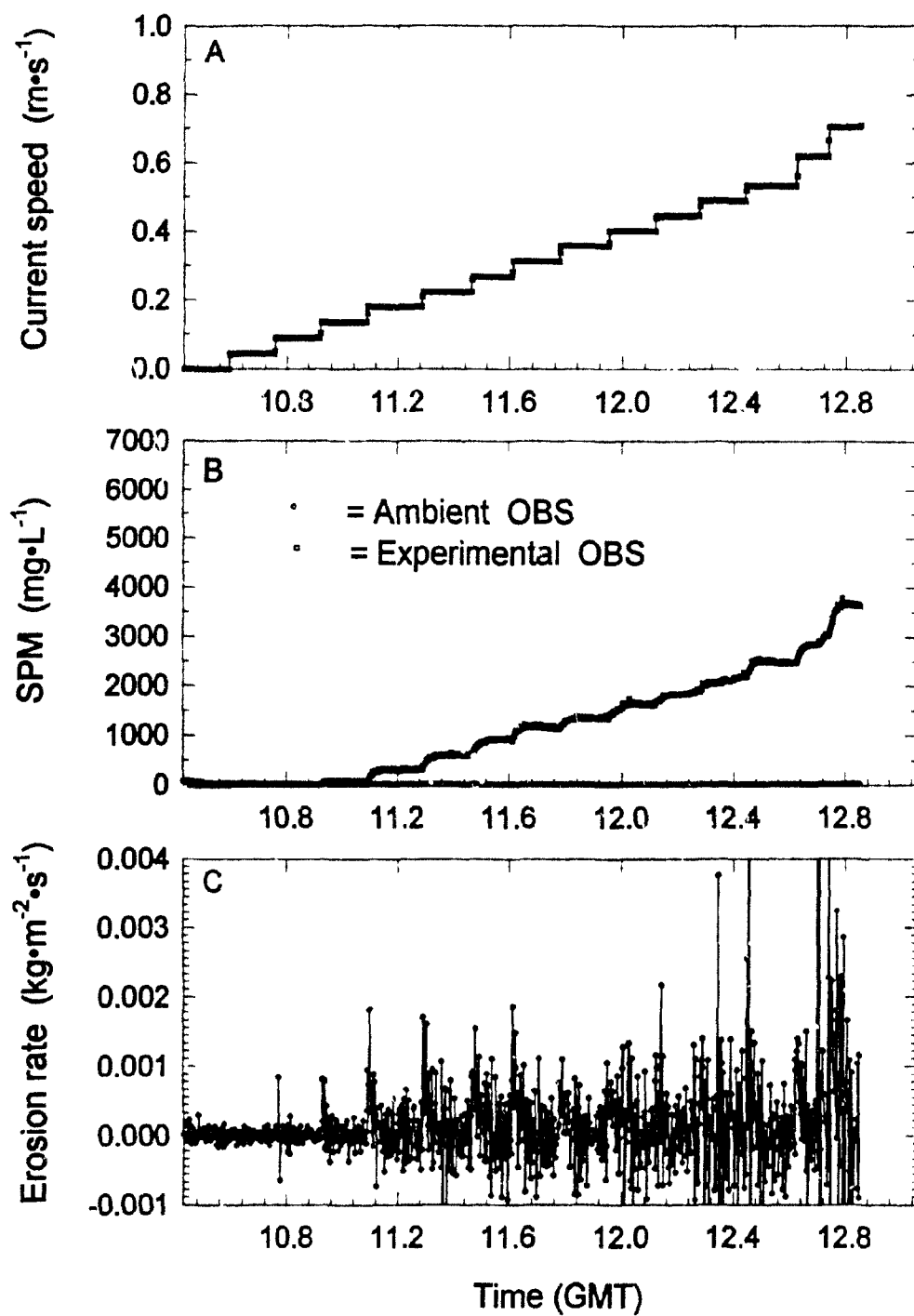


Figure A1.2: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 2 in Upper South Cove.

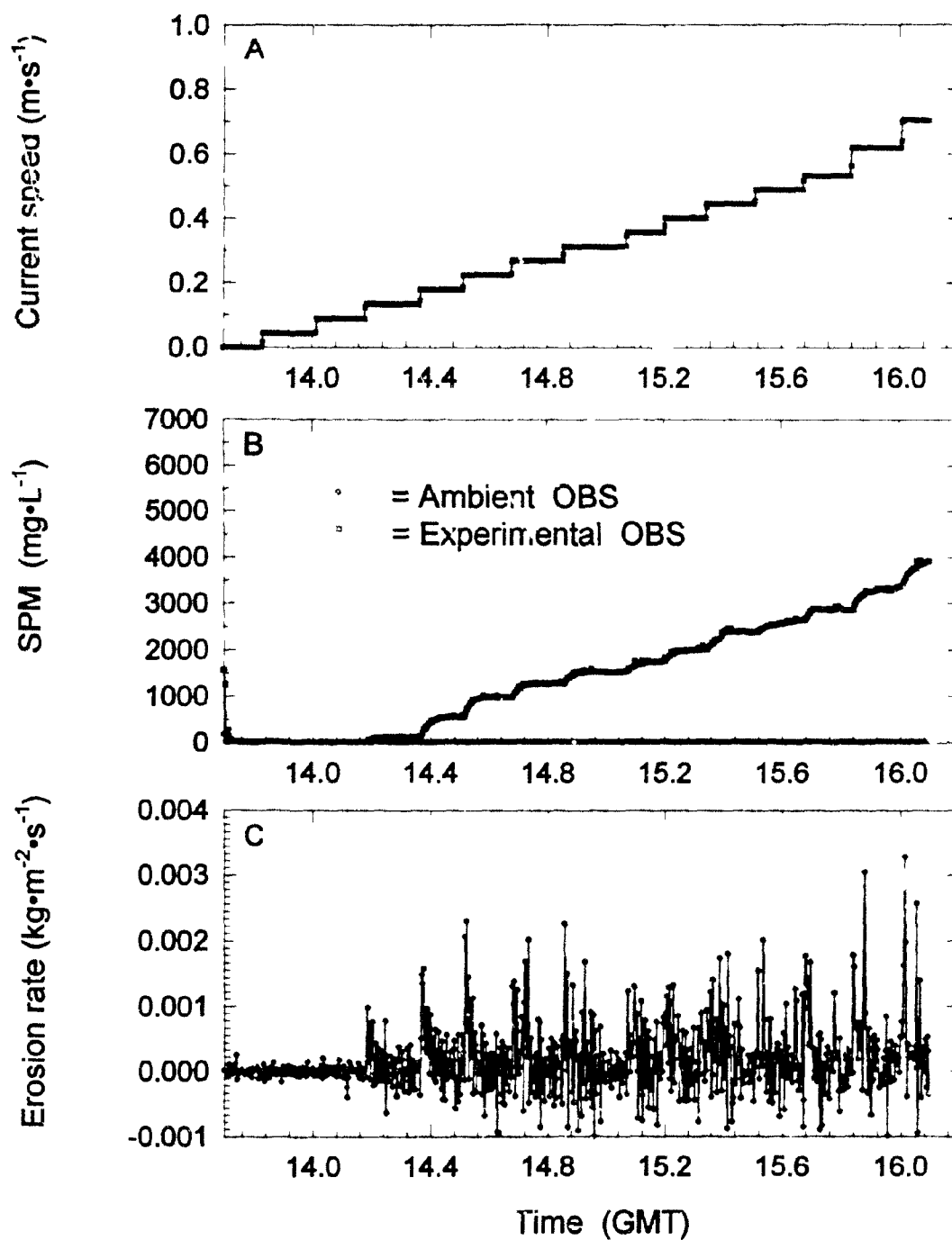


Figure A1.3: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 3 in Upper South Cove.

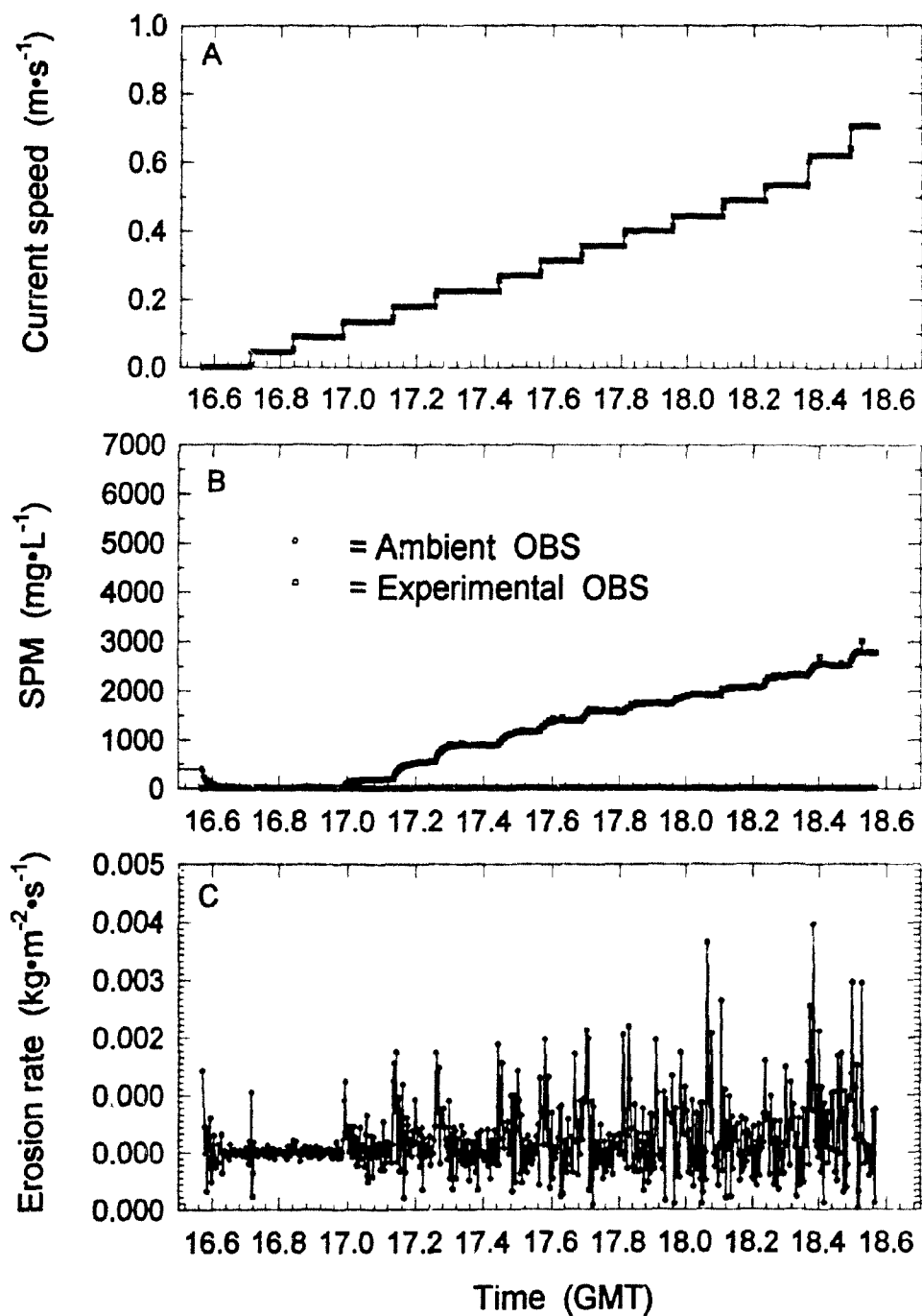


Figure A1.4: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 4 in Upper South Cove.

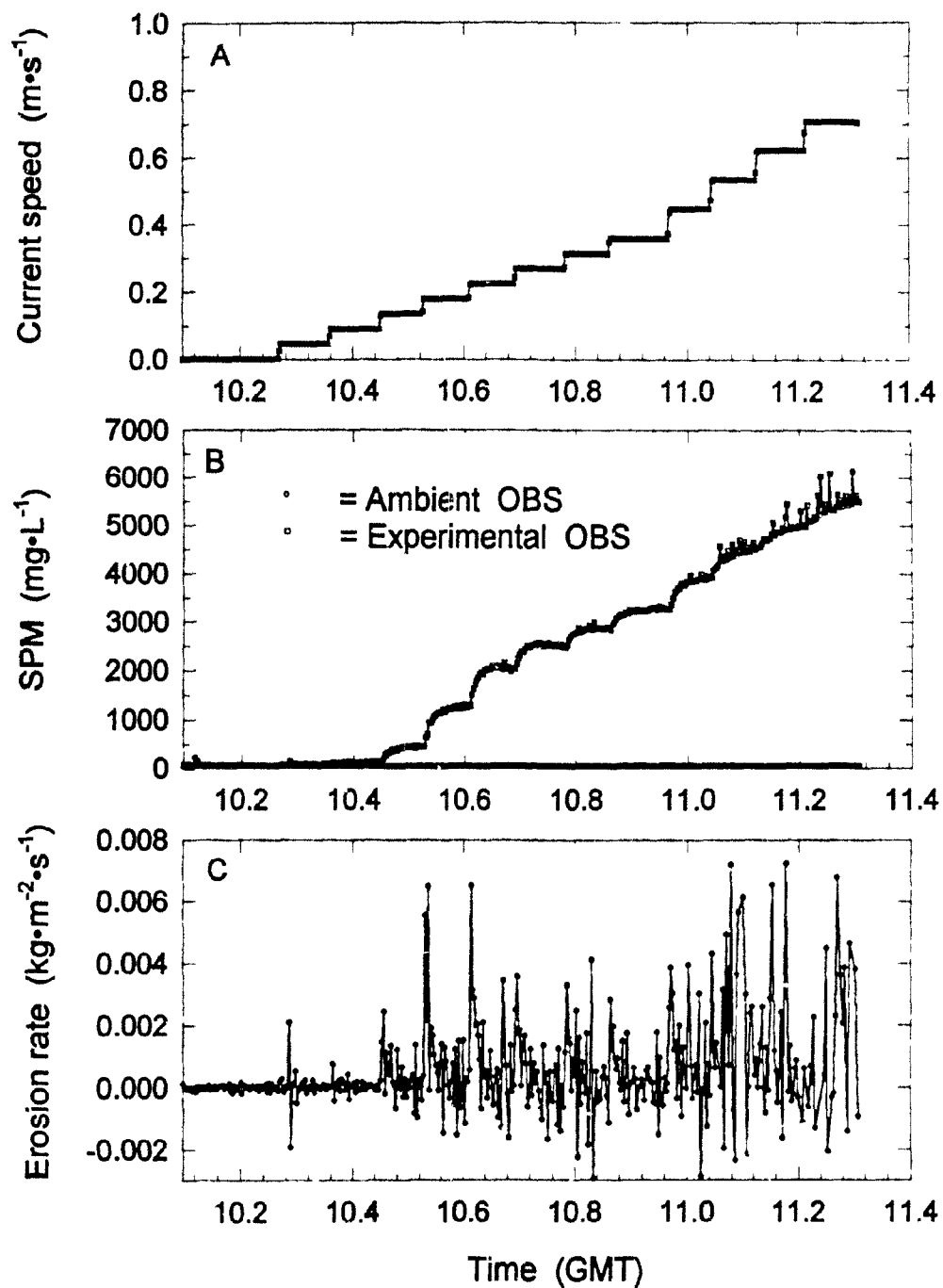


Figure A1.5: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 5 in Upper South Cove.

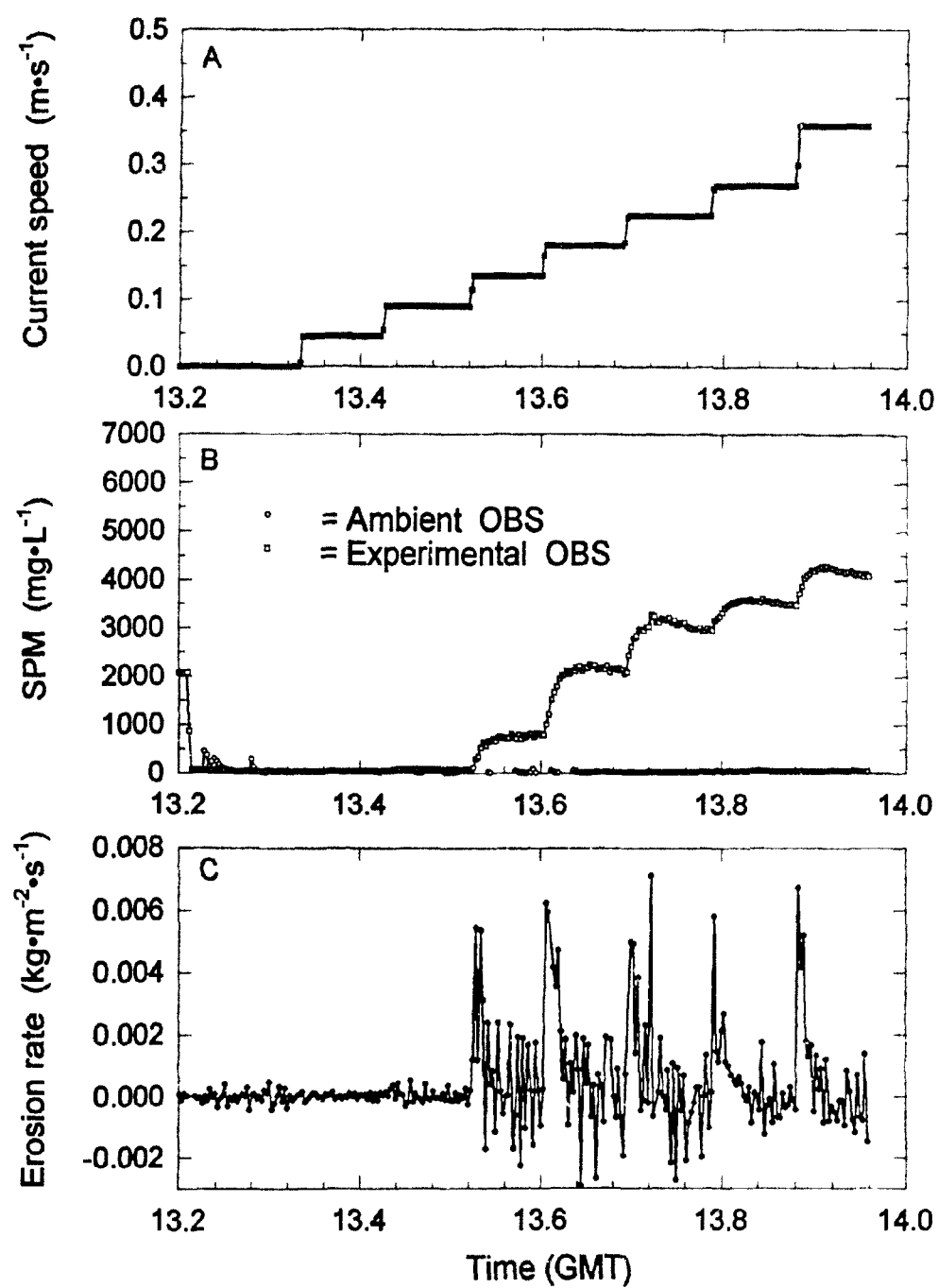


Figure A1.6: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 6 in Upper South Cove.

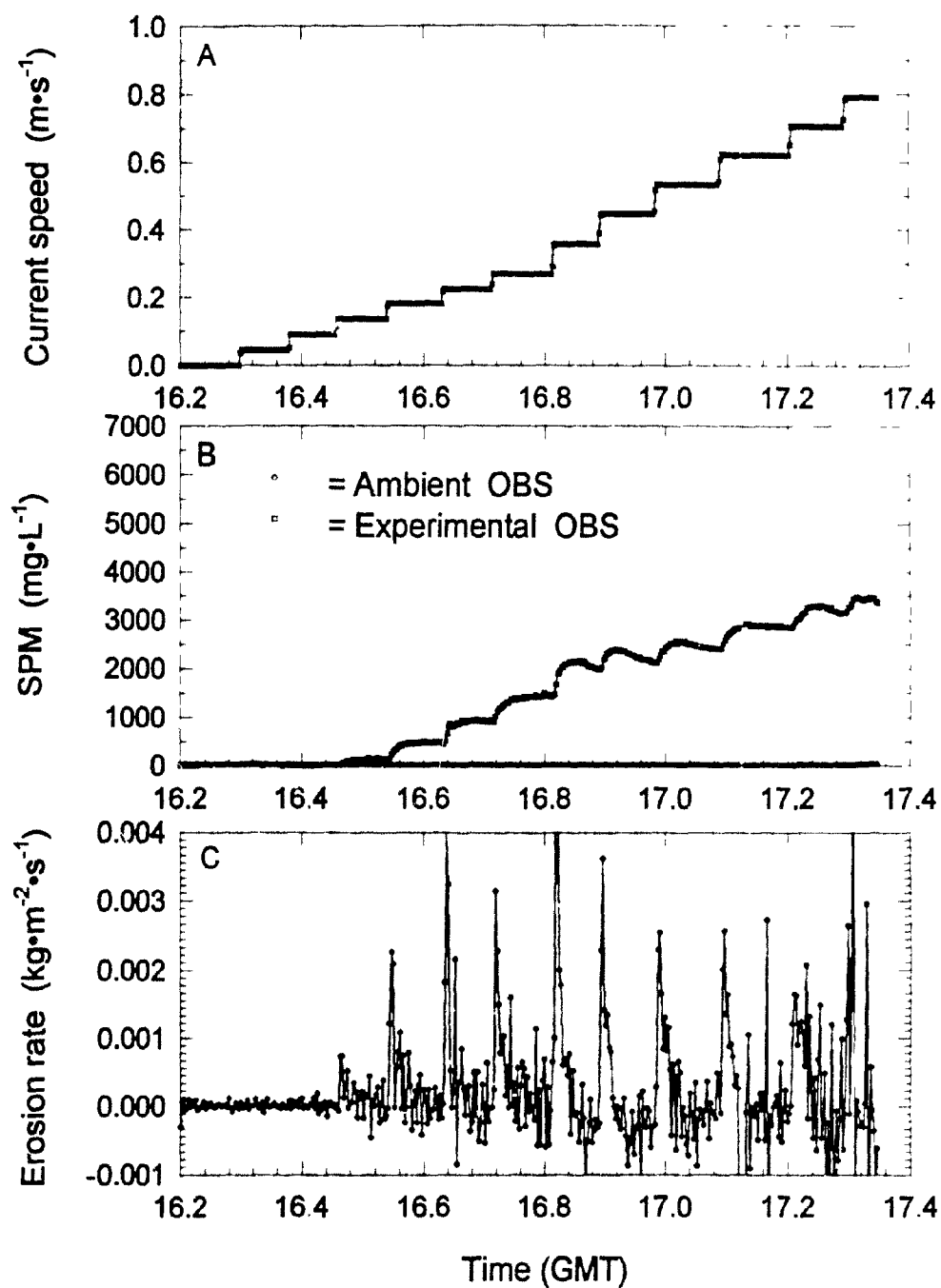


Figure A1.7: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 7 in Upper South Cove.

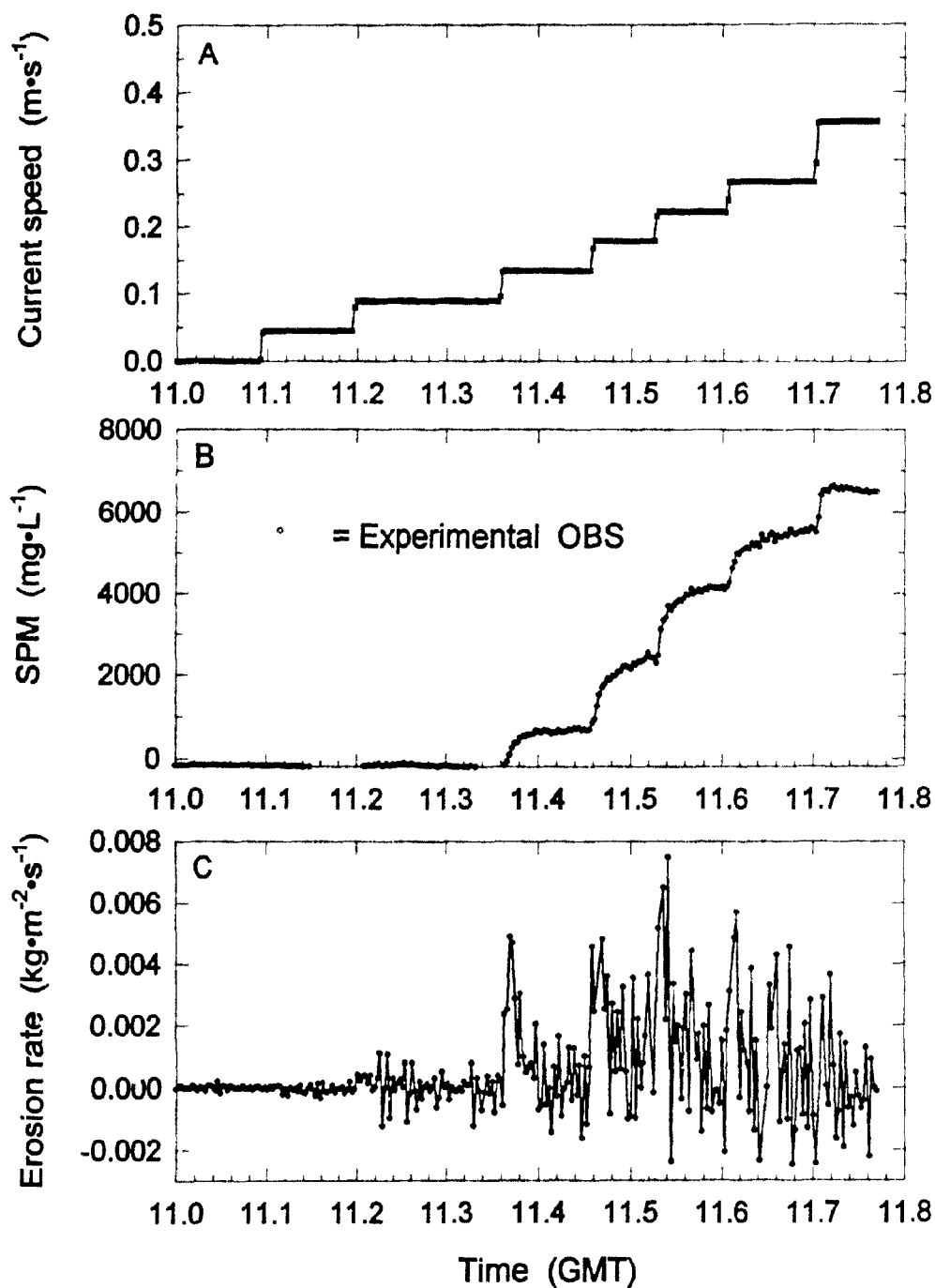


Figure A1.8: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 8 in Upper South Cove.

Appendix A2 Time-series plots of current speed, SPM, and erosion rate obtained from Sea Carousel deployments in Manitounuk Sound, Quebec

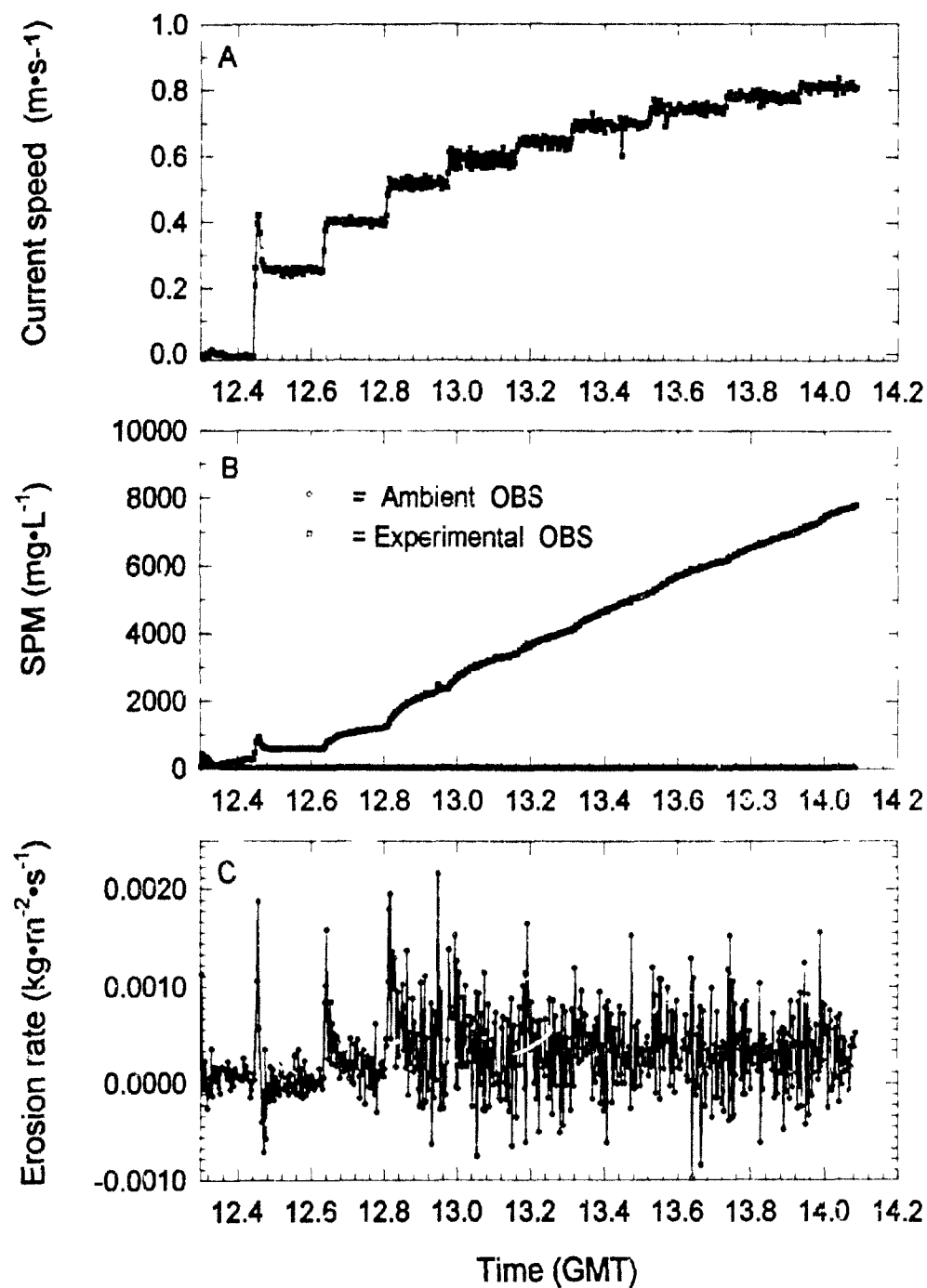


Figure A2.1: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 5 in Manitounuk Sound.

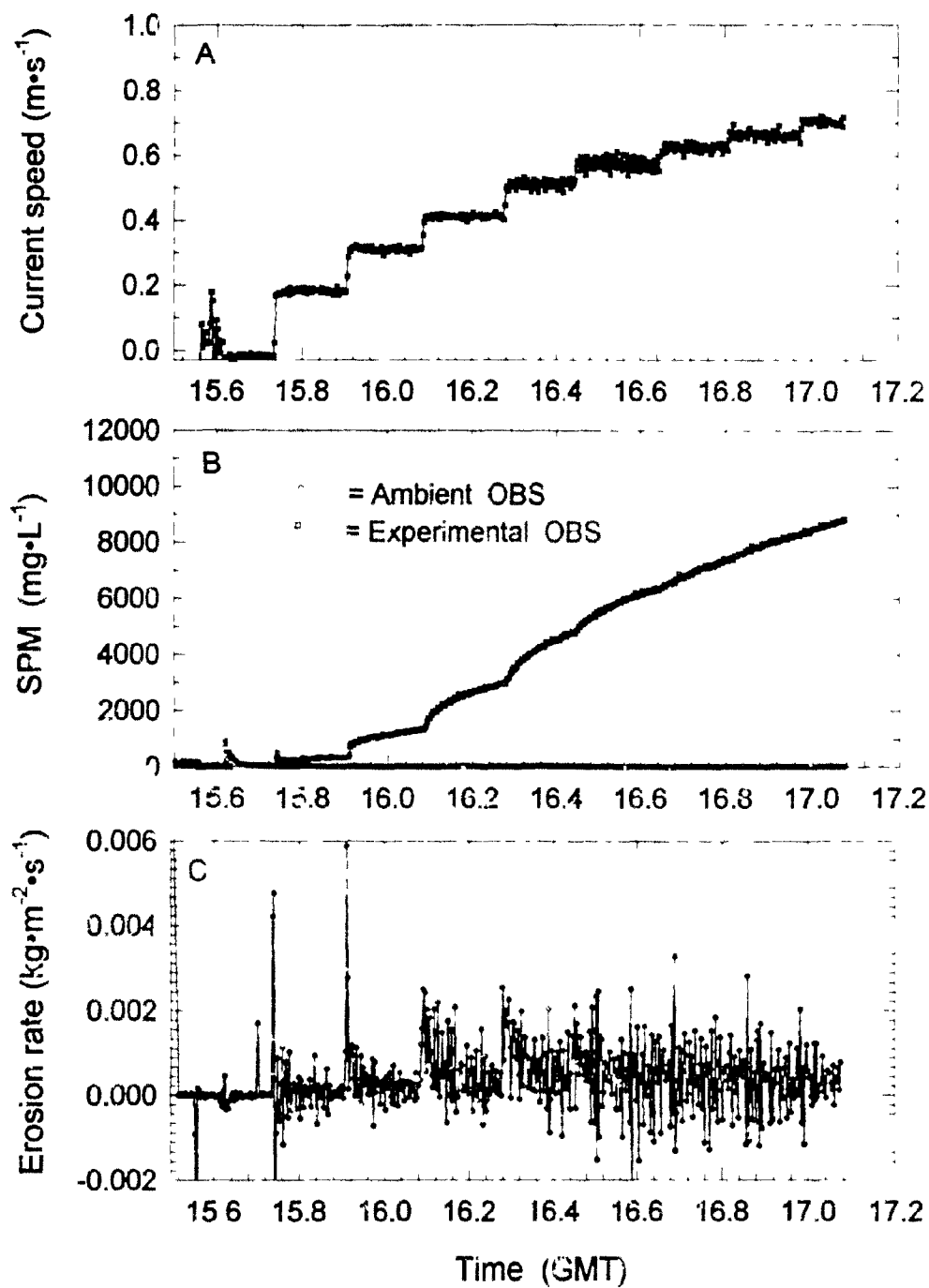


Figure A2.2: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 6 in Manitounuk Sound.

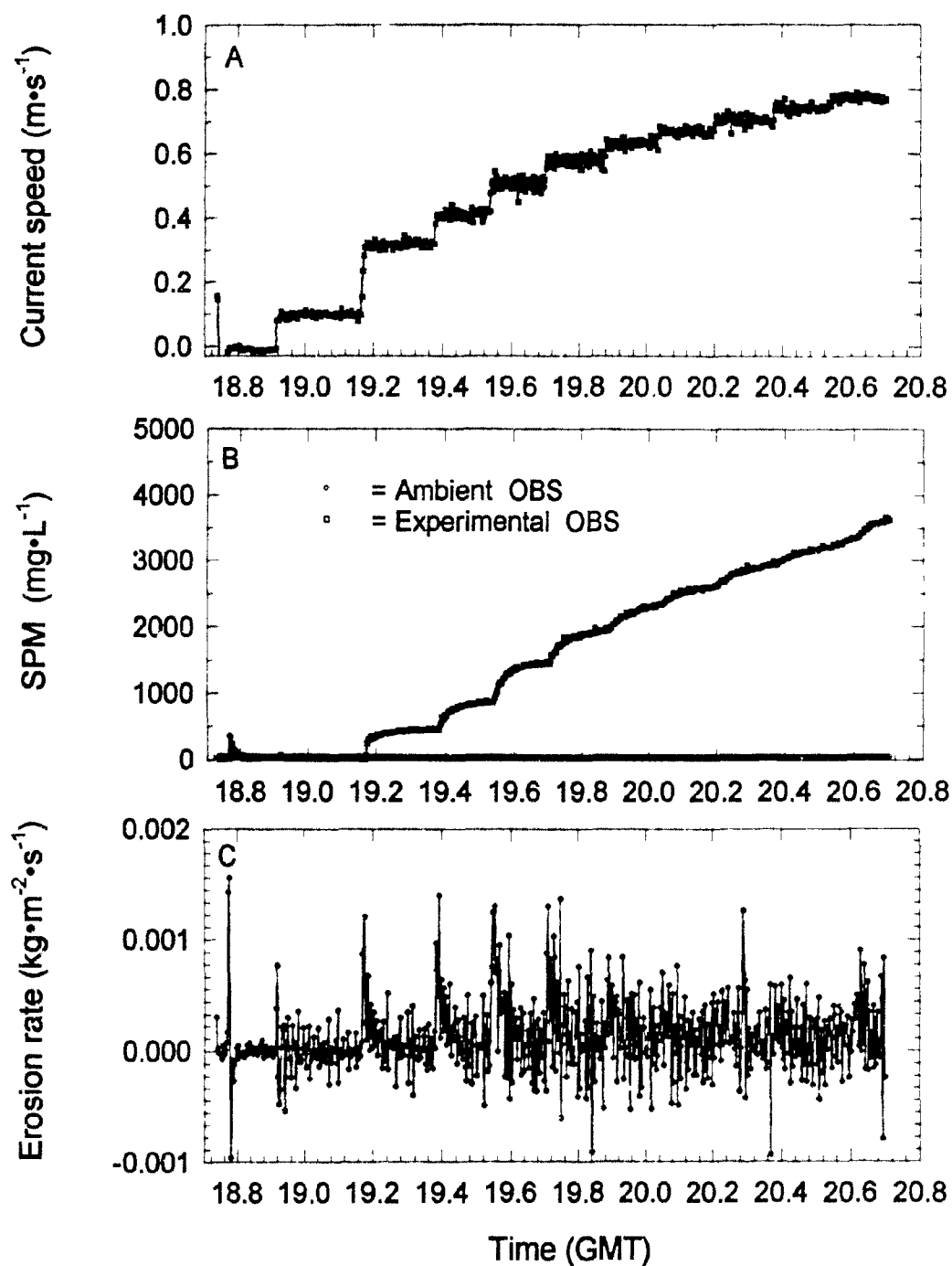


Figure A2.3: Time-series plots of current speed (A), SPM (B), and peak erosion rates (C) obtained from a Sea Carousel deployment at station 7 in Manitoulin Sound.

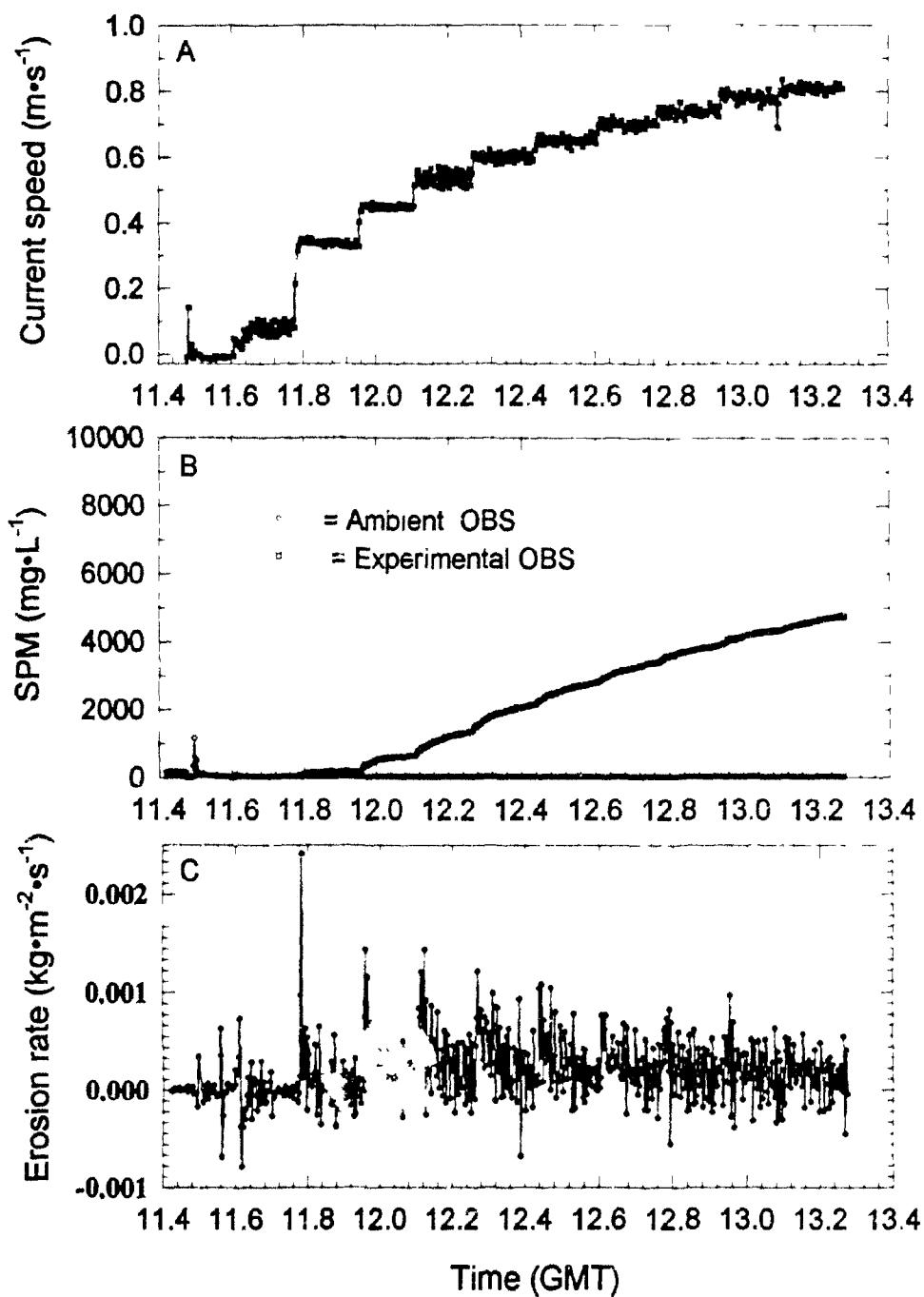


Figure A2.4: Time-series plots of current speed (A), SPM, and peak erosion rates (C) obtained from a Sea Carousel deployment at station 9 in Manitounuk Sound.

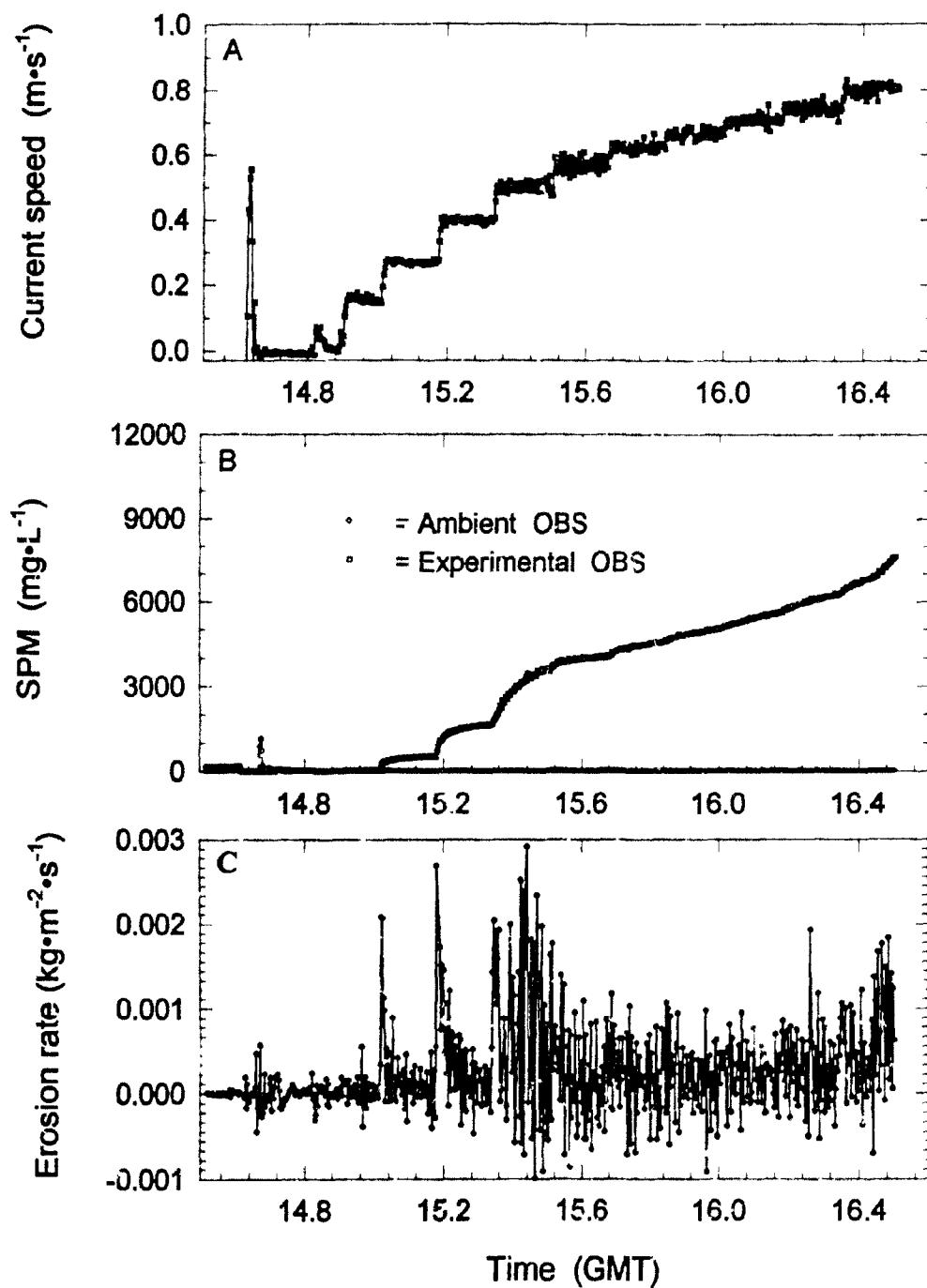


Figure A2.5: Time-series plots of current speed (A), SPM, and peak erosion rates (C) obtained from a Sea Carousel deployment at station 10 in Manitounuk Sound.

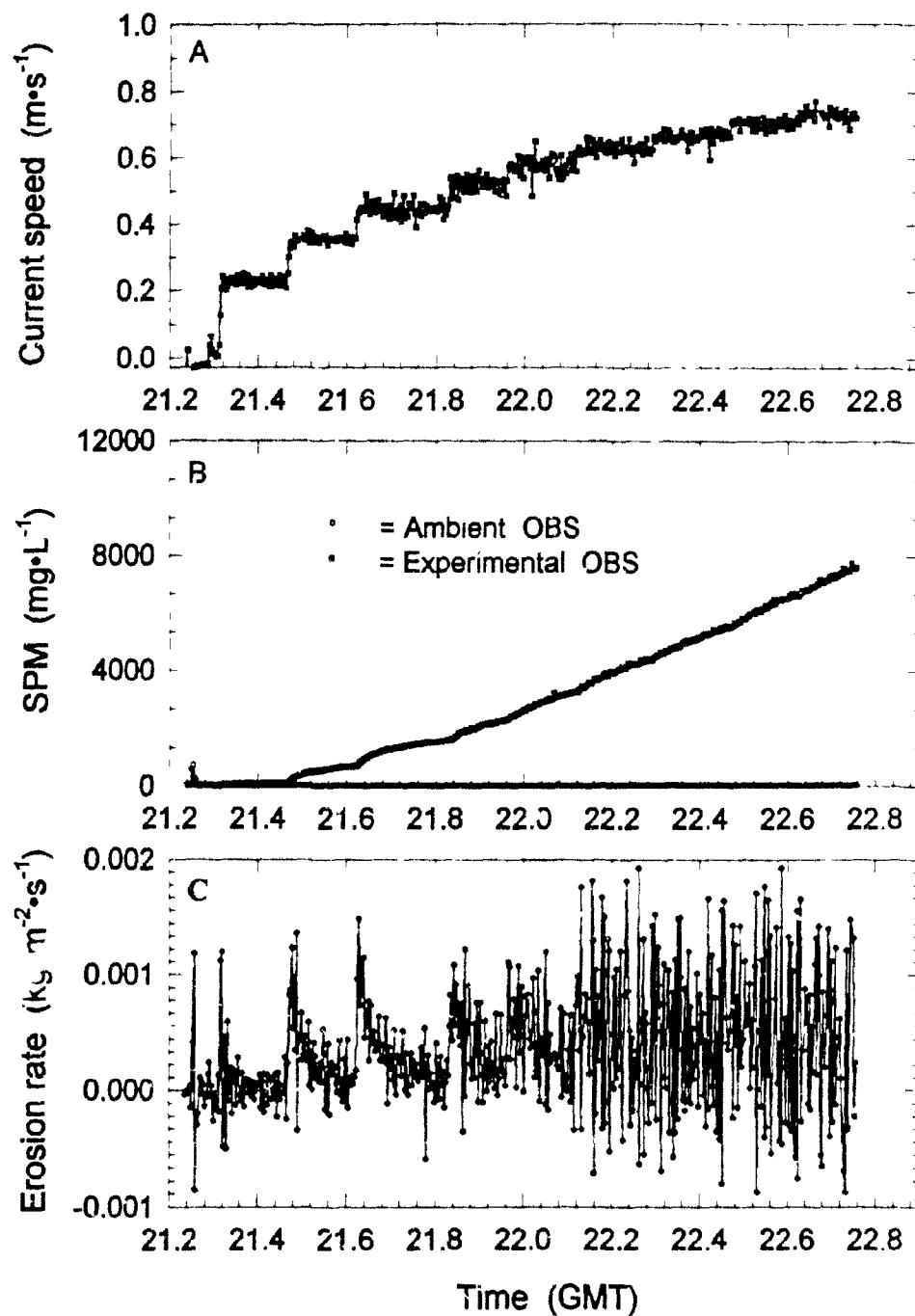


Figure A2.6: Time-series plots of current speed (A), SPM, and peak erosion rates (C) obtained from a Sea Carousel deployment at station 12 in Manitounuk Sound.

Appendix A3: Bulk density histograms of a calibration core and a natural sediment core collected in Upper South Cove

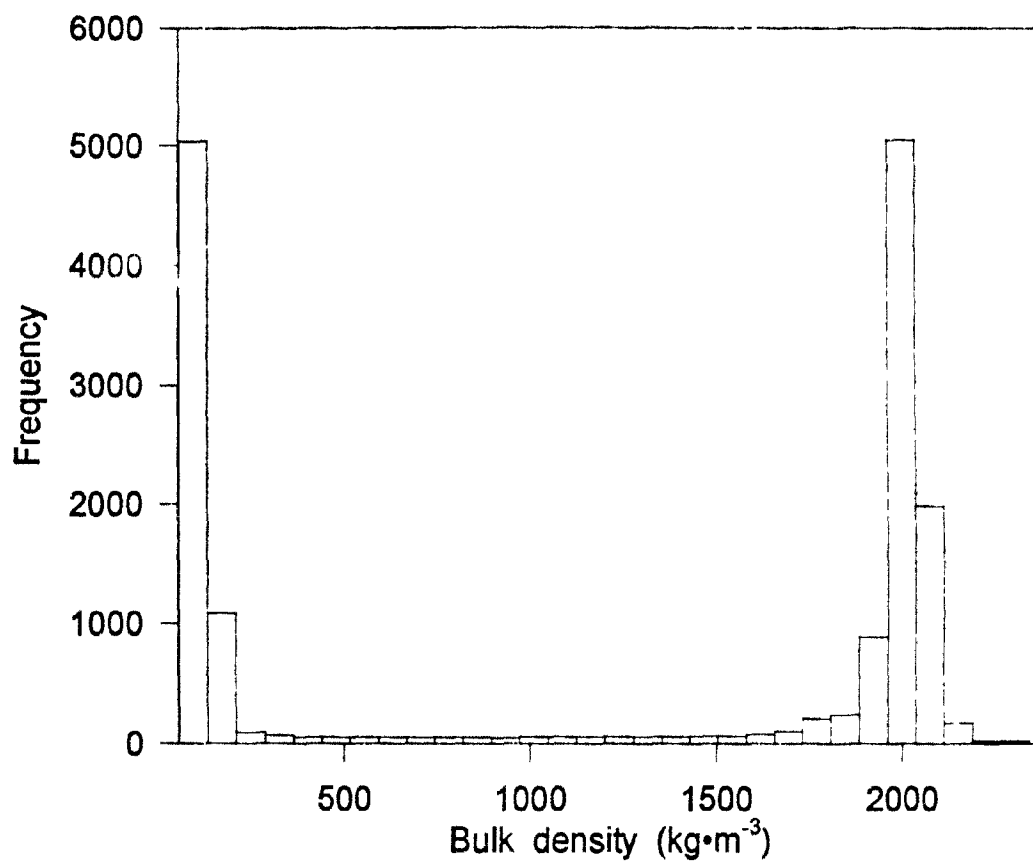


Figure A3.1: Bulk density histograms of a wedge-shaped sediment core made for calibration of the Catscan. The two peaks represent the air segment and the sediment segment of the tomogram.

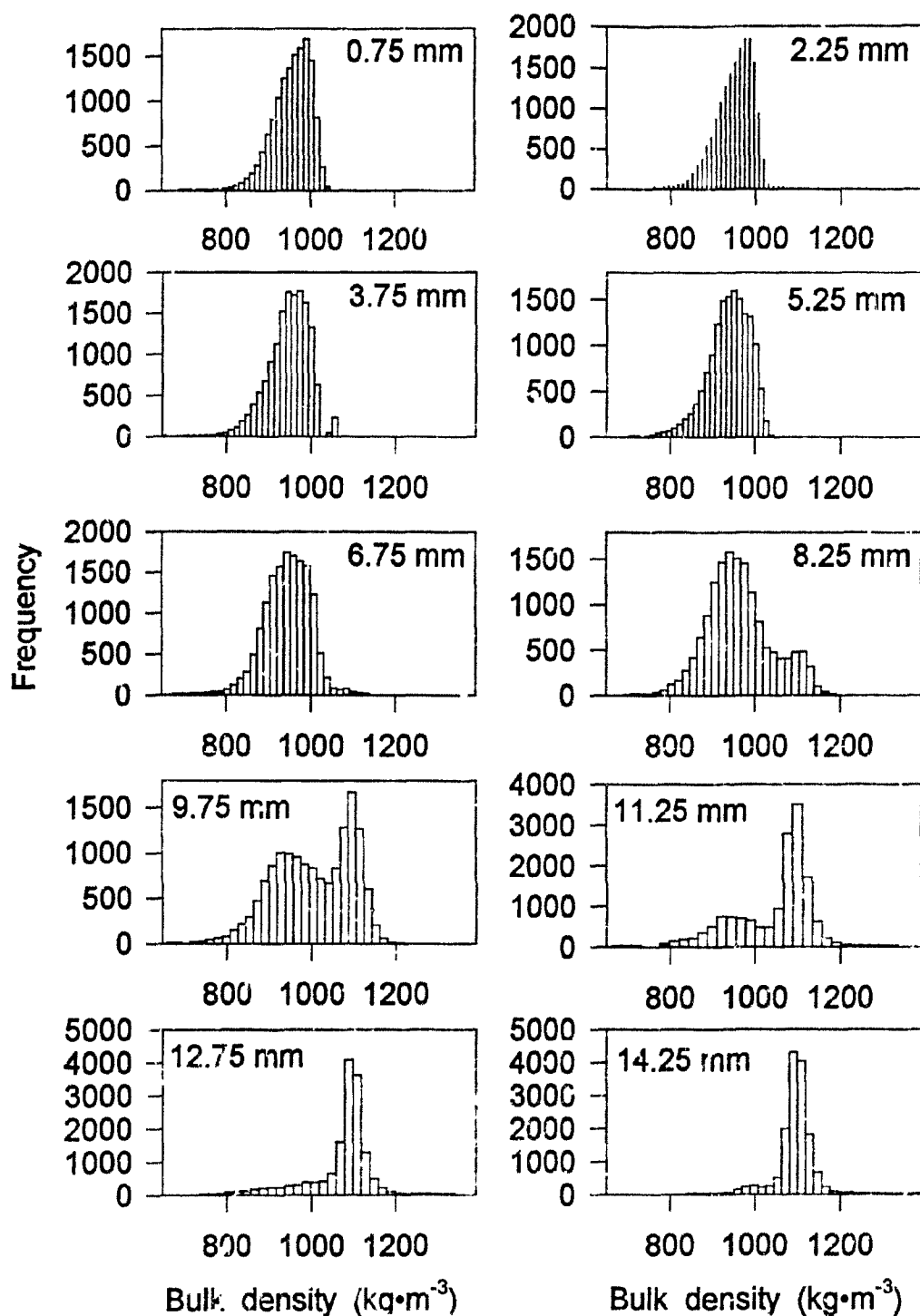


Figure A3.2: Bulk density histograms of the uppermost 15 mm of a sediment core collected at station 3 in Upper South Cove. Bulk density measurements were obtained through Catscan analysis.

REFERENCES

- Allan, G.G., J. Lewin, and P.G. Johnson 1972 Marine Polymers IV Diatom Polysaccharides *Botanica Marina*, XV: 102 - 108
- Amos, C.L., N.A. Van Wagoner, and G.R. Daborn 1988 The influence of subaerial exposure on the bulk properties of fine-grained intertidal sediment from Minas Basin, Bay of Fundy *Estuarine, Coastal Shelf Science*, 27: 1 - 13
- Amos, C.L., T.F. Sutherland, and J. Zevenhuizen 1996 The stability of sublittoral, fine-grained sediments in a subarctic estuary *Sedimentology*, 43 (1): 1 - 19.
- Amos, C.L., H.A. Christian, J. Grant, and D.M. Paterson. 1992a A comparison of in situ and laboratory methods to measure mudflat erodibility. In Falconer, R.A., S.N. Chandler-Wilde, and S.Q. Liu (Eds) *Hydraulic and Environmental Modelling. Coastal Waters, Proceedings of the Second International Conference on Hydraulic and Environmental Modelling of Coastal, Estuarine, and River Waters, Volume 1*, pp 325 - 336.
- Amos, C.L., J. Grant, G.R. Daborn, and K. Black 1992b Sea Carousel - a benthic, annular flume. *Estuarine, Coastal and Shelf Science*, 34: 557 - 577
- Amos, C.L., G.R. Daborn, H.A. Christian, A. Atkinson, and A. Robertson 1992c *In situ* erosion measurements on fine-grained sediments from the Bay of Fundy *Marine Geology*, 108: 175 - 196
- Amos, C.L., T.F. Sutherland, B. Radziejewski, and M. Doucette 1996 A rapid technique to determine bulk density of fine-grained sediments by X-ray computed tomography *Journal of Sedimentary Research*, in press
- Anderson, F.E. 1983 The northern muddy intertidal: seasonal factors controlling erosion and deposition - a review. *Canadian Journal of Fisheries Aquatic Sciences*, 40 (suppl 1): 143 - 159.
- Arfi, R. and M. Bouvy. 1995 Size, composition and distribution of particles related to wind-induced resuspension in a shallow tropical lagoon *Journal of Plankton Research*, 17 (3): 557 - 574.
- Baillie, P.W. and B.L. Welsh 1980. The effect of tidal resuspension on the distribution of intertidal epipelagic algae in an estuary *Estuarine and Coastal Marine Science*, 10: 165 - 180

- Bhosle, N.B., S.S. Sawant, A. Garg, and A.B. Wagh. 1995. Isolation and partial chemical analysis of exopolysaccharides from the marine fouling diatom, *Navicula subinflata*. *Botanica Marina*, 38: 103 - 110.
- Bricelj, V.M. and R.E. Malouf. 1984. Influence of algal and suspended sediment concentrations on the feeding physiology of the hard clam *Mercenaria mercenaria*. *Marine Biology*, 85: 155 - 165.
- Brockmann, U.H., K. Eberlein, H.D. Junge, E. Maier-Reimer, and D. Siebers. 1979. The development of a natural plankton population in an outdoor tank with nutrient-poor sea water. II. Changes in dissolved carbohydrates and amino acids. *Marine Ecology Progress Series*, 1: 283 - 291.
- Buckley, D.E., G.V. Winters, R.A. Fitzgerald, S. Penney, and K.W.G. LeBlanc. 1993. Inorganic geochemical data for marine sediments from Hudson Bay and James Bay: delta of Grande Baleine river, Manitounuk sound, and delta of La Grande river. Geological Survey of Canada, Open File Report # 2720.
- Cadee, G.C. and J. Hegemann. 1977. Distribution of primary production of the benthic microflora and accumulation of organic matter on a tidal flat area, Balgzand, Dutch Wadden Sea. *Netherlands Journal of Sea Research*, 11: 24 - 41.
- Carlton, R.G. and R.G. Wetzel. 1988. Phosphorus flux from lake sediments: Effect of epipellic algal oxygen production. *Limnology and Oceanography*, 33 (4, part 1): 562 - 570.
- Colijn, F. 1982. Light absorption in the waters of the Ems-Dollard Estuary and its consequences for the growth of phytoplankton and microphytobenthos. *Netherlands Journal of Sea Research*, 15 (2): 196 - 216.
- Cranford, P. 1995. Relationships between food quantity and quality and absorption efficiency in sea scallops *Placopecten magellanicus* (Gmelin). *Journal of Experimental Marine Biology and Ecology*, 189: 123 - 142.
- Cupp, E.E. 1977. *Marine Plankton Diatoms of the West Coast of North America*. University of California Press, Berkeley, pp. 237.
- Dale, N.G. 1974. Bacteria in intertidal sediments: factors related to their distribution. *Limnology and Oceanography*, 19: 509 - 518.
- Decho, A.W. 1990. Microbial exopolymer secretions in ocean environments: their role(s) in food webs and marine processes. *Oceanography and Marine Biology Annual Review*, 28: 73 - 153.

- Decho, A.W. 1994 Molecular-scale events influencing the macroscale of cohesiveness of exopolymers (Eds) Krumbien, W.E., D M Paterson, and L J Stal, In Biostabilization of Sediments Verlag, Oldenburg, pp 135 - 148
- Decho, A.W. 1994. Exopolymers in microbial mats assessing their adaptive roles (Eds) Stal, L.J. and P. Caumette In Microbial Mats, Structure, Development, and Environmental Significance NATO ASI Series, Vol G 35 215 - 219
- Decho, A.W. and G.R. Lopez 1993 Exopolymer microenvironments of microbial flora Multiple and interactive effects on trophic relationships Limnology and Oceanography, 38 (8) 1633 - 1645
- Decho, A.W. and D.J.W. Moriarty. 1990 Bacterial exopolymer utilization by a harpacticoid copepod: A methodology and results Limnology and Oceanography, 35 (5) 1039-1049
- Delgado, M., V.N. de Jonge, and H. Peletier 1991 Effect of sand movement on the growth of benthic diatoms Journal of Experimental Marine Biology and Ecology, 145 221 - 231.
- Dowd, M. 1991 On the prediction of bivalve growth in an aquaculture site MSc Thesis Dalhousie University, Halifax, Nova Scotia, pp 1 - 133
- Downing, J.P. and R.A. Beach 1989 Laboratory apparatus for calibrating optical suspended solids sensors Marine Geology, 86 243 - 249
- Drebes, G. 1977 Sexuality Werner, D. (Ed), In: The Biology of Diatoms Blackwell Scientific Publications, Oxford, pp 250 - 283
- Dubois, M., K.A. Gilles, J.K. Hamilton, P.S. Rebers, and F. Smith 1956 Colorimetric method for determination of sugars and related substances Analytical Chemistry, 28 350 - 356
- Eckman, J.E., A.R.M. Nowell, and P.A. Jumars 1981 Sediment destabilization by animal tubes Journal of Marine Research, 39 361 - 374
- Edgar, L.A. and J.D. Pickett-Heaps 1984 Diatoms Locomotion Round, F.F. and D.J. Chapman (Eds), In Progress in Phycological Research Vol 3, Biopress, Bristol, pp 47 - 88
- Emerson, C.W., J. Grant, A. Mallet, C. Carver 1994 Growth and survival of sea scallops *Placopecten magellanicus* effects of culture depth Marine Ecology Progress Series 108 119 - 132

- Floderus, S. and L. Hakanson. 1989. Resuspension, ephemeral mud blankets and nitrogen cycling in Laholmsbukten, south east Kattegat. *Hydrobiologia*, 176/177: 61 - 75.
- Flothmann, S. and I. Werner. 1992. Experimental eutrophication on an intertidal sandflat: effects on microphytobenthos, meio- and macrofauna. (Eds) Colombo, G., I. Ferrari, V.U. Ceccherelli, and R. Rossi. In: *Marine Eutrophication and Population Dynamics*, Olsen and Olsen, Fredensborg, pp. 93 - 100.
- Fonseca, M.S. 1989. Sediment stabilization by *Halophila decipiens* in comparison to other seagrasses. *Estuarine, Coastal Shelf Science*, 29: 501 - 507.
- Frankel, L. and D.J. Mead. 1973. Mucilaginous matrix of some estuarine sands in Connecticut. *Journal of Sedimentary Petrology*, 43: (4): 1090 - 1095.
- Frechette, M. and E. Bourget. 1985. Food-limited growth of *Mytilus edulis* L. in relation to the benthic boundary layer. *Canadian Journal of Fisheries and Aquatic Sciences*, 40: 1331 - 1342.
- Frechette, M. and J. Grant. 1991. An *in situ* estimation of the effect of wind-driven resuspension on the growth of the mussel, *Mytilus edulis* L. *Journal of Experimental Marine Biology and Ecology*, 148: 201 - 213.
- Gerdes, G., W.E. Krumbein, and H. Reineck. 1994. Microbial mats as architects of sedimentary surface structures. In: Krumbein, W.E., G. Gerdes, and H. Reineck (Eds) *Biostabilization of Sediments*, Verlag, Germany, pp. 165 - 182.
- Gordon, D.C. and C. Desplanque. 1983. Dynamics and environmental effects of ice in the Cumberland Basin of the Bay of Fundy. *Canadian Journal of Fisheries Aquatic Science*, 40 (9): 1331 - 1342.
- Grant, J. and U.V. Bathmann. 1987. Swept away: Resuspension of bacterial mats regulates benthic-pelagic exchange of sulfur. *Science*, 236: 1472 - 1474.
- Grant, J. and G. Gust. 1987. Prediction of coastal sediment stability from photopigment content of mats of purple sulphur bacteria. *Nature*, 330 (6145): 244 - 246.
- Grant, J. and G. Daborn. 1994. The effects of bioturbation on sediment transport on an intertidal mudflat. *Netherlands Journal of Sea Research*, 32 (1): 63 - 72.
- Grant, J. and C. Emerson. 1994. Resuspension and stabilization of sediments with microbial biofilms: Implications for benthic-pelagic coupling. In: Krumbein, W.E., D.M. Paterson, and L.J. Stal (Eds) *Biostabilization of Sediments*, Verlag, Germany, pp. 121 - 134.

- Grant, J., U.V. Bathmann, and E.L. Mills. 1986a. The interaction between benthic diatom films and sediment transport. *Estuarine, Coastal Shelf Science*, 23: 225 - 238.
- Grant, J., E.L. Mills, and C.M. Hopper. 1986b. A chlorophyll budget of the sediment-water interface and the effect of stabilizing biofilms on particle fluxes. *Ophelia*, 26: 207 - 219.
- Grant, J., C.T. Enright, and A. Griswold. 1990. Resuspension and growth of *Ostrea edulis*: a field experiment. *Marine Biology*, 104: 51 - 59.
- Grant, J., A. Hatcher, D.B. Scott, P. Pocklington, C.T. Schafer, G.V. Winters. 1995. A multidisciplinary approach to evaluating impacts of shellfish aquaculture on benthic communities. *Estuaries*, 18 (1A): 124 - 144.
- Grant, W.D., L.F. Boyer, and L.P. Sanford. 1982. The effects of bioturbation on the initiation of motion of intertidal sands. *Journal of Marine Research*, 40 (3): 659 - 677.
- Gray, W.G.D. 1993. Physical properties data report MV Septentrion cruise 92-028S, Manitounuk Sound gravity cores. Geological Survey of Canada Report Bedford Institute of Oceanography, pp. 1 - 30.
- Guillard, R.R.L. 1972. Culture of marine phytoplankton for feeding marine invertebrates (Eds) Smith, W.L. and M.H. Chanley. In: *Conference on Culture of Marine Invertebrate Animals*, Plenum Press, New York, pp. 29 - 60.
- Hargrave, B.T. 1972. Aerobic decomposition of sediment and detritus as a function of particle surface area and organic content. *Limnology and Oceanography*, 17: 583 - 596.
- Harper, M.A. 1977. Movements. Werner, D. (Ed). In: *The Biology of Diatoms*. Blackwell Scientific Publications, Oxford, pp. 224 - 249.
- Hatcher, A., J. Grant, and B. Schofield. 1994. Effects of suspended mussel culture (*Mytilus* spp.) on sedimentation, benthic respiration and sediment nutrient dynamics in a coastal bay. *Marine Ecology Progress Series*, 115: 219 - 235.
- Haven, D.S. and R. Morales-Alamo. 1966. Aspects of biodeposition by oysters and invertebrate filter feeders. *Limnology and Oceanography*, 11: 487 - 498.
- Hay, S.I., T.C. Maitland, and D.M. Paterson. 1993. The speed of diatom migration through natural and artificial substrata. *Diatom Research*, 8 (2): 371 - 384.
- Heckman, C.W. 1985. The development of vertical migration patterns in the sediments of estuaries as a strategy for algae to resist drift with tidal currents. *International Revue Ges Hydrobiologie*, 70: 151 - 164.

- Heinzelmann, C H and S Wallisch 1991 Benthic settlement and bed erosion A review
Journal of Hydraulic Research, 29 355 - 371
- Hinch, S , R C Bailey, R H Green 1986 Growth of *Lampsilis radiata* (Bivalvia Unionidae)
in sand and mud a reciprocal transplant experiment Canadian Journal of Fisheries and
Aquatic Science, 43 548 - 552
- Hoagland, K D , J R Rosowski, M R Gretz, and S C Roemer 1993 Diatom extracellular
polymeric substances, function, fine structure, chemistry, and physiology Journal of
Phycology, 29 537 - 566
- Holland, A F , R G Zingmark, and J M Dean 1974 Quantitative evidence concerning the
stabilization of sediments by marine benthic diatoms Marine Biology, 27 191 - 196
- Johnson, R G 1974 Particulate matter at the sediment-water interface in Coastal
Environments Journal of Marine Research, 32 (2) 313 - 330
- de Jonge, V.N 1985 The occurrence of "epipsammic" diatom populations a result of
interaction between physical sorting of sediment and certain properties of diatom
species Estuarine, Coastal and Shelf Science, 21 607 - 622
- de Jonge, V N and J van den Berghs 1987 Experiments on the resuspension of estuarine
sediments containing benthic diatoms Estuarine, Coastal and Shelf Science, 24 725 -
740
- de Jonge, D J and V N de Jonge 1995 Dynamics and distribution of microphytobenthic
chlorophyll-a in the Western Scheldt estuary (SW Netherlands) Hydrobiologia, 311
21 - 30
- Jonsson, B , K Sundback and C Nilsson 1994 An upright life-form of an epipelagic motile
diatom on the behaviour of *Gyrodinium aureolum* European Journal of Phycology, 29
11 - 15
- Jorgensen, B B 1989 Light penetration, absorption, and action spectra in cyanobacterial
mats Cohen, Y and E Rosenberg (Eds), In Microbial mats physiological ecology of
benthic microbial communities ASM, Washington, pp 123 - 137
- Jorgensen, B.B 1994 Diffusion processes and boundary layers in microbial mats Stal, L J
and P Caumette (Eds) In Microbial Mats - Structure, Development, and
Environmental Significance, pp 243 - 254
- Jorgensen, B B , N.P Revsbech, and Y Cohen 1983 Photosynthesis and structure of benthic
microbial mats Microelectrode and SEM studies of four cyanobacterial communities
Limnology and Oceanography, 28 (6) 1075 - 1093

- Jumars, P.A. and A.R.M. Nowell 1984 Effects of benthos on sediment transport difficulties with functional grouping. *Continental Shelf Research*, 3 (2) 115 - 130
- Kautsky, N. and S. Evans 1987 Role of biodeposition by *Mytilus edulis* in the circulation of matter and nutrients in a Baltic coastal ecosystem. *Marine Ecology Progress Series*, 38 201 - 212
- van de Kreeke, J. 1986 Introduction. In: *Physics of Shallow Estuaries and Bays*, Springer-Verlag, pp. 2 - 4
- Kroen, W.K. and W.R. Rayburn 1984. Influence of growth status and nutrients on extracellular polysaccharide synthesis by the soil alga *Chlamydomonas mexicana* (Chlorophyceae). *Journal of Phycology*, 20. 253 - 257.
- Krumbein, W.E. 1971. Sediment microbiology and grain-size distribution, as related to tidal movement, during the first mission of the West German Underwater Laboratory "Helgoland". *Marine Biology*, 10 101-112.
- Krumbien, W.E. 1994 The year of the slime. (Eds) Krumbien, W.E., D.M. Paterson, and L.J. Stal, In: *Biostabilization of Sediments*. Verlag, Oldenburg, pp. 1 - 8.
- Lavelle, J.W. and H.O. Mofjeld 1987. Do critical stresses for incipient motion and erosion really exist? *Journal of Hydraulic Engineering*, 113 (3). 370 - 393
- Lewin, J.C. 1955. The capsule of the diatom, *Navicula pelliculosa*. *Journal of General Microbiology*, 13: 162 - 169
- Lewin, R.A. 1956 Extracellular polysaccharides of green algae. *Canadian Journal of Microbiology*, 2 665 - 672.
- Lewin, J.C. and R.A. Lewin. 1960 Auxotrophy and heterotrophy in marine littoral diatoms. *Canadian Journal of Microbiology*, 6 (2) 127 - 134.
- Lindahl, M.T. 1972 Drag reduction by polymer additions. In: Anderson, F.E. 1983 The northern intertidal: seasonal factors controlling erosion and deposition - a review. *Canadian Journal of Fisheries Aquatic Science*, 40 (Suppl 1). 143 - 159.
- Lui, D., P.T.S. Wong, and B.J. Dutka. 1973 Determination of carbohydrates in lake sediment by a modified phenol-sulfuric acid method. *Water Research*, 7 741 - 746
- Madsen, K.N., P. Nilsson, and K. Sundback 1993. The influence of benthic microalgae on the stability of a subtidal sediment. *Journal of Experimental Marine Biology and Ecology*, 170: 159 - 177.

- Malone, T C 1980 Algal Size Morris, I (Ed) In the Physiology and Ecology of Phytoplankton Blackwell Scientific Publications, London
- Manzenreder, H, 1983 Retardation of initial erosion under biological effects in sandy tidal flats In Paterson, D M, 1994 Microbial mediation of sediment structure and behaviour (Eds) Stal, L J and P Caumette In Microbial Mats Structure, Development, and Environmental Significance, NATO ASI Series, Vol G 35 97 - 109
- Mayer, L M 1989 Extracellular proteolytic enzyme activity in sediments of an intertidal mudflat Limnology and Oceanography, 34 973 - 981
- Mayer, L M, P T Rahaim, W Guerin, S A Macko, L Watling, and F E Anderson 1985 Biological and granulometric controls on sedimentary organic matter of an intertidal mudflat Estuarine, Coastal and Shelf Science, 20 491 - 503
- McCall P L 1979 The effects of deposit feeding oligochaetes on particle size and settling velocity of Lake Erie sediments Journal of Sedimentary Petrology, 49 (3) 813 - 818
- Meadows, P S and J G Anderson 1968 Micro-organisms attached to marine sand grains Journal of the Marine Biological Association of the United Kingdom, 48 161 - 175
- Miller, M C, I N McCave, and P D Komar 1977 Threshold of sediment motion under unidirectional currents Sedimentology, 24 507 - 527
- Monti, M, C Welker, G Dellavalle, L Casaretto, and S F Umani 1995 Mucous aggregates under natural and laboratory conditions a review The Science of the Total Environment, 165 145 - 154
- Moriarty, D J W and M C Barclay 1980 Determination of organic carbon and carbonate in the same sample with an elemental analyser Laboratory Practice, 29 (11) 1 - 2
- Muschenheim, D K 1987 The dynamics of near-bed seston flux and suspension-feeding benthos The Journal of Marine Research, 45 473 - 496
- Myklestad, S 1974 Production of carbohydrates by marine planktonic diatoms I Comparison of nine different species in culture Journal of Experimental Marine Biology and Ecology, 15 261 - 274
- Myklestad, S 1977 Production of carbohydrates by marine planktonic diatoms II Influence of the N P ratio in the growth medium on the assimilation ratio, growth rate, and production of cellular and extracellular carbohydrates by *Chaetoceros affinis* var Willei (Gran) Hustedt and *Skeletonema costatum* (Grev.) Cleve Journal of Experimental Marine Biology and Ecology, 29 161 - 179

- Myklesstad, S. and A. Haug. 1972. Production of carbohydrates by the marine diatom *Chaetoceros affinis* var *willei* (Gran) Hustedt. I. Effect of the concentration of nutrients in the culture medium. *Journal of Experimental Marine Biology and Ecology*, 9: 137 - 144.
- Myklesstad, S., A. Haug, and B. Larsen. 1972. Production of carbohydrates by the marine diatoms *Chaetoceros affinis* var *willei* (Gran) Hustedt. II. Preliminary investigation of the extracellular polysaccharide. *Journal Experimental Marine Biology and Ecology*, 9: 137 - 144.
- Myklesstad, S., O. Holm-Hansen, K.M. Varum and B.E. Volcani. 1989. Rate of release of extracellular amino acids and carbohydrates from the marine diatom *Chaetoceros affinis*. *Journal Plankton Research*, 11 (4): 763 - 773.
- Neu, T.R. 1994. Ecophysiology and structure. *Biofilms and microbial mats* (Eds) Krumbien, W.E., D.M. Paterson, and L.J. Stal, In: *Biostabilization of Sediments*. Verlag, Oldenburg, pp. 9 - 15.
- Neumann, A.C., C.D. Gebelein, and G.P. Scoffin. 1970. The composition, structure, erodibility of subtidal mats, Abaco, Bahamas. *Journal of Sedimentary Petrology*, 40: 274 - 297.
- Nowell, A.R.M. and P.A. Jumars. 1987. Flumes: theoretical and experimental considerations for simulation of benthic environments. *Oceanography and Marine Biology Annual Review*, 25: 91 - 112.
- Nowell, A.R.M., P.A. Jumars, and J.E. Eckman. 1981. Effects of biological activity on the entrainment of marine sediments. *Marine Geology*, 42: 133 - 153.
- Obernosterer, I. and G.J. Herndl. 1995. Phytoplankton extracellular release and bacterial growth: dependence on the inorganic N:P ratio. *Marine Ecology Progress Series*, 116: 247 - 257.
- Parsieglä, K., B. Hudec, and T. Wippermann. 1994. Sedimentology. In: Krumbien, W.E., D.M. Paterson, and L.J. Stal (Eds) *Biostabilization of Sediments*, Verlag, Germany, pp. 241 - 256.
- Parsons, T.R., Y. Maita, and C.M. Lalli. 1984. *A Manual of Chemical and Biological Methods for Seawater Analysis*. Pergamon Press. Oxford, pp. 107 - 110.
- Paterson, D.M. 1986. The migratory behaviour of diatom assemblages in a laboratory tidal micro-ecosystem examined by low-temperature scanning electron microscopy. *Diatom Research*, 1 (2): 227 - 239.

- Paterson, D M 1988 The influence of epipellic diatoms on the erodibility of an artificial sediment The 10th Diatom Symposium, pp 345 - 355
- Paterson, D M 1989 Short-term changes in the erodibility of intertidal cohesive sediments related to the migratory behaviour of epipellic diatoms Limnology and Oceanography, 34 (1) 223 - 234
- Paterson, D M 1994 Microbiological mediation of sediment structure and behaviour In Stal, L J and P Caumette (Eds) Microbial Mats, NATO ASI Series, Vol G 35
- Paterson, D M and G R Daborn 1991 Sediment stabilization by biological action significance for coastal engineering Developments in Coastal Engineering, University of Bristol, pp 111 - 119
- Paterson, D.M and G J.C Underwood 1990 The mudflat ecosystem and epipellic diatoms, Proceedings of the Bristol Naturalists' Society, 50 74 - 82
- Paterson, D.M , R M Crawford, and C Little 1990 Subaerial exposure and changes in the stability of intertidal estuarine sediments Estuarine, Coastal Shelf Science, 30 541 - 556
- Paterson, D M., M L Yallop, and C George 1994a Spatial variability in sediment erodibility on the island of Texel In Krumbein, W E , D M Paterson, and L J Stal (Eds) Biostabilization of Sediments, Verlag, Germany, pp 107 - 120
- Paterson, D M , M Yallop, and C George 1994b Stabilization In Krumbein, W E , D M Paterson, and L J Stal (Eds) Biostabilization of Sediments, Verlag, Germany, pp 401 - 432
- Peddicord, R K 1977 Salinity and substratum effects on condition index of the bivalve *Rangia cuneata* Marine Biology, 39 351 - 360
- de Philippis, R., M C Margheri, E Pelosi, and S. Ventura 1993 Exopolysaccharide production by a unicellular cyanobacterium isolated from a hypersaline habitat Journal of Applied Phycology 5 387 - 394
- Postma, H 1961 Transport and accumulation of suspended matter in the Dutch Wadden Sea Netherlands Journal of Sea Research, 1 148 - 190
- Pinckney, J.L 1994 Development of an irradiance-based ecophysiological model for intertidal benthic microalgal production In Krumbein, W E , Paterson, D M and L J Stal (Eds) Biostabilization of Sediments, Verlag, Germany, pp 55 - 83.

- Revsbech, N.P., B.B. Jorgensen, and T.H. Blackburn. 1983. Microelectrode studies of the photosynthesis and O_2 , H_2S , and pH profiles of a microbial mat. *Limnology and Oceanography*, 28 (6): 1062 - 1074.
- Rhoads, D.C., L.F. Boyer, B.L. Welsh, and G.R. Hampson. 1984. Seasonal dynamics of detritus in the benthic turbidity zone (BTZ); implications for bottom-rack molluscan mariculture. *Bulletin of Marine Science*, 35 (3): 536 - 549.
- Round, F.E. 1971. Benthic Marine Diatoms. *Oceanography and Marine Biology Annual Review*, 9: 83 - 139.
- Round, F.E. 1982. The problem of cell size during diatom cell division. *Nova Hedwegia*, 23: 291 - 304.
- Ruz, M-H., Y. Michaud, M. Allard, T. Sutherland, and B. Ardiles. 1994. Morpho-sedimentologie et evolution des estrans de la partie centrale du detroit de Manitounuk, Hudsonie. Open File Report # 2882.
- Scoffin, T.P. 1970. The trapping and binding of subtidal carbonate sediment by marine vegetation in Bimini Lagoon, Bahamas. *Journal of Sedimentary Petrology*, 40: 249 - 273.
- Shaffer, G.P. and M.J. Sullivan. 1988. Water column productivity attributable to displaced benthic diatoms in well-mixed shallow estuaries. *Journal of Phycology*, 24: 132 - 140.
- Shields, A. 1936. Application of similarity principles and turbulence research to bed-load movement. In: Lavelle, J.W. and H.O. Mofjeld. 1985. *Journal of Hydraulic Engineering*, 113 (3): 370 - 393.
- Simpson, W.R. 1982. Particulate matter in the oceans - sampling methods, concentration, size distribution and particle dynamics. *Oceanography and Marine Biology Annual Review*, 20: 119 - 172.
- Smatecek, V. and E. Walger. 1987. Introduction. In: Rumohr, J., E. Walger, and B. Zeitzschel (Eds), *Seawater-Sediment Interactions in Coastal Waters*, Springer-Verlag, Berlin, pp. 1-14.
- Stal, L.J. 1994. Microbial mats: Ecophysiological interactions related to biogenic sediment stabilization. (Eds) Krumbien, W.E., D.M. Paterson, and L.J. Stal, In: *Biostabilization of Sediments*. Verlag, Oldenburg, pp. 41 - 53.
- Stal, L.J. and P. Caumette. 1994. Preface. (Eds) Stal, L.J. and P. Caumette. In: *Microbial Mats: Structure, Development and Environmental Significance*. NATO ASI Series, Vol G 35: v - vii.

- Stal, L.J., M. Villbrandt, and B. de Winder 1994 Ecophysiology EPS in benthic phototrophic microorganisms (Eds) Krumbien, W.E., D.M. Paterson, and L.J. Stal, In: Biostabilization of Sediments Verlag, Oldenburg, pp 377 - 399
- Sternberg, R.W. 1968 Friction factors in tidal channels with differing bed roughness *Marine Geology*, 6 243 - 260
- Stolzenbach, K.D., K.A. Newman, and C.S. Wong 1992. Aggregation of fine particles at the sediment-water interface *Journal of Geophysical Research*, 97 (C11) 17889 - 17898
- Sundback, K. 1994 The response of shallow-water sediment communities to environmental changes (Eds) Krumbien, W.E., D.M. Paterson, and L.J. Stal, In: Biostabilization of Sediments. Verlag, Oldenburg, pp. 17 - 40
- Sundback, K. and W. Graneli 1988 Influence of microphytobenthos on the nutrient flux between sediment and water: a laboratory study, *Marine Ecology Progress Series*, 43 63 - 69.
- Sundback, K. and B. Jonsson 1988 Microphytobenthic productivity and biomass in sublittoral sediments of a stratified bay, SE Kattegatt *Journal of Experimental Marine Biology and Ecology*, 122 63 - 81.
- Sutherland, A.J. 1967. Proposed mechanism for sediment entrainment by turbulent flows *Journal of Geophysical Research*, 72 (24) 6183 - 6194
- Terzaghi, K. and R.B. Peck 1967 *Soil Mechanics in Engineering Practice* John Wiley and Sons, New York.
- Underwood, G.J.C. and D.M. Paterson. 1993a Recovery of intertidal benthic diatoms after biocide treatment and associated sediment dynamics *Journal of the Marine Biological Association of the United Kingdom*, 73: 25 - 45.
- Underwood, G.J.C. and D.M. Paterson. 1993b Seasonal changes in diatom biomass, sediment stability and biogenic stabilization in the Severn Estuary *Journal of the Marine Biological Association of the United Kingdom*, 73: 871 - 887
- Underwood, G.J.C., D.M. Paterson, and R.J. Parkes 1995 The measurement of microbial carbohydrate exopolymers from intertidal sediments. *Limnology and Oceanography*, 40 (7): 1243 - 1253.
- Villbrandt, M., L.J. Stal, and W.E. Krumbein 1990. Interactions between nitrogen fixation and oxygenic photosynthesis in a marine microbial mat *FEMS Microbial Ecology*, 74: 59 - 72

- Wachendorfer, V., W.E. Krumbein, and H. Schellnhuber 1994a Bacteriogenic porosity of marine sediments - a case of biomorphogenesis of sedimentary rocks. In Krumbein, W.E., D.M. Paterson, L.J. Stal (Eds) *Biostabilization of Sediments*, Verlag, Germany, pp. 203 - 220
- Wachendorfer, V., H. Riege, and W.E. Krumbein 1994b Parahistological sediment thin sections. In Krumbein, W.E., D.M. Paterson, L.J. Stal (Eds) *Biostabilization of Sediments*, Verlag, Germany, pp. 257 - 278
- Wallace, J.C. and T.G. Reinsnes 1985. The significance of various environmental parameters for growth of the Iceland scallop, *Chlamys islandica* (Pectinidae), in hanging culture. *Aquaculture*, 44: 229 - 242
- Watling, L. 1991. The sedimentary milieu and its consequences for resident organisms. *American Zoology*, 31: 789 - 796
- Westall, F. and Y. Rince 1994 Biofilms, microbial mats and microbe-particle interactions: electron microscope observations from diatomaceous sediments. *Sedimentology*, 41: 147 - 162.
- Wildish, D.J. and D.D. Kristmanson (1984). Importance to mussels of the benthic boundary layer. *Canadian Journal of Fisheries and Aquatic Sciences*, 41: 1618 - 1625
- Wiltshire, K.H. 1992. The influence of microphytobenthos on oxygen and nutrient fluxes between eulittoral sediments and associated water phases in the Elbe Estuary. (Eds) Colombo, G., I. Ferrari, V.U. Ceccherelli, and R. Rossi. In: *Marine Eutrophication and Population Dynamics*. Olsen and Osen, Fredensborg, pp. 63 - 70.
- Yallop, M.L. and D.M. Paterson 1994 Survey of Severn Estuary. In Krumbein, W.E., D.M. Paterson, and L.J. Stal (Eds) *Biostabilization of Sediments*, Verlag, Germany, pp. 279 - 326
- Yallop, M.L., B. de Winter, D.M. Paterson, and L.J. Stal 1994 Comparative structure, primary production and biogenic stabilization of cohesive and non-cohesive marine sediments inhabited by microphytobenthos. *Estuarine, Coastal and Shelf Science*, 39: 565 - 582.
- Zevenhuizen, J., C.L. Amos, K. Asprey, Y. Michaud, M.-H. Ruz, T.F. Sutherland, and C. Tremblay. 1994. The sediment budget of Manikounuk Sound, southeastern Hudson Bay. Geological Survey of Canada, Open File Report # 2941, pp. 1 - 55
- Zobell, C.E. 1946. Marine microbiology. In: Hargrave, B.T. 1972. Aerobic decomposition of sediment and detritus as a function of particle surface area and organic content. *Limnology and Oceanography*, 17 (4): 583 - 596