

00-73

Environment Canada

Water Science and
Technology Directorate

Direction générale des sciences
et de la technologie, eau

Environnement Canada

Structure, Stability and Transformation of Contaminated
Lacustrine Surface Fine-Grain Laminae

By:

Ian G. Droppo & Carl L. Amos

TD
226
N87
no.
00-73

00-73

THE STRUCTURE, STABILITY AND TRANSFORMATION OF CONTAMINATED LACUSTRINE SURFACE FINE-GRAIN LAMINAE

Key Words: flocculation, erosion, surface fine-grain laminae, annular flume.

Management Perspective

The Kenilworth boatslip is one of the "hot spots" for the Hamilton Harbour RAP due to long-term contaminant inputs from stormwater runoff, sewer overflow, atmospheric input, direct overland flow and industrial inputs. Contemporary contaminants are housed within a surficial layer called a surface fine-grained laminae (SFGL). This layer possesses some inherent strength against erosion and as such, in a depositional environment, is eventually incorporated into the consolidated bed. *In situ* experiments were conducted using an annular flume to investigate the structure of the SFGL, its stability against erosion and its transformation into the consolidated bed. Results suggest that the SFGL's strength is strongly credited to its biostabilization by bacteria and their polymeric exudates. The weaker, less dense flocs of the SFGL were found to transform through a collapse zone, via self-weighted consolidation, into dense aggregates of the consolidated bed. Physical disturbance of the sediment broke up the sediment matrix and initially destabilized the sediment. The new surface layer underwent rapid consolidation however, suggesting a fast recovery of the biostabilized layer. This work suggests that the biology of the sediment needs to be considered when studying the erosion of sediments. Future work will use this information in the development of bed sediment erosion models.

Structure, stabilité et transformation des straticules à grains fins de surfaces lacustres contaminées

Mots clés: floculation, érosion, straticules à grains fins de surface, canal jaugeur annulaire.

Sommaire à l'intention de la direction

Les postes d'accostage de Kenilworth sont l'un des « points chauds » du PA du port de Hamilton à cause des apports de contaminants persistants dus aux eaux pluviales, aux trop-pleins d'égouts, au dépôt atmosphérique, au ruissellement direct des terres et aux rejets des industries. Les contaminants récents se logent dans la couche superficielle des « straticules à grains fins de surface » (SGFS). Cette couche est caractérisée par certaines propriétés inhérentes de résistance à l'érosion et pour cette raison, dans un milieu de dépôt, elle est tôt ou tard incorporée au lit consolidé. On a effectué des expériences *in situ* à l'aide d'un canal jaugeur annulaire afin d'étudier la structure des SGFS, leur stabilité contre l'érosion et leur transformation dans le lit consolidé. Les résultats semblent indiquer que la résistance des SGFS est fortement liée à leur biostabilisation par des bactéries et leurs exsudats polymériques. On a constaté que les floes moins résistants et moins denses des SGFS se transforment par consolidation aut pondérée, dans une zone d'effondrement, en agrégats denses du lit consolidé. Au début, la perturbation physique des sédiments brisait leur matrice et les déstabilisait. Toutefois, la nouvelle couche de surface se consolidait rapidement, ce qui semble indiquer que la couche biostabilisée se renouvelle rapidement. Ces travaux montrent l'importance d'examiner les caractéristiques biologiques des sédiments lors de l'étude de l'érosion des sédiments, et des études supplémentaires utiliseront ces informations pour l'élaboration de modèles d'érosion des sédiments des lits.

ABSTRACT: An *in situ* annular flume (Sea Carousel) was deployed in Hamilton Harbour, Lake Ontario to assess the structure, stability and transformation of lacustrine surface fine-grain laminae (SFGL). Such laminae typify depositional lacustrine environments. The critical erosion thresholds, erosion rates and internal friction coefficients were determined for natural undisturbed and physically disturbed sites. Sediment cores, taken at each site, were analyzed for bulk density using a CT scanner. Floes and aggregates pumped from the flume during erosion experiments were analyzed for morphological characteristics using conventional optical microscopy (COM) and transmission electron microscopy (TEM). The SFGL was observed to be porous, of low density, and high water content which possessed yield resistance due, in part, to binding by extracellular polymeric substances (EPS) secreted by a colonized microbial population. TEM observations showed an active biological community in the sediment promoting biostabilization. A general three-layer model is developed which depicts the organic floes of the SFGL (Layer 1) compressing within a *collapse zone* (Layer 2) to form a consolidated bed (Layer 3). Time series of erosion thresholds and friction coefficients of the disturbed bed showed that the SFGL reconsolidated rapidly, and increased in shear strength. The artificial disturbance of the sediment resulted in the incorporation of the SFGL and the collapse zone with the consolidated bed. This stimulated the process of consolidation primarily through the removal of gas and the break down of the organic fibril network. High friction coefficients and increasing density with depth in the new surface layer indicated that rapid consolidation was occurring in the disturbed plot.

Résumé

On a installé un canal jaugeur annulaire *in situ* (Sea Carousel) dans le port de Hamilton, au bord du lac Ontario, afin d'évaluer la structure, la stabilité et la transformation de straticules à grains fins de surfaces lacustres (SGFS). Ces straticules sont propres aux milieux de dépôt lacustres. On a déterminé les seuils critiques d'érosion, les vitesses d'érosion et les coefficients de friction interne à des sites naturels non perturbés et à des sites perturbés physiquement. À l'aide d'un tomodynamomètre, on a analysé des carottes de sédiments, prélevées à chaque site, afin d'en déterminer le poids volumique apparent. Lors des mesures d'érosion, on a analysé des floes et des agrégats pompés du canal jaugeur afin d'en déterminer les caractéristiques morphologiques par microscopie optique classique (MOC) et par microscopie électronique à transmission (MET). Selon les observations, les SGFS étaient poreux et caractérisés par de faibles masses volumiques et de fortes teneur en eau, ainsi que par une résistance à la rupture en partie due à des liants polymériques extracellulaires (LE) sécrétés par une population microbienne colonisée. Les observations de MET ont mis en évidence, dans les sédiments, la présence d'une communauté biologique favorisant la biostabilisation. On a élaboré un modèle général à trois couches montrant les floes organiques des SGFS (couche 1) qui se compriment dans une zone d'effondrement (couche 2) de manière à former un lit consolidé (couche 3). Des séries chronologiques des seuils d'érosion et des coefficients de friction du lit perturbé ont montré que les SGFS se reconsolidaient rapidement et que leur résistance au cisaillement augmentait. La perturbation artificielle des sédiments a causé l'incorporation des SGFS et de la zone d'effondrement au lit consolidé, ce qui a stimulé le processus de consolidation d'abord par l'élimination des gaz et par la dislocation du réseau de fibrilles organiques. Dans la nouvelle couche de surface, des coefficients de friction élevés et la croissance de la masse volumique en fonction de la profondeur indiquaient une consolidation rapide dans la parcelle perturbée.

STRUCTURE, STABILITY, AND TRANSFORMATION OF CONTAMINATED LACUSTRINE SURFACE FINE-GRAINED LAMINAE

IAN G. DROPPO¹ AND CARL L. AMOS²

¹ National Water Research Institute, P.O. Box 5050, Burlington, Ontario L7R 4A6, Canada

² Southampton Oceanography Centre, Southampton, Hampshire, SO14 3ZH, U.K.

e-mail: ian.droppo@cciw.ca

ABSTRACT: An *in situ* annular flume (Sea Carousel) was deployed in Hamilton Harbour, Lake Ontario, to assess the structure, stability, and transformation of lacustrine surface fine-grained laminae (SFGL). Such laminae typify depositional lacustrine environments and occur at the sediment-water interface. The critical erosion thresholds, erosion rates, and internal friction coefficients were determined for natural undisturbed and physically disturbed sites in order to assess changes in bed stability. Sediment cores, taken at each site, were analyzed for bulk density using a CT scanner in order to provide an intercomparison of our results. Flocs and aggregates, pumped from the flume during erosion experiments, were analyzed for morphological characteristics using conventional optical microscopy and transmission electron microscopy to evaluate the mechanism and development of the SFGL and its structure. A general three-layer model is developed which depicts the organic flocs of the SFGL (Layer 1) compressing within a collapse zone (Layer 2) to form a consolidated bed (Layer 3). The SFGL was observed to be porous, of low density, and of high water content which possessed yield resistance due, in part, to binding by extracellular polymeric substances secreted by a colonized microbial population. Transmission electron microscopy observations showed an active biological community in the sediment promoting biostabilization. Time series of erosion thresholds and friction coefficients of the disturbed bed showed that the SFGL reconsolidated rapidly and increased in shear strength. The artificial disturbance of the sediment resulted in incorporation of the SFGL and the collapse zone with the consolidated bed through mixing. This stimulated the process of consolidation chiefly through removal of gas and breakdown of the organic fibril network. Reconsolidation began with the formation of a collapse zone at the surface of the disturbed sediment. High friction coefficients and an increasing density with depth in the new surface layer indicated that rapid consolidation occurred after disturbance.

INTRODUCTION

Many environmental contaminants have pathways that are partially or wholly associated with sediment and/or biological substrates (Chapman et al. 1982). Consequently, on entering aquatic environments they find their way rapidly to the bed. An increase in bed shear stress can remobilize this material, with undesired effects on the aquatic environment (Partheniades 1986; Pettibone et al. 1996; Irvine et al. 1997). Common to many depositional cohesive beds in aquatic environments is the formation of a structurally unique surficial layer of sediment called the surface fine-grained lamina (SFGL) or surface floc layer (Droppo et al. 2001; Droppo and Stone 1994; Lambert and Walling 1988; Kranck 1981). The SFGL represents the most recently deposited material (observed to be up to 8 mm thick; Droppo and Stone 1994) and is often manifested as a "stationary fluid" undergoing primary consolidation (Dyer 1986). It is often transient, forming a temporary, low-density, high-water-content, "fluffy" deposit or blanket over the existing bed between erosion events. Much of the sediment forming the SFGL is deposited in a flocculated state (Lau and Droppo 1998; Droppo and Stone 1994). Flocs are composite particles that are formed in suspension through various physical, chemical, and biological processes (summarized in Droppo et al. 1997). Erosion of the SFGL returns a significant

amount of sediment and contaminants to the water column (Phillips and Walling 1999; Stone and Droppo 1994; Lambert and Walling 1988).

Investigations into bed sediment stability are generally restricted to laboratory flume experiments in which bed sediments are deposited under quiescent conditions, allowed to consolidate, and then eroded with incremental increases in bed shear stress (Fukuda and Lick 1980; Mehta et al. 1982; Parchure and Mehta 1985; Otsubo and Muraoka 1988). While useful in understanding the mechanics of bed failure, these experiments do not provide realistic estimates of bed failure in environments where sediments are deposited under flow or have experienced a complex stress history (e.g., rivers and many lake environments). Lau and Droppo (2000) and Droppo et al. (2001), have demonstrated that the shear stress at which a sediment is deposited (the depositional history), biostabilization, and the SFGL floc structure and strength have a strong influence on the stability of the SFGL. In addition, traditional flume experiments have not differentiated the SFGL layer from layers beneath. *In situ* flumes have been used to study sediment erosion (Young and Southard 1978; Nowell and Jumars 1987; Amos et al. 1992; Maa et al. 1993; Maa et al. 1998), but, these flumes have been deployed mainly in marine and estuarine environments (Amos et al. 1996a, Sutherland et al. 1998; Wright et al. 1997; Paterson, et al. 1994; Dade et al. 1990; Dade et al. 1996). Biology (at all benthic scales) is known to play a role in promoting sediment stability (Rhoads et al. 1978; Eckman et al. 1981; Jumars and Nowell 1984; Paterson and Daborn 1991; Dade et al. 1992; Sutherland, et al. 1998; Droppo et al. 2001). This is particularly true for the microbial population, which secretes sticky extracellular polymeric substances (EPS) that stabilize the bed because of their adhesive nature (Droppo et al. 2001; Sutherland et al. 1998; Paterson et al. 1994; Dade et al. 1990; Grant and Gust 1987; de Boer 1981). Both Droppo et al. (2001) and Paterson et al. (1994) have observed SFGLs with greater strengths than the underlying sediment as a result of this biostabilization.

In this study we use an *in situ* annular flume (Sea Carousel) to assess the bed stability of the SFGL in a contaminated, freshwater, fine-grained lacustrine environment (Hamilton Harbour, Lake Ontario). Experiments were performed on two bed types: an undisturbed control site and a disturbed site (disturbed physically and by fluidization with an injection rake). The objectives of the study were: (1) to assess the stability of the SFGL in contaminated lacustrine environments; (2) to define the evolution of the SFGL into a consolidated bed; and (3) to examine the effects of physical disturbance on bed stability and the time scales for bed (SFGL) regeneration.

THE STUDY REGION

Hamilton Harbour, situated at the western end of Lake Ontario, is a typical harbor in the Great Lakes region (Fig. 1). Its bed is characterized by cohesive sediments that are organic rich and gassy, and as a result are impoverished in benthic organisms. The harbor has an area of 2,150 hectares. It receives water from a watershed 49,400 hectares in area and is affected by the effluents of steel manufacturing industries. The study site is situated approximately 100 m away from the shore in approximately 5 to 7 m of water. According to diver reports, the lake bed is gel-like (elastic motion) and is easily fluidized and penetrated. The sediment is highly contaminated with heavy metals, PCBs, PAHs, and oil and grease because of long-term storm water runoff, sewer overflow, sewage treatment plant in-

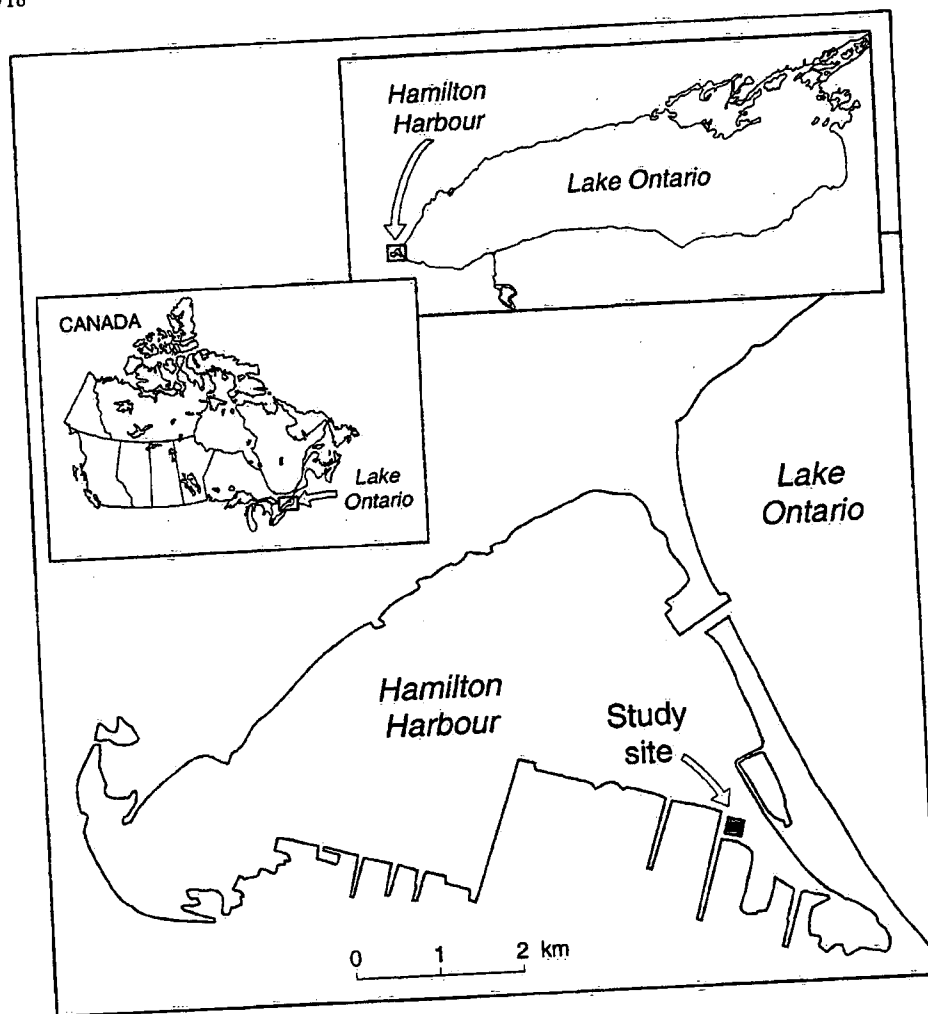


FIG. 1.—Study site for Sea Carousel deployments during the erosion experiments in Hamilton Harbour.

put, atmospheric input, direct overland flow, and industrial inputs (Remedial Action Plan for Hamilton Harbour 1992). The site is sheltered from strong currents and large waves, so it is largely a depositional setting. Adjacent to the site, however, is a shipping route for large lake freighters, which pose a problem for sediment and contaminant remobilization through propeller wash.

FIELD AND LABORATORY INSTRUMENTATION AND METHODOLOGIES

Two adjacent test plots were established just outside an active shipping area in Hamilton Harbour, Ontario, Canada (Fig. 1). The first plot was kept in its natural state as a control, and the second plot was physically disturbed and fluidized by injection of harbor water. The bed disturbance and fluidization was produced by towing an 8-m-wide injection rake through the sediments while pumping ambient water into the bed to a depth of 30 cm. This rake is used for *in situ* contaminant remediation technology (Murphy et al. 1995).

A benthic flume (Sea Carousel) was deployed at six control sites (data from Control Site 2 was discarded because of excessive burying of the Sea Carousel) and four disturbed sites in the study region. The physically disturbed and fluidized sites were tested 1, 2, 3, and 4 days following disturbance to assess the recovery rate of the bed. All deployments occurred between 17 August and 24 August 1995, when the water temperature was around 25°C.

The Sea Carousel is a benthic annular flume designed specifically for

subaqueous field deployment. The flume channel is 2.0 m in diameter, 0.15 m wide, and 0.30 m high. Flow in the channel is induced by rotating a movable lid equipped with eight equally spaced paddles. Concentrations of suspended solids (*S*), within and outside of the flume, are measured using optical backscatter sensors (OBS) calibrated with the sediment eroded within the flume. A detailed description of the Sea Carousel and its operating procedures can be found in Amos et al. (1992).

The Carousel was lowered slowly through the water column at a rate of 5–10 cm s⁻¹. This resulted in a penetration of the flume base about 4 cm into the bed. Sediment resuspended by the landing was allowed to resettle during the first 10 minutes after deployment. Each test consisted of twelve 5-minute increments of steady flow (azimuthal current speeds of 0.04, 0.09, 0.14, 0.25, 0.33, 0.40, 0.48, 0.55, 0.59, 0.66, and 0.72 m s⁻¹). Following retrieval of the Carousel, the site was marked with a yellow Grimsby float and its location was fixed with differential GPS (accurate to ± 5 m).

Bottom Sediment Sampling

A box corer was used to collect an undisturbed volume of sediment (50 × 50 × 80 cm) for subsequent subsampling. Two syringe cores (60 cm³) and a push core (30 cm) were collected from the undisturbed central part of the box core. The syringe cores were flash frozen immediately by immersion in liquid nitrogen whilst the push cores were slowly frozen. All cores were analyzed for bulk density following the CT scanner analysis described by Amos et al. (1996b).

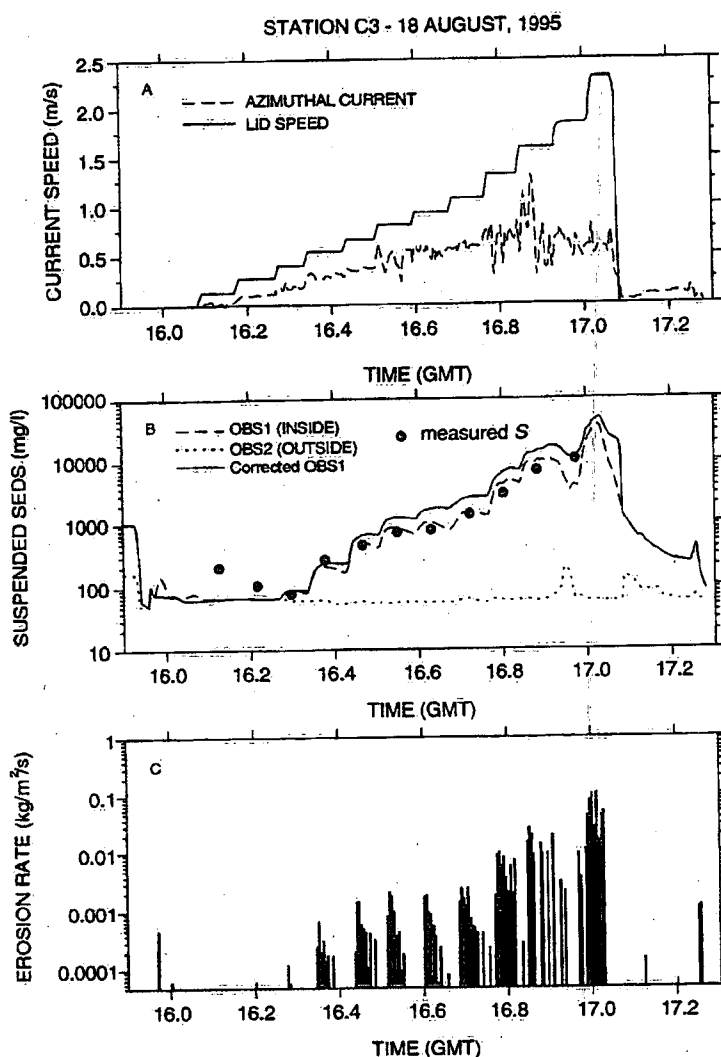


Fig. 2.—A time series plot for Control Site C-3. A) Lid rotation speed and azimuthal current speeds; B) gravimetric measured suspended solid concentrations and suspended solid concentrations (S) derived from OBS probes inside and outside of the flume; C) erosion rates calculated from dispersion-corrected suspended solid concentrations derived from the internal OBS probe.

Sampling of Water and Eroded Flocs and Aggregates

Water samples were collected from the sampling port on the outside wall of the Carousel with a foot pump. Duplicate samples were collected at each flow increment (about one minute into the increment) and analyzed for suspended sediment concentration (S) following the methods outlined by Environment Canada (1994). Structure and size of suspended and eroded particles as well as composition and porosity were studied using conventional optical microscopy (COM) and transmission electron microscopy (TEM) following the methods described by Droppo et al. (1997). The degree to which the pump sampling alters the character of the suspended particles is unknown, but work by Liss et al. (1996) and Droppo et al. (1997) suggests that freshwater flocs and aggregates are reasonably stable because of the strong bonds associated with biological binding. We therefore assume that floc sizes are representative of the population in suspension at the time of sampling.

RESULTS

Figure 2 provides an example of the calibrated time-series plots generated from the Sea Carousel at Control Site C3. Figure 2A shows lid rotation and azimuthal current speed in the flume. Significant variation in the azimuthal current speed was observed. This may be due to: (1) macroturbul-

ence produced by variable bed roughness; (2) variations in lid speed; or (3) interference on the electromagnetic flow meter caused by magnetic particles that come from the nearby steel industries. Lid speed was therefore used for the calculation of bed shear stress. Figure 2B shows S derived from the upper OBS inside and outside (ambient S) the flume, as well as the actual measured S pumped from the flume at each increment of shear stress (initial measured S in Figure 2B were uncharacteristically high, likely because of incomplete flushing of the line following the previous experiment). The OBS (inside) data were corrected for dispersion (leakage) following the methods of Amos et al. (1992) and replotted in Figure 2B. The internal upper OBS showed clear responses to the incremental current time series in Figure 2A. The internal lower OBS could not be used, because it was consistently buried or too close to the bed for accurate readings of S . The external OBS shows no significant change in the ambient S due to the experiment (i.e., low leakage). The plot of measured S generally agreed with the pumped samples. Figure 2C shows the erosion rates determined from the corrected S trends. The peaks in erosion occurred at the beginning of each increment of speed shown in Figure 2A and are relatively short in duration (less than 180 seconds).

Table 1 summarizes the results of the SFGL erosion thresholds ($\tau_{c,0}$), derived from bed shear stress at the point of increase in corrected S above ambient levels) and friction coefficients of each layer (ϕ , from synthetic

TABLE 1.—Results of Sea Carousel deployments.

Deployment Site	*SFGL $\tau_c(0)$ (Pa)	ϕ Layer 1 (SFGL)	ϕ Layer 2 (CZ)	ϕ Layer 3 (CB)
C-1	0.32	7	17	5
C-3	0.32	17	37	14
C-4	0.31	17	31	17
C-5	0.36	17	34	0
C-6	0.38	18	48	8
MEAN	0.34	15	33	9
D-1	0.17	18	1	—
D-2	0.40	21	1	—
D-3	0.28	22	2	—
D-4	0.48	25	4	6
MEAN	0.33	22	2	—

* Based on regression extrapolation of eroded suspended sediments back to ambient levels.
 τ_c —Critical bed shear stress; CZ—collapse zone; CB—consolidated bed; ϕ —Friction coefficient

cores discussed below) for all Sea Carousel deployments. In general, the variability in $\tau_c(0)$ between sites in the Control plot was minimal whereas a significant amount of variability was found within the Disturbance plot. Nevertheless, both ϕ and $\tau_c(0)$ generally increased with time.

Figures 3 and 4 are "synthetic cores" that represent a reconstructed profile of sediment strength with sediment depth (Amos et al. 1996a). The solid lines in the synthetic core plots are considered to be "failure envelopes" expressing the locus of bed strength versus depth. To do this, we have assumed that the erosion processes at each increment of applied bed shear stress had equilibrated with the sediment strength and that erosion had ceased (i.e., it is a line joining points of greatest eroded depth for each stress increment). This locus is evident as a series of straight lines that are used to interpret sedimentary structure. The intersection points of these lines define layer depth and thickness. The friction coefficient of the SFGL is used to define the relative stability of the bed layer, its consolidation state, and bed sedimentary macrostructure. Generally, a negative ϕ signifies decreasing strength with eroded depth, perhaps the result of a surface biofilm, a zero ϕ denotes no change in bed strength, and a positive ϕ conforms to a more stable bed of increasing strength typical of self-weight consolidation (Amos and Droppo 1996). Three layers of varying sediment strength were observed with depth in the control plots (Fig. 3, Table 1). The uppermost layer is recognized as the SFGL, which is characterized by a positive ϕ with intermediate values. Below the SFGL is a zone where ϕ is generally larger than that in the SFGL layer (or the layer beneath). This zone is interpreted as the "collapse zone". The consolidated bed found beneath the collapse zone, forms the rest of the sedimentary column and is characterized by a low rate of change in bed strength with depth (low ϕ).

Following water injection the strength profile with depth was destroyed (Fig. 4). The newly developed bed was composed of two layers: an upper layer of relatively high ϕ (the new collapse zone) and a layer of significantly reduced ϕ beneath (two way, two Sample T-Test, $\alpha = 0.05$) (Fig. 4A–D, Table 1) which was highly fluidized. The ϕ of the disturbed surface was significantly larger than that of the control plot (one way, two Sample T-Test, $\alpha = 0.05$). The surface friction coefficient in the disturbed plots showed an increase with time characteristic of consolidation.

The SFGL, the collapse zone, and the consolidated bed were evident in the density results derived from the CT scanner (Fig. 5). (The scatter in values of bulk density (horizontal bars around each data point) reflects the heterogeneity of each depth interval, not the error of detection.) Figure 5A taken from the control plot, indicates the presence of the three layers observed in the synthetic cores: (1) a topmost layer approximately 2 mm thick of constant density (SFGL), (2) an intermediate region (from 2 to 10 mm) of rapidly increasing density (the collapse zone), and (3) a layer that occupies the rest of the core and shows a low rate of density increase (consolidated bed or soil). Figure 5B shows the wet weight density profile from the disturbed site. It shows less scatter (greater homogeneity) relative to

the control plots, but demonstrates a similar range in densities. As observed in the synthetic cores, only two layers are apparent: (1) a surface collapse zone, approximately 6 mm thick, which rapidly increasing density, and (2) an underlying layer showing a slowly increasing density with depth. The scatter in bulk density for all cores is likely to be related to: (1) bioturbation; a population of burrowing *Oligochaetes* was observed in underwater video (taxonomy identification by T. Reynoldson, personal communication 1997); (2) poorly sorted material; and (3) trapped gas; because the sediment is anoxic (Murphy et al. 1995), a significant amount of gas is generated within the sediments.

SediGraph analysis indicates that the sediments from all sites comprised 10–15% sand, 43% silt, and the rest clay (42–47%). The sediments were poorly sorted with a mean disaggregated diameter between 4 and 6 μm . The sand fraction was largely made up of anthropogenic fly ash and other stack emissions. Analysis of major elements (EDAX) with time in the Sea Carousel showed that only SiO_2 varied throughout the deployment, systematically increasing in proportion to suspended particulate matter. All other major ions, K, Cl, Na, Mg, SO_4 , remained steady, reflecting an association with pore water rather than siliceous sediments.

Video records revealed an increase in the size of eroded material with applied stress, up to 10 mm in diameter. Rip-up flocs observed during initial bed failure were observed to be sheet-like in nature. In addition, organic strands were observed to be present within these sheet-like structures, and these appeared to contribute to the bonding of the aggregates.

Suspended particles were found to generally increase in size to an eroded depth of around 4 to 10 mm (layers 1 and 2) at the control plot and then decrease in size (layer 3) (see Table 2) to a point where the sizes approached that of the ambient suspended material (seen in steps 1 to 3, Table 2). These trends are also supported by the statistical comparison of the three distribution types (i.e., suspended sediment, SFGL flocs, and deep eroded aggregates). A modified Kolmogorov-Smirnov (K-S) test (Goldman and Lewis 1984), showed that all volume distributions were significantly different from one another ($\alpha = 0.05$), whereas the percent-by-number distributions of SFGL-derived material were significantly different from the distributions of the ambient suspended sediment and consolidated bed ($\alpha = 0.05$). There was no significant difference ($\alpha = 0.05$) between the ambient suspended sediment (steps 1 to 3) and the deeper eroded layer distributions (steps 10 and 11).

The general relationship of increasing eroded material size (flocs and aggregates) with sediment depth was supported by direct COM observations. The particle size of the ambient suspended sediment (Fig. 6A) was observed to be small relative to that of the SFGL flocs (Fig. 6B) eroded from the bed, whereas material eroded from layers of the collapse zone were larger and more dense than the overlying SFGL (Fig. 6C). The SFGL flocs were observed to be porous, of open matrix, and of a high water and biological content (i.e., low density). The greatest density (in conjunction with smaller size), was in layer 3 (steps 10 and 11).

TEM micrographs were used to observe the internal microstructure of eroded flocs and aggregates. Figure 7A shows an eroded floc collected from the SFGL; it contains an abundance of biological material, including EPS. Figure 7B shows a floc collected from the consolidated bed. The eroded material at any depth was observed to be composed of bacteria, polymeric fibrils (EPS), and inorganic particles. Although the composition of material was constant with depth, there was an apparent difference in fabric: the lower layer (Fig. 7B) had fibril bundles in a network that was convoluted and fragmented compared to the newly formed SFGL (Fig. 7A), which had a more closely linked network of individual fibrils.

DISCUSSION

Control Plot

The CT scanner, synthetic cores, and particle analysis showed that there were three zones within the sediment, which are characterized by distinct

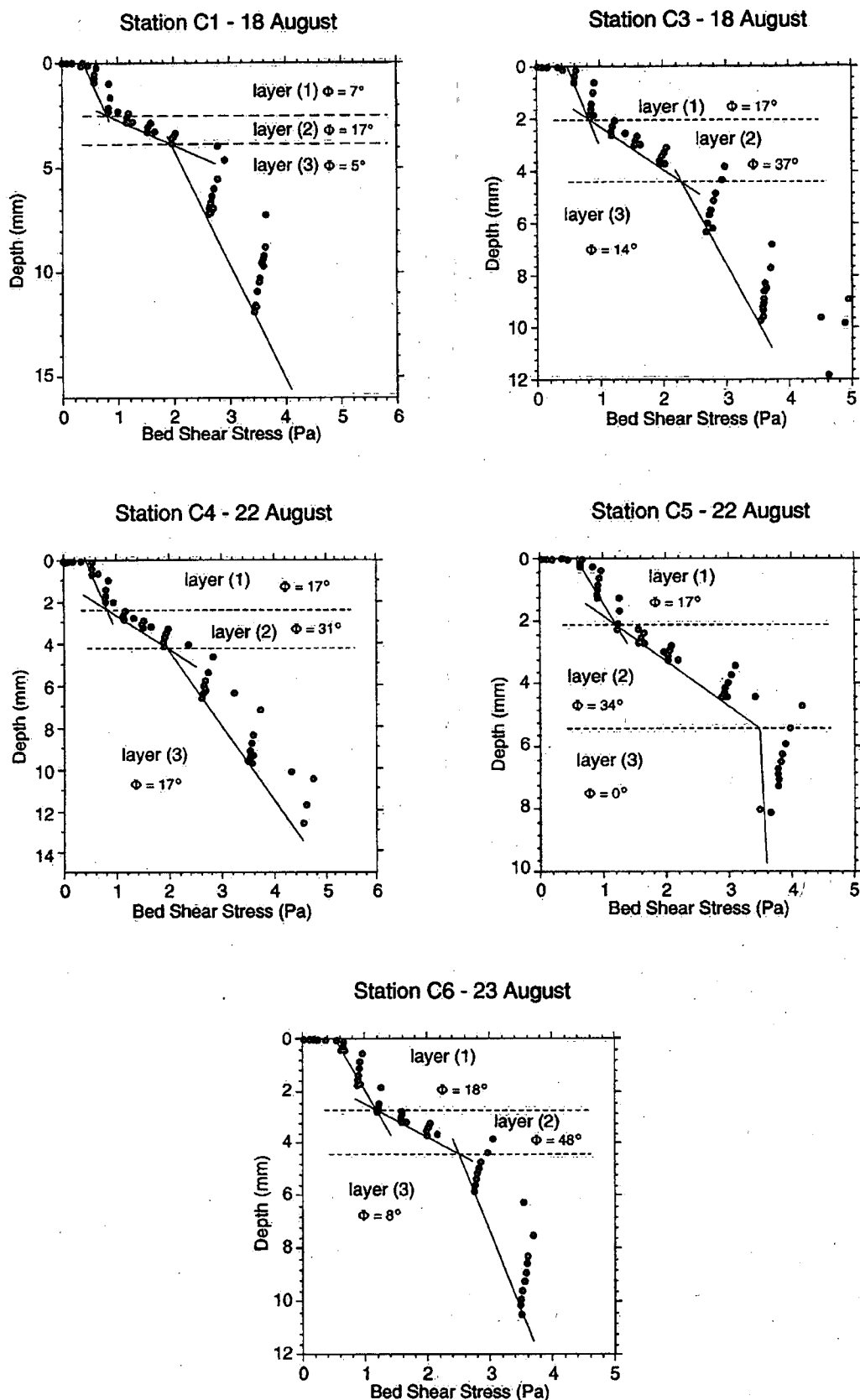


FIG. 3.—Synthetic cores for five control sites illustrating distinct sediment layers (ϕ = friction coefficient). Because deployments at sites C1 and C4 experienced power failures, some deposition occurred. This sediment was quickly eroded again upon reinitiation of shear and erosion of the consolidated bed continued.

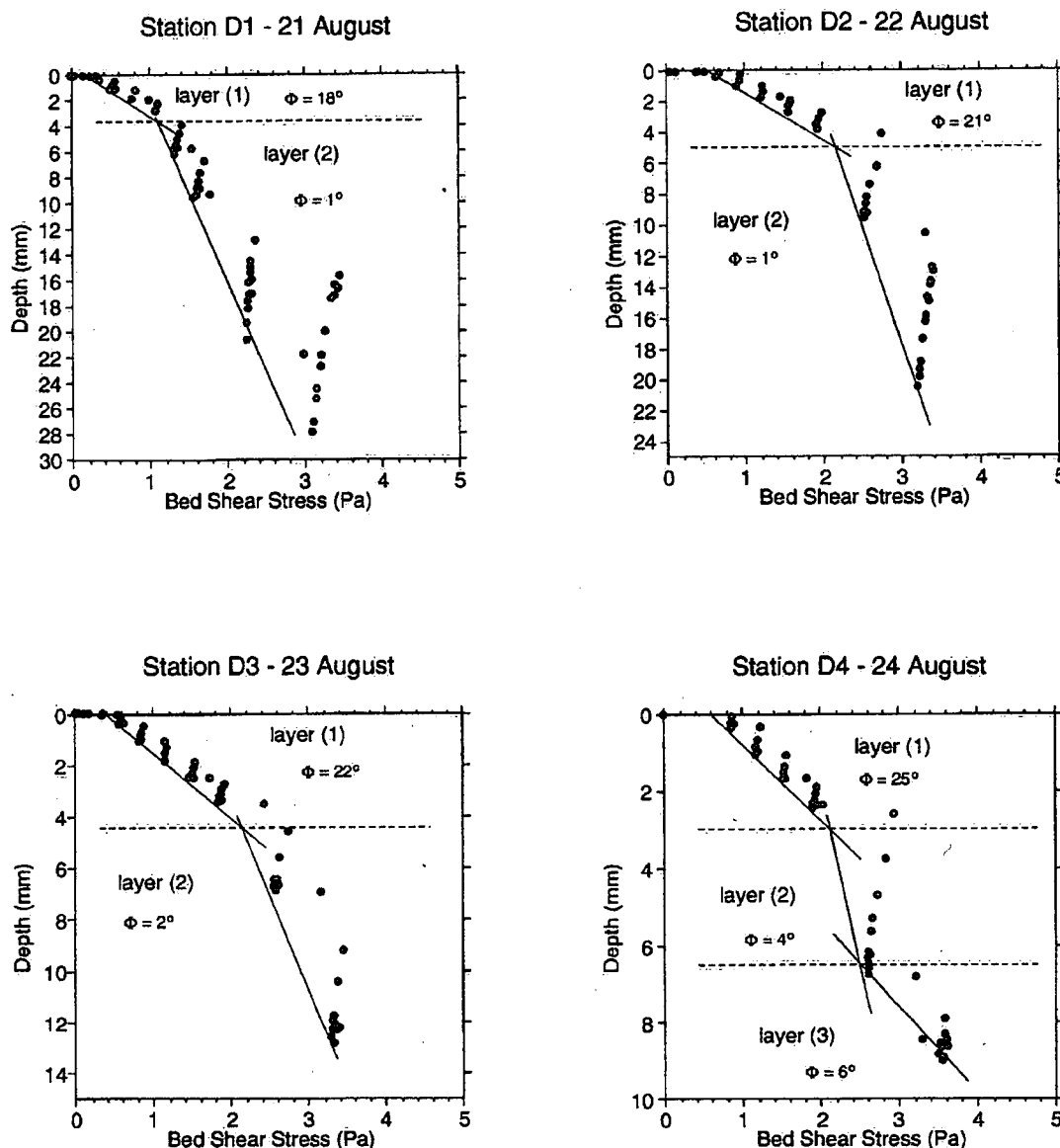


FIG. 4.—Synthetic cores for the four disturbed sites illustrating modified yet distinct sediment layers (ϕ = friction coefficient). Exact location of layer 2 in D4 is unknown because of limited data. Because deployment D1 experienced power failure, some deposition occurred. This sediment was quickly eroded again upon reinitiation of shear and erosion of the consolidated bed continued.

phases of erosion and sediment properties. Figure 8A presents a general three-layer model of the bed that depicts the transformation of the SFGL during a depositional period from open floc structure into the consolidated bed through a narrow region of collapse. Layer one is the SFGL (2–4 mm thick), which is formed by deposition of low-density flocculated material (Fig. 6A). The flocs, once deposited, are bonded together mainly through chemical and biological mechanisms (Paterson et al. 1994; Liss et al. 1996; Leppard 1997; Droppo et al. 1997; Phillips and Walling 1999); this inhibits the mechanism of collapse. The SFGL shows no signs of consolidation with depth, inasmuch as the density is constant with depth (Fig. 5A) and the friction coefficient is relatively low (Table 1, Fig. 3). Floc bonds are not physically strengthened by compaction and are easily broken upon erosion. The resultant SFGL is a low-density, open-matrix, high-water-content depositional layer inhabited by an active biological community (Figs. 6B,

7A). These properties are due to the individual SFGL flocs having the same properties (low density, open matrix, high water content) as the suspended sediment floc, minimal packing, and bioturbation by Oligochaetes. During erosion, the SFGL erodes as flocs and not as aggregates (Fig. 8B). Below a depth of approximately 2–4 mm to approximately 10 mm, the SFGL is compressed to form aggregated material in a region we call the collapse zone (Fig. 8B, Layer 2) by the mechanism of self-weight consolidation. Erosion of the collapse zone represents the initiation of aggregate and not floc entrainment (Fig. 8B). Upon erosion these aggregates are larger, denser, and of lower water content than the flocs of the SFGL (Fig. 6C). The collapse or increase in consolidation of this layer is evident by the rapid increase in density with depth (Fig. 5A) and by the high values of ϕ (Table 1). Below the collapse zone is the consolidated bed (Fig. 8A, Layer 3), in which the density remains relatively constant with depth (Fig. 5A). The

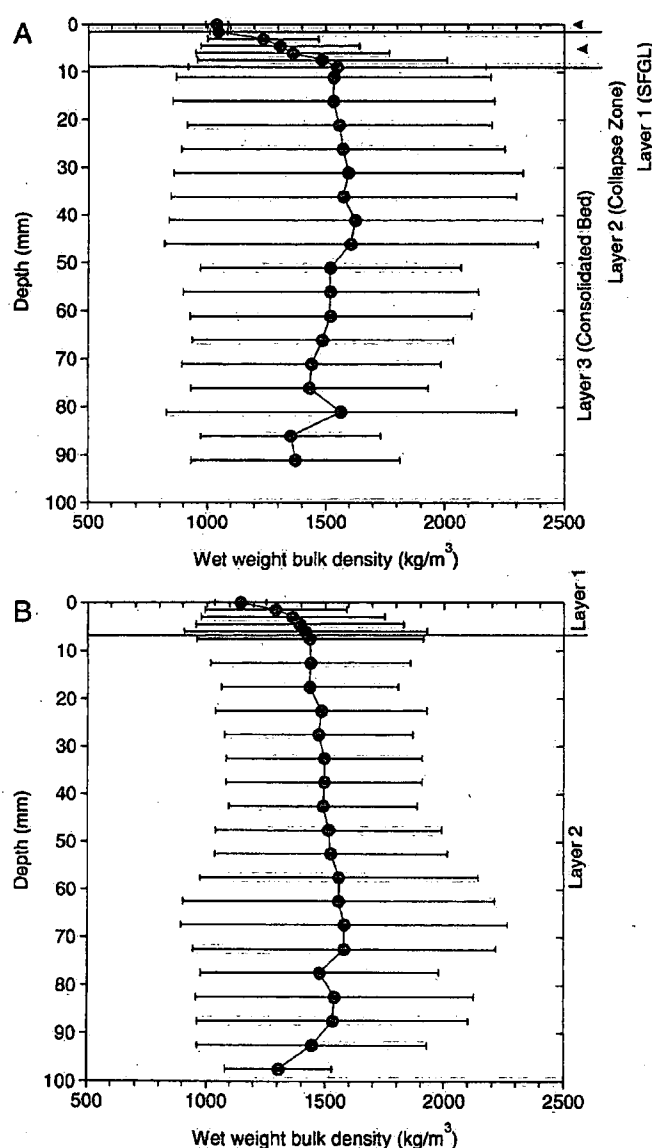


FIG. 5.—Representative wet weight bulk density profile for the A) control plot and B) disturbed plot syringe cores using CT scanner analysis. Distinct sediment layers are identified, with the scatter bars representing the heterogeneity of density for each depth interval.

minimal change in bed strength in this zone is seen by a relatively low ϕ . (The range of ϕ derived for all layers, however, is relatively large (Table 1), indicating that the structure of the sediment with depth is complex and variable; Amos and Droppo 1996). Upon erosion of this layer, further aggregates are released from the bed (Fig. 8B). As erosion continues, the proportion of SFGL flocs in suspension decreases relative to aggregates derived from the collapse zone and the consolidated bed (Fig. 8B). The measured smaller size of eroded aggregates from the compacted bed (Layer 3) (Table 2) may be due to breakup of aggregates at high shear stress.

Although there was no appreciable consolidation of the SFGL with depth, $\tau_c(0)$ was observed to vary between 0.32 and 0.38 Pa. That small variation in SFGL strength (Table 1) is suggestive of an even bed shear strength over the control plot. The critical bed shear stresses of the SFGL in Table 1 are generally three times higher than those found by Wright et al. (1997) and Maa et al. (1998) for Chesapeake Bay. However, our results

TABLE 2.—Eroded floc median spherical diameters by number and volume with depth for Control Site 3.

Velocity Step	Eroded Depth (mm)	Median Spherical Diameter by Number (μm)		Median Spherical Diameter by Volume (μm)
1	0	16.4	Suspension	227.9
2	0	15.3		154.9
3	0	17.2		271.4
4**	0.58	18.9	Layer 1	268.7
5	1.8	25.1		335.7
6	2.6	19.3	Layer 2	497.2
7	3.0	26.8		386.6
8	3.7	21.9		371.9
9	6.2	18.8		563.4
10	9.7	16.6	Layer 3	167.1
11		17.2		235.4

** = Velocity step at which SFGL erosion (bed failure) began.

conform with predictions of strength, in relation to bulk density, made by Ockenden and Delo (1988) and Mitchener and Torfs (1996). Furthermore, our results overlap with those presented by Tolhurst et al. (2000) using the EROMES device for sediment of similar density but from a marine environment. The correspondence of our measurements with other data from saline environments indicates that our stability measures are not related to salinity. The data also fall in line with the linear relationship between erosion threshold and bulk density in Amos et al. (1998). In view of this, the contamination of the sediment by coal tar and oil and grease at our study site does not appear to enhance the cohesion of the sediment and therefore its stability.

Paterson, et al. (1994) found biological activity to be largely restricted to the topmost 2 mm (i.e., within the SFGL). Video observations, COM, and TEM show that biostabilization was an important mechanism of SFGL stabilization despite low consolidation of this layer. The organic strands observed to emanate from large eroded flocs suggest the presence of a strong organic component binding particles together. TEM imaging suggests that it is the EPS fibril matrix (produced by bacteria) that was most responsible for the biostabilization of the SFGL (Fig. 7). The EPS fibrils are cohesive colloids (fiber diameter between 4 and 20 nm; Leppard 1992; Leppard 1997) that form a substantial matrix within the sediment and help bind particles together (Droppo et al. 1997; Liss et al. 1996; Filella et al. 1993; Leppard 1992). Defarge et al. (1996), suggest that these three-dimensional fibril matrices are inherent within microbial inhabited sediments and represent the framework for the sediment itself. Single fibrils are common in SFGL flocs (Fig. 7A), whereas fibril bundles are more abundant in aggregates formed in lower layers (Fig. 7B). This transformation in fibril association with depth is likely due to compaction and possible biodegradation. It is likely that the fibril bundles have greater strength (relative to single fibrils), contributing to the greater stability of the lower sediment layers. Such fibril changes with depth may help explain the observed increase in eroded size of flocs and aggregates through the SFGL and collapse zone (Table 2). These fibril structures, regardless of their location in the sediment, are important bridging and binding mechanisms within the individual particles of flocs and aggregates and between the composite particles in the bed as a whole. Dade et al. (1990) and Dade et al. (1996) have shown that EPS contained within marine sand beds and clay-seawater suspensions significantly increases bed stability. They found that exopolymers present in clay bed sediments at concentrations in the order of 0.01% of a typical clay particle mass increased critical bed shear stress for erosion by 60%. Droppo et al. (2001) found EPS to have similar effects in studies of Hamilton Harbour sediments in a laboratory annular flume. They found that biostabilization could result in a tenfold increase in shear stress required to initiate erosion.

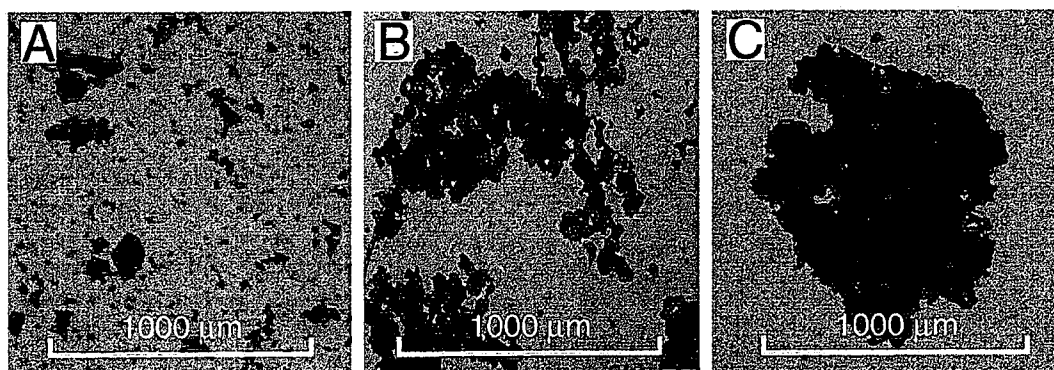


FIG. 6.—Representative COM micrographs of A) ambient suspended sediment (background suspended sediment resident within Hamilton Harbour at the time of experiments); B) SFGL eroded flocs; and C) collapse zone rip-up aggregates.

Disturbed Plot

The disturbed plot provided the opportunity to investigate further the factors that influence SFGL stability and to observe consolidation effects after a well-defined mixing event. Following disturbance, the strength profile with depth was significantly modified, with no third layer present (with the exception of D4) and a significantly reduced ϕ for the second layer (Fig. 4). This low ϕ (Table 1, Layer 2) is indicative of the fluidization of the sediment at depth by the injection rake. Artificially disturbing the sediment resulted in incorporation of the SFGL and the collapse zone with the consolidated bed, which stimulated the process of collapse mainly by removal of gas and breakdown of the organic fibril network. The reduction in the gas content of the sediment may be reflected in the lower standard deviations of the wet weight bulk densities within the disturbed plots (Fig. 5B) relative to the control plot (Fig. 5A). The new surface layer constitutes the collapse zone, because it had a higher friction coefficient (Table 1) and rapidly increasing bed density with depth, suggesting greater consolidation (Fig. 5B). Although the new surficial layer is disturbed, its higher ϕ , relative to Layer 2 suggests that it was undergoing greater consolidation. This is likely due to degassing of the sediment and strong recent biostabilization enhanced by warm water temperatures and high nutrient levels, providing a more cohesive surface layer (Paterson and Daborn 1991; Paterson et al. 1994; Sutherland et al. 1998). The increasing ϕ and $\tau_c(0)$ for the disturbed surface layer over the four-day period (Table 1) indicates some temporal strengthening of the sediment with depth and at the surface. This is likely due to the dewatering and consolidation of the sediment following distur-

bance and active biostabilization. The initial disturbance resulted in a significant reduction in erosion threshold (0.17 Pa), which is likely to be related to the breaking of the biostabilized layer and incorporation of the SFGL and collapse zone into the consolidated bed. After four days, the erosion threshold had risen to 0.48 Pa. Layer 2 does not show any signs of strengthening over the four-day period inasmuch as ϕ remains close to zero. The effects of the weakened underlying sediment (due to disturbance and fluidization) is evident from erosion rates that are twice as high for the disturbed plot as for the control plot.

CONCLUSIONS

The erosion of lacustrine sediments is related to the highly complex interrelationship between benthic hydrodynamics, benthic biology and cohesive sediment properties. We present a general three-layer model of the bed that progresses from an SFGL through a collapse zone to a consolidated bed. From the erosion experiments, eroded particle structure was found to evolve from low-density flocs of the SFGL to dense aggregates of the consolidated bed. The erosion of intermediate forms (aggregated flocs) took place during erosion of the collapse zone.

The SFGLs were found to exhibit an inherent shear strength due mainly to biostabilization. Visual inspection (video, COM, and TEM) of eroded flocs with depth suggests that it is the microbial communities' secretion of EPS forming a strong matrix throughout the sediment that adds to the cohesive strength of the sediment. Erosion experiments in the control plot showed an increase in eroded floc and aggregate size with eroded depth,

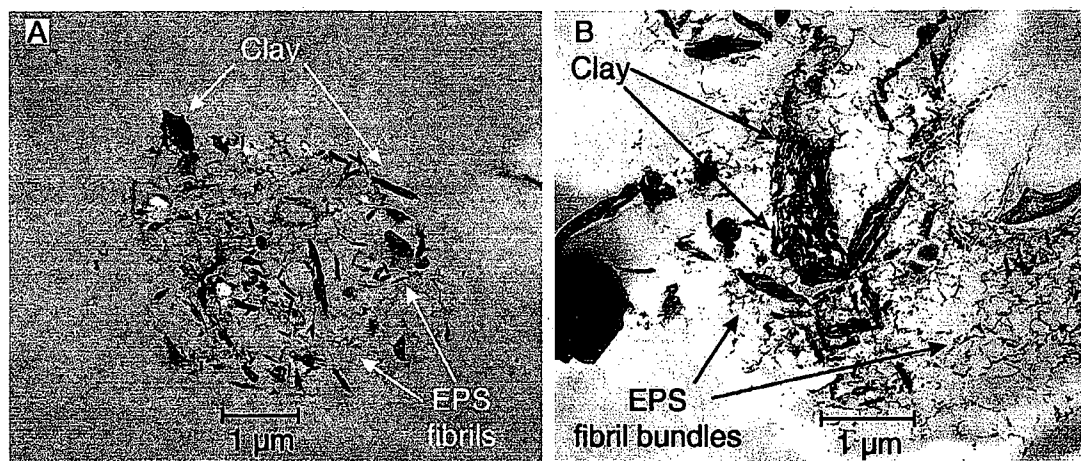


FIG. 7.—Representative TEM micrographs of A) SFGL eroded flocs and B) consolidated-bed rip-up aggregates.

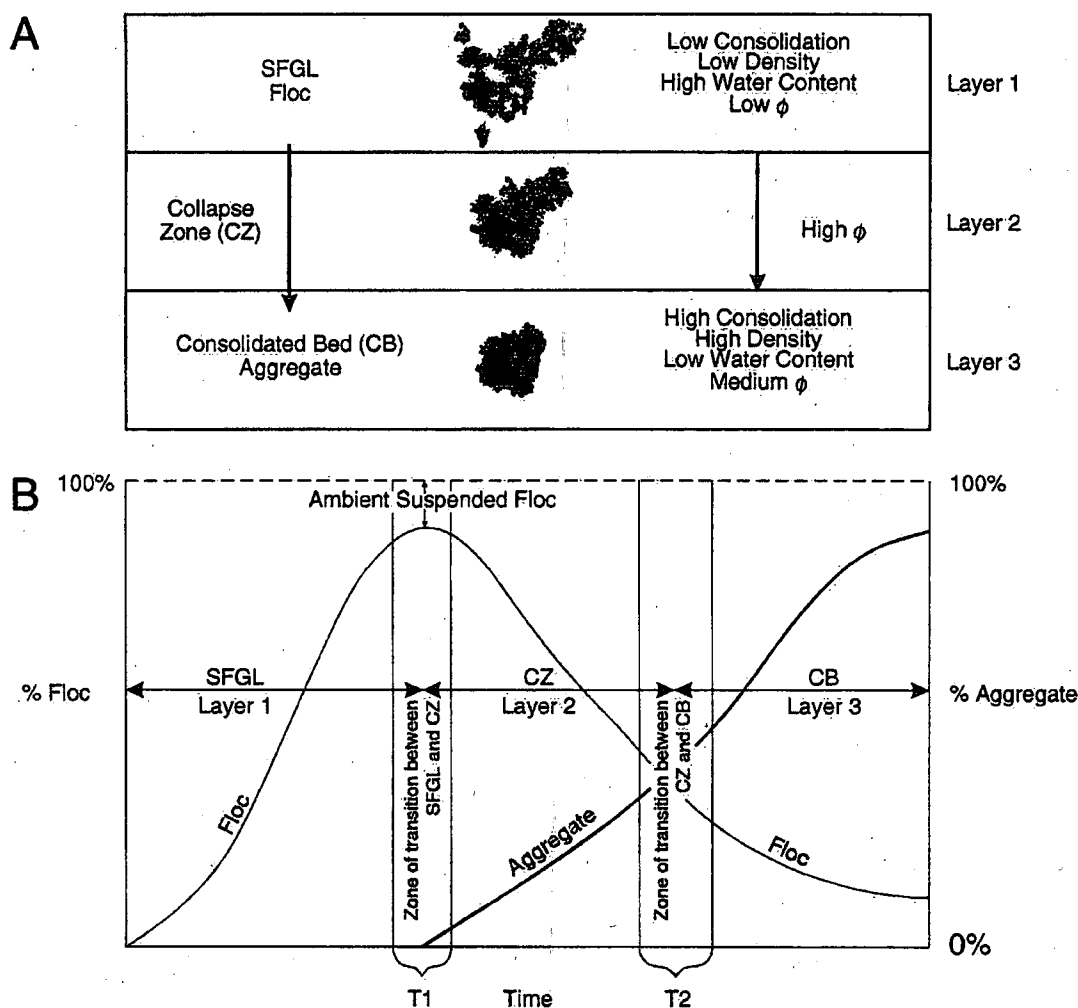


FIG. 8.—General three-layer model of cohesive bed sediment illustrating A) the transformation of the SFGL into the collapse zone (CZ) and finally into the consolidated bed (CB) during a depositional period and B) conceptualization of an erosion sequence for the three-layer model. Note that initially the flocs of the SFGL erode (forming the entire suspension, with the exception of the ambient suspended flocs) followed by the aggregates of the CZ, and finally the CB. As erosion continues, the proportion of flocs in suspension decreases relative to aggregates. The exact time at which erosion is initiated at a new layer is indeterminate (T1, T2).

even though the shear stress was increasing. This is attributed to increasing compaction with depth, as suggested by general increases in density of eroded flocs and aggregates with depth, but also to the strong binding effect of the EPS. It was unclear whether the reduced size of the eroded aggregates from the consolidated bed was due to breakage of suspended aggregates and flocs eroded at lower bed shear stresses or if it was an actual reduction in size of eroded aggregates. Physical disturbance and fluidization of the sediment undoubtedly broke up much of the sediment matrix and initially destabilized the sediment, particularly at the depth where friction coefficients were close to zero. While the control plot SFGL and the collapse zone were artificially incorporated into the consolidated bed, the new surface layer underwent rapid consolidation. The high friction coefficient of the surface layer of the disturbed plot (higher than that of the control plot) was attributed in part to the fast recovery of the biostabilized layer due to high nutrient levels and temperatures and by degassing of the surficial sediment layer. A better understanding of how SFGL microstructure (with particular emphasis on the biological community and EPS network) influences surficial bed stability will assist in the more accurate prediction of sediment and contaminant erosion.

ACKNOWLEDGMENTS

The authors would like to thank Dr. T. Murphy for providing the water injection system, and A. Robertson, H. Don, R. Murphy, C. Jaskot, M. West, and D. Clattenburg for their technical assistance. The critical reviews of P. Wiberg, J. Syvitski, L. Sanford, and an anonymous reviewer were greatly appreciated.

REFERENCES

- AMOS, C.L., BRYLINSKY, M., SUTHERLAND, T.F., O'BRIEN, D., LEE, S., AND CRAMP, A., 1998, The stability of a mudflat in the Humber estuary, South Yorkshire, UK, in Black, K.S., Paterson, D.M., and Cramp, A., eds., *Sedimentary Processes in the Intertidal Zone*: Geological Society of London, Special Publication 139, p. 25-43.
- AMOS, C.L., AND DROPPA, I.G., 1996, The stability of remediated lakebed sediment, Hamilton Harbour, Lake Ontario, Canada: Geological Survey of Canada, Open File Report # 2276.
- AMOS, C.L., GRANT, J., DABORN, G., AND BLACK, K., 1992, Sea Carousel—a benthic annular flume: *Estuarine, Coastal and Shelf Science*, v. 34, p. 557-577.
- AMOS, C.L., SUTHERLAND, T.F., AND ZEVENHUIZEN, J., 1996a, The stability of sublittoral, fine-grained sediments in a subarctic estuary: *Sedimentology*, v. 43, p. 1-19.
- AMOS, C.L., SUTHERLAND, T.F., RADZIEWSKI, B., AND DOUCETTE, M., 1996b, A rapid technique to determine bulk density of fine-grained sediments by X-Ray computed tomography: *Journal of Sedimentary Research*, v. 66, p. 1023-1025.

- CHAPMAN, P.M., ROMBERG, G.P., AND VIGERS, G.A., 1982, Design of monitoring studies for priority pollutants: *Water Pollution Control Federation Journal*, v. 54, p. 292-297.
- DE BOER, P.L., 1981, Mechanical effects of micro-organisms on tidal bedform migration: *Sedimentology*, v. 28, p. 129-132.
- DADE, W.B., DAVIS, J.D., NICHOLS, P.D., NOWELL, A.R.M., THISTLE, D., TREZLER, M.B., AND WHITE, D.C., 1990, Effects of bacterial exopolymer adhesion on the entrainment of sand: *Geomicrobiology Journal*, v. 8, p. 1-16.
- DADE, W.B., NOWELL, A.R.M., AND JUMARS, P.A., 1992, Predicting erosion resistance of muds: *Marine Geology*, v. 105, p. 285-297.
- DADE, W.B., SELF, R.L., PELLERIN, N.B., MOFFET, A., JUMARS, P.A., AND NOWELL, A.R.M., 1996, The effects of bacteria on the flow behavior of clay-seawater suspensions: *Journal of Sedimentary Research*, v. 66, p. 39-42.
- DEFARGE, C., TRICHET, J., JAUNET, A.-M., ROBERT, M., TRIBBLE, J., AND SANSONE, F.J., 1996, Texture of microbial sediments revealed by cryo-scanning electron microscopy: *Journal of Sedimentary Research*, v. 66, p. 935-947.
- DROPPO, I.G., LAU, Y.L., AND MITCHELL, C., 2001, The effect of depositional history on contaminated bed sediment stability: *Science of the Total Environment*, v. 266, p. 7-13.
- DROPPO, I.G., LEPPARD, G.G., FLANNIGAN, D.T., AND LISS, S.N., 1997, The freshwater floc: A functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties: *Water, Air and Soil Pollution*, v. 99, p. 43-53.
- DROPPO, I.G., AND STONE, M., 1994, In-channel surficial fine-grained sediment laminae (Part I): Physical characteristics and formational processes: *Hydrological Processes*, v. 8, p. 101-111.
- DYER, K.R., 1986, *Coastal and Estuarine Sediment Dynamics*: New York, John Wiley & Sons, 342 p.
- ECKMAN, J.E., NOWELL, A.R.M., AND JUMARS, P.A., 1981, Sediment destabilization by animal tubes: *Journal of Marine Research*, v. 39, p. 361-374.
- ENVIRONMENT CANADA, 1994, *Manual of Analytical Methods, Volumes 1 and 2*: National Laboratory for Environmental Testing, Environmental Conservation Service, Ecosystem Conservation Directorate, Burlington, Ontario.
- FILLELA, M., BUFFLE, J., AND LEPPARD, G.G., 1993, Characterization of submicrometre colloids in freshwaters: evidence for their bridging by organic structures: *Water Science and Technology*, v. 27, p. 91-102.
- FUKUDA, M.K., AND LICK, W., 1980, The entrainment of cohesive sediments in fresh water: *Journal of Geophysical Research*, v. 85, p. 2813-2824.
- GOLDMAN, A.S., AND LEWIS, H.D., 1984, Particle size analysis: Theory and statistical methods, in Fayed, M.E., and Otten, L., eds., *Handbook of Powder Science and Technology*: New York, Van Nostrand Reinhold, p. 1-30.
- GRANT, J., AND GUST, G., 1987, Prediction of coastal sediment stability from photopigment content from mats of purple sulphur bacteria: *Nature*, v. 330, p. 244-246.
- IRVINE, K.N., DROPPO, I.G., MURPHY, T.P., AND LAWSON, A., 1997, Sediment resuspension and dissolved oxygen levels associated with ship traffic: Implications for habitat remediation: *Water Quality Research Journal of Canada*, v. 32, p. 421-437.
- JUMARS, P.J., AND NOWELL, A.R.M., 1984, Effects of benthos on sediment transport: difficulties with functional grouping: *Continental Shelf Research*, v. 3, p. 115-130.
- KRANCK, K., 1981, Particulate matter grain-size characteristics and flocculation in a partially mixed estuary: *Sedimentology*, v. 28, p. 107-114.
- LAMBERT, C.P., AND WALLING, D.E., 1988, Measurement of channel storage of suspended sediment in a gravel-bed river: *Catena*, v. 15, p. 65-80.
- LAU, Y.L., AND DROPPO, I.G., 2000, Influence of antecedent conditions on critical shear stress of bed sediments: *Water Research*, v. 34, p. 663-667.
- LAU, Y.L., AND DROPPO, I.G., 1998, Flume experiments with Hamilton Harbour coal pile deposits: National Water Research Institute, Contribution no. 98-024, CCIW, Burlington, Ontario, Canada.
- LEPPARD, G.G., 1992, Evaluation of electron microscopic techniques for the description of aquatic colloids, in Buffle, J., and van Leeuwen, H.P. eds., *Environmental Particles*: Boca Raton, Florida, Lewis Publishers, v. 1, p. 231-289.
- LEPPARD, G.G., 1997, Colloidal organic fibrils of acid polysaccharides in surface waters: electro-optical characteristics, activities and chemical estimates of abundance: *Colloids and Surfaces*, 120, p. 1-15.
- LISS, S.N., DROPPO, I.G., FLANNIGAN, D., AND LEPPARD, G.G., 1996, Floc architecture in wastewater and natural riverine systems: *Environmental Science and Technology*, v. 30, p. 680-686.
- MAA, J.P.-Y., SANFORD, L., AND HALKA, J.P., 1998, Sediment resuspension characteristics in Baltimore Harbor, Maryland: *Marine Geology*, v. 146, p. 137-145.
- MAA, J.P.-Y., WRIGHT, L.D., LEE, C.-H., AND SHANNON, T.W., 1993, VIMS Sea Carousel: A field instrument for studying sediment transport: *Marine Geology*, v. 115, p. 271-287.
- MEHTA, A.J., PARCHURE, T.M., DIXIT, J.G., AND ARIATHURAI, R., 1982, Resuspension potential of deposited cohesive sediment beds, in Kennedy, V.S., ed., *Estuarine Comparisons*: New York, Academic Press, p. 591-609.
- MITCHENER, H., AND TORGES, H., 1996, Erosion of mud/sand mixtures: *Coastal Engineering*, v. 29, p. 1-25.
- MURPHY, T., MOLLER, A., AND BROUWER, H., 1995, *In situ* treatment of Hamilton Harbour sediment: *Journal of Aquatic Ecosystem Health*, v. 4, p. 195-203.
- NOWELL, A.R.M., AND JUMARS, P.A., 1987, Flumes: theoretical and experimental considerations for simulation of benthic environments: *Oceanography and Marine Biology: An Annual Review*, v. 25, p. 91-112.
- OCKENDEEN, M.C., AND DELO, E.A., 1988, Consolidation and erosion of estuarine mud and sand mixtures—an experimental study: Wallingford, U.K., Hydraulics Research Station, Report No. SR149.
- OTSUBO, K., AND MURAOKA, K., 1988, Critical shear stress of cohesive bottom sediments: *Journal of Hydraulic Engineering*, v. 114, p. 1241-1256.
- PARCHURE, T.M., AND MEHTA, A.J., 1985, Erosion of soft cohesive sediments: *Journal of Hydraulic Engineering*, v. 111, p. 1308-1326.
- PARTHENIADES, E., 1986, Turbidity and cohesive sediment dynamics, in Partheniades, E., and Nihoul, J.C.J., eds., *Marine Interfaces Ecohydrodynamics*: Amsterdam, Elsevier Science Publishers, p. 515-550.
- PATERSON, D.M., AND DABORN, G.R., 1991, Sediment stabilisation by biological action: significance for coastal engineering, in Peregrine, D.H., and Loveless, J.H., eds., *Developments in Coastal Engineering*: Bristol, U.K., University of Bristol Press, p. 111-119.
- PATERSON, D.M., YALLOP, M. AND GEORGE, C., 1994, Stabilization, in Krumbein, W.E., Paterson, D.M., and Stal, L.J., eds., *Biostabilization of Sediments*: New York, Springer-Verlag, p. 401-432.
- PETTBONE, G.W., IRVINE, K.N., AND MONAHAN, K.M., 1996, Impact of a ship passage on bacteria levels and suspended sediment characteristics in the Buffalo River, New York: *Water Research*, v. 30, p. 2517-2521.
- PHILLIPS, J.M., AND WALLING, D.E., 1999, The particle size characteristics of fine-grained channel deposits in the River Exe Basin, Devon, U.K.: *Hydrological Processes*, 13, p. 1-19.
- REMEDIATION ACTION PLAN (RAP) FOR HAMILTON HARBOUR, 1992, *The Remedial Action Plan: Goals, Options and Recommendations, Stage 2A Report*, v. 2, ISBN Number 0-7778-0533-2.
- RHOADS, D.C., YINGST, J.Y., AND ULLMANN, W.J., 1978, Seafloor stability in central Long Island Sound: Part I. Temporal changes in the erodibility of fine-grained sediments, in Wiley, M.L., ed., *Estuarine Interactions*: New York, Academic Press, p. 221-244.
- STONE, M., AND DROPPO, I.G., 1994, In-channel surficial fine-grained sediment laminae (Part II): Chemical characteristics and implications for contaminant transport in fluvial systems: *Hydrological Processes*, v. 8, p. 113-124.
- SUTHERLAND, T.F., AMOS, C.L., AND GRANT, J., 1998, The effect of buoyant biofilms on the erodibility of sublittoral sediments of a temperate microtidal estuary: *Limnology and Oceanography*, v. 43, p. 225-235.
- TOLHURST, T.J., REITHMÜLLER, R., AND PATERSON, D.M., 2000, *In situ* versus laboratory analysis of sediment stability from intertidal mudflats: *Continental Shelf Research*, v. 20, p. 1317-1334. Wright, L.D., Schaffner, L.C., and Maa, J.P.-Y., 1997, Biological mediation of bottom boundary layer processes and sediment suspension in the lower Chesapeake Bay: *Marine Geology*, v. 141, p. 27-50.
- YOUNG, R.A., AND SOUTHWARD, J.B., 1978, Erosion of fine-grained marine sediments: Sea-floor and laboratory experiments: *Geological Society of America, Bulletin*, v. 89, p. 663-672.

Received 12 June 2000; accepted 22 January 2001.

Environment Canada Library, Burlington



3 9055 1017 5569 1



Environment
Canada

Environnement
Canada

Canada

Canada Centre for Inland Waters

P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre

11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

St. Lawrence Centre

105 McGill Street
Montreal, Quebec
H2Y 2E7 Canada

Place Vincent Massey

351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

Centre canadien des eaux intérieures

Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

Centre national de recherche en hydrologie

11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

Centre Saint-Laurent

105, rue McGill
Montréal (Québec)
H2Y 2E7 Canada

Place Vincent-Massey

351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada