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Flocculation on a muddy intertidal flat in Willapa Bay, Washington, Part I: A regional survey of the grain size of surficial sediments

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ABSTRACT

Bottom sediments were collected on a muddy tidal flat in Willapa Bay (southwestern Washington State) and analyzed for grain size using a Coulter Multisizer. The disaggregated inorganic grain size (DIGS) distributions obtained from the sediment were then analyzed using conventional methods including median diameter, *d50*, the largest 25% of the grain size in the population, *d75*, skewness, and kurtosis. In addition, the inverse model of Curran et al. (2004) was used to provide process-based parameters for description of the size distributions. To examine small-scale spatial differences in grain size, the results of the analysis were plotted against seabed elevation, obtained from USGS LiDAR data. Results reveal a strong inverse correlation between the mass fraction deposited to the seabed as flocs, which is called the "floc fraction", and elevation on the tidal flat but failed to show any correlation with conventional grain-size descriptors. The dependence of floc fraction on elevation arises mainly due to the differences in size distributions between secondary tidal channels and tidal flats. The extent of flocculation in sediments deposited in the channels of the Shoalwater tidal-flat system is seasonal. Greater precipitation in the winter months is associated with periods of increased suspended-sediment concentrations, which favours more extensive flocculation and the formation and maintenance of low-strength, high-water-content muds. During the summer dry season, lower suspended-sediment concentrations lead to reduced floc fractions in the channels, while the size distributions on the flats resemble those in winter.

1. Introduction

Many of Earth's coastlines are fringed by intertidal deposits, which provide important habitat for wildlife but unfortunately also act as repositories for contaminants (e.g., Widdows and Brinsley, 2002). Intertidal deposits serve as natural coastal defences that will respond in poorly understood ways to future rises in sea level (e.g., Reed et al., 1999; Widdows and Brinsley, 2002; Townend and Whitehead, 2003; Kirwan et al., 2010). The varied roles for intertidal deposits have motivated substantial research into the morphology of intertidal deposits, as well as studies of the processes that control their morphology.

Knowledge about sediment transport is vital to understanding intertidal deposits. The processes driving sediment erosion, deposition, and transport in these environments are numerous, complicated, and inter-related (Eisma, 1998). Water motions are induced by tides, wind-driven currents, waves, density contrasts, and drainage from flats (Le Hir et al., 2000). Biophysical interactions are important, with sediment affecting the biota and biota affecting sedimentary processes (e.g., Austen et al., 1999; Black et al., 2002; Widdows and Brinsley, 2002). Sediments in intertidal deposits are characteristically heterogeneous, with marked variability in sediment size and composition (Eisma, 1998; Holland and Elmore, 2008).

Flocculation is a sedimentary process that is particularly important to the behaviour of intertidal deposits. The term is used to describe the clumping of many small particles into large aggregates (flocs) that sink much faster than their component particles (e.g., McCave, 1984). Flocculation is fostered by elevated sediment concentration, which promotes frequent particle collisions. It is also favored by moderate turbulence in the water column, which increases the rate of particle encounter, however, vigorous turbulence disrupts flocs (e.g., Eisma and Li, 1993; Hill et al., 2001; Winterwerp and van Kesteren, 2004; Manning and Dyer, 2007). Particle composition and modes of bonding also affect extent of flocculation (e.g., Hill et al., 2007). As a rule,

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elevated sediment concentration, combined with low-to-moderate turbulence intensities are the most favourable for floc formation (e.g., Milligan et al., 2007), and these conditions are typical as tidal currents slacken during the approach to high or low water (e.g., Eisma and Li, 1993; Dyer et al., 2000; Christiansen et al., 2000).

Flocculation plays several important roles in intertidal environments. It affects water-column optical properties, and hence conditions for primary production, by repackaging small numerous particles into large flocs (Boss et al., 2009; Hill et al., 2011). By increasing the settling velocity of suspended sediment, flocculation increases the clearance rate of the water column when currents and waves wane (e.g., Kranck and Milligan, 1992; Eisma and Li, 1993; Manning and Dyer, 2007). But perhaps most importantly, flocculation enhances the depositional flux of silts and clays, known collectively as mud, to the seabed (e.g., Kranck and Milligan, 1991; Kranck et al., 1996a,b; George et al., 2007).

Mud content of the seabed affects a variety of properties and processes in intertidal deposits. Muds can have high porosity (i.e., water content), which can reduce sediment strength (Toorman, 1996; Seifert et al., 2008). Mud content, and more specifically clay content, affects the erodibility (van Ledden et al., 2004) and the erosional sorting (Law et al., 2008) of mixed-grain-size sediments. This can lead to abrupt changes in the texture of surficial sediments from mud to sand (Law et al., 2008) and cause accompanying effects on sediment biota (van de Koppel et al., 2001; Ysebaert and Herman, 2002). Increases in the mud content of the bed have been associated with increased primary productivity by microphytobenthos (i.e., marine benthic microalgae), which in turn can create a positive feedback loop by increasing particle adhesion and reducing the erodibility of mud in the bed sediment (van de Koppel et al., 2001). These changes can cascade to higher trophic levels and affect the macrobenthic community (Ysebaert and Herman, 2002). Finally, increases in the mud fraction, and more specifically the <16 μm fraction, can play a large role in the trapping and sequestration of surface-reactive pollutants such as heavy metals, PCBs, PAHs, and other persistent organic compounds (Zwolsman et al., 1996; Milligan and Loring, 1997; Santschi et al., 1997; George et al., 2007).

The importance of flocculation to the formation of intertidal deposits has spurred investigations that can be broadly grouped into three categories: modelling studies, field studies of suspended flocs, and textural studies of bed sediments. Modelling studies offer the possibility of examining the roles of flocculation over a range of spatial and temporal scales, and modelling studies of the hydrodynamics of intertidal areas are growing increasingly accurate. Unfortunately, improvements to sediment dynamic models in intertidal zones have lagged, both due to complexities associated with cohesive sediments and flocculation and due to lack of data against which to evaluate model predictions (Lumborg and Windelin, 2003; Lumborg and Pejrup, 2005; French, 2009). The lack of data arises in part from the difficulty of making measurements in intertidal environments (Dyer et al., 2000). Shallow water and soft sediments can make intertidal mud flats difficult and dangerous to traverse by boat or by foot. Furthermore, repeated wetting and drying leaves salt crystals and films on sensor surfaces that quickly degrade the quality of data obtained with optical instruments. Despite these difficulties, in situ observations of suspended sediments show that flocs are abundant in intertidal areas, but also that the processes controlling abundance and size of flocs are numerous and complex (van der Lee, 2000; Dyer et al., 2000; Voulgaris and Meyers, 2004; Uncles et al., 2006). This complexity, combined with the lack of extensive spatial and/or temporal in-situ observations, makes it difficult to develop an integrated understanding of how flocculation affects sedimentation on a broader scale.

The third means of studying flocculation is analysis of bed sediment texture. This technique has not been applied widely because the process of flocculation complicates the interpretation of sedimentary deposits (Chang et al., 2006). A promising tool in the understanding of the deposition and transport of fine-grained cohesive sediments is a process-based analysis of disaggregated inorganic grain size (DIGS) distributions (Kranck and Milligan, 1991, Kranck et al., 1996a,b; Curran et al., 2004). A DIGS sample is one in which all organics have been removed, and any bonds between the remaining inorganic component grains have been disrupted. The size distribution (DIGS) can be inverted to infer how much of a deposit was delivered to the seabed as flocs versus single grains. In general, this approach relies on the assumptions that material in suspension is composed of flocs or single grains and that flocs incorporate into their structure all suspended sediment sizes in an unbiased way (Kranck et al., 1996a,b; Curran et al., 2004). Deposition of flocs does not alter the overall size distribution of the remaining suspended population. Single-grain settling, however, does sort particles according to size, thereby producing evolution in the size distribution of the remaining population (Kranck et al., 1996a,b). In short, analysis of DIGS provides a parametric description of the size distribution that accounts for the dominant depositional processes. The process-based parameterization of DIGS is commonly used to quantify the spatial or temporal changes in flocculation in the overlying water column that were responsible for the changes in the texture of fine-grained bottom sediments (Christiansen et al., 2000; Curran et al., 2004; Fox et al., 2004; Milligan and Law, 2005; George et al., 2007; Milligan et al., 2007). Of these references, Christiansen et al. (2000) focused on intertidal sediment, showing that the fraction of sediment deposited as flocs decreased along a transect extending from the edges of a secondary channel into the interior of a vegetated salt marsh. The goal of this present paper is to apply the process-based parameterization method to the DIGS to develop an integrated, regional understanding of the role of flocculation in determining the spatial and temporal variations of grain size for mixed-grain-size beds on a muddy, mesotidal tidal flat in southwestern Washington State. A companion paper, Hill et al. (2013), uses in-situ observations of suspended particle size and current speed to examine flocculation dynamics in a secondary channel and on an adjacent flat. Together, these two studies clarify the mechanisms responsible for producing finer grained bottom sediments and higher deposition rates in the channels and on the banks as compared to their adjacent flats.

2. Methods

2.1. Overview

The study took place in the Shoalwater Bay tidal-flat complex, Willapa Bay, Washington, USA, as part of an Office of Naval Research (ONR) initiative to investigate the dynamics of muddy tidal flats. Willapa Bay is a bar-built estuary located immediately north of the Columbia River on the Pacific coast. It stretches over 30 km in length from north to south and is 5–10 km wide. Willapa Bay has mixed semi-diurnal tides with a mean tidal range of 2.7 m. Tidal range varies by 20% over the length of the estuary and up to 50% on spring-neap tidal cycles (Banas et al., 2004). The Shoalwater Bay mesotidal mudflat is approximately 4 km (north-south) long by 5 km wide (east-west) and is found at the southern end of Willapa Bay. It is surrounded by deeper channels to the north, east, and west (Fig. 1). The Naselle and Bear Rivers discharge near and into Shoalwater Bay, respectively. The Naselle accounts for up to 20% of the freshwater input to the Willapa Bay system (Banas et al., 2004). Larger rivers such as the North and