Fluid Mud in Energetic Systems: FLUMES II

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

Grant # N00014-06-1-0325 Amendment Number P0002

Timothy G. Milligan
Fisheries and Oceans Canada
Bedford Institute of Oceanography
1 Challenger Drive
Dartmouth, Nova Scotia, CANADA B2Y 4A2
Phone: (902) 426-3273 fax: (902) 426-6695 email: milligant@mar.dfo-mpo.gc.ca

Grant # N00014-08-1-0389

LONG-TERM GOALS

The goal of this research is to develop greater understanding of the dynamics of fluid mud and its role in the transport and deposition of sediment on the continental margin. In particular, we seek 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, in situ measurements of vertical gradients of velocity, suspended-sediment concentration, and fluid density throughout the water column, including the fluid-mud layer are necessary. In addition to these parameters, the thickness of the fluid mud layer through accelerating and decelerating flows must be measured.

The Peticodiac River located in the Upper Bay of Fundy was selected as the study site. The Peticodiac Estuary is a macro-tidal environment that has been modified by the construction of a causeway in the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **Fluid Mud in Energetic Systems: FLUMES II**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Boston College,Dept of Geology and Geophysics,140 Commonwealth Ave,Chestnut Hill,MA,02467**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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. Maximum tidal currents are now on the order 2 m s^{-1} and suspended-sediment concentrations 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.

The Peticodiac River Estuary now provides 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. Flow speeds can be varied by timing the experiments to coincide with the spring neap tidal cycle and by modifying the release of freshwater through the control structure. 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 Peticodiac 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.

For water-column sampling in high flow conditions a streamlined underwater buoyancy (SUBS) package designed at the Bedford Institute of Oceanography (BIO) was modified for use as an instrument profiler (Fig. 1). Current shear is determined using two Marsh McBirney electromagnetic current meters mounted 60 cm apart on the front of the package. An Ocean Sensors CTD and an optical backscatterance sensor (OBS) are mounted through the front and side of the package respectively. A sample port is co-located with the OBS and connected to a series of pumps to provide suspended sediment for OBS calibration and grain size analysis. To determine the depth of the lutocline and continuously monitor flow velocities, a dual frequency Knudsen echo sounder and an RD Instruments ADCP are mounted on a surfboard tethered to the bridge next to the location of the profiling package. Instruments are deployed from specially designed davits mounted on the bridge deck. Measurements are made every 45-60 minutes over tidal cycles.

All work is being conducted collaboratively between Tim Milligan of the Bedford Institute of Oceanography (BIO) and Gail Kineke of Boston College (BC). Brent Law (BIO) and graduate students Kristy Heath and Michelle Lermon (BC) provide technical support in the laboratory and field.

WORK COMPLETED

FLUMES I: Design and construction of the initial instrument package and davits was completed in May 2006. Two field experiments were carried out over two 1-week periods in June and August 2006. The June experiment was used to test equipment and observe high flow conditions. The August experiment coincided with a spring tide during a period of maximum seasonal sediment deposition in the Petitcodiac.

Data analysis of the 2006 data is complete and results have been presented at the AGU Fall meeting, December 2006, and at the INTERCOH conference in Brest France, September 2007. Kristy Heath's Masters thesis is undergoing final revisions and her work was presented at the Estuarine Research Federation (now Coastal and Estuarine Research Federation) meeting in November 2007. Publications are in progress. Complete interpretation requires observation of the breakdown of the lutocline sheduled for October 2008.

FLUMES II: The work in 2008 has focused on preparation for the next field experiment scheduled for October 2008. The objective for this experiment is to capture intermediate flow conditions that should produce sufficient flow on the ebb to cause the resuspension of the fluid mud layer. The disappearance of Ocean Sensors, Inc. resulted in the inability to acquire spare parts for the Ocean Sensors CTD which served as the main controller and logger for the SUBS. Thus, a significant redesign of the profiling package was required. The Ocean Sensors CTD was replaced with an RBR CTD and a new pump controller was designed and built at BIO. A second SUBS was modified to hold an ADV and OBS5.

In preparation of the upcoming field experiment, a laboratory pre-calibration was performed comparing the response of different optical sensors for redundancy in the field. The sensors included two D&A Instruments OBS5s (internally recording high concentration sensors), a D&A Instruments OBS3 logged with an RBR CTD, two Seapoint Turbidity Sensors logged with RBR CTDs. Field calibration of an OBS3 using the *in situ* sediment samples collected was completed in 2007 yielded response up to ~250 g l^{-1}. This calibration takes advantage of the non linear 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 1995). The OBS5s (internally recording with two detectors) respond from 0-40 g l^{-1} Seapoint sensors to ~ 20 g l^{-1}.

Another goal for the October experiment is to make direct turbulence measurements over a range of suspended sediment concentrations. ADVs are routinely used in fine-grained sedimentation and transport studies, but the performance in very high sediment concentrations (1-100+ g l-1, i.e. fluid mud) has not been well documented. D. Velasco of Sontek/YSI has used samples provided by Kineke to test the response of ADVs at fluid mud concentrations. His results are that for low velocity ranges (long pulse lags), valid velocity data can be collected up to ~50 g/l, ~28 g/l, and ~18 g/l for the 5, 10 and 16 MHz ADVs, respectively (Velasco and Huhta 2007). We will further test the ADV response under more energetic conditions.

RESULTS

The June 2006 experiment occurred during a period of unusually high outflow of fresh water due to a period of prolonged rainfall prior to sampling. The August 2006 experiment occurred during a period of low outflow. Thus measurements were made during two end-member conditions: high outflow of fresh water with moderate concentrations (generally less than 10 g l^{-1}) and tidal flows of saltwater, high concentration suspensions (often greater than 10 g l^{-1} and up to 366 g l^{-1}).

An example from the August 2006 experiment shows water column profiles of density (due to salinity and temperature) and suspended-sediment concentration from early flood to early ebb with lower fluid density at the bottom that is compensated by the high suspended-sediment concentrations of the suspension (Fig.2). Approximately 1.5 hours after the passage of the tidal bore (at~15:00) and a fully mixed turbulent flow, the water column begins to stratify and a high-concentration bottom layer forms persisting through the ensuing ebb (Fig.3). Measured suspended-sediment concentrations reached 286 g l^{-1} and low shear rates of 0.13 s^{-1} in the upper water column increased to ~0.50 s^{-1} through the lutocline 1 m above the bed, and decreased to ~0 within the fluid mud. At concentrations above 10 g l^{-1} the gradient Richardson number was consistently greater than ¼ suggesting suppression of turbulence (Fig. 4).

The threshold condition of free-stream velocity to the integrated buoyancy anomaly ($u_\infty/B^{1/2}$ <2; Trowbridge and Kineke 1994) for the formation of a high-concentration bottom layer was tested for all profiles during the August experiment (Fig. 5). In general, the threshold condition is met for the profiles during decelerating conditions coinciding with the formation of a distinct lutocline, clearing of the upper water column, and increasing concentrations near the bottom (Figs. 2,5). The formation and settling of the lutocline was also confirmed by the dual frequency echo sounder (Fig. 3). Whether the condition holds for accelerating conditions and resuspension is unclear and will be investigated during the next field experiment. While a gradient Richardson number dependence appears to be appropriate for the formation of fluid mud, other formulations might be better for resuspension of fluid mud (e.g. a flux Richardson number) and require investigation.

The disaggregated inorganic grains size (DIGS) of the sediment samples shows that during the period of high freshwater discharge the suspension was unflocculated (Fig. 6). The size spectra for samples collected from the surface and bottom of the water column show that only the coarsest material settled as flood current velocities approached zero. Material below 20 μm remained in suspension indicating that little or no flocculation was occurring (Kranck, 1980). In contrast, as current speed decreased in August all particles in suspension were removed at an equal rate leading to rapid clearing of the upper water column and the creation of the fluid-mud layer. Rapid flocculation at high sediment concentration is essential for rapid deposition and the formation of fluid mud (Hill et al. 2000; Milligan et al. 2007). Observations of the DIGS over the entire sampling period show an increase in coarse material near bottom that likely leads to the development of the silty base layer found in the tidalites located along the banks of the Petitcodiac.

IMPACT/APPLICATION

Our observations will help refine our understanding of formation and maintenance of fluid mud in sheared flows and to test threshold conditions for the suppression of turbulence and carrying capacity of turbulent flows (Trowbridge and Kineke 1994). These criteria (e.g. critical Richardson number) have been used to ‘set’ a maximum concentration to drive a gravity flow. This approach has been used in the STRATAFORM and EuroSTRATAFORM projects to model the density underflow observed on the Eel Shelf (Friedrichs et al. 2000; Wright et al. 2001; Scully et al. 2002) and to predict gravity flows off the Po River (Friedrichs and Scully 2007). These models assume a critical Richardson number of ¼ , but field observations of shear and density gradients in high concentrations have been limited before now.

RELATED PROJECTS

G. Kineke is a co-PI on an ONR MURI project, “Mechanisms of Fluid-Mud Interactions Under Waves.” This project includes 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 is to examine the various mechanisms of water wave dissipation over muds and field, laboratory, and theoretical approaches will be employed.

REFERENCES

Curran, K.J., T.G. Milligan, G. Bugden, B. Law, and M. Scotney. (2004). Suspended Sediment, Water Quality, and Hydrodynamics of the Petitcodiac River Estuary, New Brunswick (2002–2003). Can. Tech. Rep. Fish. Aquat. Sci. 2516: xi + 88 p.

Friedrichs, C. T. and M. E. Scully (2007). Modeling Deposition by Wave-Supported Gravity Flows on the Po River Subaqueous Delta: From Seasonal Floods to Prograding Clinoforms. Continental Shelf Research 26:2092-2107.

Friedrichs, C. T., L. D. Wright, et al. (2000). Bottom-boundary-layer processes associated with fine sediment accumulation in coastal seas and bays. Continental Shelf Research 20: 807-841.

Hill, P.S., T.G. Milligan and W.R. Geyer (2000) Controls on effective settling velocity of suspended sediment in the Eel River flood plume, Continental Shelf Research 20, 2095-2111

Kineke, G.C. and R.W. Sternberg (1992). Measurements of high concentration suspended sediments using the Optical Backscatterance Sensor. Marine Geology, 108:253-258.

Kranck, K. (1980) Experiments on the significance of flocculation in the settling behaviour of fine grained sediment in still water. Canadian Journal Earth Science 17, 1517-1526.

Milligan, T. G., P. S. Hill and B. A. Law (2007) Flocculation and the loss of sediment from the Po River plume. Continental Shelf Research 27, 3-4: 309-321.

Scully, M. E., C. T. Friedrichs, et al. (2002). Application of an analytical model of critically stratified gravity-driven sediment transport and deposition to observations from the Eel River continental shelf, Northern California. Continental Shelf Research 22: 1951-1974

Trowbridge, J.H. and G.C. Kineke (1994). Structure and dynamics of fluid muds on the Amazon continental shelf. Journal of Geophysical Research, 99(C1):865-874.

Velasco, D.W. and D.W. Huhta (2008). Experimental verification of acoustic Doppler velocimeter (ADV®) performance in fine-grained, high sediment concentration fluids. Physics of Estuaries and Coastal Seas (PECS) 2008 Conference. Liverpool, UK, August 25-28, 2008.

Wright L. D., W. J. Wiseman Jr. Z.-S. Yang, B. D. Bornhold, G. H. Keller, D. B. Prior and J. N. Suhayda (1990) Processes of marine dispersal and deposition of suspended silts off the modern mouth of the Huanghe (Yellow River). Continental Shelf Research, 10, 1-40.

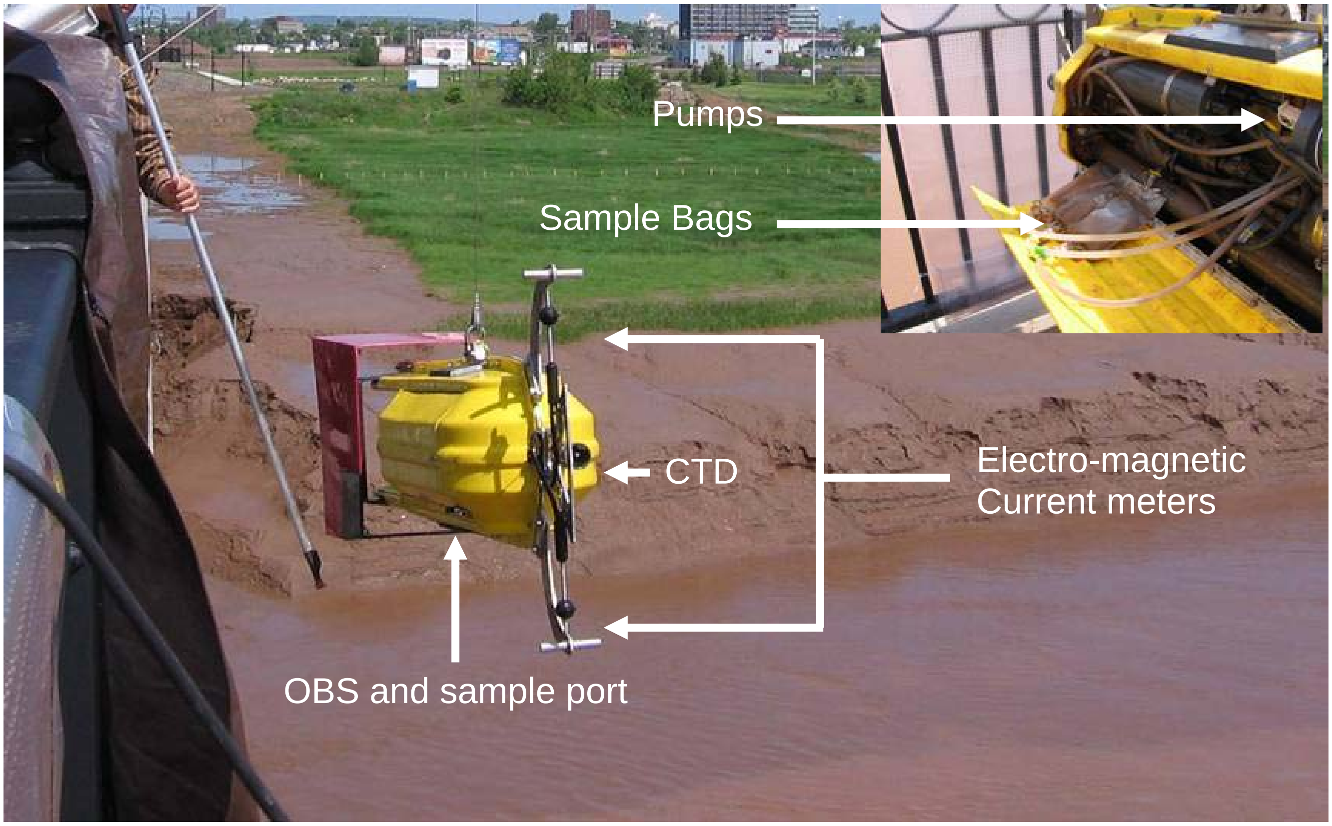

Figure 1: Image of the SUBS profiling package being deployed in the Petitcodiac River in August 2006 to observe the behaviour of fluid mud in a sheared flow. Instruments mounted on the package include a D&A optical backscatterance sensor (OBS) and sample port/pump system for collecting in situ samples, an Ocean Sensors CTD and Marsh McBirney electromagnetic current meters. Inset shows layout pf pumps and sample bags inside the housing.

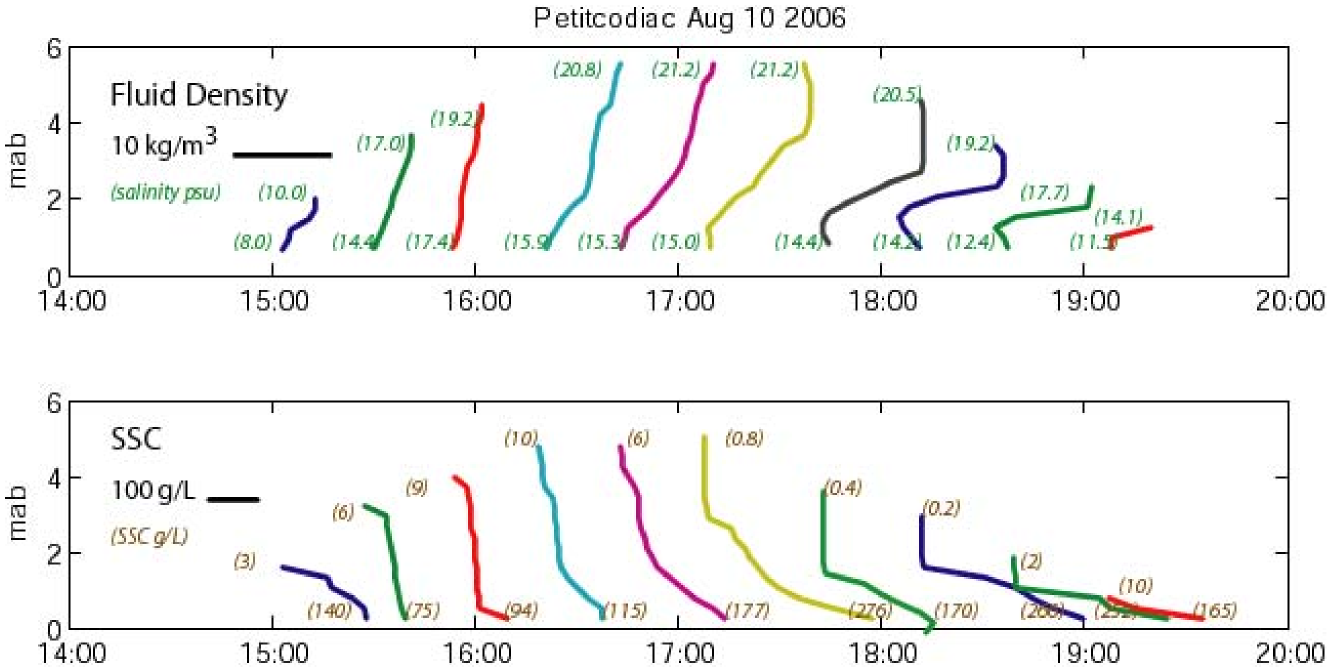

Figure 2. Water column profiles collected over a tidal cycle in the Petitcodiac River, August 10 2006. The y axis represents the distance from the bottom in meters and the x axis represents the time for each profile. The upper panel shows profiles of fluid density due to salinity and temperature. The lower panel shows profiles of suspended sediment concentration (g/L). Numbers in parentheses located at the top and bottom of each profile represent discrete values determined for those depths.

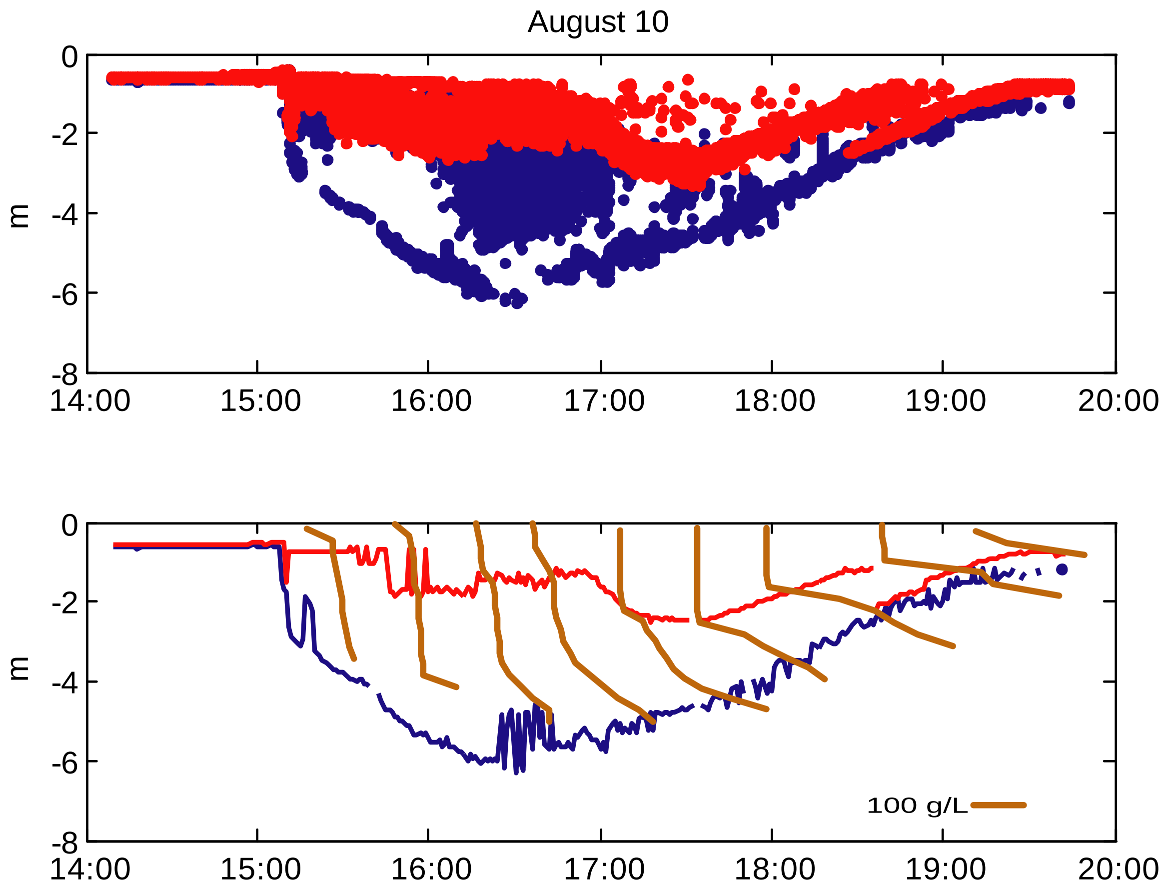

Figure 3. Dual-frequency echosounder for August 10 2006. Above: raw data with high frequency returns in red, low frequency returns in blue. Bottom: maximum depth return for 1 minute data blocks in blue, mode depth return for 1-minute data block in red. Suspended-sediment profiles from Figure 2b are superimposed showing good agreement between appearance and settling of the lutocline measured with the SUBS package and the echosounder.

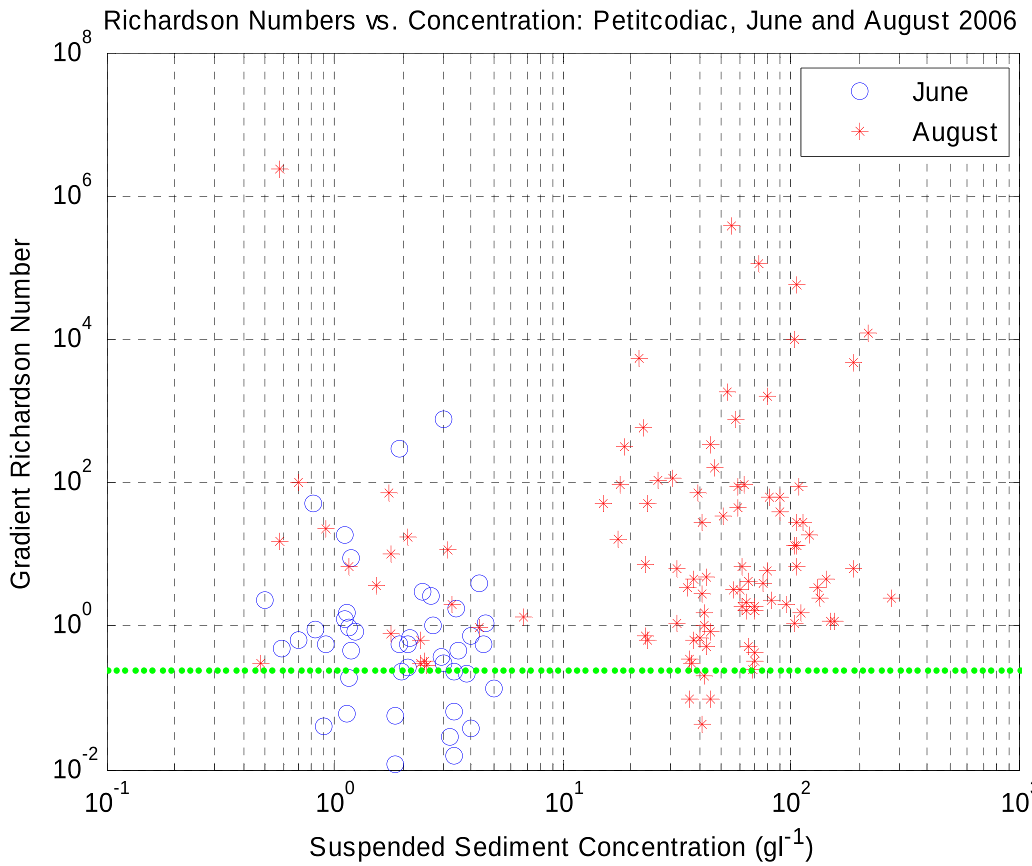

Figure 4. Graph of Gradient Richardson number vs. Suspended-Sediment Concentration for experiments conducted in June (blue open circles) and for August (red crosses) 2006. For suspended-sediment concentrations > 10 g/L Ri_g, is generally greater than the critical value of ¼ (green dashed line). A large range of Ri_g is observed for suspended-sediment concentrations < ¼, although there is a cluster around ¼ to 1.

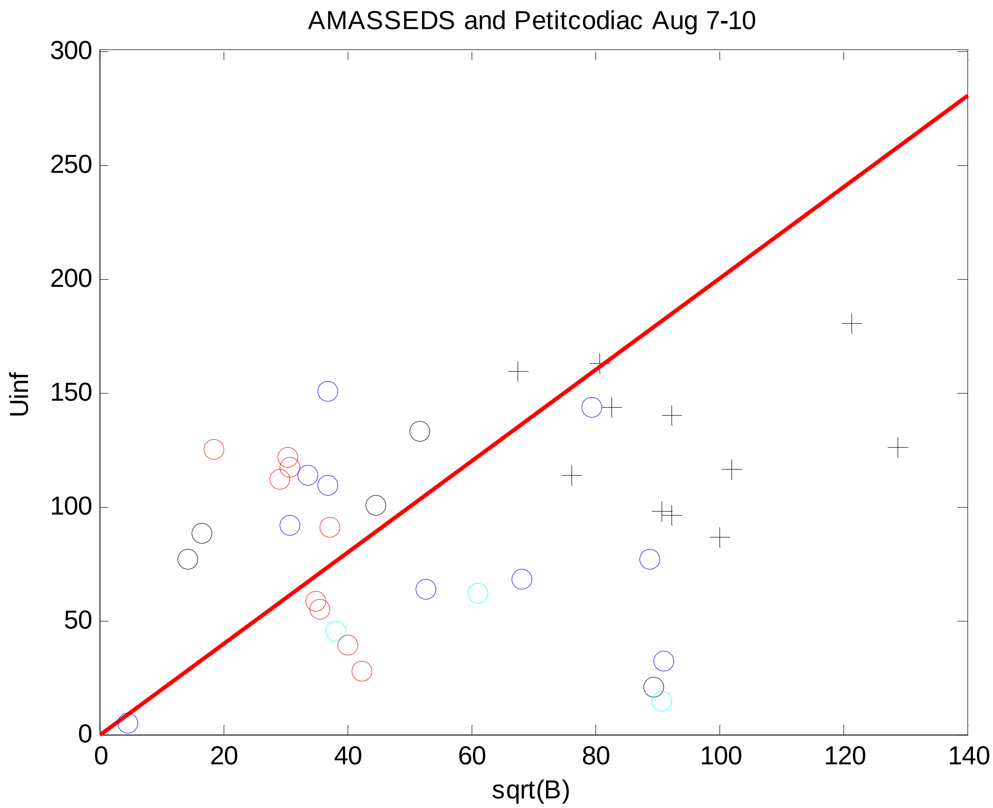

Figure 5. Free-stream velocity (Uinf) versus the square root of the integrated buoyancy anomaly (B). Results from FLUMES I are shown as open circles and prior results from AMASSEDS (Trowbridge and Kineke 1994) are indicated by crosses (+). Results from Aug 10 (Fig. 2) are shown in red. High-concentration bottom suspensions are expected for values below the red line.

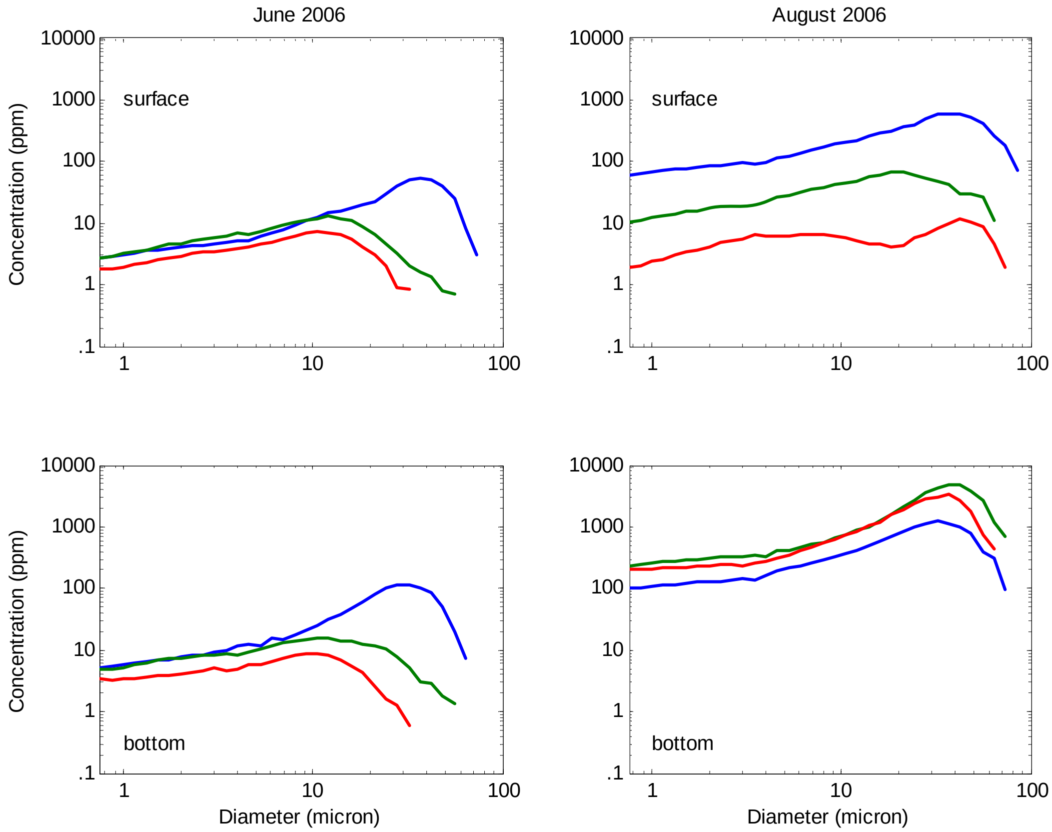

Figure 6. Disaggregated grain size for surface and bottom suspended sediment samples taken in June (fresh water) and August (salt water) for maximum (blue) and decelerating flows. The upper panels show the log of the concentration in parts per million vs log diameter for the surface samples and the lower panel show the bottom samples. The spectra for June, when no fluid mud was observed, are typical of single grain settling and those for August, when fluid mud was observed, are typical of floc settling.