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# Deposition by seasonal wave- and current-supported sediment gravity flows interacting with spatially varying bathymetry: Waiapu shelf, New Zealand

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ABSTRACT

The Waiapu River sedimentary system, New Zealand, provides a prototype for investigating the relative importance of wave- versus current-supported gravity flows on continental shelf deposition. A two-dimensional model was used to represent gravity-driven sediment transport and deposition on the Waiapu shelf over an annual cycle of storm events and associated Waiapu River floods. Model inputs of waves and wind-driven currents were derived from WAVEWATCH III hindcasts and constrained by benthic tripod data. The 12-month model run included a low-energy period (September 2003 to May 2004) with weak waves and currents and low river discharge, and a high-energy period (May to August 2004) with stronger waves and wind-driven currents and more frequent river floods. Model results suggested that during the low-energy period, riverine sediment was trapped between the 20- and 80-m isobaths. During the high-energy period, sediment was deposited obliquely across the shelf between the 60- and 120-m isobaths. The predicted deposit locations for the low- and high-energy periods, respectively, were consistent with short- and long-term observed accumulation patterns based on $^{7}$Be and $^{210}$Pb activity [Kniskern, T.A., Kuehl, S.A., Harris, C.K., Carter, L., 2010. Sediment accumulation patterns and fine-scale strata formation on the Waiapu River shelf, New Zealand. Marine Geology 270, 188–201]. Gravity flows were mainly wave-supported landward of the 60-m isobath, but became increasingly current-supported as wave orbital velocity attenuated in deeper water. Both analytical theory and numerical results indicated that wave-supported gravity currents were sensitive to local water depth and favored deposition parallel to isobaths as depth increased. In contrast, current-supported gravity currents were more sensitive to spatial variations in seabed slope, with seaward decreases in slope and along-shelf embayment of bathymetry favoring transport convergence and deposition. We conclude that the longer term (~100 yr) shelf-oblique mud deposit on the Waiapu shelf mainly reflects current-supported gravity flows responding to local variations in seabed slope and curvature of isobaths.



## 1. Introduction

Through most of the last half century, sediment gravity flows were largely considered insignificant for the dispersal of riverine sediment across continental shelves because few shelves are steep enough to provide sufficient gravity forces to maintain autosuspension, and few river effluents are turbid enough to directly produce hyperpycnal discharges. This opinion has been fundamentally challenged by more recent field observations and hydrodynamic theory which indicate that gravity flows can occur on relatively gentle slopes when transport convergence concentrates sediment, and waves and/or currents provide sufficient turbulence to maintain hyperpycnal layers in suspension (Sternberg et al., 1996; Ogston et al., 2000; Traykovski et al., 2000; Wright et al., 2001). Sediment gravity flows suspended by tidal currents were first documented offshore of the Yellow River (Wright et al., 1988; 1990) and Amazon River (Cacchione et al., 1995; Sternberg et al., 1996). Soon after, studies focusing on the Eel and Po shelves as part of the STRATAFORM and EuroSTRATAFORM programs (e.g., Ogston et al., 2000; Traykovski et al., 2000; Harris et al., 2005; Friedrichs and Scully, 2007; Traykovski et al., 2007) indicated that wave-supported sediment gravity flows could also play an important role in the across-shelf transport of fine sediment.

Wave-supported gravity flows have been particularly well studied in the last decade, in part because they were observed in both the STRATAFORM and EuroSTRATAFORM projects (Ogston et al., 2000; Traykovski et al., 2000, 2007), and also because bottom orbital velocities can be easily estimated from widely available surface wave parameters (Friedrichs and Wright, 2004). Wave-induced flows are supported by velocity shear associated with wave orbital velocity within the thin wave boundary layer. Reduced shear and strong sediment stratification at the top of the layer restricts the suspension from diffusing upward, potentially leading to very high sediment

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concentrations in the wave boundary layer. Fluid mud with sediment concentrations as high as 80 kg/m$^3$ were inferred within the wave boundary layer on the Eel shelf (Traykovski et al., 2000; Wright et al., 2001). The capacity of such flows to hold suspended sediment is limited by a balance between velocity shear and sediment-induced stratification as scaled by the Richardson Number (Wright et al., 1999, 2001). Deposition from these flows can then be estimated using the gradient of near-bed orbital velocity with depth (Traykovski et al., 2000; Scully et al., 2002) and by depth-dependent changes in bed slope (Friedrichs and Scully, 2007).

Tripod observations collected on the middle continental shelf offshore of the Waiapu River, New Zealand (Fig. 1) in 2004 provided the first clear indication that gravity flows supported by along-shelf wind-driven currents could also be an important mode of across-shelf sediment dispersal (Ma et al., 2008). In contrast to thin (<10 cm) and dense (concentration ~10–100 kg/m$^3$) wave-supported gravity flows, the current-supported gravity flows on the Waiapu shelf were significantly diluted (depth-averaged sediment concentration ~4 kg/m$^3$ within sea water), and extended over a layer as thick as 1~2 m (Ma, 2009). Compared to wave orbital velocities (based on wave buoys or wave hindcasts), near-bed sub-tidal currents are less predictable. As a result, predicting the locus of deposition caused by current-supported gravity flow has presented additional challenges (Wright and Friedrichs, 2006).

To our knowledge, the Waiapu shelf is the first site to date where sediment gravity flows supported by non-tidal mid-shelf currents have been documented (Ma et al., 2008). Such flows are likely to be recognized elsewhere in the future. To better understand the ramifications of such flows, this paper applies a two-dimensional model for wave- and current-supported sediment gravity-driven flows to the Waiapu River shelf. The main objectives of the paper are (i) to determine the likely roles during low- and high-energy periods that sediment gravity flows play in forming the muddy deposits on the Waiapu shelf, (ii) to investigate the effects of currents versus waves on gravity flows and resulting shelf deposition, and (iii) to better understand the relative roles of local water depth and spatially varying bed slope in determining the location of depocenters formed by gravity flows.

## 2. Site description

The Waiapu River drains a small mountainous basin (~1700 km$^2$), characterized by steep terrain, heavy rainfall (~2.4 m/yr), unconsolidated soft Tertiary mudstone and siltstone, and historical deforestation (see Hicks et al., 2004). As a result, its sediment yield (~20,000 T km$^2$/yr) is among the highest in the world (Milliman and Syvistki, 1992). Its water discharge is episodic over both inter- and intra-annual timescales, and almost all of the discharge is associated with floods caused by cyclonic storms. Hyperpycnal river mouth plumes may occur in the Waiapu system during flood, i.e., total suspended solids in the river can exceed 40 kg/m$^3$ (Mulder and Syvitski, 1995; Hicks et al., 2004). At the river mouth, fine-grained materials (>90%) dominate the sediment load (Hicks et al., 2000).

Due to the small drainage basin of the Waiapu River, the river–ocean system is strongly coupled in that the weather systems that produce heavy rains and river flows also create energetic waves and wind-driven currents in the coastal ocean (c.f. Wheatcroft, 2000). Bottom tripods deployed on the middle shelf (40–60 m) offshore of the Waiapu in 2004 indicated that significant wave heights reached 3.5–5.0 m during storms (Ma et al., 2008). In addition, currents at the tripod sites were observed to be strong, exceeding 1 m/s at the surface and reaching 0.5 m/s near the seabed. Large-scale circulations influence the region, including the southwestward East Cape Current over the continental slope (Carter et al., 2002; Chiswell, 2000).

The mid-to-outer continental shelf offshore of the Waiapu River mouth is composed of Holocene sediment that is locally over 100 m thick (Orpin et al., 2002), sitting atop as much as 1 km of Pleistocene sediments (Lewis et al., 2004). On the Waiapu inner shelf, thinner Holocene facies exhibit significant spatial variation, with river-plume and event deposits dominating north and south of the river mouth, respectively (Wadman and McNinch, 2008). On the mid-to-outer shelf the average modern accumulation rate is about 1.5 cm/yr, with

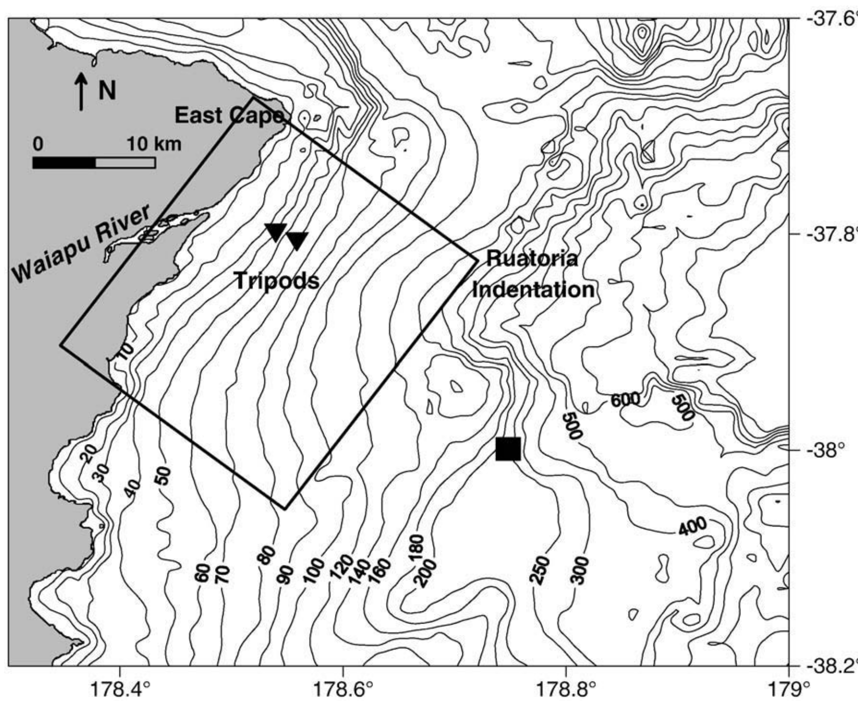


**Fig. 1.** Waiapu continental shelf (with bathymetry), northern island of the New Zealand. Two tripods (from Ma et al., 2008) at 40-m and 60-m isobaths shown as triangles. Domain of the 2-D gravity-driven flow model shown as the bold square, which covers an area of ~29 km × 25 km. The location of NOAA WAVEWATCH-III global model node used for wind and wave forcing shown as a square.