FINAL REPORT
Fluid Mud in Energetic Systems: FLUMES II

Gail C. Kineke
Dept of Earth and Environmental Sciences
Devlin Building 213
Boston College
140 Commonwealth Ave.
Chestnut Hill, MA 02467
Phone: (617) 552-3655 fax: (617) 552-2462 email:gail.kineke@bc.edu

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LONG-TERM GOALS

The goal of this research was to develop greater understanding of the dynamics of fluid mud and its role in the transport and deposition of sediment in coastal environments. In particular, we sought greater understanding of the processes that influence the formation and maintenance of fluid mud in energetic environments.

OBJECTIVES

The research is a process-based study that addresses three primary objectives:

- Determine controlling factors in the formation and destruction of fluid mud under a sheared flow
- Verify Richardson number dependence for suppression of turbulence and carrying capacity of a high-concentration suspension
- Evaluate effects of mixed grain size on high-concentration suspensions

APPROACH

To evaluate the controls on fluid-mud formation and the influence of sediment-induced stratification on flow, a suite of instrumentation was assembled to make in situ measurements of vertical gradients of velocity, suspended-sediment concentration (SSC), and fluid density throughout the water column. In addition to these parameters, the thickness of a fluid mud layer through accelerating and decelerating flows was measured in an environment characterized by high concentration bottom suspensions.

The Petitcodiac River located in the Upper Bay of Fundy was selected as the study site. The Petitcodiac Estuary is a macro-tidal environment that has been modified by the construction of a causeway in the late 1960s. During construction, depositional rates downstream of the causeway were on the order of 1 cm day^{-1} resulting in a decrease in the cross-sectional area of up to 90% within one year of closure. Typical maximum tidal currents are on the order 1-2 m s^{-1} and SSCs regularly exceed 10 g l^{-1} and can reach 300 g l^{-1} (Curran et al., 2004). At slack tide, sediment settles rapidly forming fluid-mud layers on the order of 1-2 m thick. In April 2010, the causeway gates were permanently opened to re-establish tidal flow throughout the estuary.

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The Petitcodiac River near Moncton, New Brunswick serves as an ideal natural lab where the formation and destruction of fluid mud can be studied under a sheared flow with a quasi-steady current and without the complicating effect of waves. Measurements are carried out from a bridge that provides a solid framework for instrument deployment thus eliminating many of the challenges of shipboard operations in high-current environments. The Petitcodiac has a distinct advantage over laboratory studies in terms of scale and avoids the practical issues of dealing with the quantities of mud required to create a fluid-mud layer and maintaining flume equipment at these high concentrations of suspended sediment.

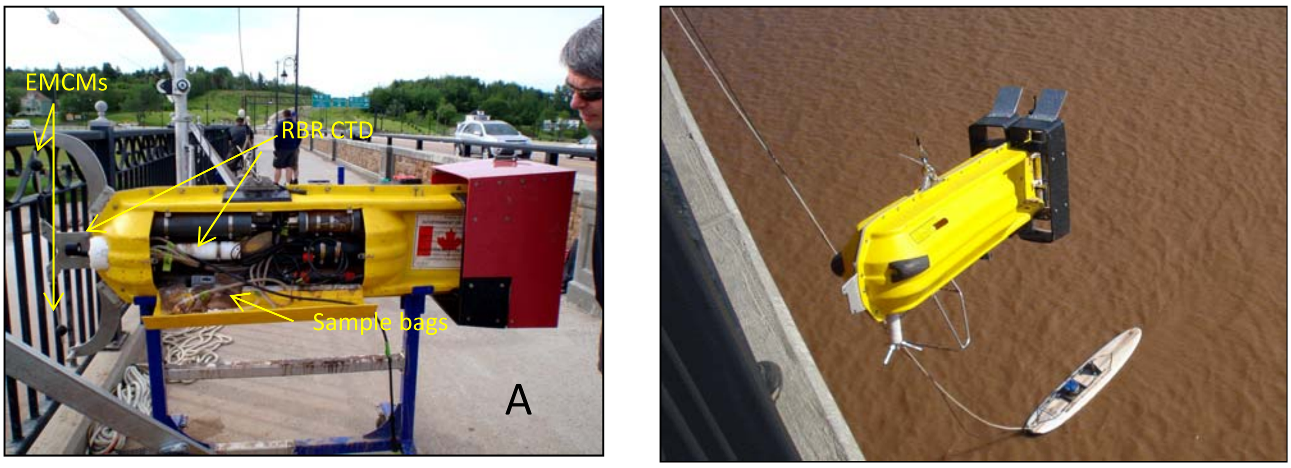

Figure 1: Photographs of the modified SUBS packages deployed in the Petitcodiac River. Left panel (A) shows the interior of SUBSI with the RBR CTD and sample bags exposed. The Marsh McBirney electromagnetic current meters are located on the front of the package near the railing and the OBS and sample port are situated on the opposite side near the front. The right panel (B) shows a SUBS modified to hold a Sontek ADV at the front, a D&A OBS5 in the center and a downward looking Nortek AquaDopp at the tail (SUBSII). Also seen in this panel is a surfboard with a 1.2 MHz RDI ADCP and dual frequency Knudsen echo sounder.

For water-column sampling in high flow conditions, a streamlined underwater buoyancy (SUBS, Open Seas Instrumentation Inc.) package designed at the Bedford Institute of Oceanography was modified for use as an instrument profiler (Fig. 1A; SUBSI). The addition of lead weights to the package in place of the normal buoyancy permits vertical profiling from a bridge at current speeds in excess of 1 m s^{-1}. A CTD and an optical backscatterance sensor (OBS) were mounted through the front and side of the package respectively. The original SUBS profiling package was redesigned in 2008 to accept an RBR XRX-620 CTD and data logger in place of the original Ocean Sensor OS200 CTD and logger. Suspended sediment for OBS calibration and grain size analysis was collected at three depths by pumping water from a sample port co-located with the OBS. A new control system for the pump samplers was also developed in 2008.

For all years, current shear was determined using two Marsh McBirney electromagnetic current meters (EMCMs) mounted 60 cm apart on the front of the CTD sampling package. In 2009 these measurements were augmented with the addition of a second SUBS package that was modified to accept a Sontek ADV, a D&A OBS5 through the bottom of the package, and a downward looking Nortek AquaDopp profiler on the tail (Fig. 1B; SUBSII). In 2010, the Sontek ADV was omitted and the package was modified to accept a 90^{o} Head Nortek AquaDopp profiler mounted through the front of the package.

To observe the formation of the lutocline and continuously monitor flow velocities, a dual frequency Knudsen echo sounder and a 1.2 MHz RD Instruments ADCP were mounted on a surfboard tethered to the bridge next to the location of the profiling package. In 2009 a second 1.2 MHz ADCP and a 2.5 MHz rotary sonar were deployed using a second surfboard (Fig. 2). The ADCPs and Knudsen echo sounder sample continuously, SUBSI (CTD/OBS/EMCMs/in situ samples) was deployed approximately every 30 minutes, and SUBSII (ADV/Aquadopp/OBS5) was deployed nearly continuously (every 15 minutes).

Figure 2: Photo of the instrumented surfboards deployed from the bridge in the Petitcodiac River. Upper board consists of a 1.2 MHz RDI ADCP and a Dual Frequency (50 and 200 kHz) Knudsen echosounder. The lower board has a 2.5 MHz rotary sonar and 1.2 MHz RDI ADCP mounted on it. The wake between the boards is caused by a SUBS package just below the surface.

All work was conducted collaboratively between Gail Kineke of Boston College (BC) and Tim Milligan and Brent Law of the Bedford Institute of Oceanography (BIO). Alex Hay (Dalhousie) participated in the 2009 and 2010 sampling programs.

Two experiments were carried out during the FLUMESII project in June 2009 and November 2010. Conditions in the river varied considerably between June 2009 when the Petitcodiac was dominated by tidal flow with very low fresh water input due to the prevention of salt water intrusion through the gate structure and November 2010 when tidal flow had been re-established. Combined with the experiments conducted under the FLUMES project we were able to study the behavior of high concentration suspensions under a range of conditions. The variation in river flow provided an opportunity to study suspended sediment, current shear and the formation and resuspension of fluid mud.

For each experiment, initial casts with the CTD/OBS SUBS package were made just prior to the passage of the tidal bore and continued approximately every 30 minutes until water levels during the ebb were less than 1 m. Casts with the ADV/OBS5/AquaDopp SUBS were made nearly continuously over the tidal cycle with 1-minute integrated samples being collected approximately every 0.5 m.

Continuous observations of current speed and depth of the lutocline were made using the surfboard-mounted ADCPs and the dual frequency Knudsen echosounder. An example of the combined measurements of the SUBSI package and the Knudsen echosounder for June 2009 are summarized in Figure 3. The close comparison of total water depth from the two different instrument packages ~ 10 m apart, as well as good agreement in the depth to the lutocline using acoustic (dual frequency echosounder) and optical (optical backscatterance) methods is encouraging for combining measurements from different instruments to obtain coverage over a range of conditions. The acoustic instruments are helpful at defining gradients in the water column, e.g. the lutocline, but were limited by high concentrations for actual concentrations.

Calibration of the OBS was accomplished using the in situ sediment samples that range from ~0.1 - 450 g l^{-1}. This calibration takes advantage of the nonlinear response of the OBS at concentrations greater than ~5 g l^{-1} that was demonstrated for fluid mud on the Amazon Shelf (Kineke and Sternberg, 1992).

Disaggregated Inorganic Grain Size (DIGS) analysis for the suspended sediment samples was carried out for all pumped samples.

RESULTS

Conditions observed during the June 2009 experiment were similar to those in 2007. Initially the system was dominated by tidal flow which resulted in salinities ranging from 1 to 14 psu and near-bottom SSC values in excess of 400 g l^{-1}. The passage of the tidal bore created a mixed-water column with SSCs on the order of 30-100 g l^{-1} (Fig. 4). As current velocity decreases, a lutocline forms and near-bottom concentrations increase rapidly to greater than 100 gl^{-1} (Figs. 3, 4). The initial settling rate during the formation of the lutocline is ~6 cm s^{-1} . The fluid mud layer remains coherent throughout the ebb. After the release of water from the head pond on June 22, salinities were below 1 psu and maximum near-bottom SSC values decreased to 52 g l^{-1}.

In November 2010, the maximum salinity observed being 21 psu and SSC values during the passage of the bore reached 20-90 g l^{-1} and maximum bottom concentrations reached 180 g l^{-1} (Fig. 5a). The greater range in salinity and lower values for maximum SSC reflect the influence of the full tidal exchange through the gate structure. While flood velocities were of the same order as those previously observed during gate-closed conditions the ebb velocities were significantly higher. This resulted in a much shorter period of time between the end of the flood and the initiation of the ebb flow.

Initial analysis of the 2010 Knudsen and SSC results suggest the development of 1-2 m fluid-mud layer with lower sediment concentrations than previously observed. Unlike the layer formed in August 2006 and June 2009, this layer was unstable under the ebb flow. The Knudsen records show wave like oscillations on the lutocline that eventually reached the surface and dissipated under increasing ebb flow (Fig. 5a,b).

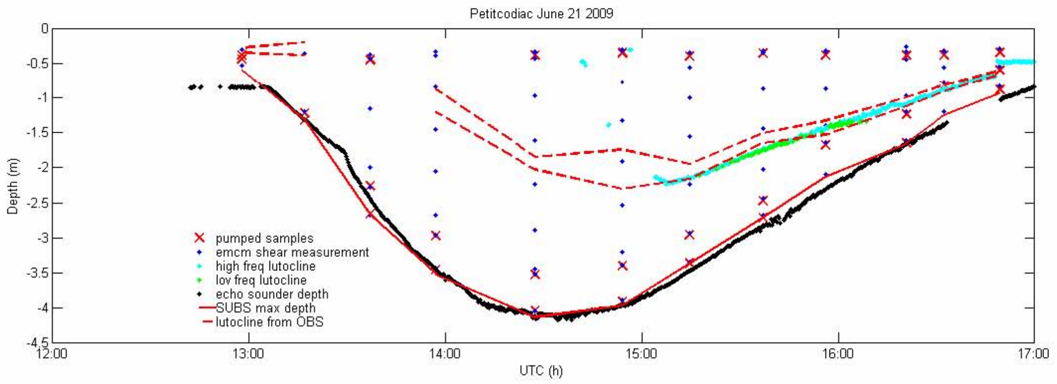

Figure 3: Summary of 2009 sampling from the SUBSI profiler and Knudsen dual frequency echo sounder mounted on a surfboard 10 m away. The close comparison of water depth from the two different instrument packages, as well as good agreement in the depth to the lutocline using acoustic (dual frequency echo sounder) and optical (optical backscatterance) methods is encouraging for combining measurements from different instruments to obtain coverage over a range of conditions.

To date, the threshold condition suggested by Trowbridge and Kineke (1994) for the carrying capacity of a flow appears to hold, but implies a critical gradient Richardson number between 0.25 and 1 for the rapid formation of a high concentration layer (Heath 2009).

In 2009 the evolution of the DIGS during the period when the flood slows and reverses shows a dramatic difference between the normal flood current conditions with the causeway closed June 21 and the freshwater release event of June 22 (Fig. 6). While the concentration immediately after the passage of the tidal bore varied by an order of magnitude (solid black lines in Fig. 6), the size distribution of the material suspended by flooding current was similar. Salinity on June 22 was on the order of 20 psu but was <1 psu during the discharge of river water. Key differences in settling behavior following resuspension and mixing by the flood tide are the lack of floc settling on the 22nd shown by the approximately constant DIGS distribution and concentration over the period of low flow speed and the evolution of the modal peak in the distributions for the flocculated samples collected at 14:15, 14:30 and 15:00 on the 21st at 10 and 50 cm above bottom (blue and green curves, respectively). In the flocculated suspension below the lutocline, the concentration in the <20 µm size classes remains constant whereas the concentration in the >20µm fraction increases. This would suggest that within the dense bottom layer floc settling is completely hindered but single grains can penetrate to the bottom, although their settling is also hindered. In the unflocculated suspension, there is sufficient time over the 45minute sampling period for all particles >20 µm to be removed from suspension. The effective gelling of the flocs below the lutocline combined with the continued settling of the single grains through the dense bottom layer could explain the formation of the varves observed in the Petitcodiac estuary (Fig. 7). These varves separate along a coarse silt layer which abruptly changes to fine grained, unsorted mud.

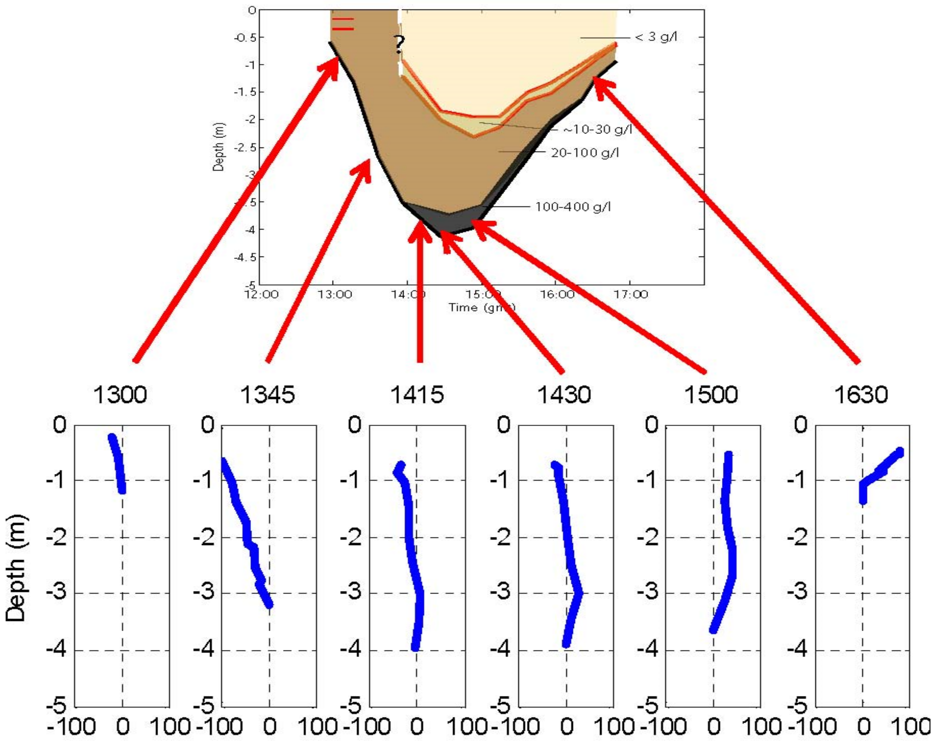

Figure 4: Pumped suspended samples were used to convert optical backscatterance measurements to suspended sediment concentration, although the calibration result was noisy, with large uncertainty at high concentrations. Mean velocity profiles obtained by the ADV profiling package (SUBSII) show strong flood currents, ~ 1 m s^{-1} at the surface at 1345, followed by rapid clearing of the upper water column and formation of a high-concentration bottom layer by 1415. Currents reverse during the ebb at the bottom (beginning at 1415) yet unusually strong winds blowing up the channel delayed the change in direction at the surface.

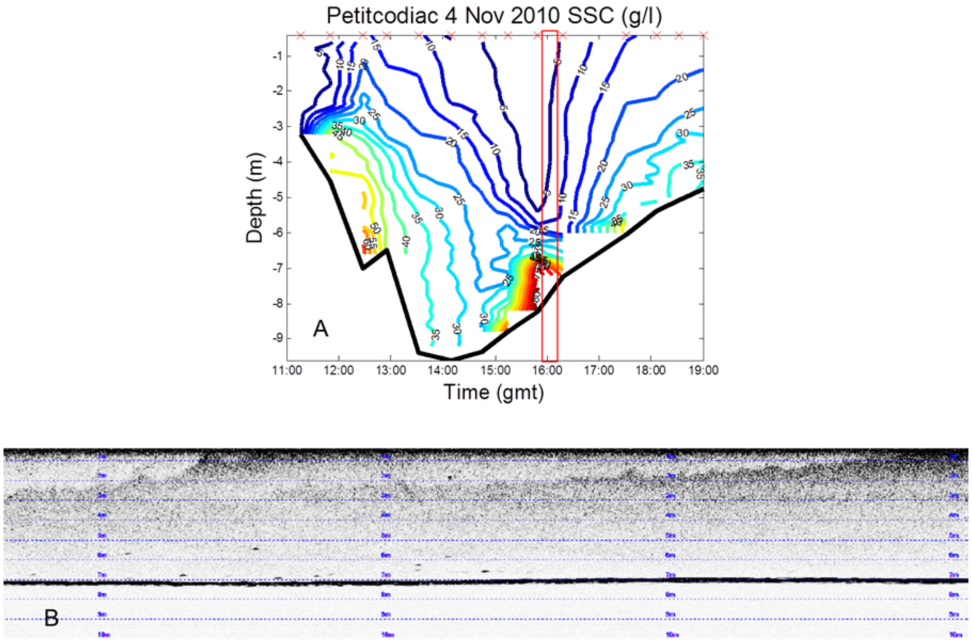

Figure 5: Time series of suspended-sediment concentration in November 2010 (A). Strong resuspension occurred with the passage of the bore at 1146, followed by settling and fluid mud formation. Shortly after the start of the ebb at 1530, resuspension off the lutocline mixed sediments to the surface. Wave-like oscillations were recorded by the Knudsen echsounder (B)during the time period outlined in red in (A).

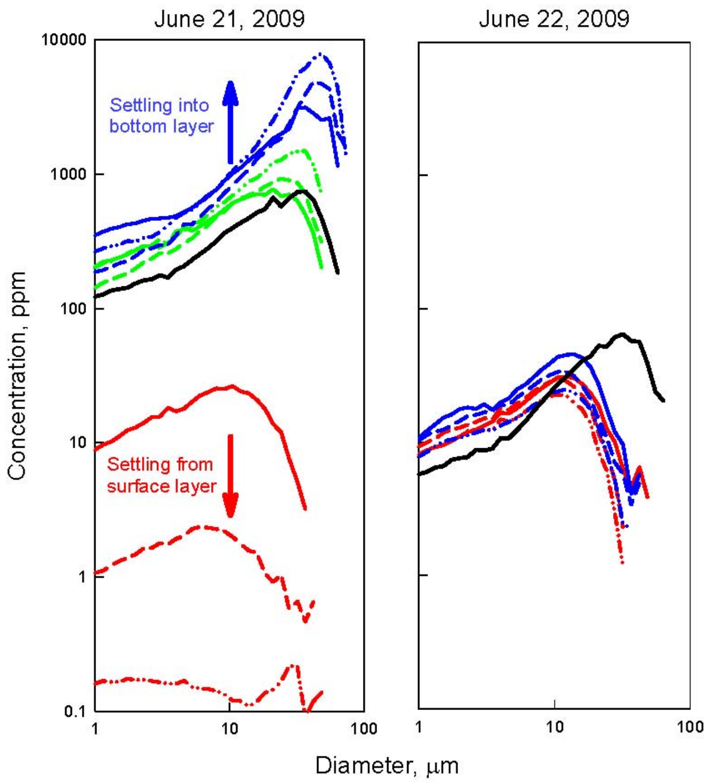

Figure 6: Disaggregated inorganic grain-size distributions for samples collected in 2009 at 30 cm below the surface (red), 10 cm above bottom (blue) and50 cm above bottom(green) during maximum flood when flow speeds went from approximately -0.25 (solid line) to 0 (dashed line) to +0.25 cm s-1 (dashed and dotted line). The black line is the size distribution of the suspension immediately after the passage of the tidal bore. The surface salinity range on June 21 was 14-19 and on June 22was <1. Data for the 50 cm above bottom samples on June 22 were omitted for clarity but were the same as those for 10 cm above bottom.

Figure 7: Image of the varved sediment that accumulates on the banks of the Petitcodiac River at Moncton during periods of rapid accumulation. The varves separate along a coarse silt layer.

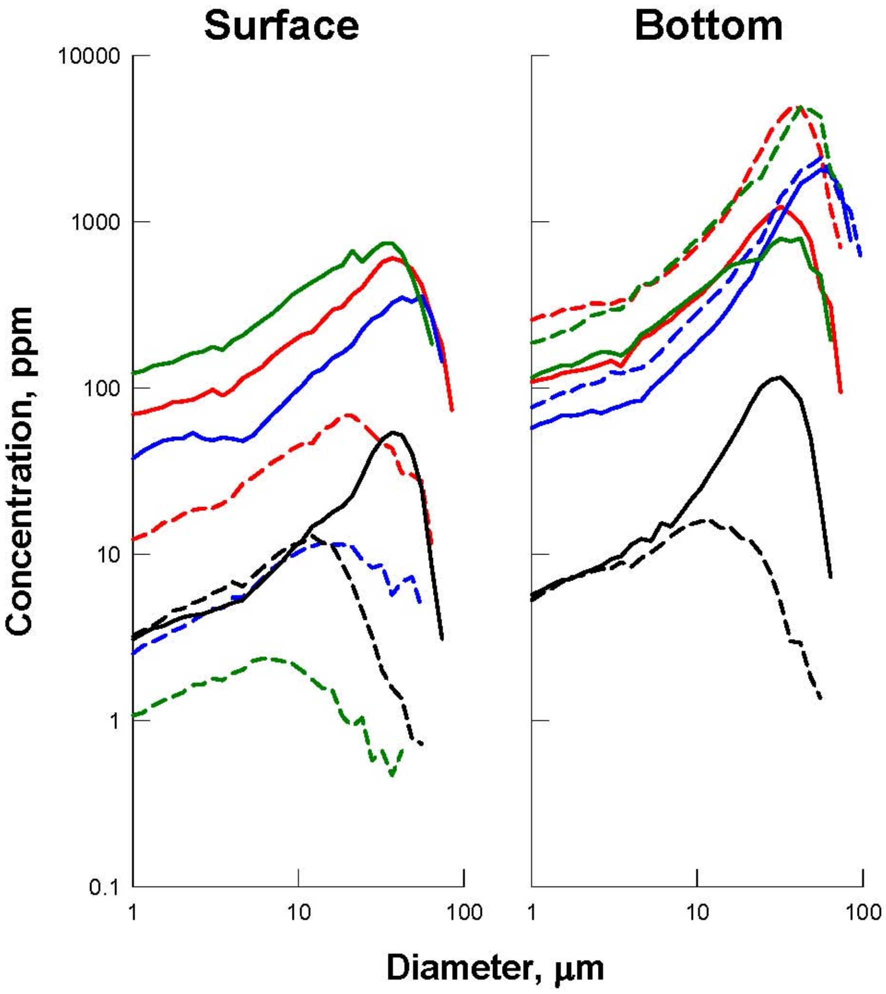

Figure 8: DIGS plots for surface (left) and bottom (right) sediments collected in June 2006 (black), August 2006 (red), June 2009 (green) and November 2010 (blue). Solid lines represent samples collected immediately after the passage of the bore and dashed lines samples collected at low current velocity at high tide. See text for discussion.

In November 2010, the same pattern of floc settling during the decrease in flow was observed. While the concentration was lower, the size distribution of both the sediment suspended during the passage of the bore and during settling was the same.

Comparison of DIGS for the November 2010 samples with those from the earlier experiments showed the sediment suspended during the passage of the bore was similar in all years (Fig 8). The DIGS distributions of both the surface samples depleted during settling and the high concentration bottom layer varied only when fresh water dominated the flow. In this case, single grain settling left did not remove material < 20 µm from the suspension and coarse sediment was removed equally from the suspension at all depths. For all other experiments floc settling dominated and the DIGS distributions evolved in the same manner with the greatest variation appearing to be due to the initial concentration. The lowest final concentration was associated with the largest initial concentration and is consistent with experimental results that suggest that higher suspended sediment concentrations lead to more rapid clearance of the water column (Milligan et al., 2007)

IMPACT/APPLICATION

Our recent observations are refining our understanding of current shear at the lutocline surface. These observations improve our understanding of the formation and maintenance of fluid mud in sheared flows and to further test threshold conditions for the suppression of turbulence and carrying capacity turbulent flows (Trowbridge and Kineke, 1994). Multiple measurements with different instruments provide a unique dataset on how acoustic instruments behave in high-concentration sediment suspensions. Our data confirm the importance of salinity and sediment concentration in the formation of fluid-mud layers in macrotidal estuaries.

RELATED PROJECTS

During the course of FLUMESII, G. Kineke was a co-PI on an ONR MURI project, “Mechanisms of Fluid-Mud Interactions Under Waves.” This project included investigators from Johns Hopkins (Dalrymple, Shen), Woods Hole Oceanographic Institution (Trowbridge, Traykovski), MIT (Liu, Mei,Yue) and Memorial University (Bentley). The major objective of this study was to examine the various mechanisms of water wave dissipation over muds, using field, laboratory, and theoretical approaches.

T. Milligan was a co-PI on the ONR Tidal Flats project in Willapa Bay looking at sediment flux and its impact on sediment strength.

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