

## **Processes Controlling Transfer of Fine-Grained Sediment within and Between Channels and Flats on Intertidal Flats**

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### **LONG-TERM GOALS**

A long-term goal of our sediment transport and accumulation investigations is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. The general goal of this project is to investigate how forcing processes (e.g., tidal asymmetry, winds, river discharge and biological activity) affect the sediment-transport dynamics that act to import fine-grained sediment. The resulting product is the formation of mud-flat environments with complex morphology (e.g., multiple scales of tidal channels, differing geotechnical and textural characteristic of flats). This project investigates processes that transfer fine-grained sediment in intertidal settings between channels and flats and within channels, and relates them to the temporary and longer-term deposits found in those environments – when, why and how do suspended sediments transfer from the loose, unconsolidated deposits found in channels to the flat environments? Specifically, we are trying to answer the question: What role do tidal (semidiurnal, fortnightly), riverine and other seasonal (winds/waves, temperature, and biological glue) processes have on the transfer of sediment between tidal-flat environments and how is this manifested in terms of channel and flat deposits (temporary and longer)?

### **OBJECTIVES**

Previous work in shallow tidal environments leads to the following conceptual model of tidal-flat sediment-transport processes:

*Tidal asymmetry causes flood-tide currents to generate boundary-layer processes and water-column mixing that act to pump fine sediment onto the flats. Ebb-tide currents deliver sediment from smaller tributary channels to major distributary channels where high-concentration processes either store or episodically transfer sediment from the system – the net sum of these processes varies temporally and spatially over intertidal flats.*

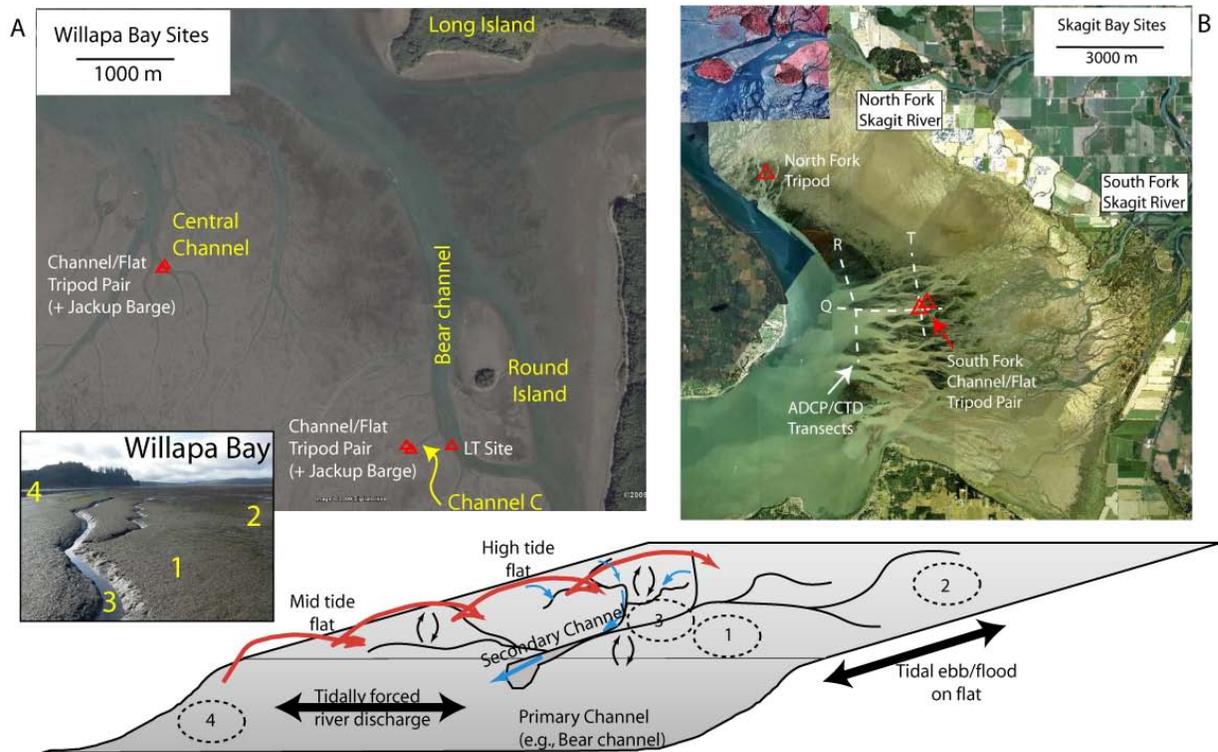
The dominant processes involved in this sediment cycle control terms in the budget of sediment on tidal flats (Fig. 1). These include advected input from rivers, erosion/deposition at the seabed, and transport of sediment in and out of each sub-environment (e.g., primary/secondary channels, flats, etc.). Our studies seek to evaluate these processes over time scales from tidal (semidiurnal, fortnightly,

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**Figure 1. Location maps for studies in A) Willapa and B) Skagit Bay, and conceptual diagram of characteristic tidal-flat environments: 1) mid flat, 2) high flat, 3) secondary channel, and 4) primary channel/river. Red arrows indicate shoreward settling/scour lag fluxes, small black arrows indicate resuspension on the tidal flat, blue arrows indicate flux and trapping in the secondary channel environments, and delivery back to the primary channel**

and lunar monthly), to event (e.g., wind storms), to seasonal, and potentially to interannual in order to address the following objectives:

1. Evaluate *water-column sediment-flux* factors such as currents, suspended-sediment concentrations and sediment characteristics on tidal flats in key environments (on the mid-flat, in a secondary tidal distributary, and in the adjacent primary tidal/river channel), including their vertical distribution throughout the water column.
2. Relate water-column sediment-flux dynamics to *seabed changes* in porosity and grain size (resulting from deposition, erosion, bioturbation and dewatering/dessication) through observation of seabed elevation fluctuations and close interaction with participants exploring seabed processes.
3. Determine the *linkages between environments* (e.g., import to or export from the flat and between channels and flats) through spatial studies of sediment flux and suspended-sediment characteristics.
4. Foster *scientific interaction* with other participants to investigate the spatial variations in transport processes on the tidal flat. This includes participants who are evaluating relationships between

remotely observed signatures and active sediment-transport processes, and those who will be using models to predict three-dimensional dispersal of sediment and evolution of seabed characteristics.

## **APPROACH**

The work we have performed under the Tidal Flats DRI has focused on the processes controlling the transfer of fine-grained sediment within and between channels and flats on two contrasting meso-tidal flat environments. Studies on the tidal flats of Willapa Bay and Skagit Bay in collaboration with other groups are ongoing and are starting to fill important gaps in our understanding. The primary study site is in Willapa Bay (Fig. 1a). The tidal flats on the south end of Willapa Bay provide a natural laboratory to study tidal-flat processes as they contain many morphologic attributes typical of tidal flats (e.g., fine-grained sediment, meandering channels), have strong tidal forcing (2-4 m tidal range), and a large expanse where the dominant forcing by tides is modulated by short-fetch waves and limited river discharge. This study area allows us to focus on asymmetries in tidal processes with little influence of river discharge. In comparison, the Skagit River tidal flats (Fig. 1b) have similar tidal and wind forcing, but are dominantly composed of sand and have a large river input of freshwater and sediment. They provide study areas with more complex dynamical forcing due to the interaction between tidal and riverine processes; this allows us explore the dynamical differences where tidal asymmetry is impacted by episodic large discharge of freshwater and sediment.

Tidal-flat studies require specialized sensors and platforms designed to capture the processes and products without impact to the soft seabed, particularly in the muddy environment of Willapa Bay. For time-series studies, we have deployed instrument suites on small frames that have minimal impact to the sediment-water interface. We have developed methods that allow access instrumentation at high to mid tides from a small boat, or jack-up barge, leaving the seabed undisturbed. The jack-up barge has proven to be a valuable tool that increases spatial coverage in tidal-flat studies. It is a unique facility that has enabled the evaluation of velocity and suspended-sediment profiles, sediment size and settling velocity, along with validation through physical samples of the water column and seabed.

Instrument suites to address the objectives of this project consist of acoustic current meter systems for high-resolution current, wave and bed-elevation measurements; ABS (acoustic backscatter system) and FOBS (fiber optic backscatter system) sensors spanning the variable-depth water column to collect profiles of suspended-sediment concentration; and integrated temperature and salinity sensors. Spatial profiling has been a limited aspect of previous tidal-flat studies, and therefore the understanding of how processes vary between locations is lacking. We are using a small profiling system that can be deployed from a moveable platform (small boat or jack-up barge) with sensors to measure water-column stability, velocity, suspended-sediment concentration, and particle characteristics (in situ suspended-sediment samples). Video systems for sediment size and settling velocity estimates have been deployed during ebb and flood tides at multiple sites. High-frequency profiling from the jack-up barge allows us to estimate turbulence and shear stresses throughout the water column. These sensor systems have successfully allowed us to examine sediment dynamics to understand the transfer of sediment between and within channels and flats.

## **WORK COMPLETED**

Field work was initiated in summer 2008, and is continuing to the present. At Willapa Bay, a long-term monitoring station was installed on the southern tidal flats of Willapa Bay (Fig. 1). This station

has been maintained over the year encompassing the focus experiments conducted by participants in this location. In the focus experiments (March and July 2009), sensor suites were located in channel/flat pairs, one in each of two secondary channels (channel C and Central channel) and one on the flat next to each channel. Simultaneous detailed temporal studies were performed from the jack-up barge deployed in various configurations to examine flux into and out of a discreet region. Both the small tripods for fixed instrument sites and the jack-up barge have been found to be ideally suited for this work in muddy intertidal flats.

At Skagit Bay, two sites on the outer part of the tidal flats were occupied to study shallow intertidal processes, one off the north fork and one off the south fork (Fig. 1b). Instrumentation was deployed during 1) the spring freshet in June 2009, 2) the fall storm/flood period in November 2008, and 3) the summer low-river-discharge period in August 2008.

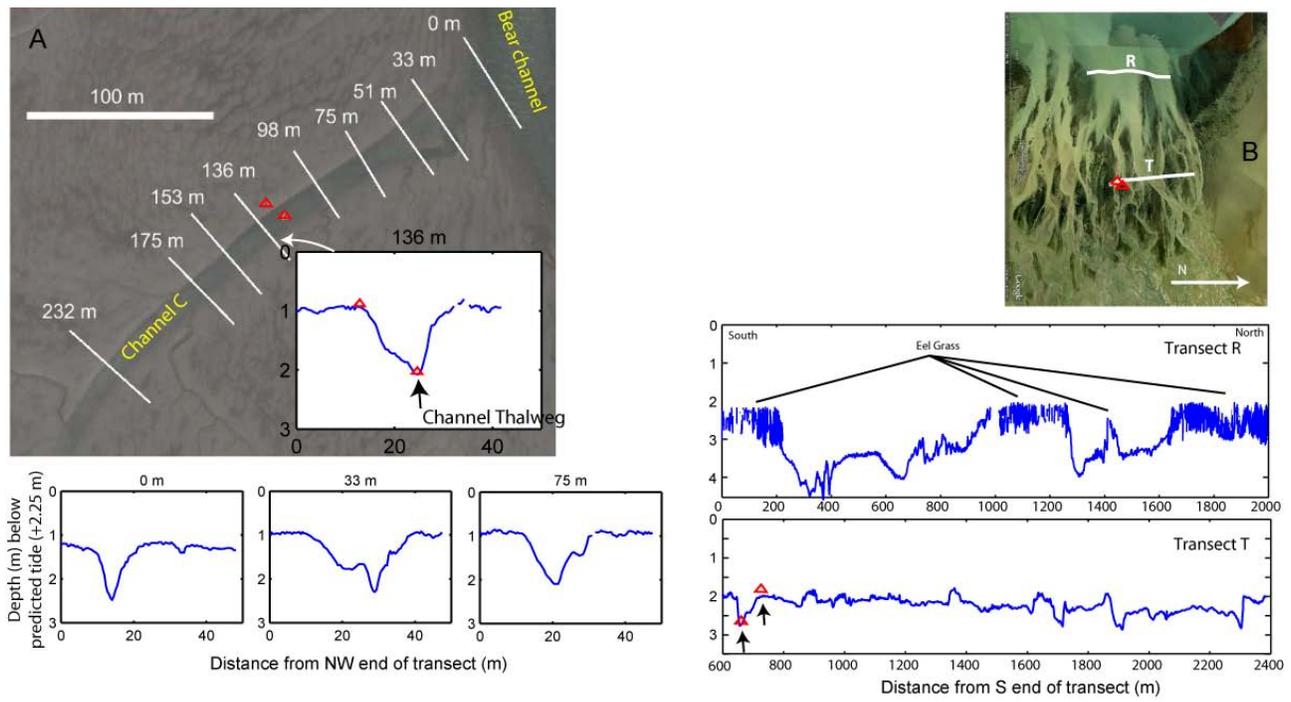
In both areas, spatial studies of currents (small boat mounted ADCP), salinity, temperature and suspended-sediment concentration have been conducted over the flats. These studies helped to determine the site of instrumentation in the long-term and focus experiments, and provide data to plan further focused studies on the southern Willapa flats.

## **RESULTS**

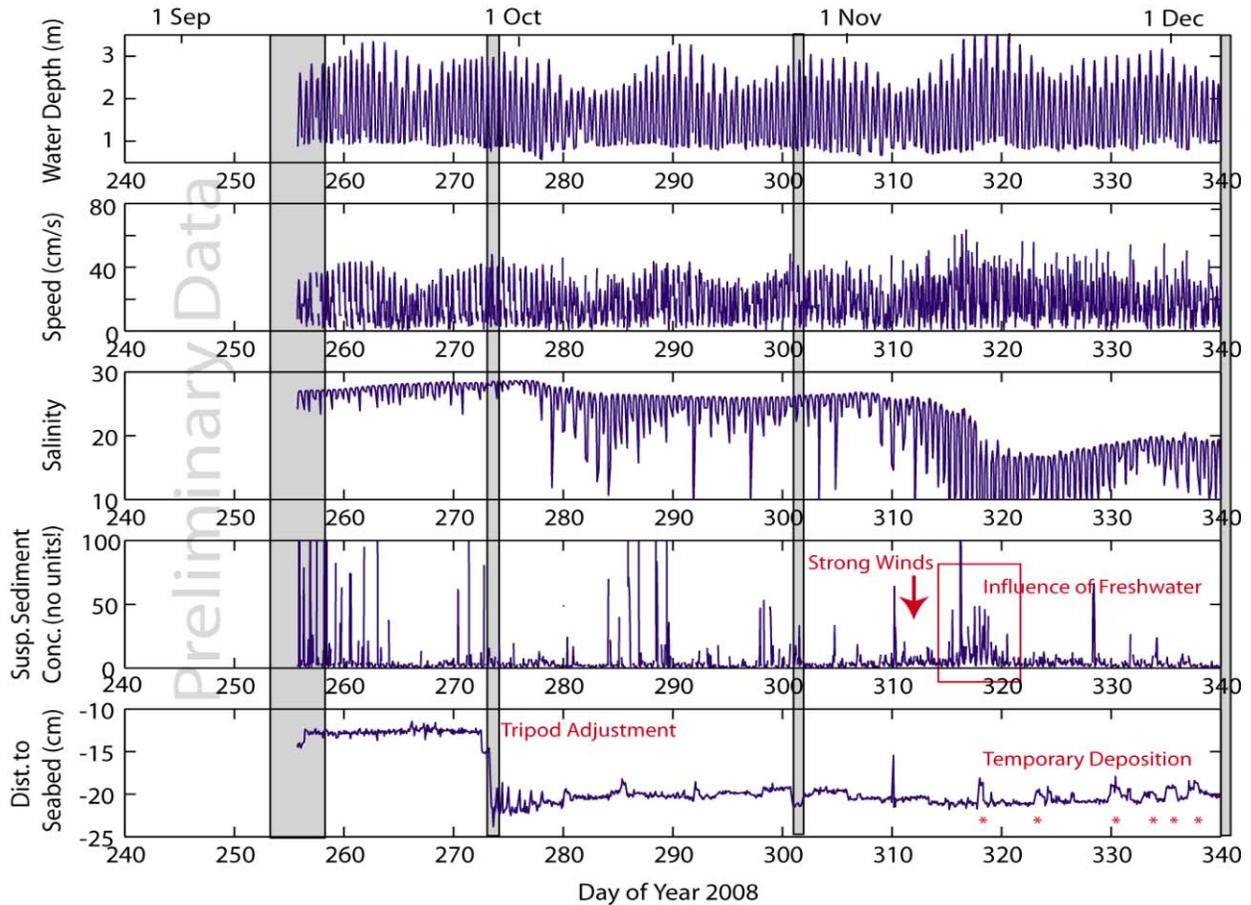
Analysis efforts are presented being undertaken, and results presented here are a subset from our Tidal Flats DRI research efforts to date. Synthesis and integration will be undertaken in the coming year. Efforts in analysis have been focused on Willapa Bay studies in order to adequately plan the final field studies in the coming year. In both Willapa and Skagit Bays, much progress was made in evaluation of methods and techniques to deploy and maintain instrumentation in this challenging environment.

*Setting - channel morphology.* In the process of deploying and retrieving instrument packages, and performing water-column profiling studies, we have collected bathymetric profiles of primary and secondary channels in both study areas. The variation in morphology between different types of channels (Fig. 2) suggests that processes by which they formed also vary. In Willapa Bay, channel C (secondary channel and site of focused studies in Mar and Jul 2009) has an asymmetric “V” shape that evolves in morphologic form from its entrance in Bear channel to reaches over 200 m upstream. Based on exploration, the side with lower slope (e.g., toward the NW of the transect located ~136 m from the entrance; inset of Fig. 2) typically retains some of a seasonal mud drape throughout the year leading to an import of fine-grained sediment to the flats, while the thalweg and steep side do not.

In contrast, channels on the southern Skagit flat are more braided and sandy in nature, forming a complex flat topography making it difficult to evaluate the channel/flat transfer. The braided channels coalesce into deep (~2 m), broad (~400 m) conduits that export fine-grained material off the flats.



**Figure 2. Transects across A) channel C in Willapa Bay (selected transects shown), and B) south Skagit flats. The morphology of the channels vary with distance from the mouth. The red triangles identify the location of tripods**



**Figure 3.** Example of data from the Long-Term (LT) site from September 2008 to December 2008. The data record is available to the present. Note the change in salinity starting in mid-November and the temporary deposition on the seabed during this autumn season

*Willapa Bay long-term monitoring.* This site is located in a primary channel, Bear channel, near the outlet of a secondary channel (Fig. 1a). Over the past year, insights have been gained on seasonal variations in the system (e.g., the observation of seasonal mud drapes over the channels in Mar 2009 that was absent in Jul 2009). In addition to providing valuable scientific results, these data provide a framework for the focused experiments, and the ability to plan future field efforts. Motivating results for further analysis include the following:

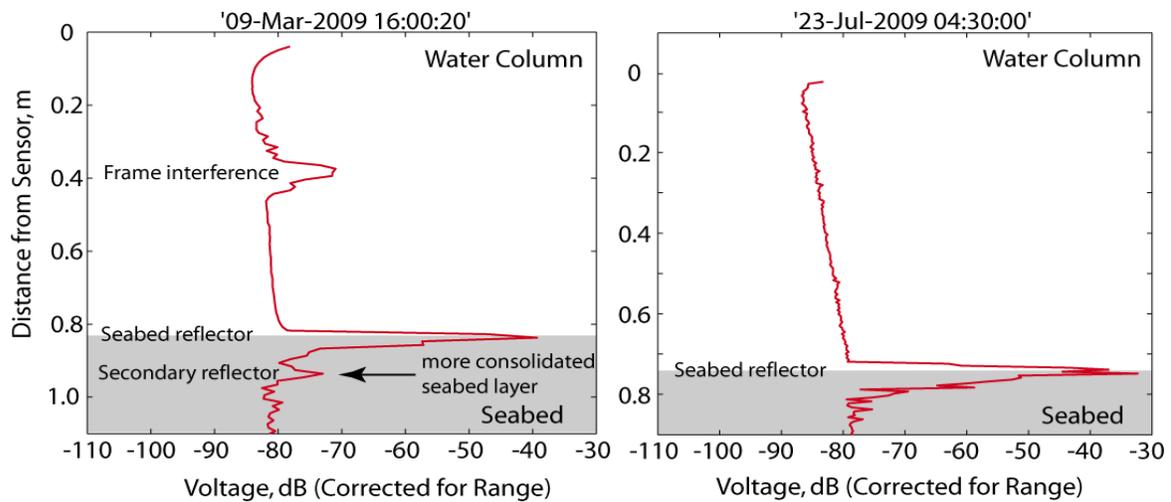
- Over seasonal time scales, variability is clearly observed in the forcing mechanisms on the flats (Fig. 3). For example, mid-November through January, the influence of winds and precipitation cause a vast reduction in salinity over the flats (from salinity of ~28 in Sept 2008 to ~12 in Jan 2009), and strong salinity gradients that set up conditions of frontal trapping.
- Temporary deposition (1-3 cm; Fig. 3) occurs in short events (diurnal periods) in Bear channel. Sediment is deposited on the ebbing tide and is typically resuspended after a single tidal cycle.

Seasonally, these temporary deposition events were recorded most frequently during maximal tidal salinity gradients in the period of November through January (Fig. 3).

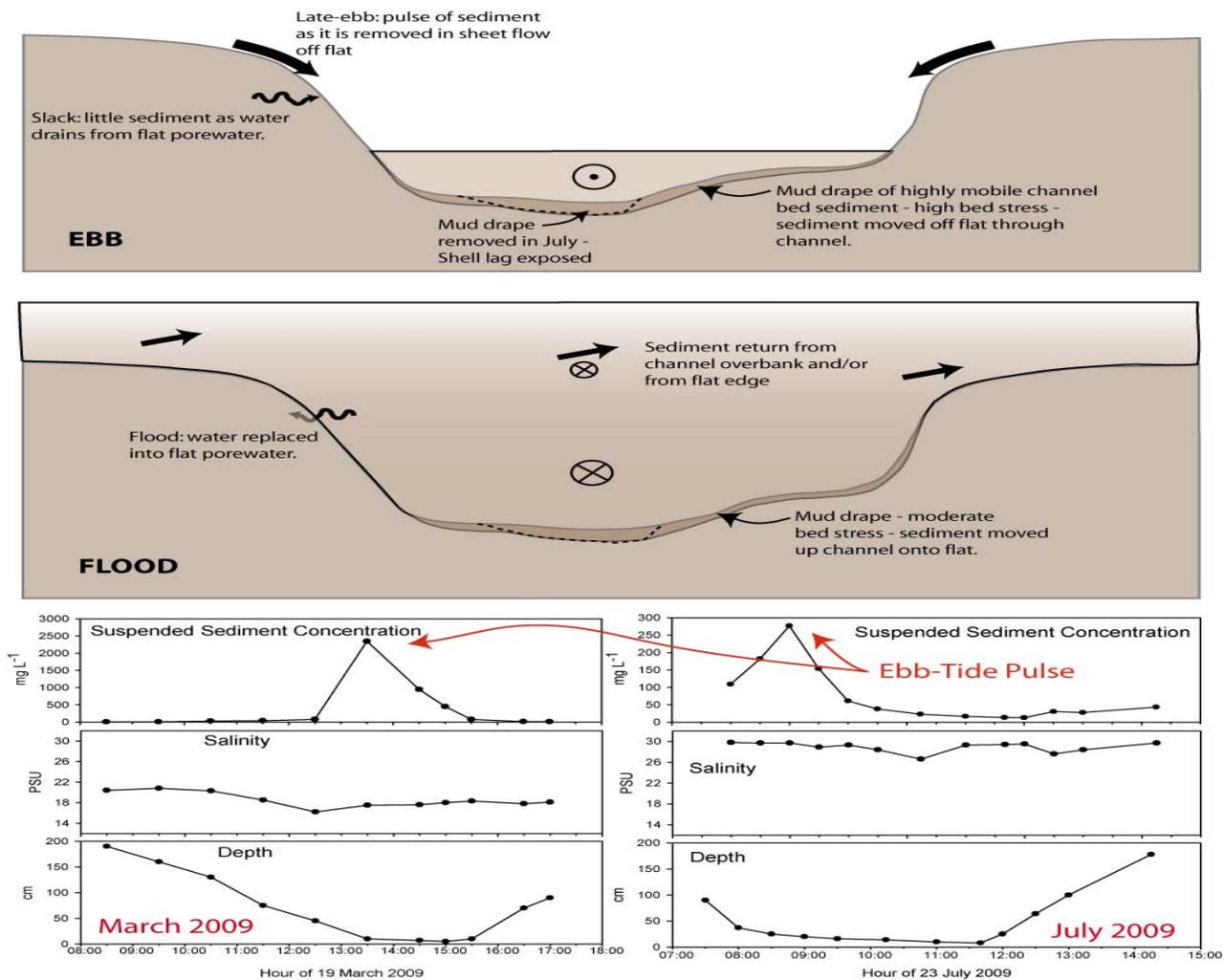
- Over semi-diurnal tidal time scales, there is a pulse in velocity and suspended-sediment concentration on the ebbing tide that is observed throughout the record. The magnitude of sediment flux associated with the pulse varies as a function of wind and precipitation and focus studies have begun to investigate this phenomena in more detail.

*Willapa Bay focus experiments (Mar 2009 & Jul 2009).* A channel/flat tripod pair, combined with spatial studies focused on processes in secondary channels (Fig. 1a). A major seasonal difference between the two focus experiments was the presence of a drape of ~6-10 cm of unconsolidated sediment over channel C in March that was underlain by a more-dense layer as observed in acoustic backscatter (Fig. 4). In July, this unconsolidated layer was removed from the thalweg of the channel with a few “shoals” of mud residing mainly along the gently sloped channel side (Fig. 2a). The channel thalweg had a lag layer of shell hash.

- In the secondary channels, temporary deposition on diurnal time scales, similar to that seen in Bear channel during Nov – Jan 2008, was not observed in either Mar or Jul 2009. There was no evidence of tidally generated fluid-mud formation that might explain diurnal deposition, but a reflector within the seabed in Mar 2009 correlates with the thickness of unconsolidated sediment (sketched in Fig. 5) suggesting temporary deposition on a seasonal time scale.



**Figure 4. Typical profiles of acoustic backscatter response at 2 MHz in a) March 2009 and b) July 2009. A secondary seabed reflector lies ~ 10 cm below the primary seabed reflector in March 2009 indicating a contrast in seabed density**

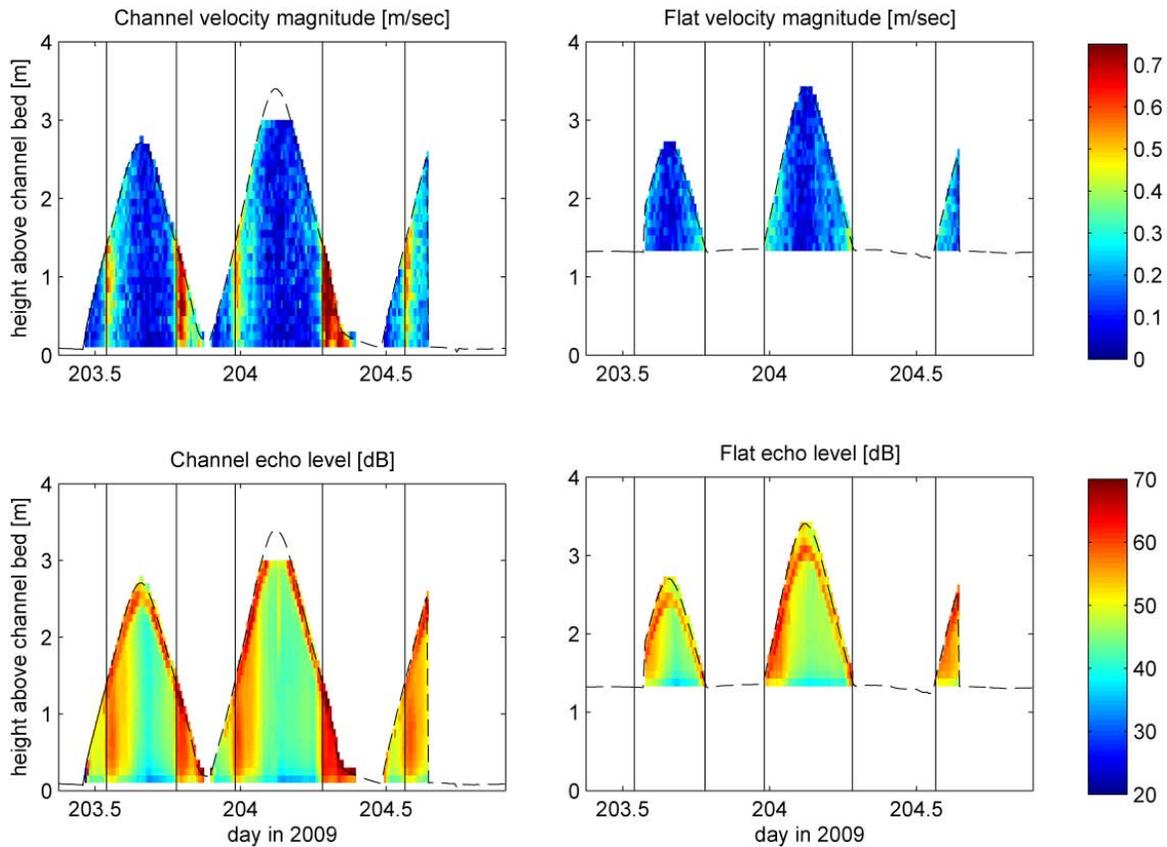


**Figure 5. Sketch of secondary channel at late ebb and late flood to illustrate the differences in processes moving sediment on and off the flats. Note different SSC scales between March and July 2009**

The pulse of sediment flux seen at the long-term site was also observed in the secondary channel (Fig. 5). On the ebbing tide, concentrations exceeded 2 g/L during spring tides in March 2009, and were lower (~0.2 g/L) during similar tides in July 2009. The pulse is likely associated with high shear stresses on the mid flat created as the water level reached conditions for sheet flow. Seasonal changes in erodibility due to consolidation and organic factors must control the amount of sediment resuspended.

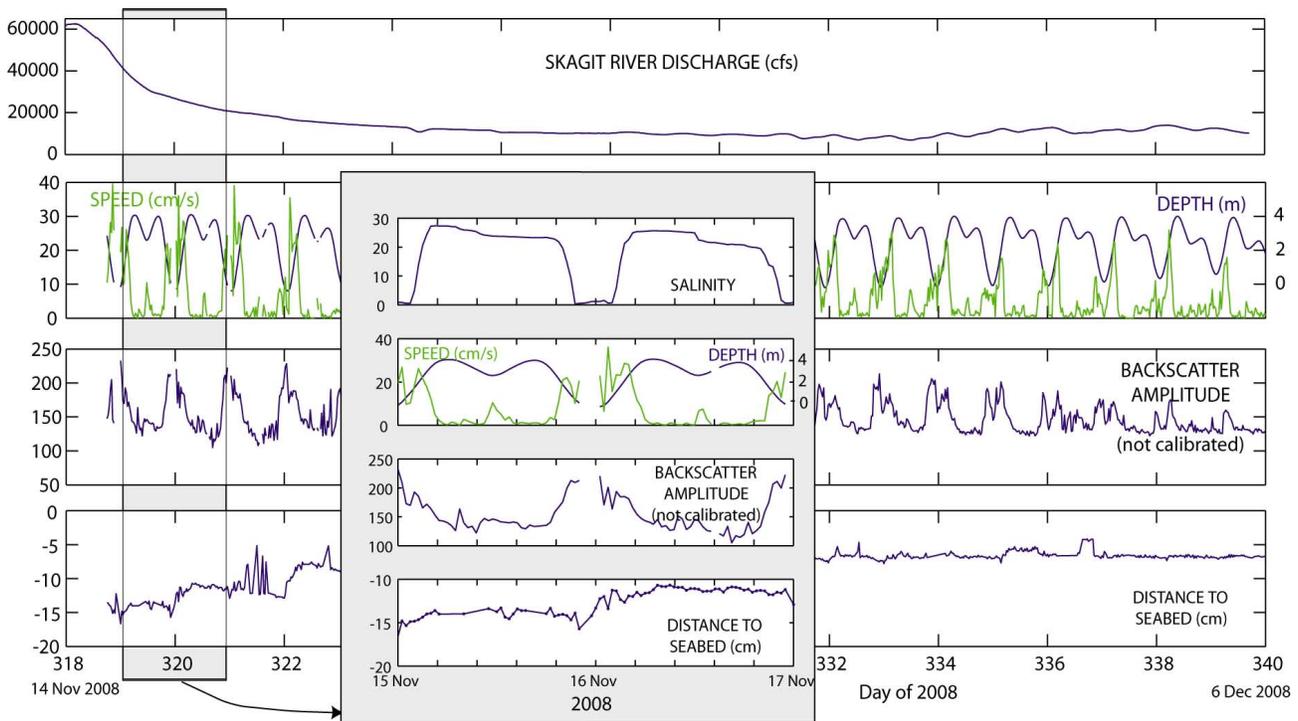
- Current profiles in the axis of the channel and on the nearby flat show the evolution of the flood and ebb currents through the tidal cycle (Fig. 6). On the flooding tide, the currents within the channel increased to a maximum of ~60 cm/s as the water level reached the flat level. As the flats overtopped, the currents dropped by about half in the channel with even lower flows over the flat. On the ebbing tide, within less than 20 min the velocities in the channel accelerated to extremely high values (up to 100 cm/s) as the water surface fell to the flat level. Currents

remained strong in the channel through the remaining falling tide. These velocities combined with the acoustic backscatter indicate a strong ebb-tide pulse in the sediment flux. Over a full tidal cycle, the relative ebb and flood fluxes suggests that the net transport in the channel moves sediment off the flats.



**Figure 6. Velocity and backscatter magnitude profiles from a channel and flat pair of Aquadopp current profilers located at channel C. The elevations are relative to the elevation of the channel floor. The backscatter peak near the sea surface is due to surface interference, but the ebb-tide pulse of sediment in the channel is clearly seen**

*Skagit Bay experiments.* At the two sites on the outer part of the tidal flats occupied in Skagit Bay, river discharge plays a large role in the transport dynamics. Although the river delivers 3-4 Mt of sediment per year, the flats are dominantly sandy, indicating a system that exports fine-grained sediment. Less analysis has been conducted on Skagit data to date, and following are a few preliminary results from these efforts:



**Figure 7. Data from the south fork Skagit outer tidal flats site. These data span a period of flooding of the Skagit River at the beginning of the record to relatively low-flow conditions at the end of the record. The inset data shows the increased current speeds, suspended-sediment concentration (represented by uncalibrated backscatter) at low tidal elevations. This is also when deposition occurs at the seabed (decreased distance to seabed relative to tripod sensors)**

- Suspended-sediment concentrations on the Skagit flats are seasonally variable. Near-surface samples (i.e., predominantly fine-grained) ranged from 1 to 125 mg/L in spring freshet and low-flow periods and 2 to 230 mg/L during flood conditions.
- Net currents on the outer flat near the north fork were directed toward the east, oblique across and along the tidal flat during low discharge periods. During the Nov 2008 storm/flood period, the net direction did not change, but currents weakened. In contrast, on the outer flat near the south fork, net currents were aligned with channel morphology.
- Although the net currents tend toward the northeast on the north end of the Skagit flats, results off the south fork suggest the net fine-grained sediment flux is driven by the timing between the release of river-derived sediment to the flats and the tidally controlled currents on the flat. Similar to conditions found in Willapa Bay, sediment concentration was highest at low tidal elevation (Fig. 7) and currents were strong in the channel when the water-surface elevation was less than or equal to that of the surrounding flats (Fig. 2). Deposition in the channel thalweg was seen when the river was at peak discharge during the low slack tide. The fine-grained

particles were rapidly delivered to the constrained region between Whidbey Island and the Skagit flats, where larger-scale circulation controls their fate.

## **IMPACT/APPLICATIONS**

To understand the source-to-sink sediment transfer from rivers to marine deposition, we must develop our understanding of the gateway between the land and ocean -- shallow-water regions spanning the tidally influenced river to the inner shelf. Tidal flats are one type of environment found in this shallow-water realm. The transport and deposition of fine-grained sediment varies over the range of tidal-flat morphologies, which may predominantly import or export sediment, yet our understanding of why these differ is limited. Seabed properties of tidal flats are linked to the mechanisms and rates of transport and deposition on the flats, and our studies in Willapa and Skagit Bays aim to enhance the ability to predict these properties in other areas. Our studies of sediment transport and deposition also provide insight for coastal management that can be transferred to other tidal-flat environments, allowing evaluation of the impacts of humans and invasive species on sediment dynamics. Both of the sites being studied have areas under consideration for restoration. The data from our hydrodynamic studies in Skagit Bay are being utilized by ecosystem researchers at the University of Washington.

This study is providing valuable collaborations with other research groups working under the Tidal Flats DRI, particularly by providing dynamic measurements in Willapa Bay. Understanding the transport regime is integral to understanding the properties of the seabed. Remotely sensed circulation and sediment flux can be ground-truthed with our in situ observations. Our data provides validation for modeling and laboratory studies concerning transport on tidal flats. The year-long monitoring package allows the group to monitor and observe during less-frequent events, gives context to the seasonal focus experiments and will aid the interpretation of imagery that has been obtained.

## **RELATED PROJECTS**

The Tidal Flats DRI projects are tightly knit. This work will provide interactions with all participants through field efforts, meetings, shared results and scientific discussions. Focus experiments in Willapa Bay have been coordinated among a group of investigators, including those at University of Washington (Oceanography and APL), Oregon State University, Dalhousie, Bedford Institute, University of Virginia. Data has been, and will continue to be shared as groups start their integration and synthesis work. In addition to colleagues from University of Washington, experiments in Skagit Bay were coordinated with investigators from Woods Hole and Arete.

The two small instrumented tripods were deployed on the outer Skagit tidal flats in a study coordinated with an NSF project (Simenstad, UW) investigating ecosystem dynamics. This collaboration has enabled sharing of boat time, personnel, and data products to better understand the residence time of particulates on different parts of the tidal flats.

## **PUBLICATIONS (2008-2009)**

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### *Abstracts*

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- Nittrouer, C., Lee, K., Ogston, A. (2009) Export of Mud from the Skagit River Tidal Flats. Coastal and Estuarine Research Federation 20<sup>th</sup> Biennial Conference, Portland OR, 1-5 November 2009.
- Ogston, A., Lee, K., Boldt, K., Hale, R., Nittrouer, C. (2009) Tidal Asymmetry of Sediment-Transport Dynamics on Intertidal Flats: Two Contrasting Examples. Coastal and Estuarine Research Federation 20<sup>th</sup> Biennial Conference, Portland OR, 1-5 November 2009.