Contrasting modes of shelf sediment dispersal off a high-yield river: Waiapu River, New Zealand

Lisa D. Addington, Steven A. Kuehl⁎, Jesse E. McNinch

Virginia Institute of Marine Science, P.O. Box 1346, Gloucester Point, VA 23062, USA

Received 8 June 2006; received in revised form 13 March 2007; accepted 9 April 2007

Abstract

Recent studies of continental margins suggest that small, high-yield rivers are capable of generating shelf sediment-gravity flows, an idea that fundamentally alters our understanding of material flux from the continents to the ocean. Discharge measurements indicate that the Waiapu River, North Island, New Zealand reaches hyperpycnal concentrations (>36 kg m⁻³) on a yearly basis. This study contrasts shelf-edge basins with a broad trough along the shelf-edge off the Waiapu River, testing whether there is evidence that shelf sediment-gravity flows propagate to topographic lows. Observations and measurements through geochemical and sedimentological analyses of sediment cores, EM1002 swath bathymetry, and Chirp sub-bottom profiles suggest differing transport modalities on the outer shelf. In general a southern trough-shaped region exhibits high terrigenous inputs and non-steady-state ²¹⁰Pb profiles, whereas the northern basins contain steady-state ²¹⁰Pb profiles and increased marine influence. Sediment-gravity flows dominate accumulation in the southern region, whereas within the northern portion, surface plume sedimentation is indicated. Overall this study suggests that sediment-gravity flows could be bypassing the northern basins, perhaps a result of oceanographic influences and bathymetric steering as they seek a more direct route across the shelf.

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Keywords: sedimentation; sediment-gravity flow; hyperpycnal flow; Waiapu River; New Zealand

1. Introduction

Terrigenous sediments are generally delivered to the shelf via rivers either as a positively buoyant hypopyc- nal plume, neutrally buoyant isopycnal plume, or a negatively buoyant hyperpycnal plume. Hyperpycnal plumes, a phenomenon that until recent years had been thought of as rare in the marine environment, are now considered to occur frequently off the mouths of small-

to medium-sized mountainous rivers and have been found to play a significant role in the delivery and burial of terrestrial matter offshore (Mulder et al., 2003). These flows occur when river discharge has a higher density than the water in the receiving basin. In the marine environment, suspended-sediment concentrations in freshwater plumes on the order of 36 kg m⁻³ are necessary to exceed the density of saline waters in the receiving basin. Environmental conditions acting to increase the concentration of sediment in order to form hyperpycnal plumes include: the presence of easily erodible soil, occurrence of extreme geological events, and the location within a small river catchment that experiences episodic floods (Mulder et al., 2003).
Rivers with the highest sediment yields, and hence the ability to generate hyperpycnal inflows, frequently coincide with areas of intense tectonic activity (Milliman and Syvitski, 1992). Small rivers, specifically those located in southern Asia and islands of the Western Pacific, compose a large percentage (∼70%) of global sediment discharge (Milliman and Meade, 1983), hence developing an understanding of such rivers is key to our understanding of mass transport, cycling, and burial of terrestrial matter in the oceans.

In addition to river-initiated hyperpycnal flows, other mechanisms operating in the coastal ocean off river mouths serve to concentrate sediments near the seabed, allowing for gravity-driven transport in the bottom boundary layer. Studies on the shelf off the Eel River in California have shown that flood sediment leaves the river within a buoyant plume and settles toward the seabed landward of the 50 m isobath. During intense storms this sediment remains in suspension within the bottom boundary and travels off-shore as high-density fluid mud flows (Traykovski et al., 2000; Wheatcroft and Borgeld, 2000). Rapid settling of sediment from surface plumes and estuarine-like circulation can also concentrate sediment and allow gravity-driven transport (Kineke and Sternberg, 1995; Mulder and Syvitski, 1995). Near-bed fluid mud layers have been observed on shelves adjacent to some of the world’s largest rivers (Amazon River (Kineke and Sternberg, 1995), Yellow (Wright et al., 1988, 1990), and Zaire (Eisma and Kalf, 1984)). Recent studies have analyzed the complex dispersal patterns of sediment off small- to medium-sized rivers. The Sepik River, Papua New Guinea is an example of a river plume that has shown evidence of a divergence in sediment transport with a portion of the riverine sediment remaining within a buoyant plume as well as flocculated sediment being transported within hyperpycnal and isopycnal plumes (Kineke et al., 2000; Walsh and Nittouer, 2003). These few case studies suggest that the delivery and burial of sediment off small- to medium-sized rivers is affected by a variety of transport processes that have not traditionally been considered in continental margin studies. Our developing understanding of gravity-driven flows requires additional case studies of small mountainous river dispersal systems to reveal the full range of operative processes and resulting sedimentation patterns.

The Waiaupu River drains a small watershed (1734 km²) along the mountainous and tectonically active north-east region of the North Island, New Zealand. Easily erodible mudstone of the east coast of New Zealand, high rainfall, tectonic activity, small catchment size, and the effects of deforestation produce high concentrations of sediment in the local rivers. A sediment yield of 20520 t km⁻² yr⁻¹ has been calculated for the Waiaupu River (Hicks et al., 2003), one of the highest in the world, making this river likely to have a high frequency of hyperpycnal plume formation. Therefore the Waiaupu represents a natural laboratory for the study of this important process.

As a result of tectonic activity, the Waiaupu continental margin is partitioned into a number of discrete basins, including several shelf-edge basins that constitute our study area. This study contrasts shelf-edge basins with a broad trough along the outer shelf, testing whether there is evidence of different modes of sediment delivery to these areas (Figs. 1 and 2). Through targeted coring and acoustic observations of the shelf-edge, differences in patterns of sediment accumulation along the outer shelf and within the intra-basin regions are elucidated.

2. Background

2.1. Geological and oceanographic setting

The Waiaupu River drains the northeast coast of New Zealand’s North Island, part of a collision margin where the Pacific plate is being obliquely subducted beneath the Australian plate. A large percentage of the catchment contains a portion of the East Coast Allochthon (Page et al., 2001), which through tectonic thrusting has become crushed, sheared, and therefore highly susceptible to erosion. Compressional forces across the margin result in rapid uplift of the River’s headwaters (up to 4 mm yr⁻¹; Brown, 1995) and subsidence of the shelf which has created accommodation for a thick (over 100 m) post-last glacial maximum sequence (Orpin et al., 2002).

The upper reaches of the Waiaupu River begin as a single channel, but the river becomes braided within the lower 26 km. In the upper reaches the terrain is predominantly sandstone and mudstone, which changes to gravel in the lower segment (Page et al., 2001). The average annual rainfall for the watershed is 2400 mm yr⁻¹ with large storms having a recurrence interval between 2.6 and 3.6 yr across the reaches of the Waiaupu (Hicks, 1995). The Waiaupu catchment’s composition of sheared and fractured mudstone, high rainfall, and land use practices have given rise to the highest sediment discharge in New Zealand (∼35 Mt yr⁻¹) and among the highest sediment yields of rivers on earth (Hicks et al., 2003). During high flood events, suspended-sediment concentrations up to 90000 mg l⁻¹ have been measured (Hicks and Griffiths, 1992). Available discharge data suggests that river sediment concentrations annually exceed the threshold for hyperpycnal inflow (36 g l⁻³) to the coastal ocean.
The Waiapu empties out of East Cape onto a narrow shelf characterized by a complex morphology typical of collision margins. Previous swath bathymetric studies have revealed the presence of a major debris avalanche deposit on the slope (the Ruatoria) (Carter et al., 1996; Lewis and Barnes, 1999; Collot et al., 2001), a series of

Fig. 1. Bathymetric map of the shelf and upper slope off the Waiapu River (Upper Panel). Detailed map of study area (Lower Panel) showing locations of high-resolution seismic reflection profiles (T1–T4) and coring locations (black circles). Kasten cores are designated after the individual transects and alphabetically, increasing seaward. For example the core furthest left along T1 is labeled KC 1A.
outer-shelf basins, and shore-parallel plateaus on the shelf edge.

The east coast of the North Island of New Zealand is influenced by a number of oceanic currents, primarily the East Cape Current and the Wairarapa Coastal Current. The East Cape Current flows southward along the shelf break with speeds up to 25 cm s\textsuperscript{-1} at 100 m water depth (Chiswell, 2000). The Wairarapa Coastal current flows towards the north, landward of the East Cape Current, with a mean current velocity of about 20 cm s\textsuperscript{-1} (Chiswell, 2000). The East Cape region is dominated by waves moving in a northeasterly direction with heights generally less than 3 m (Pickrill and Mitchell, 1979). During the active winter-storm season wave heights greater than 10 m have been recorded (Ma et al., submitted for publication).

3. Approach and methods

3.1. Study approach

An initial survey of the study area was conducted using multibeam and Chirp sub-bottom profiling in order to select coring locations. Sediment cores were examined using a variety of geochemical and sedimentological techniques to determine recent sediment accumulation patterns and infer transport mechanisms. \(^{210}\text{Pb} (t_{1/2} = 22.3 \text{ yr})\) and \(^{7}\text{Be} (t_{1/2} = 53 \text{ d})\) measurements were made to determine sediment accumulation rates on centennial (e.g., Nittouer et al., 1979) and seasonal (e.g., Giffin and Corbett, 2003) scales, respectively. Organic carbon content and composition (i.e., C, N, and \(\delta^{13}\text{C}\)) were measured to determine the relative influence of marine and terrestrial sources (Leithold and Hope, 1999). Standard sedimentological studies (X-radiography, grain size) were performed to help with understanding the physical and biological environment of the core sites and in interpreting the \(^{210}\text{Pb}\) profiles.

3.2. Acoustic data acquisition

A high-resolution multibeam survey was conducted in May, 2004 using a hull-mounted Simrad EM1002 system, aboard the \textit{R/V Kilo Moana}. The EM1002 has a frequency of 95 kHz, 111 beams per ping, a maximum ping rate of greater than 10 Hz, and a coverage sector up to 190°. An Edgetech SB-512i (Chirp) was utilized for sub-bottom profiling, with a frequency range of 500 Hz–12 kHz, a vertical resolution of 8–20 cm, beam width of 16°–32°, and a towing speed up to 7 km. Depth of sub-bottom penetration ranged from 5 to 60 m depending on the sediment type.

3.3. Survey and sampling

In May 2004, a grid of along and across shelf transects of both the Chirp and multibeam was run on the outer shelf. Cores were collected from four across-shelf chirp survey lines in order to ground-truth the seismic data and for sedimentological and geochemical studies (Fig. 1B). Each

Fig. 2. Visualization of shelf morphology based on EM1002 swath bathymetry collected from the \textit{R/V Kilo Moana} in 2004. Colored areas correspond to depth intervals as indicated on the color bar. Transects (T1–T4) and core locations (blue squares) are the same as shown in Fig. 1. The northern and southern regions, as discussed in the text, are outlined in the solid and dashed boxes, respectively.
of these transects begins approximately 20 km from the river mouth. At the shelf-edge the study-site is divided into two sections with the northern basin region lying within 5 km of the southern region (Fig. 2). Cores were targeted based on features observed from the multibeam including: the shelf shoreward of the basin, shoreward basin-edge, basin-low, seaward edge, and seaward plateau for each basin (Fig. 1B). Twenty-five kasten cores were collected with lengths ranging from 0 to 250 cm. Processing included the removal of sections measuring 30 cm × 10 cm × 2 cm for X-radiography as well as sampling at 2 cm intervals for post-cruise laboratory analysis. The subcores were X-radiographed on board for sedimentary structure analysis. Box cores (0–50 cm) were targeted at the same locations as the kasten cores in order to recover undisturbed samples near the sediment–water interface. Processing is similar to that used for the kasten cores in that it involves the removal of slabs for X-radiography except that 6-inch diameter PVC tubes were used to collect subcores from which 1 cm sub-samples were extruded.

3.4. Laboratory techniques

Alpha spectrometry measurement of the $^{210}$Po daughter was used as a proxy for $^{210}$Pb activity (Flynn, 1968) following the procedure laid out by Nittrouer et al. (1979). Supported $^{210}$Pb levels were estimated on an individual core basis by averaging values at depth where total $^{210}$Pb activities became uniformly low. A common supported level could not be used due to the large variation in these values across the study region, ranging from 0.8 to 1.81 dpm g$^{-1}$. For $^7$Be analysis gamma spectroscopy was employed using planar intrinsic germanium detectors. Counts per minute (cpm) were converted to decays per minute (dpm) by taking into account the intensity of 477 keV photon for $^7$Be and the detector efficiency measured through a North American Scientific NIST traceable mixed gamma standard.

Sieving was used to separate the sand fraction from the silt and clay of the samples. Silt and clay fractions of the samples were quantified using pipette analysis (Gee and Bauder, 1986).

Organic matter content and composition (i.e., C, N and $\delta^{13}$C) were measured for selected samples. Surface samples from box cores had been frozen prior to analysis, however kasten cores that were analyzed had been stored at room temperature for 6 wk and then at a temperature of 5 °C for 24 wk before analysis. The samples were dried for 36 h at a temperature of 62 °C, ground, and acidified within muffled scintillation vials.

![Figure 3](image)

Fig. 3. A) Chirp sub-bottom profile along transect 1. Gravity coring (kasten corer) locations are shown (KC 1A–G), and open circles with the slash indicate sites where core retrieval was nil. Kasten core site KC 1B recovered only a small amount of stiff sediment in the nosepiece. The sub-surface arrow beneath KC 1E indicates a prominent acoustic reflector underlying an acoustically transparent drape. B) Excess $^{210}$Pb activity profiles along transect 1. Logarithmic decrease in activity with depth in the seabed allowed for the calculation of $^{210}$Pb accumulation rates for all of the profiles.
using 10% HCl. Samples were dried again and weighed into tin capsules that had been rinsed with methanol. Analyses were performed at UC Davis Stable Isotope Facility using a continuous flow Isotope Ratio Mass Spectrometer (IRMS).

4. Results

4.1. Shelf-edge morphology

EM1002 bathymetry reveals a gently dipping and smooth mid-shelf which transitions into an outer-shelf comprised of multiple depressions before reaching the slope that is dissected by numerous canyons (Fig. 2). Within the northern region, 25 km directly off the mouth of the Waiapu, there exist small-scale localized basins including a set of bi-lobed basins measuring 8 km², found along transects 2 and 3, as well as a smaller 4 km² basin slightly to the northeast along transect 1. The landward side of the basin walls is generally steeper than the seaward side. Contrastingly, within the southern region the outer shelf can be described as a relatively smooth trough-like feature, within which exist a series of subtle shore parallel ridges.

4.2. Sub-bottom features

4.2.1. Transect 1

The chirp record for the northernmost transect is characterized by 2 prominent reflectors (Fig. 3A). The most shoreward reflector is relatively flat and crops out at the shoreward edge of the basin. The other main reflector appears within the basin, near KC 1C, where overlying sediments first thicken moving offshore towards the plateau before thinning further seaward until the reflector crops out in the next basin offshore. Several other older (deeper) reflectors also crop out along the subsequent basin’s wall in the vicinity of KC 1F (Fig. 3A).

4.2.2. Transect 2

Similar to transect 1, this transect reveals two prominent reflectors which are discontinuous across the area, and which crop out on the landward face of the inner and outer basins, respectively (Fig. 4A). Within this basin there exists what appears to be a series of fill layers, represented by a number of strong reflectors. Also similar to transect 1, several reflectors crop out along the landward wall of the outer basin.

![Fig. 4. A) Chirp sub-bottom profile of transect 2, the northern lobe of the bi-lobed basin (see Fig. 2). Gravity coring (kasten corer) locations are shown (KC 2A–D), and the open circle with the slash indicates a site where core retrieval was nil. The sub-surface arrows beneath KC 2A and KC 2C indicate prominent acoustic reflectors landward and seaward of the basin. B) Excess $^{210}$Pb activity profiles along transect 2. Logarithmic decrease in activity with depth in the seabed for KC 2A and KC 2C allowed for the calculation of $^{210}$Pb accumulation rates for these profiles. KC 2B could not be modeled as steady-state accumulation, and activity values less than 0.1 dpm g$^{-1}$ observed in the middle of the core are indistinguishable from background levels.](image-url)
4.2.3. Transect 3

The profile passes through the southern portion of the central bi-lobed basin but extends further seaward to a third basin in the vicinity of KC 3F (Fig. 5A). The inner portion of this profile is remarkably similar to that of transect 2, with two discontinuous reflectors with analogous variations in thickness and geometry of overlying sediments. The sediment lobe along the seaward edge of the basin and plateau, although thinner within this profile, corresponds to that within transect 2. When examining the reflectors shoreward of the individual basins as well as those extending from the topographic low towards the seaward plateau along transects 1, 2, and 3, similarities in acoustic return as well as depth below the seafloor are evident.

4.2.4. Transect 4

The southernmost transect is distinct from transects 1–3 in that multiple shallow reflectors are present along the shelf landward of the basin (Fig. 6A). With the exception of the deepest reflector all of these appear to crop out just seaward of KC 4A. Prominent reflectors and overlying units immediately seaward of the basin are comparable to those observed in the northern transects.

4.3. Pb-210

Apparent $^{210}$Pb accumulation rates were calculated only for the cores that displayed logarithmic decrease with depth because this is an indication of steady-state conditions. Using the constant flux, constant supply model, $^{210}$Pb accumulation rates were calculated using the slope of the $^{210}$Pb excess values within the non-supported (i.e., excess activity) region (e.g., Appleby and Oldfield, 1978). Using this approach, accumulation rates are considered maximum values because biodiffusion is assumed to be negligible (Nittrouer et al., 1984). This assumption can be confirmed only in the cases where physical stratification dominates the sedimentary structure as observed in X-radiographs. The approach of using bomb $^{137}$Cs as an independent check on the $^{210}$Pb accumulation rates was not possible as $^{137}$Cs levels were typically below minimum detectable limits, probably a result of low fallout levels in the Southern Hemisphere (Tsumune et al., 2003).

![Fig. 5. A) Chirp sub-bottom profile of transect 3, the southern lobe of the bi-lobed basin (see Fig. 2). Gravity coring (kasten corer) locations are shown (KC 3A–E), and the open circle with the slash indicates a site where core retrieval was nil. The sub-surface arrows beneath KC 3A and KC 3D indicate prominent acoustic reflectors landward and seaward of the basin. B) Excess $^{210}$Pb activity profiles along transect 3. Logarithmic decrease in activity with depth in the seabed for KC 2A, KC 2D and KC 2E allowed for the calculation of $^{210}$Pb accumulation rates for these profiles. An accumulation rate was not calculated for KC 3C as high activities in a nearly homogeneous surface layer quickly drop to supported values.](image-url)
4.3.1. Transect 1

The \(^{210}\text{Pb}\) profiles along transect 1 can be characterized as steady-state, allowing for the calculation of accumulation rates within all of the cores (Fig. 3B). The highest rates of accumulation (1.1–1.4 cm yr\(^{-1}\)) were within the topographic-low and on the seaward edge of the basin, with lowest rates (0.2 cm yr\(^{-1}\)) found shoreward of the basin. The presence of laminations in the X-radiograph images suggests that these profiles have not been strongly affected by biodiffusion and hence the \(^{210}\text{Pb}\) rates are considered reliable. Additionally, it is unlikely that biodiffusion, which typically affects the upper \(\sim\) 10 cm of the seabed (Peng et al., 1979), would have appreciably affected the \(^{210}\text{Pb}\) profiles which extend to depths exceeding 100 cm as in the cases of KC 1C, 1D and 1E.

4.3.2. Transect 2

Within transect 2 a total of 3 cores were collected, with a failed attempt at coring a seaward depression due to the presence of stiff, consolidated sediment (Fig. 4B). The basin-low, KC 2B, exhibits a non-steady-state profile reaching supported levels of \(^{210}\text{Pb}\) activity at a depth of around 25 cm and remains at these levels to a depth of 110 cm, where a spike in activity almost equal to surface activities is detected. The seaward edge of the basin shows the highest accumulation rates (0.8 cm yr\(^{-1}\)), with lower rates (0.3 cm yr\(^{-1}\)) on the shelf landward of the basin.

4.3.3. Transect 3

With the exception of KC 3C from the basin center, the cores from transect 3 show predominantly steady-state profiles (Fig. 5B). There is a trend of increasing accumulation rates moving further offshore along this transect. The basin site (KC 3C) contains nearly uniform excess activity values within the top 25 cm, which quickly drop to supported values.

4.3.4. Transect 4

In contrast with the profiles from transects 1–3, all of the cores from transect 4 show distinct non-steady \(^{210}\text{Pb}\) profiles along this transect. The far right profile (not shown on the above Chirp record is from a core taken within a canyon incising the slope). Profiles from this transect display markedly non-steady-state signatures, where activities fluctuate down core. Accumulation rates have been approximated for three of the cores by removing the low-activity spikes and plotting a best-fit line. No rate was calculated for KC 4C due to the extreme non-steady-state character.

Fig. 6. A) Chirp sub-bottom profile of transect 4. The break in the sub-bottom record seaward of KC 4C indicates a gap in field data collection. Gravity coring (kasten corer) locations are shown (KC 4A–D), and the open circle with the slash indicates a site where core retrieval was nil. B) \(^{210}\text{Pb}\) profiles along the same transect. The far right profile (not shown on the above Chirp record is from a core taken within a canyon incising the slope). Profiles from this transect display markedly non-steady-state signatures, where activities fluctuate down core. Accumulation rates have been approximated for three of the cores by removing the low-activity spikes and plotting a best-fit line. No rate was calculated for KC 4C due to the extreme non-steady-state character.
profiles where activities fluctuate downcore, most evident in KC 4C (Fig. 6B). In addition KC 4C contains relatively low-activities throughout the core compared to values across the region, with maximum excess values of 4.5 dpm g\(^{-1}\) compared to average surface excess values of 14.5 dpm g\(^{-1}\) for this transect. \(^{210}\)Pb accumulation rates were approximated for 3 of the cores in this transect by removing the spikes of low \(^{210}\)Pb activity and running a regression on the remainder of the profile. The rates calculated along this transect are relatively high compared to others in the region ranging from 0.8 to 1.1 cm yr\(^{-1}\). A rate could not be calculated for KC 4C due to the extreme non-steady nature of this profile, however excess activities extend to a depth of more than a meter below the seabed surface, suggesting rates on the order of cm yr\(^{-1}\).

4.4. \(^{7}\)Be distribution

The 0–1 cm interval was analyzed within all box core samples for \(^{7}\)Be activity. With the exception of sites KC 1C and KC 3C, \(^{7}\)Be activities were near the lower limit of detectability for our detectors (< \(0.2\) dpm g\(^{-1}\)). Sites KC 1C and KC 3C showed surface activities of 0.6 dpm g\(^{-1}\), significantly lower than activities observed in shallow water depths (< 50 m) by Kniskern et al. (2006) from box cores collected during the same cruise.

4.5. Sedimentary structure

X-ray radiographs were taken to assess the relative degree of physical versus biological sedimentary structure (Fig. 7). The X-radiograph images exhibited in Fig. 7 are from the topographic rise of each transect, which represents the high accumulation regions. Each transect varies in the extent of reworking, but some general trends are observed. Transect 1 appears to exhibit both preservation of physical stratification as well as evidence of biological reworking. The poor resolution in KC 2C restricts interpretation of the stratigraphy within this core, however there does appear to be a thick, more opaque layer present, evidence of either a coarse-grained deposit or compacted sediment. In transect 3, biological mixing dominates with little evidence of preserved physical stratification. In transect 4 physical stratification dominates, evident in the presence of alternating X-ray transparent and opaque layers, with very little alteration by biological reworking.

4.6. Organic matter

\(\delta^{13}\)C, %C, and %N were determined for the 0–1 cm box core samples and the entire length of 2 kasten cores,
one within the southern region, KC 4C, and one within the southern lobe of the central bi-lobed basin, KC 3D. A predominantly terrestrial signature for KC 4C was detected with more negative $\delta^{13}$C values and low N/C values (Fig. 8). KC 3D shows a much more marine signature, with less negative $\delta^{13}$C values and higher N/C values. All of the surface carbon samples have a more marine signature compared to KC 4C, but compare well with the down-core carbon of KC 3D. Data was also collected for the box cores along transects 1 and 2, which are not shown, but whose values fall within the same region as these surface values.

5. Discussion

5.1. Seismic stratigraphy and recent accumulation patterns

5.1.1. Northern basins

Throughout the northern basin region the sub-bottom profiles are generally similar in nature with minor exceptions (Figs. 3A, 4A and 5A). The key pattern that persists throughout this region is the presence of an acoustically transparent sediment lobe extending seaward from the individual basins, implying that there are similar mechanisms at work within the northern study-site. The similar acoustic return of the reflectors underlying this sediment lobe as well as the occurrence of these reflectors at corresponding depths below the seafloor is an indication that these represent the same geologic horizon along each transect. The basin-low in transect 1 differs from those in transects 2 and 3 in that fewer reflectors are present, with one deep reflector that crops out just seaward of the topographic high. The thick fill within the basin-low of transect 1 could be an indication that the most northern basin-low has received a higher supply of sediment compared to the bi-lobed basin.

Reflectors within the basin-lows of the bi-lobed basin along transects 2 and 3 could potentially be explained by the occurrence of gravity flows of older material from the area just shoreward of these basins. Just shoreward of these basin-lows along the steeply sloping seafloor, only very short, highly compacted cores containing very stiff mud were retrieved, a further indication that older, consolidated material is exposed in this area. The thickness of the sediment lobe along the seaward edge of the basin decreases moving from transect 2 to transect 3, suggesting that there is a potential decrease in either sedimentation or long-term accumulation of material moving towards the south.

$^{210}$Pb accumulation rates support this interpretation showing lower rates along the shelf shoreward of the basins when compared to the seaward side of the basin and the seaward plateau (Figs. 3, 4 and 5B). In both transects 2 and 3 the profiles within the topographic lows contain a surface layer with uniform $^{210}$Pb activity, which quickly reaches supported levels. These $^{210}$Pb profiles indicate a relatively uniform layer of sediment that has been mixed by either biological or physical processes and overlie an older unit. Within the basin-low of transect 2 the high-activity spike at a depth of around 110 cm is further indication that this basin-low is likely affected by slumps from the basin edge. Transect 1 differs from the other transects in that accumulation rates are uniformly high, including within the basin low. This observation is consistent with the thick sediment lobe observed in the sub-bottom profile for this transect.

5.1.2. Southern shelf

In transect 4 the thickness of the sediment overlying the shallowest reflector within the topographic low is fairly uniform, indicating that deposition and subsequent preservation of material is occurring at similar rates along the topographic low and plateau. Within transect 4 all of the $^{210}$Pb profiles can be classified as non-steady evident by the presence of low activity spikes within each profile. KC 4E was collected within a canyon along the slope, indicating that the same mechanisms responsible for the existence of the low-spikes in $^{210}$Pb activity acting along the outer-shelf have affected regions as far seaward as the slope.

5.2. Evidence for contrasting sediment dispersal modes

5.2.1. Steady-state

Steady-state $^{210}$Pb profiles are expected when there is a constant accumulation of sediment with uniform initial activity values in a region. The northern basin area is dominated by these types of profiles with few exceptions.

The decreasing $^{210}$Pb accumulation rates moving from transect 1 to transect 3 (Figs. 3–5B), increasing degree of reworking shown within the X-radiograph images (Fig. 7), and the persistence of the sediment lobe throughout the northern region (Fig. 3–5A) suggest that the dominant mechanism of transport is through hemipelagic settling, with maximum deposition occurring furthest north. X-radiographic observations of laminated sediments in transect 1 eliminates the possibility that the steady-state profiles present were somehow “smoothed” by intense bioturbation in the surface mixed layer. Furthermore, the idea that hemipelagic settling dominates in this area is consistent with the observed offshore increase in sediment accumulation rate with corresponding increase in the thickness of the
sediment lobe in the northern area, suggesting that local oceanographic circulation patterns could play a dominant role in focusing sediments seaward of the basins.

5.2.2. Non-steady-state

In contrast with the northern basins, the southern transect reveals distinctive non-steady character at all of the sites cored. Four mechanisms have been identified which could allow for the development of non-steady-state profiles in this area. One possibility is that grain-size is affecting the $^{210}$Pb activity due to the change in scavenging potential as a function of particle surface area (He and Walling, 1995). Another potential cause is a mass movement of $^{210}$Pb poor sediments into the system. Additionally, during large floods which result in extensive surface (hypopycnal) plumes, the greatly increased amount of suspended-sediments deplete available $^{210}$Pb from the water column at greater rates than it is being supplied to the region through advection of oceanic waters (Sommerfield et al., 1999). Alternatively, sediment-gravity flows could be responsible for the intervals with decreased $^{210}$Pb excess activities. When a gravity flow is produced it is transported along the seafloor with less interaction with the seawater compared to that of sediments delivered via surface plumes thereby scavenging less $^{210}$Pb from the water column (Kineke et al., 2000). These latter two mechanisms both posit supply-limited $^{210}$Pb scavenging as the cause of low particle activities, but differ in terms of transport mode. The viability of each of the four mechanisms in contributing to observations of non-steady-state on our study area is discussed below.

Grain size analysis was performed to determine whether the low activity spikes were a function of changes in grain-size throughout the length of the core. If changes in grain-size were the cause of the low-activity spikes then it would be expected that larger grains would be detected at the lower-activity intervals. In fact, just the opposite is observed. For example, the presence of clay-rich layers in KC 4C coincides with the low $^{210}$Pb spikes (Fig. 9). A similar observation was made by Sommerfield et al. (1999) on the continental margin off the Eel River, who attributed the correlation of clay-rich layers and low $^{210}$Pb spikes to major river flood events. We can confidently rule out the possibility that particle surface area controls non-steady-state profiles in our study area based on our grain-size analyses.

Within the northern region, two non-steady profiles are present (KC 2B and KC 3C) within the topographic lows of the bi-lobed basin. The non-steady nature of these cores, compared to the adjacent cores on each transect, the presence of a relatively uniform surface mixed layer with activities that quickly drop to supported values, and the location within a topographic low are consistent with the idea that slumping from the nearby slopes has affected these sites. Although slumping seems plausible in the northern basins, the absence of steep erosional slopes adjacent to all of the non-steady sites in the south indicates that other mechanisms are at play here.

Rapid across-shelf delivery of sediment from the river mouth, as would be predicted from a major flood or hyperpycnal flow, would be expected to result in a sediment deposit with a dominantly terrestrial signature. Organic carbon analyses of kasten cores from the northern (KC 3C) and southern (KC 4C) areas reveal a remarkable contrast; whereas the non-steady-state core from the south (KC 4C) has a strong terrestrial signature with indication of vascular plant material, the northern core (KC 3C) has a consistent mixed marine/terrestrial signature (Fig. 8). This observation of such contrasting organic carbon signatures, with both sites being equidistant from the river mouth, suggests a divergence in the method of transport delivering sediment to the outer shelf. Although we cannot completely rule out the possibility that a large flood-derived surface plume may be directed off-shelf exclusively over the region of the southern trough, this scenario...
seems unlikely given that surface plumes are steered by prevailing surface currents, which could vary between floods and hence should result in more widespread deposition and a more consistent carbon signature between the northern and southern areas. The non-steady $^{210}$Pb profiles in the south, together with a terrestrial C3 vascular plants downcore carbon signature existing exclusively within the southern trough-like feature suggest that the rapid offshore transport of riverine material to this trough occurs predominantly as near-bed sediment-gravity flows.

5.2.3. Temporal and spatial variations in sediment delivery to the outer shelf

Although the sediment input to the southern trough appears to be dominated by rapid across-shelf transport, probably as hypervcynal flows, analysis of surface sediment suggests that this input is episodic. Organic carbon analyses of surface samples (0–1 cm box core interval) allow us to assess the origin of organic material deposited within the few months preceding sample collection (as opposed to longer-term averages evident in downcore analyses). The results show that the most recent sedimentation has a mixed marine and terrestrial signal, similar to the downcore record for the northern core KC 3D (Fig. 8). This observation suggests that surficial sediment in both the northern and southern areas has been delivered primarily by hemipelagic settling in the few months prior to core collection. Independent support for this conclusion comes from the analysis of $^7$Be activities in the same samples, which reveal very low specific activities across the region. As $^7$Be is an effective marker for recent rapid flood sediment delivery to the shelf, the absence of a significant $^7$Be signal is consistent with the idea that no such inputs occurred immediately prior to our sampling. Taken together, results of the downcore and surficial analyses imply that over a 100-year time scale the material preserved in the southern region is primarily a result of sedimentation during episodic transport events, and that the more marine dominated sediment, although present at the surface, is not effectively preserved over the longer term. In contrast, the northern area appears to preserve the mixed marine/terrestrial signal in both surface and downcore records, suggesting an absence of episodic inputs in this area.

6. Conclusions

Major conclusions for this study include:

• The northern and southern outer-shelf regions off the Waiapu River receive sediment inputs from contrast- ing transport modes, where sediment-gravity flows dominate inputs to the southern trough in contrast with more steady hemipelagic sedimentation in the north.

• In the northern region, higher $^{210}$Pb accumulation rates, moving seaward from the basins is likely caused by focusing effects of local circulation patterns. This focusing appears to have been maintained over longer time scales based on agreement between the $^{210}$Pb rates and seaward thickening of the Holocene sediment lobe observed in the seismic reflection record.

• Although fine-grained sediments with $\delta^{13}$C signatures between typical terrestrial C3 plants and marine end-member values are found in surficial sediments throughout the area, the subsurface sediments in the southern trough have values indicating a greater long-term terrestrial contribution.

References


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