

## Introduction and Statement of the Problem

For more than twenty years the possible occurrence of shelf turbidity currents has been a topic of heated debate. In a series of dueling papers, members of the oceanographic and geologic community argued about the probability that turbidity currents could exist on the relatively flat continental shelf. Significant evidence from the geological record suggested to early workers that gravity-driven flows were common on ancient shelves (Hamblin and Walker, 1979; Wright and Walker, 1982; Dott and Bourgeois, 1982; Leckie and Walker, 1982; Walker, 1984). However, observations in the modern indicated that storms did not produce turbidity currents but instead formed shore-parallel geostrophic flows (Swift et al., 1986). In addition, theoretical arguments suggested that turbidity currents could not maintain themselves over the small slopes of the continental shelves (Pantin, 1979; Parker, 1982; Swift, 1985). A major disconnect exists, therefore, between oceanographic and theoretical studies and those of ancient sedimentary successions that contain considerable evidence for cross-shelf sand transport (Leckie and Krystinik 1989). In short, there is still no explanation for how sand is transported by storms from shorelines across the shelf. Although facies models exist for storm-dominated shelves, the basic mechanism of transport and deposition for such models is unresolved. This is an astonishing gap in our knowledge of a major marine depositional system.

A hint at the solution of the problem has come from recent, sophisticated oceanographic exploration of modern, large-supply, fine-grained environments. The discovery of dense, mobile bottom nepheloid layers (or fluid muds) on many margins around the globe (e.g., the Amazon: Trowbridge and Kineke, 1994; northern California: Traykovski et al., 2000; northern Papua New Guinea: Kineke et al., 2000) has suggested that large sediment supply in combination with wave-orbital and tidal motions and/or steep slopes can produce gravity-driven transport. In this case, the gravity-driven transport is confined within the oceanic Ekman layer and therefore disconnected from large-scale motions (such as the coast-parallel currents that were described by Swift et al., 1985). Affiliated studies involving the stability of river plumes has shown that rapid delivery of fine sediment to the bottom boundary layer is possible by convective processes (Parsons et al., 2001a). Though the mechanics of these flows are not strictly identical to a hyperpycnal plume, the deposits derived from them should be nearly indistinguishable from the hyperpycnal plumes discussed in the literature (Mulder and Syvitski, 1995). Finally, if wave energy is significant, high-density suspensions formed in the bottom boundary layer near a river mouth can be maintained, eventually resulting in downslope transport.

Myrow and Southard (1996) sought to incorporate the various processes typically examined in modern oceanographic observations within the context of the geologic record. They imagined a continuum of sediment-transport processes governed by geostrophic, gravity-driven and wave-dominated motions. Depending on the contribution of each mode, different styles of sedimentation would result. However, they did not address, which modes exist in nature, which ones are common, and the quantitative limits of each component of flow that defines each type of transport process. In light of the new oceanographic data, Myrow et al. (2002) reexamined the combined wave and gravity-flow subset of the Myrow and Southard (1996) continuum. By comparison to the shelf turbidites of Walker (1984) and others, Myrow et al. (2002) proposed that wave-modified turbidity currents might represent an important mechanism for deposition of tempestites in the rock record. Like the earlier paper (Myrow and Southard, 1996), the primary weakness of the hypothesis is the lack of experimental studies to test the viability of such flows under controlled conditions.

More fundamentally, there is a paucity of knowledge about the interaction of particles and turbulence in concentrated wave boundary layers. Suspensions have been investigated for

decades; however, there are relatively few robust physical models that encapsulate the complex interactions between particles and fluids in even the simplest settings (monodisperse suspensions in a quiescent fluid: Brenner and Mucha, 2001; monodisperse suspensions in isotropic turbulence: Aliseda et al., 2002). The combination of the existing geological evidence with advances of two-phase fluid mechanics yield a series of questions that we plan to address in the proposed research. They are:

- • What are the physical properties of a wave-supported, high-density suspension for a wide variety of grain sizes, including sand, under natural conditions?
  - • How does the addition of gravitational forcing (i.e., slope) affect these suspensions?
  - • How much fine material (silt and clay) is required to produce a high-density suspension and gravity-driven motion for each slope?
  - • How much of this fine material is retained in the deposit?
  - • What characteristics of ancient deposits allow for recognition of the relative importance of gravity-driven and wave-supported components of combined flows?
  - • What is the nature of the ancient depositional systems under which wave-modified turbidity currents originate?

Addressing these questions requires knowledge of relatively disparate fields. Previous investigations of sediment gravity flows have focused on different parts of the problem by neglecting one or more physical processes. As a result, we will first discuss systems that are regulated only by wave motion (high-density suspensions), followed by flows that are only regulated by the negative buoyancy supplied to the water column by sediment (gravity currents). A few studies have discussed both effects (wave-enhanced, gravity-driven flows); however, they have almost exclusively been confined to examinations of muddy systems. In the last section, we will explore the utility of ancient deposits for elucidating the depositional mechanics of combined flows with both wave and excess weight (gravitational) components.

These questions will be addressed through a combination of experimental and field studies. Such an integrated study will provide an empirical background and better understanding of the fundamental physics of combined wave and gravity driven flows. The experimental work will be done with a combined flow duct capable of tilting up to 15°. Detailed fieldwork will be done on formations known to contain tempestites that are likely to have been deposited from gravity-driven combined flows.

## **High-density suspensions**

High-density suspensions are concentrated ( $> 10$  g/l) sediment-laden bottom nepheloid layers defined by the presence of a sharp discontinuity in the vertical sediment concentration profile called a lutocline. High-density suspensions have been the topic of field, theoretical and experimental investigations since they were first found in the Severn Estuary, UK (Kirby and Parker, 1977). These studies, primarily led by the engineering community, have attempted to address the problems that high-density suspensions pose to harbor infill and pollutant dispersion in fine-grained estuaries. The primary conclusion of these engineering investigations is that bottom-boundary-layer turbulence, wave-induced liquefaction, hindered setting and flocculation maintain high-density suspensions.

One mechanism that has been hypothesized for forming high-density suspensions is bed liquefaction by waves. Several theoretical studies have assumed that mud beds are subject to liquefaction when the pore pressure exceeds the cohesive forces in the bed (Lindenburg et al., 1989). Liquefaction changes the rheology of the bed and allows rapid erosion (Mehta, 1991). When erosion exceeds the entrainment of sediment, a high-density suspension can form (Ross and Mehta, 1989). Bed compaction has been found to be critical for liquefaction in laboratory studies (Maa and Mehta, 1987).

Another possible mechanism for creating a high-density suspension is when the settling flux of sediment exceeds sediment consolidation (Ross and Mehta, 1989). When a column of water with high turbidity is advected into a less turbulent environment, the flow may become “supersaturated” with sediment. In numerical simulations, supersaturation has been shown to lead to a gravitational collapse of the water column (Winterwerp, 2001). As sediment is removed convectively from the water column, a high-density suspension forms at the bed. Very near the bed where concentrations are high ( $> 10$  g/l), sediment settling slows dramatically due to hindered-settling effects. This leads to a convergence of sediment near the bed and a confined high-density suspension is formed at the bottom (Ross and Mehta, 1989). However, water-column collapse has not been documented in the field or in the laboratory (Winterwerp, 2001).

Field observations used in the aforementioned formulations were typically obtained from estuarine environments. In order to model these environments, laboratory experiments were performed but they examined very small waves (i.e., wave heights less than 10 cm and wave periods less than 1 s) that did not produce a fully turbulent boundary layer. These experiments also used very fine sediment ( $\sim 2$   $\mu\text{m}$ ) and did not have a sloping bed (Maa and Mehta, 1987). Several authors call upon the need to test formulations under more realistic wave periods, heights and boundary layers (Maa and Mehta, 1987; Vinzon and Mehta, 1998; Winterwerp, 2001). In some investigations, waves were substituted by oscillatory shear in annular flumes (Winterwerp and Kranenberg, 1997), which has a different vertical profile of turbulence characteristics than well-developed wave boundary layers. In addition, most theoretical models have assumed no horizontal sediment flux and hence no gravitational forcing (Ross and Mehta, 1989). Therefore, lutocline formation and sediment transport on continental shelves may be significantly different than the relationships previously hypothesized for estuarine environments would predict.

## **Gravity currents**

Gravity currents in marine systems are generally divided into two broad categories: turbidity currents (dilute flows) and debris flows (concentrated, non-Newtonian flows). Turbidity currents have been studied extensively in a wide variety of numerical, analytical and laboratory studies (Simpson, 1997). Due to their rare occurrence and destructive power, detailed observations have not been made for turbidity currents in the field, although there is abundant evidence (e.g., meandering channels, sediment waves, fan deposits) that turbidity currents are an active process. Unlike high-density suspensions, the sediment in turbidity currents is maintained in suspension by turbulence generated from the buoyantly driven motion of the current itself. Turbidity currents transport large amounts of sediment from the continental slope to the deep sea through a dynamic feedback called “ignition” (Parker, 1982). Ignition occurs on relatively steep slopes ( $> 1^\circ$ ) when sediment entrained by the current exceeds deposition, causing acceleration of the flow and an increased sediment load. The increased sediment load

causes further acceleration and erosion, and so on. On slopes insufficient to maintain its suspension, the feedback will happen in reverse: rapid deposition and deceleration, until the current loses its identity. Besides being constrained to relatively steep slopes, turbidity currents must have a significant component of fine-grained sediment (Gladstone et al., 1998; Salaheldin et al., 2000). The fine-grained component or “washload” is essential in maintaining the production of turbulence, the suspension and ultimately the buoyantly driven flow.

Despite the voluminous literature associated with turbidity currents, very few studies have been performed in which the ambient fluid was anything but quiescent. The only work to investigate gravity-current propagation in an energetic ambient is a series of studies related to the characterization of gravity currents in the presence of grid-generated turbulence. Grid-generated turbulence can be easily characterized due to its attractive isotropic properties (Hopfinger and Toly, 1976). As a result, Thomas and Simpson (1985) examined the propagation of a saline-current front on a flat surface (i.e., no slope) in the presence of grid-generated turbulence. They found that grid-generated turbulence slowed the gravity current until the kinetic energy of the grid exceeded the potential energy contained within the gravity current, at which point the flow would “mix out” (i.e., cease to propagate as a gravity current). Later, Noh and Fernando (1991) extended their work to an inclined plane. Noh and Fernando (1991) generated gravity currents with both aluminum particles and salt; however, they always used a steeply sloping bed of 24° (much steeper than even the steepest parts of the continental slope where natural gravity currents are expected to occur: Mullenbach, 2002) and only examined the turbulent head of the gravity current. Like the earlier workers, Noh and Fernando (1991) concluded that background turbulence decreases the velocity of gravity current heads.

When the concentration of particles becomes high, rheology (described by the constitutive equations governing the relationship between stress and strain) plays a key role (Coussot, 1994; van Kessel and Kranenburg, 1996; Mohrig et al., 1998; Parsons et al., 2001b). Debris flows (or mudflows) are formed when particle-particle interactions become dominant. However, all of the work investigating the rheology of debris flows has been focused on situations where mixing with the ambient (i.e., the water column or atmosphere) was regulated solely by shear associated with gravity-driven motion. These researchers have agreed that when coarse material (i.e., gravel) is absent from the grain-size distribution, the rheology of muddy slurries can be characterized by the general Herschel-Bulkley formulation:

$$(1)$$

where  $\tau$  is the applied shear stress,  $\tau_c$  is the critical shear stress,  $u$  is the velocity in the principal direction of motion,  $y$  is perpendicular to the direction of motion,  $n$  is an empirical exponent, and  $K$  is a linear coefficient that takes the form of a dynamic viscosity when  $\tau > \tau_c$ . For a Newtonian fluid,  $n = 1$  and  $K = \mu$ . All of the aforementioned studies have concluded that concentrated mud does not obey a Newtonian rheology. Most often, mud that is dominated by clay (clay content in excess of 10% by mass) behaves as a Bingham fluid ( $n = 1$ ,  $\tau_c > 0$ ; Coussot, 1994; Parsons et al., 2001b).

It is important to mention that these studies overestimate the importance of inter-particle forces in wave-supported boundary layers. Local shear stresses will always be elevated due to the orbital motions. These stresses are significantly greater than the shear stresses associated only with downslope motion, but it is uncertain what this effect has on the rheology regulating downslope movement. Further, the high strain rates could cause the engagement of sand within the fluid mechanical continuum, as hypothesized by Parsons et al. (2001b). Resolving these effects and incorporating them into models of wave-supported lutoclines represents a fundamental limitation of existing knowledge.

## **Wave-enhanced, gravity-driven flows**

Most of the work on the fluid mechanics of bottom boundary layers that possess both gravitational and wave motions has been performed by sea-going oceanographers. Scientists investigating the muddy coast of northeastern South America were the first to formulate the idea of a “fluid mud” (Eisma et al., 1978; Wells and Coleman, 1981), a concentrated, fine-grained dispersion contained primarily within the bottom wave boundary layer that has a tendency to flow downslope. They noticed that if sediment supply to the bottom boundary layer were too fast to permit consolidation of a mud bed, the dense bottom boundary layer would flow under the influence of gravity, delivering sediment into deeper water. Later, the AMASEDS program exhaustively sampled the bottom boundary layer on the Amazon margin and found that a concentrated ( $> 100$  mg/l) slurry formed within a few cm of the rigid bed. The slurry, though dominated by the tidal currents, was ultimately advected downslope due to its negative buoyancy (Kineke et al., 1996). Recent evidence has found this feature on numerous other coasts (northern California: Traykovski et al., 2000; northern Papua New Guinea: Kineke et al., 2000). The joint conclusion of these projects is that where sediment supply is large, fine-grained, gravitational movement of a fluid mud tends to be the dominant mode of transporting sediment offshore.

Several studies have investigated the ability of predominantly sandy environments to produce gravity-driven motions. Inman et al. (1976) attempted to do this in their observations of sandy turbidity currents in Scripps Canyon. However, they consistently lost their equipment when gravity-driven flows dramatically increased canyon velocities. Despite the loss of equipment, their investigation implies the existence of flows that move under the influence of waves and excess-weight forces. More recently, scientists have identified gravity-driven transport in settings where the gravitational flux is significantly smaller, and therefore not as hazardous (Storlazzi and Jaffe, 2002; Wright et al. 2002). Though Storlazzi and Jaffe (2002) do not attribute the downslope motion of their flows to a gravity current, Wright et al. (2002) document gravity-driven transport with nearly identical observations on the Atlantic margin. In both cases the shear stress associated with downslope movement was small compared with that produced by wave motions.

Modeling efforts associated with these field programs have focused on developing a way to characterize the concentration from basic properties of the wave field and physical properties of the sediment supplied near the bed (Trowbridge and Kineke, 1994; Rodriguez and Mehta, 2000; Wright et al., 2001, 2002; Parsons et al., 2002). Despite the significant number of analytical and field studies, no laboratory data exists on these complicated flows. As a result, theoretical models have had to assume simple relations between the velocity and sediment-concentration distribution in the vertical dimension.

To close the equations of motion, the models generally have some combination of the following four assumptions:

1. 1. Newtonian fluid with an eddy-viscosity turbulence closure
2. 2. Couette boundaries
3. 3. The stratification within the bottom-boundary layer is regulated by a constant, critical Richardson number
4. 4. Conservative scalar approximation

Most existing models have focused attention on the second assumption (e.g., Wright et al., 2001, 2002). It is not clear that mixing will be intense throughout a fluid mud (as the critical Richardson number implies), but field data seems to qualitatively agree with the model (Wright et al., 2001). The implicit assumption of a Newtonian fluid possessing an eddy viscosity is potentially more troublesome. For instance, recent work indicates that the concept of an eddy viscosity is not appropriate when sediment concentrations are high, even in highly sheared flows (Baas and Best, 2002). It is also not certain that fluid mud behaves as a Newtonian fluid, in light of this same evidence (Baas and Best, 2002). Considering these models have flexible empirical parameters that can be adjusted (e.g., a drag coefficient), non-Newtonian and higher-order turbulence (i.e., turbulence not encapsulated within an eddy viscosity) effects could mask themselves as inappropriate variation in the empirical parameters. It is necessary to test these models against laboratory data to properly define the roles of each of these parameters. The appropriate description of modern environments and correct interpretation of ancient storm deposits require the accurate description of these physical parameters.

## **Background: Tempestites**

Storm-generated sandstone beds have been recognized since the early 1970's and much debate ensued over the mechanisms for cross-shelf sand transport (see Introduction). Duke (1990) and Duke et al. (1991) attempted to explain many aspects of ancient storm-deposited sandstone beds as a function of the unique aspects of the bottom boundary layer of geostrophic combined flows. The bottom boundary layer includes a thin (~ 10 cm) wave-dominated boundary layer that exhibits high instantaneous bed shear stresses on the bed and a thicker (< 20 m) current-dominated boundary layer. The result is a combined-flow boundary layer produced by the nonlinear interaction of waves and currents that has bottom shear stresses that are higher than the sum of each component (Grant and Madsen, 1979; Dyer and Soulsby, 1988; Cacchione and Drake, 1990). Cacchione and Drake (1990) describe the changes in orientation and magnitude of shear stresses during each wave oscillation for combined flows in which storm waves are superimposed on a geostrophic current oriented at a low angle to shore.

Duke (1990) suggested that offshore sediment transport and unimodal paleocurrents, particularly sole marks, resulted from the asymmetry of shear stress in such flows (Snedden et al., 1988; Cacchione and Drake, 1990) due to the addition of the offshore component of force of the geostrophic current to the storm waves during their seaward stroke. Thus, paleocurrent indicators would reflect the direction of maximum instantaneous shear stress in the thin boundary layer created by the oscillatory-flow component of the combined flow. Myrow and Southard (1996) suggest that although geostrophic combined flows produced some unusual sole marks on ancient sandy storm deposits (Martel and Gibling, 1994; Beukes 1996), other markings (e.g., flutes) are

inconsistent with such an origin and that they form instead by strong unidirectional flow prior to the onset of deposition. They argued that sedimentary rocks record a wide range of shallow-marine storm deposits that reflect varying degrees of influence of three fundamental processes: waves, geostrophic currents, and gravity acting on suspended sediment or excess-weight forces. The latter refer to the down-slope component of the excess weight (per unit volume) of a high-density suspension relative to clear water. They contended that in certain instances the turbulence added by storm waves could maintain and/or enhance suspended-sediment concentrations and thus increase excess-weight forces in flows, even if autosuspension was not achieved. Although ancient storm deposits likely record a continuum of intermediate flows, there seems to be two end-members. First, there are tempestites, typified by Cretaceous deposits of the Western Interior Seaway, that are generally medium to thick bedded and contain parallel lamination, quasi-planar lamination and large-scale HCS (spacing  $> 0.5$  m). These beds are dominated by the stratification of upper flow regime plane bed and large-scale 3D wave-dominated bedforms developed at and just below the plane bed stability field (i.e., large hummocky bedforms). Such beds record the remobilization and wave reworking of a considerable amount of sediment, and may reflect the final accumulation of sand that was incrementally moved offshore by multiple storms.

Secondly, there are thin-bedded storm deposits with well-developed sole markings, including flutes, and a wide range of stratification styles and sequences that include abundant, small-scale (spacing  $< 0.5$  m), 2D and 3D bedforms of wave and combined-flow origin. The latter have evidence for initial deposition under powerful unidirectional flow and subsequent relatively rapid deceleration. The middle and upper parts of these beds reflect a progressive increase with time in the role of wave oscillations. These beds reflect single, short-lived, catastrophic events developed in shallow water settings, as reflected by small-scale 2D and 3D bedforms. These beds commonly occur within ancient deltaic successions, and in cases show evidence of nearshore bypass (e.g., Myrow, 1992a). Some workers (e.g., Bartolini et al., 1975) have interpreted such storm deposits as the deposits of shelf turbidity currents, but definitive evidence for flows dominated by excess-weight forces is generally lacking. Myrow et al. (2002) provide one of the few examples from the ancient that conclusively demonstrate deposition under combined flows with strong excess-weight force components or wave-modified turbidity currents. They outlined a number of characteristics of such beds, including (1) Bouma-like sequences, (2) pronounced grading, (3) well-developed, unmodified (by waves) flute marks, (4) abundant combined-flow ripple cross-stratification, and (5) parallelism of the orientations of 3 and 4 with an independently derived shoreline orientation. Facies relationships suggested a possible link to riverine floods and the development of hyperpycnal flows, but exposures were not sufficient to unequivocally demonstrate such a causal mechanism. Much more work is required to understand ancient storm-generated sandstone beds that reflect deposition from wave-modified turbidity currents. For instance, little or nothing is known about their depositional framework, lateral extent, and depositional mechanics. This is particularly true for storm deposits whose origins are potentially related to deposition from hyperpycnal flows produced by riverine floods.

## **Research Goals**

Our research goals can be summarized as the test of four interrelated hypotheses:

1. *High-density suspensions of geologic importance are the product of mixing within the wave boundary layer and are therefore constrained to the height of the wave boundary layer.*

Previous laboratory experiments of high-density suspensions have only investigated relatively weak (wave height < 10 cm) and laminar (wave orbital velocity < 10 cm/s) flows. We seek to examine turbulent, high-sediment-supply wave boundary layers. From our initial observations (Figure 3), we hypothesize that the high-density suspensions are directly a result of the wave boundary layer height. This is similar to the hypothesis set forth by the observations of Traykovski et al. (2000). If this hypothesis proves correct, the height of the wave boundary layer presumably exerts some influence on the types of bedforms observed underneath high-density suspensions.

2. *Predominantly sandy flows can also produce high-density suspensions and wave-induced gravity currents.*

Myrow et al. (2002) hypothesized that wave boundary layers could maintain high concentrations in fine sand. However, there has not been a set of physical experiments that have demonstrated this to be true. Some recent modern field observations have indirectly shown this to be possible (Storlazzi and Jaffe, 2002; Wright et al., 2002). We will perform experiments analogous to the preliminary experiments shown in Figure 3 that will identify whether or not high-density suspensions can form when the substrate is made entirely of sand. If the hypothesis is proved to be false, we will identify the grain-size transition at which point high-density suspensions are no longer possible. This will help constrain and inform the interpretation of ancient storm deposits.

3. *For a given slope, grain-size distribution and wave environment, there is an "equilibrium" sediment load and gravitational flux of sediment associated with a high-density suspension.*

Once we ascertain the range in grain sizes under which high-density suspensions are stable, we will begin to identify the relationship between the wave environment, slope and near-bed concentration, for each grain size distribution. We hypothesize that there will be a unique relationship between a given grain-size distribution, slope and wave environment, and the resulting concentration distribution. Preserved deposits are necessarily supplied more heavily than equilibrium allows (i.e., they are net depositional). However, identification and quantification of the geometry of the bedforms associated with equilibrium in a variety of wave and slope settings will aid in assessing the commonality of ancient hyperpycnal flows.

4. *Knowing the equilibrium sediment loading and bedform stability for a wide range of conditions, allows for the interpretation of the sediment supply and other environmental variables in ancient storm deposits.*

We will examine three field sites that have purported wave-modified turbidites with potentially variable degrees of influence of gravity-driven flow and waves. Our laboratory experiments should be directly applicable to interpretation of tempestites. The combination of experimental and field data will help define both the characteristics of a wide range of combined flows and the conditions under which

various bed types form. These conditions include changes in base level, sediment supply and wave regime, and other aspects of depositional systems (e.g., sequence stratigraphic framework, geomorphology) that lead to such flows on ancient margins.

## **Preliminary Experiments: Facility and Results**

In response to the need for laboratory data regarding the issues described above, we have constructed a facility that will be able to identify the underlying physical relationships between a wave environment and the gravitational flux of material in sediment-laden gravity currents. The facility consists of a sealed recirculating channel that currently can tilt to any slope between 0-7°. The duct has the capability to tilt up to 15°, but minor modification is needed. At the upstream end, a motor drives a piston to produce waves. The result is a duct that can accommodate both oscillatory and gravitational motions (Figure 1). The piston was designed such that the experimental range of the waves is close to that which characterizes shallow marine nearshore and shelf environments. In addition, the flume is equipped with a removable false floor that allows the placement of a 15-cm-thick sediment bed.

A micro-acoustic-Doppler velocimeter (microADV) has been mounted near the center of the flume in-order to measure the stream-wise, cross-stream and vertical components of velocity. The mount allows the microADV to be adjusted vertically so that profiles of velocity can be taken. Several tests using only tap water have been performed to identify the working range of the flume. These tests have revealed that the flume can maintain clean sinusoidal oscillations for periods up to 5 seconds and wave orbital velocities up to 0.4 m/s. The shear stresses associated with these motions are significantly larger than the size of wave-induced oscillations required to mobilize the material on continental shelves (Cacchione et al., 1999). It is only slightly smaller than the largest storms observed on modern continental shelves (Puig et al., 2002). The flume is capable of larger waves, in excess of 10-second periods and 1 m/s wave orbital velocities, but further flume modification would be required. An algorithm has been developed to process the velocity data from the microADV. The program consists of a technique to subtract off a phase-averaged wave from the time-series in order to make better estimates of the turbulent properties of the flow. These measurements reveal a wave boundary layer with a thickness on the order of 1 cm and little (< 10%) background turbulence above the wave boundary layer.

Preliminary tests were performed in order to calibrate the recirculation rate with the gravitational (downslope) flux. These tests used a conservative (saline) gravity current in place of a sediment suspension to identify the interactions a near-bottom density interface has with a long-period oscillatory flow in the absence of particle-fluid interaction effects. For these experiments, a relatively high-density salt solution (density = 1.1 kg/m<sup>3</sup>, equivalent to a sediment concentration of 100 kg/m<sup>3</sup>, which is somewhat greater than the concentrations in high-density suspensions observed by Trowbridge and Kineke, 1994, on the Amazon margin) was dyed and poured into the empty flume until a layer thickness of approximately 15 cm was achieved. The rest of the flume was filled with fresh tap water (density = 1.0 kg/m<sup>3</sup>). A very sharp interface (pycnocline) developed between the dense salty layer and the fresh ambient due to the strong density stratification. Immediately after modest waves were turned on (period = 5 s, orbital velocity = 0.18 m/s), the dense layer began to mix with the ambient. Contrary to the assumptions of fluid-mud models, the density stratification did not damp the turbulence associated with the waves. In a matter of minutes, the dense salty layer “mixed out”. That is, the brine

that was originally concentrated at the bottom of the wave tank became well mixed (distributed evenly) throughout the water column.

Since a lutocline, a stable interface below which a high concentration of sediment can be maintained, is known to exist in the laboratory and in the field, the aforementioned experiment was repeated with sediment. The false floor of the flume was removed and replaced with dry manufactured silica silt, with a median size of 20  $\mu\text{m}$ . The flume was filled with fresh tap water and waves were turned on (period = 3 s, orbital velocity = 0.35 m/s). During the next minute, the sediment bed liquefied and spread laterally in the flume until it was of uniform thickness and the surface of the bed was smooth and level. After a few minutes of oscillatory flow, a dense layer of suspended sediment became visible above the bed. Although detailed measurements were not made, the layer was visibly distinct. The upper surface of the high-density suspension (lutocline) stabilized approximately 1.5 cm above the stationary bed, a level that was nearly coincident with the top of the wave boundary layer. The lutocline did not move vertically and was believed to be in a steady equilibrium position for the remainder of the experiment (~ 2 hr).

About one hour into the experiment, the bed underwent some major morphological changes. As viewed through the side of the flume, sediment seemed to be entrained from the liquefied bed and entrained into the high-density suspension. However, the sediment was not entrained uniformly. Instead, a series of diapir-like structures that were semi-evenly spaced on the order of 10 cm. As fine sediment was entrained into the high-density suspension, coarse sediment was left behind. The bed interface developed into ripple-like forms as shown by the “cats-eye” lens of coarse sediment in Figure 2C.

## **Preliminary Conclusions and Relevance to Research Goals**

Our preliminary experiments have identified a key difference between concentrated bottom-boundary-layers of salt and sediment. If existing fluid-mud models were correct, the salt and sediment would have been behaved identically for the same density contrast. Our failure to sustain a concentrated saline bottom boundary layer, while being able to produce a concentrated-sediment bottom boundary layer (in almost every case where bed shear stresses are significant enough to mobilize sediment) indicates that some essential physical process is being left out of current models of wave-enhanced, gravity-driven flows (e.g., Wright et al., 2001, 2002).

Two possible effects can explain the difference between salt and sediment. First, the downward flux associated with particle settling (whether ballistic or by convective processes: Parsons et al., 2001; Winterwerp, 2001) may be sufficient to maintain a balance with the upward flux associated with mixing. It is unlikely that the ballistic settling rate  $v_s$ , governed by Stokes law, is significant ( $v_s \sim 0.05$  mm/s, Figure 2C). However, a number of researchers (Parsons et al. 2001a; Winterwerp, 2001; McCool, 2002) have documented that convective processes (particularly at the concentrations observed in wave boundary layers) can become extremely large ( $> 1$  cm/s). In particular, preliminary observations indicate that small plumes of sediment initially mixed out of the wave boundary layer can be observed collapsing back into that layer. Further experiments

and analytical modeling will be required to identify whether this represents a plausible explanation of the saline-sediment difference.

In contrast, it could be that, unlike ions in a salt solution, which have a relatively small effect on the viscosity of the fluid, sediment particles substantially affect the rheology of the wave boundary layer. Careful measurement of velocity and concentration within the wave boundary layer should allow us to identify whether Newtonian approximations are valid. We would also expect to see large differences associated with grain-size variations if rheology were playing a key role (rheology is highly dependent on grain-size: Parsons et al., 2001b).

## **Preliminary Field Observations**

To address the hypotheses listed in the Research Goals section we have chosen to focus on three study areas:

- • Minturn Formation of central Colorado (Figure 2A)
- • Chapel Island Formation of southeast Newfoundland
- • Westward Ho! and Bude Formations of southwest England

Deep familiarity with the Chapel Island Formation, and reconnaissance of the other formations has allowed us to formulate the hypotheses in the Research Goals section above. For example, the Minturn Formation records a wide range of deltaic subenvironments from fluvial; marginal marine, including interdistributary bay, and more open marine environments (Houck, 1997). These well-exposed strata show a complex stratigraphic architecture that reflects deposition within fan-deltas developed in association with high topographic relief in a tectonically active setting. A remarkable facies with turbidite-like beds developed within the lower reaches of incised valleys. This facies consists of graded beds with tool marks produced by abundant plant material that are interbedded with dark green shale. They contain evidence for strong unidirectional flows and the minor influence of storm-generated waves. Our initial work indicates that these beds have characteristics that are unusual compared to the bulk of ancient storm deposits. In particular, these beds contain abundant climbing, current and combined-flow ripple cross-stratification. Some beds record the early acceleration phase of these events, a phenomenon that is nearly absent in the record of deep-sea turbidites or shelf tempestites. In these beds, climbing ripple divisions at the bases are overlain by upper plane bed lamination and a second division of climbing-ripple lamination (Figure 2B).

## References

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