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Recent sedimentation patterns and facies distribution on the Poverty Shelf, New Zealand

Lila E. Rose *, Steven A. Kuehl

Virginia Institute of Marine Science, College of William and Mary, 1208 Greate Road, Gloucester Point, VA 23062, USA

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ABSTRACT

Modern sediment dispersal and accumulation on the Poverty Shelf off the Waipaoa River, New Zealand, is investigated using X-radiographic, radio-isotopic and physical property analyses of nearly 200 box and Kasten cores collected in January 2005 aboard the *R/V Kilo Moana*. The high-yield, small mountainous Waipaoa River empties onto a tectonically active, narrow margin and represents an important analog for shelf sedimentation in similar environments worldwide. X-radiographs and bulk-density measurements from a multi-sensor core logger show three distinct facies on the shelf where physical and/or biological factors dominate strata formation. Spatial distribution of these facies delineates a radial pattern with distance from the river mouth, from areas dominated by stratified layers on the inner shelf to mottled muds on the outer shelf, demonstrating a continuum of controls from wave reworking to episodic and extreme wet event sedimentation, despite a tectonic framework that supports rapid accumulation in two recently identified shelf depocenters. Analysis of short-lived ^{7}Be ($t_{1/2}=53$ days) reveals a broad spatial distribution across- and along-shelf in surface sediments, suggesting rapid transport from the Waipaoa source. However, beryllium-7 inventories are consistent with centennial-scale trends observed by other researchers using longer-lived ^{210}Pb analyses, with highest inventories in the shelf depocenters. Box core bulk-density analyses show lower than average bulk densities within these depocenters, and higher than average bulk densities on the inner shelf and between the depocenters. These observations confirm rapid deposition of low-density muds in the depocenters, with higher bulk-density, possibly physically reworked sediments, remaining off the mouth of Poverty Bay and between the depocenters. Based on this single observational period, there appears to be no fundamental difference between seasonal and longer-term accumulation patterns on the Poverty Shelf.

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1. Introduction

Processes governing siliciclastic sedimentation on continental shelves involve tectonic, climatological, physical, biological, geochemical and morphodynamic factors that interact along a spectrum of space and time scales, and ultimately control fine-scale sedimentary structures and shelf stratigraphy. Historically, much attention has focused on large river systems located on passive margins, which often present shelf accumulations exhibiting clinoform geometry. This archetypal river system is characterized by a vast catchment area, low sediment yield and suspended sediment concentration entering the coastal ocean onto wide continental shelves. Examples include the Amazon, Niger, Mississippi, Ganges–Brahmaputra, and Yangtze Rivers, among many others.

A recent paradigm shift has illuminated the disproportionate impact of small, mountainous riverine systems in supplying sediment to the global ocean, conservatively estimated at an annual flux of 20 Bt (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Syvitski et al., 2005). Small mountainous rivers are typically characterized by steep gradients, large loads (relative to catchment area and river discharge), high sediment yields and are often located on tectonically active margins whose catchments are strongly impacted by regional precipitation and periodic wet storm events (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Walsh and Nittrouer, 2009). Wet storms, as defined by Wheatcroft (2000), are storm events with concomitant rain on land and elevated wave action on the continental shelf. Work in these systems (e.g. Eel, Columbia, Waiapu) highlights their ability to disperse sediment efficiently and reveals that adjacent continental shelves are often the repository of terrestrial materials and record event responses of rivers within their strata (e.g., Miller and Kuehl, this issue; Sommerfield and Nittrouer, 1999; Crockett and Nittrouer, 2004; Blair et al., 2004; Brackley, 2006; Nittrouer et al., 2007; Wadman and McNinch, 2008).

The Waipaoa River, located on the tectonically active east coast, North Island, New Zealand is a small, steep, high-yield mountainous river system that is one of two focus areas in the Margins Source-to-Sink (S2S) program (MARGINS, 2003). The Waipaoa Sedimentary System (WSS; includes the Waipaoa River, Poverty Shelf and Slope) was chosen to investigate the dynamic changes in sediment transfer from land to sea with reference to global climate change, anthropogenic influences and tectonic forcing. Strong sedimentary signals and accumulation rates on

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* Corresponding author. Tel.: +1 804 684 7679; fax: +1 804 684 7250.
E-mail addresses: lilarose@vims.edu (L.E. Rose), Kuehl@vims.edu (S.A. Kuehl).

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the order of 1 cm yr^{-1} on the Poverty Shelf (Miller and Kuehl, this issue; Orpin et al., 2006) suggest the shelf strata might contain a high-resolution record of sedimentation over the last century. The primary objective of this study is to characterize recent (seasonal to decadal timescales) sediment distribution and modern strata on the Poverty Shelf using X-radiograph and radio-isotopic analyses. Spatial distribution of sedimentation patterns and facies from X-radiographs, ^{7}Be, and sediment bulk-density measurements from nearly 200 sediment cores serve as the basis for this study. This paper compliments the work of Miller and Kuehl (this issue) who determined centennial-scale accumulation rates and a sediment budget for the Poverty Shelf using ^{210}Pb geochronology.

2. Regional setting

The Waipaoa River drains a small catchment (2205 km^2) along the actively deforming Hikurangi Margin, between the Pacific and Australian plates (Fig. 1). Annual average sediment yield for the Waipaoa is ~6800 t km^{-2} yr^{-1}; however, annual sediment delivery to the marine environment varies widely, dependant on the magnitude and frequency of storm events (Hicks et al., 2004). Tectonism causes regional uplift in the catchment's headwaters of up to 4 mm yr^{-1} with concomitant subsidence along the coastal Poverty Bay Flats and Poverty Shelf (Brown, 1995; Foster and Carter, 1997). Over 95% of sediment from the East Cape derives from soft, fine-grained rocks, including fissile Cretaceous to Paleocene mudstone and argillite in the headwaters of the Waipaoa to Tertiary siltstone and mudstone in the lower basin (Foster and Carter, 1997; Page et al., 2001; Hicks et al., 2004). Gully erosion within the catchment is an important modern erosional process, and frequent landsliding occurs during extreme rainfall events (Hicks et al., 2000).

Imprinted upon the natural geomorphologic catchment characteristics is a long history of human disturbance. Polynesian settlers to the east coast, North Island (ca. 700 y BP) initiated widespread and aggressive burning of indigenous forest (Wilmshurst et al., 1997; Wilmshurst, 1997). Further land-use changes, post-European arrival, included continued deforestation and conversion of scrubland to pasture, destabilizing the landscape and causing regular mass failures. The result is increased erosion rates up to 6 times greater than pre-European settlement (Page et al., 1994a,b; Wilmshurst, 1997; Wilmshurst et al., 1997; Eden and Page, 1998; Tate et al., 2000; Page et al., 2000, 2001). Due to the combination of highly erodable lithologies within the catchment, increased erosion attributed to land-use practices, and an annual average rainfall of between 1 and 2.5 meters, the Waipaoa River supplies an average total annual sediment load of between 13 and 15×10^6 t yr^{-1} to the ocean (Griffiths, 1982; Hicks et al, 2000). Significant storm events, associated with mass wasting and flushing of stored catchment sediments, such as the 100-year Cyclone Bola in 1988, can increase the annual load considerably (Page et al., 1994a,b; Brackley, 2006).

Waipaoa River effluent enters Poverty Bay (Fig. 1) via hypopycnal flow during fair-weather conditions and is speculated to be transported via hyperpycnal flow during intense wet storm events with a recurrence interval on the order of 40 years (Foster and Carter, 1997; Hicks et al., 2000). Under typical conditions it is entrained into an anticlockwise gyre before being transported to Poverty Shelf (e.g., Stephens et al., 2001; Brackley, 2006; Wood, 2006). According to Wood (2006), fair-weather conditions on the Poverty Shelf are characterized by wave heights of 1.11 m and periods of 7.71 s during which “mud-activating

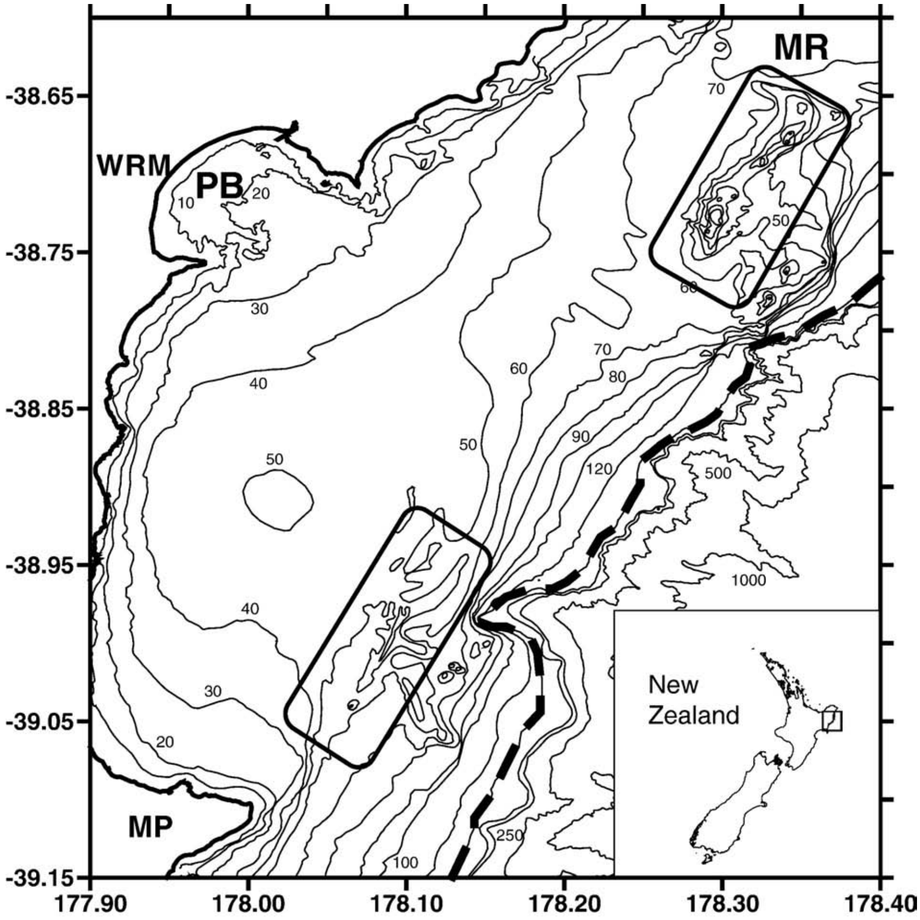

Fig. 1. Location map of New Zealand with study area enlarged to show shelf bathymetric isobaths (in meters; courtesy NIWA). Dashed bold line indicates the approximate shelf break at 150 m water depth. Ariel (north) and Lachlan (south) anticlines are identified with rectangles. WRM = Waipaoa River Mouth, PB = Poverty Bay, MR = Monowai Rocks, MP = Mahia Peninsula.

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wave base" (depth of wave-induced non-cohesive mud resuspension) is 30.2 m, whereas storm conditions typically display wave heights of 1.98 m, periods of 9.41 s and a mud-activated wave base of 52.3 m. Local Poverty Shelf and Slope current circulation is not well documented, however the extension of the Wairarapa Coastal Current around the Mahia Peninsula is thought to create a mean ambient current flow to the northeast along the shelf, which can be intensified by storm swell from the south (Chiswell, 2000; Stephens et al., 2001; Wood, 2006). At the shelf break, seaward of the Ariel and Lachlan anticlines, the warm, saline East Cape Current travels south (Carter et al., 1996; Foster and Carter, 1997; Chiswell, 2005).

Previous investigations of the WSS identified increased modern sedimentation rates and a fining-upwards signature in shelf cores, interpreted to be a result of deforestation, agriculture and Holocene climate change (Wilmshurst, 1997; Foster and Carter, 1997; Gomez et al., 2004). A single depocenter or "mid-shelf mud belt" of accumulating sediments on the inner and middle Poverty Shelf, morphologically controlled by a synclinal basin, was previously identified using seismic reflection studies and analysis of surface sediments (Foster and Carter, 1997). Mud dispersion on the shelf is thought to be controlled primarily by wind and associated currents and sediment supply (Foster and Carter, 1997). It was speculated that relatively little sediment input by the Waipaoa escaped to the outer shelf and beyond because of the tectonic barrier created by the Lachlan and Ariel anticlines, Mahia Peninsula and Monowai Rocks on the northern Poverty Shelf, resulting in a seemingly "closed" system (Foster and Carter, 1997; Brackley, 2006). This interpretation has been revised based on high-resolution seismic and ^{210}Pb analyses from the January 2005 *R/V Kilo Moana* cruise, with the identification of two discrete mid-shelf depocenters (Fig. 2) separated by a region of little net accumulation (the bypassing region) as well as a third depocenter at the shelf break (Miller and Kuehl, this issue; Gerber et al., this issue; Orpin et al., 2006; Kuehl et al., 2006). Also, Walsh et al. (2007) noted an area of off-shelf export near Lachlan Canyon although its role in the budget is not well quantified. Wood and Carter (this issue) classify several facies based on grain size modalities of surficial sediments and also recognized the three distinct depocenters.

3. Materials and methods

3.1. Sampling plan

A suite of 87 box cores (maximum length 61 cm; Fig. 2) were collected in a dense grid on the shelf adjacent to the Waipaoa River, aboard the *R/V Kilo Moana*, during low-flow conditions (Fig. 3) in January 2005. An Ocean Instruments BX-series Box corer was used to collected cores between ~26 and ~75 m water depths, with a few at deeper sites, seaward of the two anticlines. Box cores typically retrieve up to 0.5 m of sediment and almost always preserve the sediment–water interface, useful for evaluation of the spatial and temporal distribution of surface seabed sediment characteristics on the continental shelf. If the sediment surface was clearly disturbed due to improper deployment, a second core was attempted and if washout was evident, the core was carefully subsampled only if the washout section could be avoided. A set of 85 Kasten cores (maximum length 270 cm) were also retrieved for radio-isotopic and sediment budget analyses at almost all of the box core sites (Miller and Kuehl,

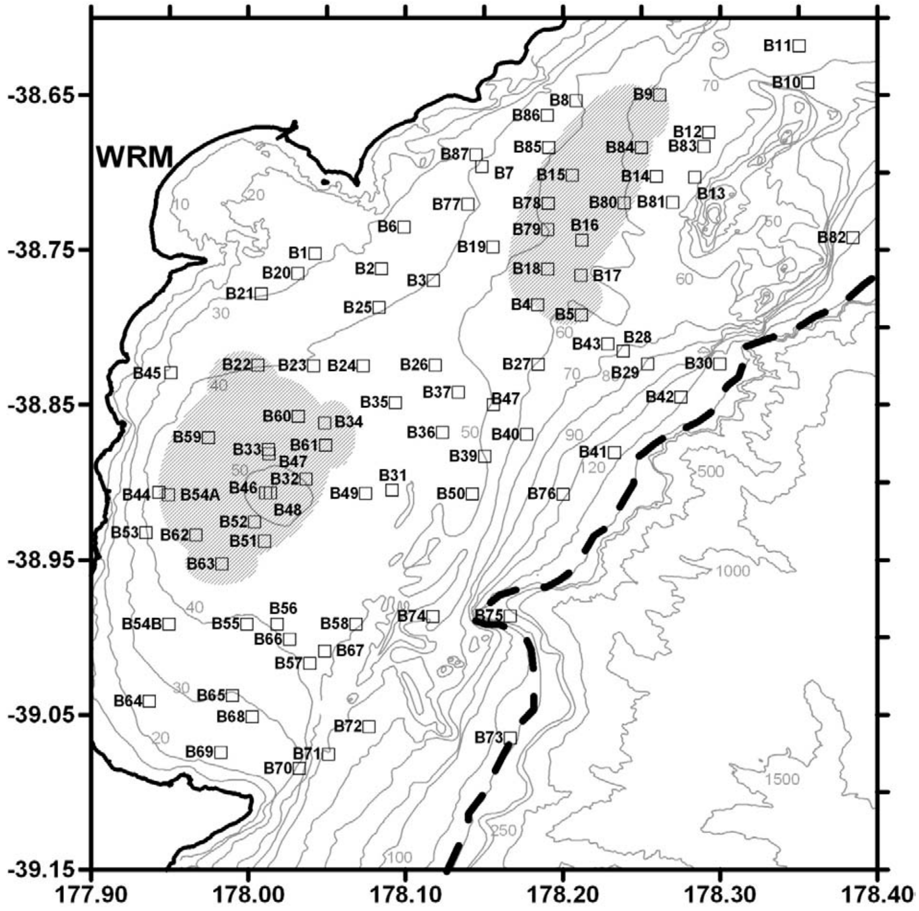

Fig. 2. Locations of 87 box cores collected on the Poverty Shelf in January, 2005 aboard the *R/V Kilo Moana*. Locations of cores are denoted by black squares and core names are labeled in bold (e.g., **B1**). Shaded regions delineate southern and northern depocenters defined by ^{210}Pb accumulation rate data (>0.5 cm yr^{-1} accumulation) from Miller and Kuehl (this issue). Dashed line indicates the approximate shelf break at 150 m. WRM = Waipaoa River Mouth.

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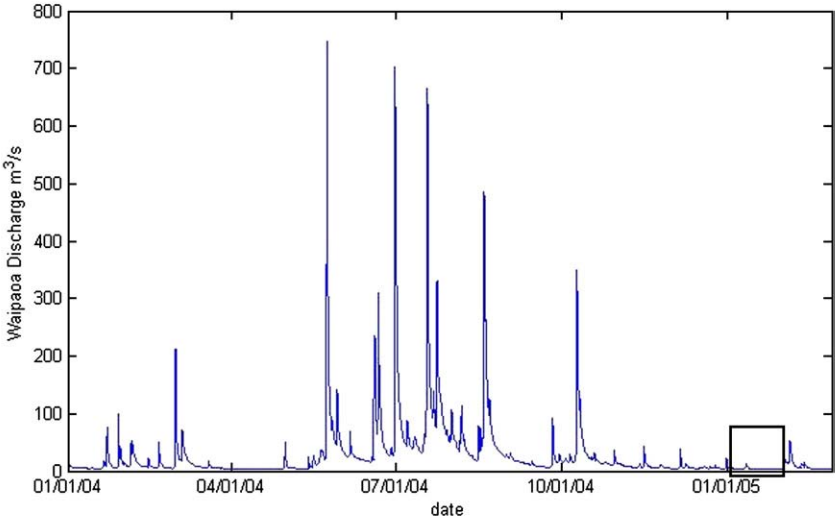

Fig. 3. Waipaoa River discharge at Kanakanaia from January 1, 2004 to February 28, 2005. Bold rectangle indicates time of cruise. Note that there was a roughly 3-month period where no high discharge events were recorded prior to the cruise.

this issue). Accumulation rates derived from these Kasten cores were used to define specific regions along Poverty Shelf (Fig. 2).

3.2. X-radiography

Digital X-radiographic negatives were obtained from 2.5-cm-thick rectangular subcores of each box core, providing a nearly instantaneous image of sedimentary structures within a core. X-radiographs show relative changes in sediment bulk-density downcore; high bulk-density sediment, such as pebbles, shell hash or sand reduce X-ray penetration and result in light greys, whereas low bulk densities are seen as dark grey or black. Using Varian Paxscan® Imaging software (VIVA), each image was adjusted for optimal balance and contrast, and full cores were mosaiced together using Adobe Photoshop®. Digital X-radiographs were characterized by the degree of bioturbation along with identification of primary and secondary sedimentary structures. Based on these observations, facies distributions on the shelf were determined and then mapped.

3.3. Bulk-density

On-board processing of box cores included use of a Geotek® Multi-Sensor Core Logger (MSCL) to record continuous downcore physical properties including gamma attenuation, *p*-wave velocity, magnetic susceptibility (SI) and derived acoustic impedance. MSCL measurements were made at centimeter and half-centimeter intervals. Subsamples were taken every 20 cm for laboratory bulk-density measurements and were used to ground-truth the MSCL bulk-density and porosity logs. Wet bulk-density and fractional porosity were calculated using gamma ray attenuation, and dry bulk-density was then calculated assuming a grain density of 2.65 $\mathrm{g\,cm^3}$ (quartz) and water density of 1.025 $\mathrm{g\,cm^3}$. All bulk-density measurements reported herein are dry bulk-density.

3.4. ^{7}Be

^{7}Be is a cosmogenic radionuclide that decays by beta emissions and is useful in tracking recent river sediment dispersal on the order of months/seasons to the shelf (e.g., Sommerfield et al., 1999). Measurements of ^{7}Be ($t_{1/2}=53$ days) were performed immediately upon conclusion of the cruise. Surface sediment samples (from 0 to 1-cm depth) from each box core were prepared for gamma spectroscopy analyses on one of three LEGe (Low Energy planar intrinsic Germanium) detectors. Samples were homogenized and wet-packed into Petri dishes and counted for 90,000 s. Specific activity (dpm $\mathrm{g^{-1}}$) was calculated using the ^{7}Be peak intensity at 477 keV. Detector efficiency was determined by calibration with a mixed gamma standard. If ^{7}Be was detected at the surface, samples were prepared, in discrete centimeter intervals of depth into core, until no activity was detected, resulting in a total of 202 samples analyzed.

4. Results

4.1. Sedimentary structures

X-radiographs show a variety of sedimentary structures (Fig. 4a–d) including prominent thick layers and thin laminations, a range of layer contacts from sharp to wavy and other structures such as cross-bedding, ripples and burrows. The extent of physical structures preserved was assessed qualitatively for each core, to visually distinguish percent core dominated by layers and laminations. Degree of bioturbation was also assessed qualitatively for each core, visually accounting for burrow frequency and mottling, as well-bioturbated sediments can often be hard to distinguish from unbioturbated homogenous pelagic sediments. Secondary sedimentary structures were also observed, including dewatering structures.

4.2. Bulk-density

Dry bulk-density measurements (calculated from MSCL fractional porosity) for box cores were averaged. Mean bulk-density for shelf cores was $1.21\pm0.22\ \mathrm{g\,cm^{-3}}$. The average bulk-density for each core from the surface to 5 centimeters depth was also determined, in order to compare with ^{7}Be measurements (see Section 4.3) which found the typical depth of ^{7}Be penetration to be 4–5 cm. Mean bulk-density of cores from the surface to 5 cm interval was $1.12\pm0.25\ \mathrm{g\,cm^{-3}}$. As an independent check on X-radiograph interpretations, MSCL dry bulk-density profiles were overlain onto them (Fig. 5) to look at relative changes downcore. Generally, the bulk-density profiles were in agreement with X-radiographs (i.e. higher bulk-density corresponded to lighter grey areas on the X-radiographs).

Distribution maps of average core bulk-density (Fig. 6a) and average bulk-density between the surface and 5 cm interval (Fig. 6b) reveal two central locations of low bulk-density on the shelf roughly consistent with the location of the northern and southern depocenters. Bulk-density data were broken into these two categories in order

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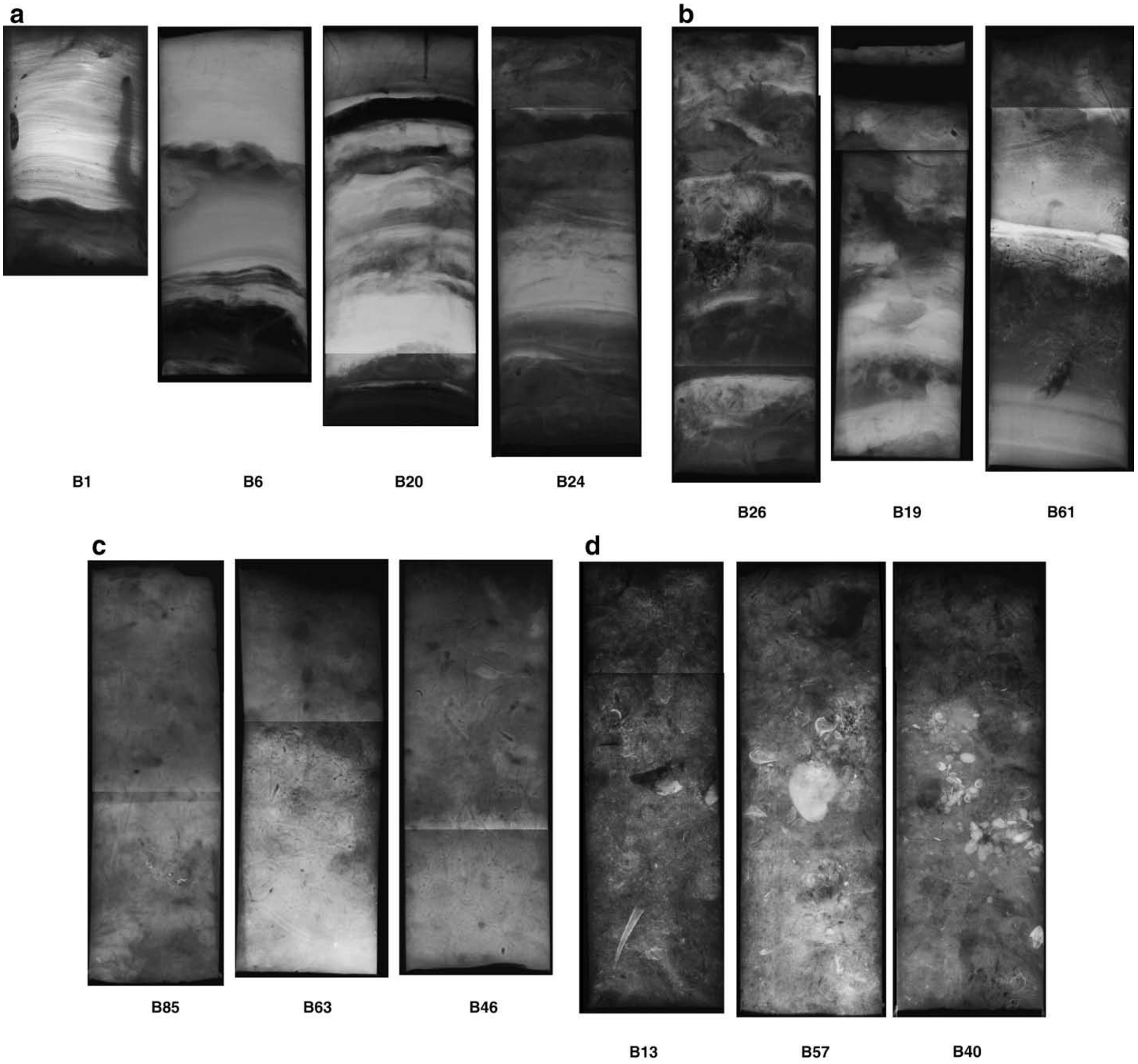

Fig. 4. X-radiographic examples of facies classifications from box cores on the Poverty Shelf. Images are X-ray negatives, where lighter greys = higher bulk-density; darker greys = lower bulk-density. The width of each X-radiograph represents 10 cm. X-radiographs are labeled with corresponding box core number. a) Interbedded/laminated muds and sands (ILMS) facies, ranging from physically laminated sands on the right to interbedded mud and sands on the left. b) Mixed layers and mottles (MLM) facies. c) Mottled muds (MM) facies. d) Shell hash and pebble rubble.

to eliminate the influence of any low-density surface layer to compare with whole core means as well as to compare with ^{7}Be measurements which found the typical depth of ^{7}Be penetration to be 4–5 cm. The highest bulk densities occur flanking the anticlines, associated with pebbles, gravel and shell hash found in these areas (Figs. 1, 4d) and offshore of the mouth of Poverty Bay associated with the ILMS facies, especially the physically laminated sands end-member (Fig. 4a).

Bulk-density data were plotted by shelf location: northern and southern depocenters, and bypassing and shelf regions (Fig. 7). These location designations were based on previous accumulation rate data derived from ^{210}Pb geochronology (Miller and Kuehl, this issue; Fig. 2). Not surprisingly, surface samples always had lower bulk densities than the whole core averages (Fig. 7). Unpaired *t*-tests found significant differences ($P<0.05$) in measured parameters of mean bulk-density and mean bulk-density from the surface to 5 cm interval between several of the designated shelf locations (Table 1A, B).

4.3. ^{7}Be

Average surface sample activity of ^{7}Be was 0.54 ± 0.50 dpm g^{-1} and ranged from no activity, adjacent to Poverty Bay and flanking the landward side of Lachlan Anticline, to 2.71 ± 0.03 dpm g^{-1} in the southern depocenter (Fig. 8a). ^{7}Be ($t_{1/2}=53$ days) specific activity from surface samples reveals a generally broad distribution across- and along-shelf, with highest activities in the southern depocenter (Fig. 8a). Activities exceeded 0.50 dpm g^{-1} in 40% of the surface sediments analyzed. Several shelf break cores also had moderate ^{7}Be surface sample activities. ^{7}Be was detected to 5 cm depth in some locations. The average

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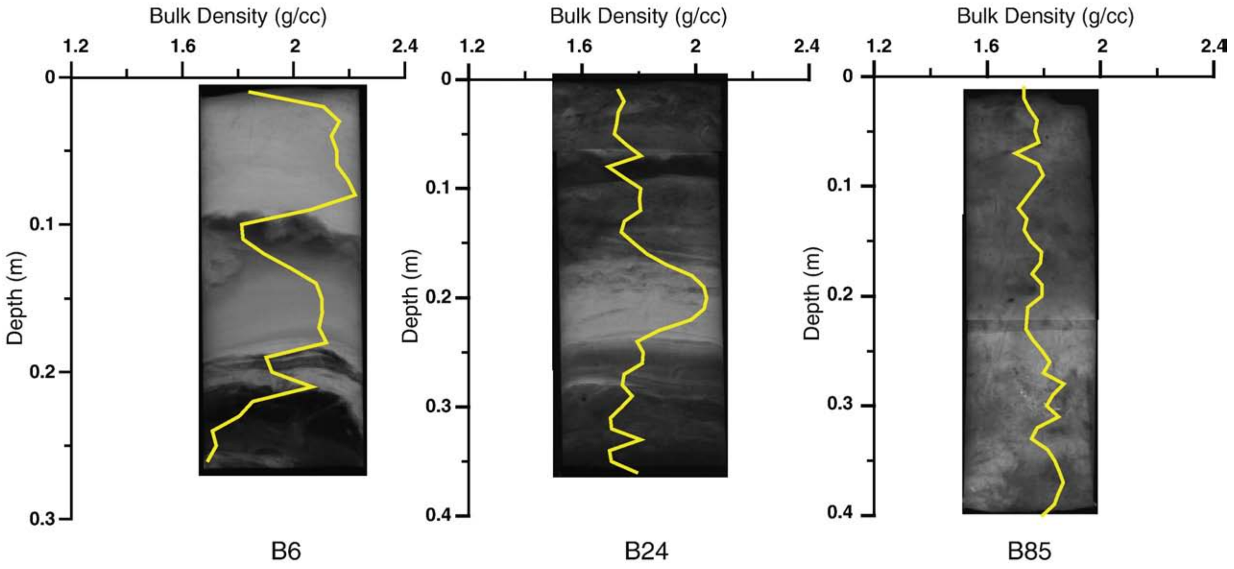

Fig. 5. Examples of X-radiographs from each facies classification with measured multi-sensor core logger (MSCL) bulk-density profiles overlain. B6 = ILMS; B24 = MLM; B85 = MM.

^{7}Be inventory for the southern and northern depocenters, the shelf break and the bypassing regions are 1.38 ± 0.96, 1.15 ± 0.93, 0.53 ± 0.62, and 0.59 ± 0.47 dpm cm^{-2} (respectively; Figs. 7, 8b). *T*-tests show that there are significant differences ($P<0.05$) in ^{7}Be inventory between the southern depocenter and the bypassing region, the southern depocenter and the shelf break, and the northern depocenter and the bypassing region (Table 1C).

5. Discussion

5.1. Facies descriptions and distribution

Cores were categorized based on the primary sedimentary structures and degree of bioturbation revealed by X-radiographs. Three dominant facies were identified on the Poverty Shelf as follows: (1) interlaminated muds and sands facies (ILMS), (2) mixed layers and mottles facies (MLM), and (3) mottled muds facies (MM; Fig. 4a, b, c). Examples of sediments that differ from these facies includes isolated samples of shell hash or well-rounded pebbles that flank the landward sides of both anticlines, and these are likely small pockets resulting from *in situ* shedding of emergent, highly fissile Cretaceous to Paleocene mudrock (Figs. 1, 4d). A distribution map of the three main facies was developed (Fig. 9), which reveals a broad, fan-like geometry radiating out from the mouth of Poverty Bay across- and along-shelf, reflecting the strong control of river sedimentation on Poverty Shelf.

5.1.1. Interbedded/laminated muds and sands (ILMS) facies

The ILMS extends along the inner shelf for ~20 km, seaward of Poverty Bay, and is comprised of physically laminated nearshore sands that grade offshore into interbedded sands and muds (Fig. 4a, Fig. 9). This facies is centered around 30–40 m water depth but is never deeper than 50 m. X-radiographs within the ILMS facies reveal considerable variability. For example, cores closest to Poverty Bay display finely laminated and crossbedded sands with climbing ripples (Fig. 4a; e.g., B1), indicative of energetic physical processes and rapid deposition, while others have alternate units of laminated sand and mud (Fig. 4a; e.g. B6, B24). Interbedding of muds and sands is observed, as well as more massive high-density graded units, some diffusely layered, punctuated by occasional lower density layers (Fig. 4a).

The ILMS facies are clearly the result of physical processes affecting emplacement on the seabed and syn- and post-depositional processes such as wave reworking, soft sediment deformation and winnowing. The ILMS facies is only found near Poverty Bay mouth, on the inner shelf above fair-weather wave base (Wood, 2006). High bed shear stresses from waves and currents hinder fine sediment from settling and benthic infaunal communities from forming in the shallow inner shelf waters (Wood and Carter, this issue; Foster and Carter, 1997; Brackley, 2006). Within the ILMS, the dissipation time for an event layer is likely extremely short due to the high physical energy of the system. The dissipation time of an event bed refers to the amount of time necessary to completely destroy it, while the transit time of a layer is the time it takes a signal to move from the mixed layer (where it is subjected to destruction by various physical and biological agents) to the zone of preservation (Wheatcroft and Drake, 2003; Wheatcroft et al., 2007).

5.1.2. Mixed layers and mottles (MLM) Facies

The ILMS facies quickly grades seaward into the narrow and elongate MLM facies (Figs. 4b, 9). The MLM facies is unconfined by bathymetry, fingering both across-shelf and along the mid-shelf, from the 30 m isobath south of Poverty Bay mouth to roughly 60 m water depth in the northern depocenter (9). Cores within the MLM facies displayed both physical and biological structures (burrows, tubes), often with partially intact layers disrupted by burrowing (Fig. 4b, e.g. B26). The MLM facies straddles a boundary environment where sedimentary strata record a dynamic balance between physical and biologic operators on the shelf. Layers are produced during times of higher wave energy or episodic sedimentation, reflecting oceanic storm conditions via southern swell and stochastic wet event sedimentation, respectively. Wholly or partially preserved sandier, high-density layers in this facies likely reflect higher bed shear stresses due to increased wave and current energy (Fig. 4b, e.g. B61), especially on the inner mid-shelf, above the storm-activated wave base. The MLM facies is interpreted to be where event layers are wholly or partially preserved, and transit time of a unit and dissipation time of a terrestrial signal are in constant flux. During

Fig. 6. Spatial distribution of average sediment dry bulk densities (g cm^3) along and across the continental shelf. The dashed line at 150 m indicates the shelf break. WRM = Waipaoa River Mouth. a) Average bulk-density of whole core. b) Average bulk-density from the surface to 5 cm depth of each core.

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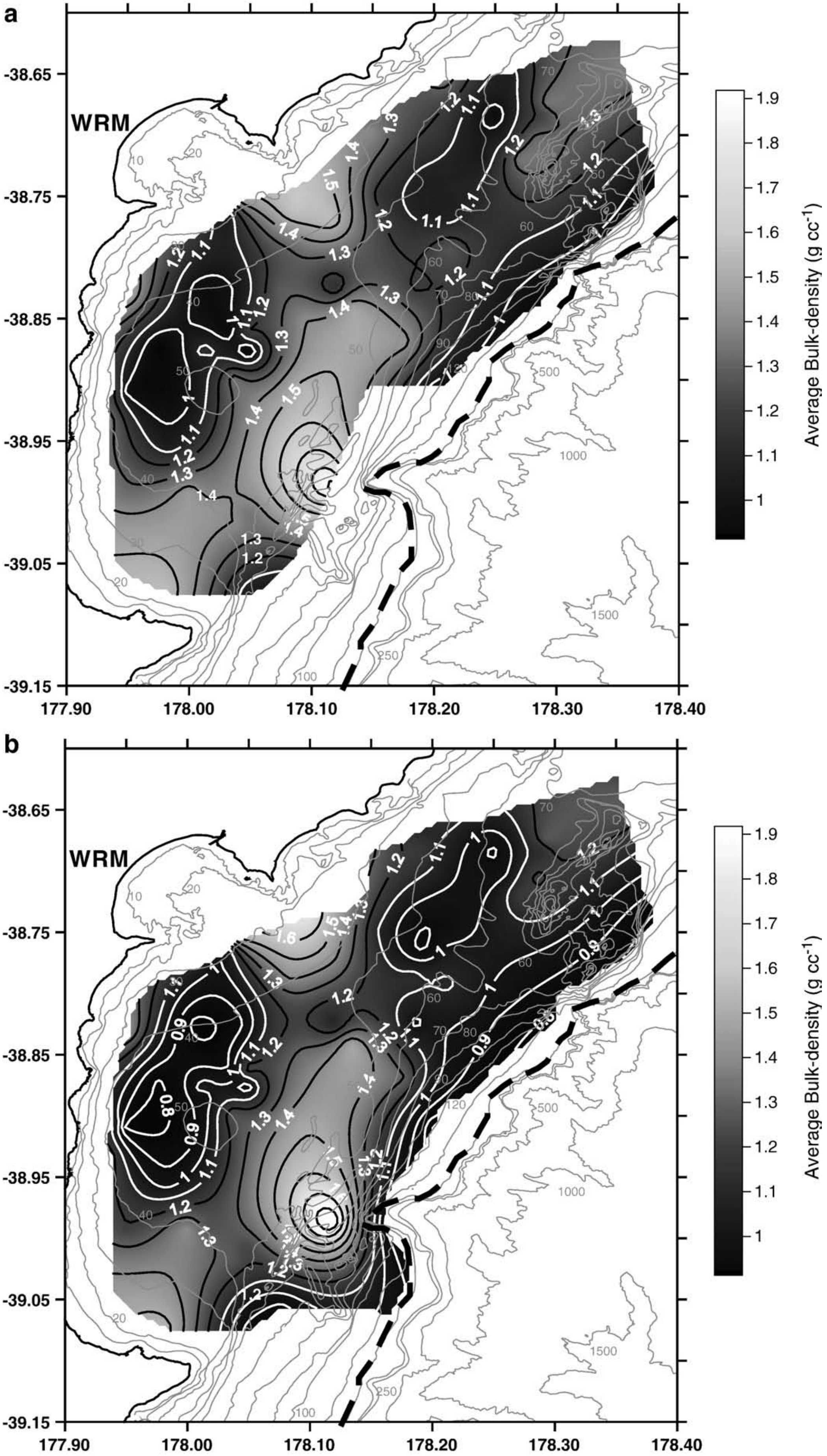

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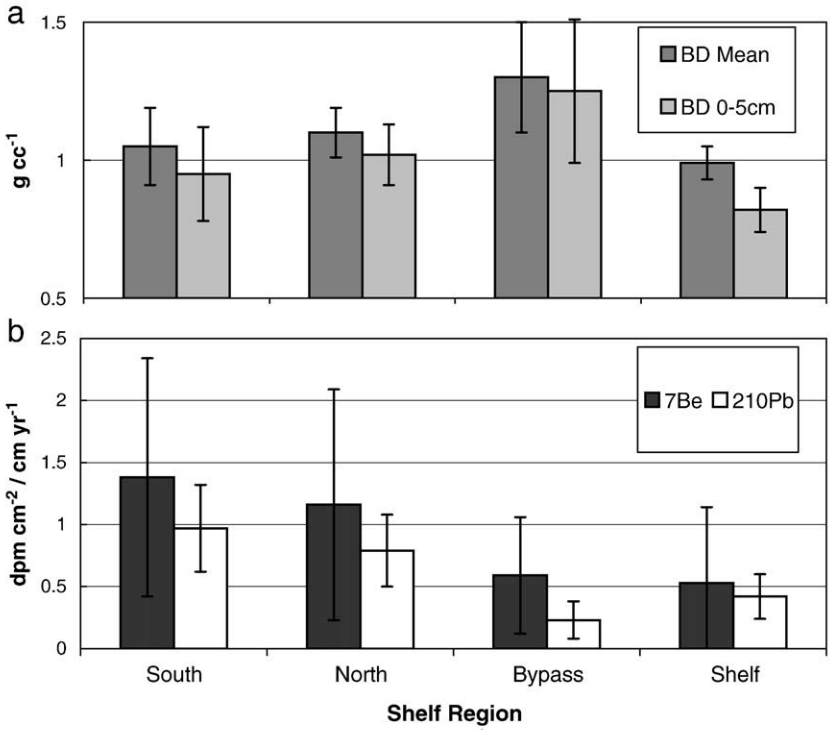

Fig. 7. Bar graph of measured sediment properties averaged by shelf regions with standard deviation from mean shown. Shelf regions (southern and northern depocenters, bypassing and shelf break areas) are defined by ^{210}Pb accumulation rate data from Miller and Kuehl (this issue). a) Bulk-density average and bulk-density from the surface to 0–5 cm interval average (g cm^3). b) ^{7}Be inventory (dpm cm^{-2}) and ^{210}Pb (cm yr^{-1}).

periods of increased sediment discharge (e.g., winter, when storm frequency and intensity increase and/or during large magnitude floods; Griffiths, 1982; Page et al., 2001; Hicks et al., 2004), strata are likely emplaced on the shelf within the MLM facies. This was seen with the unit deposited by Cyclone Bola in 1988 on the inner shelf (Brackley, 2006). A geochemically distinct storm sequence was observed on the mid-shelf, with increased clay content, percent organic carbon, and a terrestrial δ^{13}C signature (Brackley, 2006).

Table 1
T-test results (*P*-values) to test the differences in parameters between sub environments on the shelf.

	South	North	Bypass
A. Mean BD			
North	0.25		
Bypass	0.00*	0.00*	
Shelf	0.29	0.01*	0.00*
B. BD surface-5 cm			
North	0.26		
Bypass	0.00*	0.01*	
Shelf	0.07	0.00*	0.00*
C. ^{7}Be			
North	0.57		
Bypass	0.01*	0.03*	
Shelf	0.05*	0.14	0.83
D. ^{210}Pb			
North	0.21		
Bypass	0.00*	0.00*	
Shelf	0.00*	0.01*	0.03*

Significant results ($P < 0.05$) are indicated by an asterisk (*). Shelf regions (southern and northern depocenters, bypassing and shelf break areas) are defined by ^{210}Pb accumulation rate data from Miller and Kuehl (this issue). A) Mean bulk-density (g cm^{-3}). B) Mean bulk-density surface to 5 cm depth averages (g cm^3). C) ^{7}Be Inventories (dpm cm^{-2}). D) ^{210}Pb accumulation rates (cm yr^{-1}).

Benthic communities were also found to be significantly depleted in both abundance and diversity in this flood deposit (Foster and Carter, 1997; Brackley, 2006). This is akin to strata observed on the Eel River margin on the west coast of the USA during extraordinary wet storm sedimentation events (Leithold and Hope, 1999; Wheatcroft and Borgeld, 2000; Nittrouer et al., 2007). Primary structures, such as stratified graded beds, along with high bulk densities indicate that physical reworking plays a role in remobilizing and depositing sediments (Fig. 4b, e.g. B19, B61). However, these layers are partially destroyed by burrows and are intermixed with muddier, bioturbated sediment, emplaced during comparatively quiescent periods (Fig. 4b, B26). Burrows reveal a benthic community is sustained, likely during low-flow summer months and perhaps during normal hypopycnal pelagic sedimentation, especially as water depth increases below fair-weather wave base. This facies is thus interpreted to reflect a transitional depositional environment where both physically and biologically produced sedimentary characteristics can be distinguished. Based on observations on the Eel margin, the greatest potential for preservation of terrestrial signals on the Poverty Shelf would likely be from wet storm event layers emplaced within the MLM facies in the depocenters, where Miller and Kuehl (this issue) record the highest shelf accumulation rates.

5.1.3. Mottled mud (MM) facies

The MM facies extends along- and across-shelf from the MLM facies to the shelf break (Fig. 9). The MM facies (Fig. 4c) is indicative of strong bioturbation/reworking of sediment resulting in the destruction and loss of visible primary physical sedimentary structures. Evidence of these organisms includes burrows and burrow remnants and tubes, which create the “mottled” character of this facies. According to Wood (2006), only under storm conditions is mud resuspended deeper than 50 m water depth on the Poverty Shelf; the relatively infrequent physical disturbance creates a favorable environment for benthic biogenic activity. Living organisms were retrieved during coring, including worms, brittle stars and shrimp;

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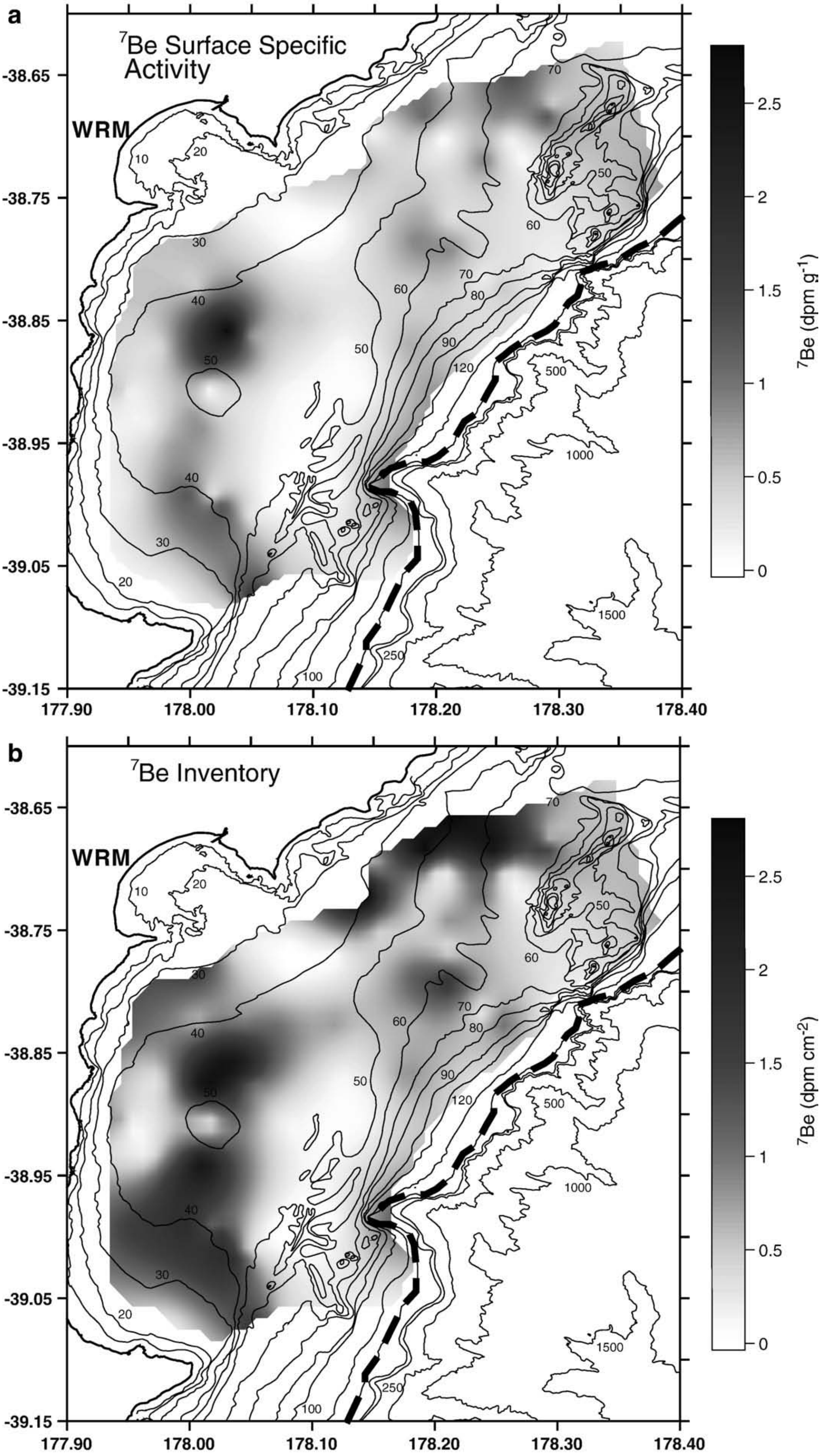

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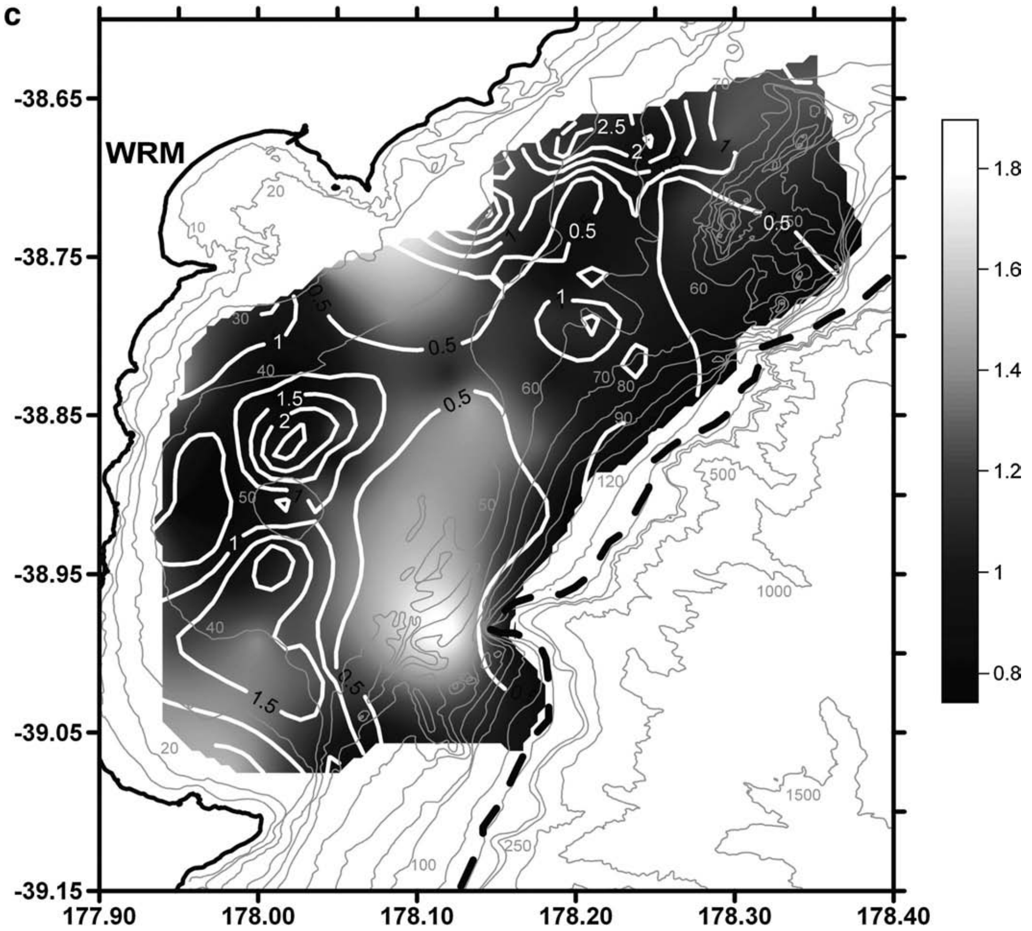

Fig. 8. Spatial distribution of ^{7}Be surface specific activities (dpm g^{-1}) and inventories (dpm cm^2) on the continental shelf. Scale and color bar are the same for each map. The dashed line at 150 m indicates the approximate shelf break. WRM = Waipaoa River Mouth. a) Surface (0–1 cm) specific activity (dpm g^{-1}). b) ^{7}Be inventories (dpm cm^{-2}). c) Average surface-5 cm bulk-density (g cm^3) with ^{7}Be inventory (dpm cm^{-2}) contours overlain.

scaphopod and various bivalve shells were also present in cores of the MM facies. Although physical primary sedimentary structures are absent, geochemical results indicate that extremely large, episodic floods or storms, like the 100-year Cyclone Bola (1988) event, remain identifiable by grain size and stable isotopes even if not visually detectable in X-radiographs (Gerald and Kuehl, 2006; Brackley, 2006).

5.2. *^{7}Be activity and sediment dispersal*

As ^{7}Be supply on a river margin derives primarily from riverine input (e.g., Sommerfield et al., 1999), its distribution provides evidence that Waipaoa River sediment is broadcast throughout the Poverty Shelf over short timescales and that some sediment rapidly bypasses the anticlines and is transported to the outer shelf and slope (Fig. 8a). The only locations where surface activities were not detectable included the landward flank of the Lachlan Anticline, where surface sediments are coarse (Fig. 4d) and possibly derived from erosion of uplifted material, and directly at the mouth of Poverty Bay, where surface sediments are reworked and mainly sandy (ILMS facies; Fig. 4a). ^{7}Be inventory measurements (activity integrated over depth) are important because they can enable distinguishing between isolated, recent deposition or more persistent, thicker (and potentially) more continuous deposition. ^{7}Be inventories clearly reveal highest deposition to be within the southern and northern depocenters, with modest presence outside the depocenters (Figs. 7b, 8b). Sample collection was during the austral summer, during which the east coast of the North Island experiences characteristically reduced wet storm frequency (Page et al., 1994a,b; Wilmshurst, 1997). Discharge measurements at Kanakanaia gauging station on the Waipaoa River show it was experiencing low-flow conditions prior to and during sampling, with the most recent high discharge in October 2004 (Fig. 3). ^{7}Be inventories reported here are consequently considered to be conservative values.

The northern and southern depocenters have similar ^{7}Be surface activities and inventories; there is no statistically significant difference in variation of ^{7}Be inventories or ^{210}Pb accumulation rates of the depocenters (Table 1C, D). Although water depths are similar within the depocenters, the locus of highest ^{7}Be activity in the northern depocenter is closer to shore than that of the southern depocenter (Fig. 8b). A broad, wedge-shaped area emanating from southern depocenter also has high inventories, suggesting rapid river effluent transport in this direction; this area is also sheltered by the Mahia Peninsula (Fig. 8b) and may be subject to less intense wave reworking, increasing deposition. In contrast, the areas directly offshore of Poverty Bay and along the bypassing region between the two mid-shelf depocenters are notably devoid of ^{7}Be activity (Fig. 8b). The zone offshore of Poverty Bay, above fair-weather wave base (Wood, 2006), is interpreted to be highly reworked (ILMS; Fig. 4a), and comprised largely of sandy, high bulk-density sediments (Fig. 8c). Here, ^{7}Be-bearing particles such as clay and silt are either never deposited or preferentially removed by wave reworking.

Inventory and surface activities of ^{7}Be at the shelf break, where low bulk-density muds are found, are relatively low compared to the depocenters (Figs. 7, 8c). Lower ^{7}Be inventories on the shelf break could be due to anomalous short-term sedimentation, longer sediment transit times to this location as well as the slower accumulation rates in comparison to the northern and southern shelf depocenters. Sediment

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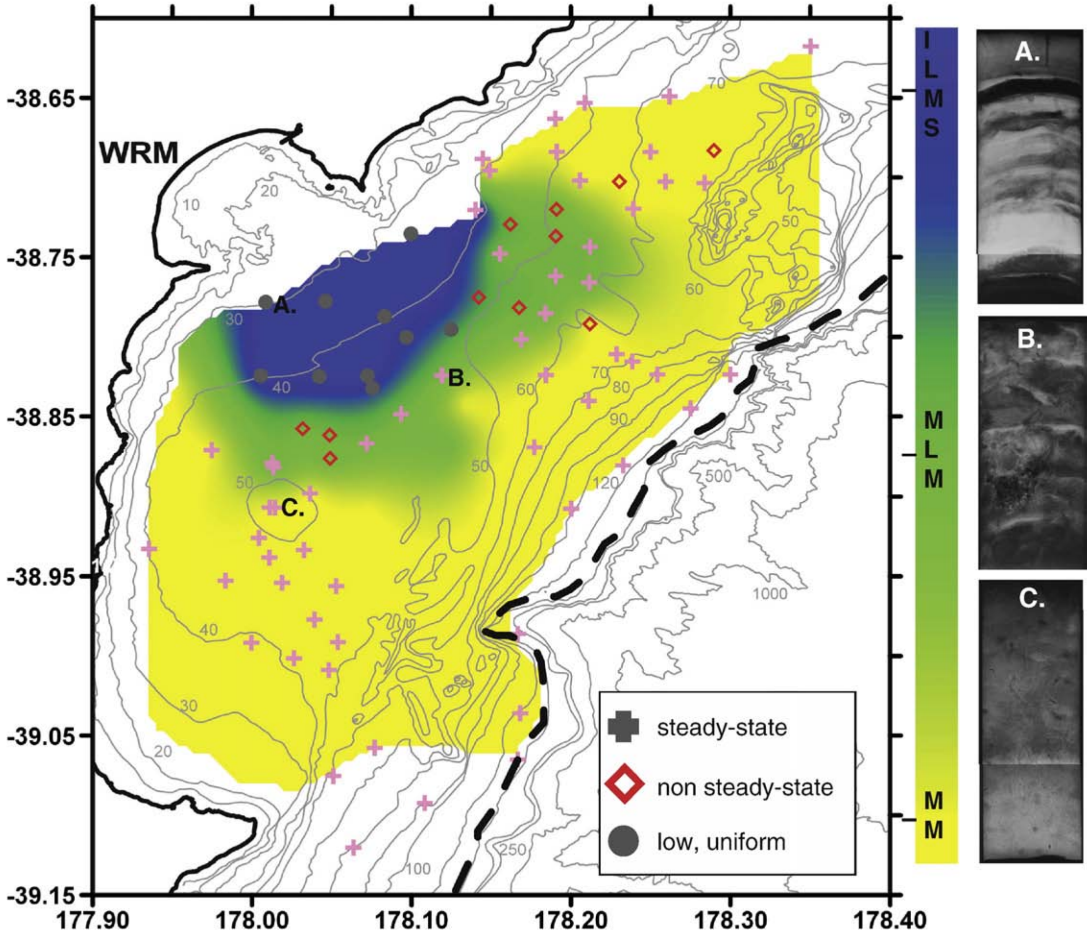

Fig. 9. Spatial distribution of regional facies on Poverty Shelf with characteristic ^{210}Pb activity profiles from Kasten Cores overlain. Golden Software Surfer® was used to map the distribution of facies. A raster map based on a grid is applied to the facies designations (from Fig. 4) and then the image is color-smoothed. X-radiographic examples of each facies are as follows: A is B20, B is B26, and C is B46. Location of letter on map is approximate location of core on shelf. Blue = interbedded/laminated sands and muds (ILMS); Green = mixed layers and mottles (MLM); Yellow = mottled muds (MM). Symbols represent type of activity profiles: grey circles = low, uniform activity; pink plus signs = steady-state; red diamonds = non-steady-state (Miller and Kuehl, this issue). The dashed line at 150 m indicates the shelf break. WRM = Waipaoa River Mouth.

deposition here is likely derived from either Waipaoa River sediments that bypassed the anticlines, or sediment that was transported around the promontory of the Mahia Peninsula via the Wairarapa Coastal Current and/or by the southward-flowing East Cape Current. We favor the former idea, as it is unlikely that ^{7}Be accumulation on the shelf break could be solely supported by lateral input of sediments delivered from sources outside the WSS via surface currents. The presence of ^{7}Be at shelf break locations in January 2005 thus suggests Waipaoa effluent was actively being transported across-shelf, remarkably even during seasonal low-flow conditions (austral summer; Fig. 3). In comparison, moderate ^{210}Pb accumulation rates ($<0.5\ \mathrm{cm\ yr^{-1}}$, Fig. 7b), have shown that the shelf break is a secondary zone of deposition on the centennial timescale (Miller and Kuehl, this issue).

Shelf circulation may (or may not) bring an influx of sediment to other locations seasonally, but this study did not re-occupy core sites on a seasonal basis to test this idea. During austral winter, with higher river discharge and generally stronger waves, ^{7}Be would likely be found at higher activities broadcast throughout the shelf. Although the timescale represented by ^{7}Be is a few months at maximum, the spatial depositional patterns compare favorably with Holocene deposition interpreted from seismic studies and with ^{210}Pb accumulation rates (Fig. 10a). This suggests that, though affected by short-term transport and deposition, the ultimate distribution of sediment accumulation patterns is fundamentally the same, emphasizing the importance of tectonics on decadal sedimentation in this system (Miller and Kuehl, this issue; Gerber et al., this issue; Orpin et al., 2006; Kuehl et al., 2006).

5.3. Sedimentation patterns on Poverty Shelf

Radio-isotopic and physical properties of sediment in the upper meter of the Poverty Shelf seabed reveal two distinct patterns that shed light on their formative processes and underlying control. The sedimentation patterns described by short-lived ^{7}Be and bulk-density measurements are consistent with those of ^{210}Pb accumulation rates, which show centennial-scale accumulation is highest within the northern and southern depocenters on the shelf (Miller and Kuehl, this issue; Fig. 10a, b). Interestingly, the depocenters are disconnected from the radial facies distribution which emanates from the mouth of Poverty Bay (Fig. 9). Multiple facies are found within the two shelf depocenters, suggesting accumulation rates do not solely dictate strata formation. The addition of ^{210}Pb geochronology from Kasten cores taken in the same locations as box cores (Miller and Kuehl, this issue) add insight into these conflicting patterns. Miller and Kuehl (this issue) describe three distinct types of ^{210}Pb activity profiles on the Poverty Shelf: 1) a low, uniform activity profile indicative of little excess ^{210}Pb, 2) steady-state profiles from which centennial-scale accumulation rates were generated, and 3) non-steady-state profiles. These characteristic ^{210}Pb activity profiles reveal links between processes operating on the shelf creating modern sedimentary strata

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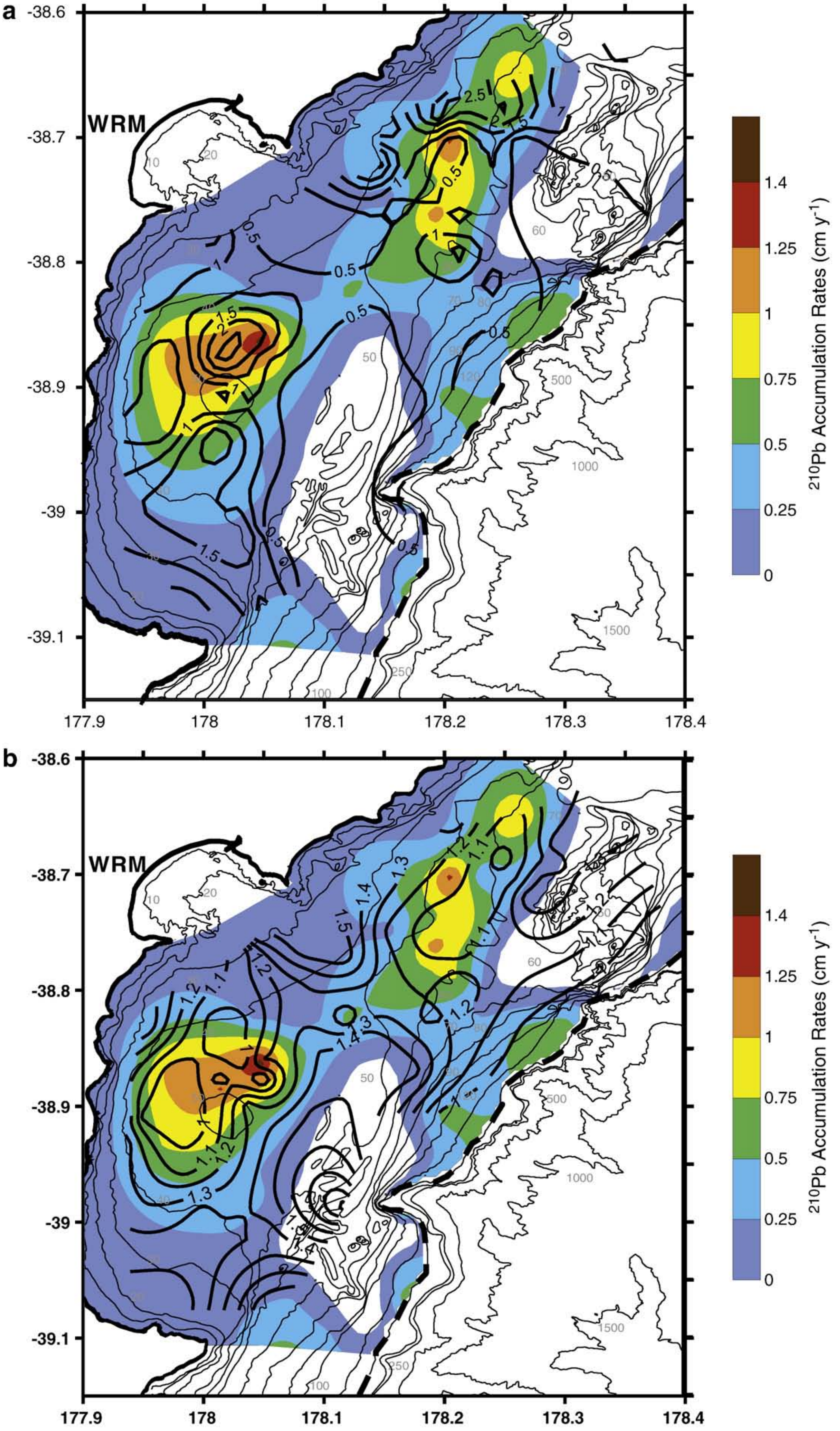

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and the distribution of sedimentary facies; their type and occurrence correspond extremely well with facies distribution (Fig. 9).

All ^{210}Pb profiles found to have low, uniform activities are located within the ILMS facies (Fig. 9, grey circles). Miller and Kuehl (this issue) interpret this activity profile as being indicative of intense physical reworking that would presumably homogenize sediments while removing fines, which are likely to have the highest activities. Wood (2006) found that surface sand content decreased seaward from a high of ~55% in the ILMS, while surface mud (silt + clay) increased towards the depocenters (surface samples taken from splits of box cores from this study). Sedimentary structures, such as finely laminated and crossbedded sands (Fig. 4a) in the ILMS facies confirm that wave and current energy are the dominant influences on sedimentary formative processes in this region of little net accumulation.

Steady-state ^{210}Pb profiles (log decrease of excess ^{210}Pb activity; Fig. 9, pink plus signs) are located within the MM facies, primarily at deeper sites that experience less frequent remobilization, where sediment accumulation is typically high, but bioturbation is also strong. The lowest bulk densities and highest ^{7}Be inventories are also found here. In the MM facies, biological mixing intensity is the main determination of strata destruction on the shelf along with a combination of reduction in wave energy, and reduced sand content. Interestingly, non-steady-state ^{210}Pb activity profiles are found almost exclusively within the MLM facies (Fig. 9, red diamonds). Event layers have been linked with non-steady ^{210}Pb activity profiles (Kniskern et al., this issue), suggesting that the MLM facies is an environment where event layers are preserved. This preservation potential is likely driven by a dynamic balance between sediment supply and delivery, water depth and dissipation time.

Just as multiple facies are observed within depocenters, so are multiple types of ^{210}Pb activity profiles (Fig. 9). Non-steady-state profiles correspond with cores on the landward flanks of the two depocenters within the MLM facies, while steady-state cores are located in the centers of the depocenters (MM facies) where highest accumulations are found. Wood (2006) suggests the two depocenters are isolated from each other based on surface sediment grain size modalities, providing evidence that Waipaoa discharge is secondary to hydrodynamic interactions and sediment transport to the depocenters. Steady-state ^{210}Pb profiles, characteristic of areas of lower accumulation on the mid-shelf between the two depocenters (Miller and Kuehl, this issue) may indicate that along-shelf variation in accumulation rate does not necessarily translate into differences in profile characteristics. It is likely, then, that the two depocenters do not receive equal supply, just as the hydrodynamic climate influencing the depocenters may have some differences (e.g., the Mahia Peninsula promontory sheltering the southern depocenter revealed by ^{7}Be inventories). Traditionally, sediment supply is regarded as having first order control on facies distributions. However, the ^{210}Pb activity profiles confirm that other processes responsible for the observed facies progression on the Poverty Shelf are more important, such as episodic wet event sedimentation (within the MLM; Fig. 9) and water depth. Sedimentary structure formation is clearly independent of the underlying tectonic forces, which influence sediment accumulation rates on multiple timescales.

5.4. Sedimentary patterns and facies comparison with other continental shelves

The distribution of facies on the Poverty Shelf has both notable similarities and differences with other active and passive margin shelves around the world. The small, mountainous Eel River, in Northern California, for example, is an excellent analog to the Waipaoa River, as it drains a small catchment (9000 km^{2}), and its flow is episodic and seasonally driven (Sommerfield and Nittrouer, 1999). The Waipaoa and Eel have comparable sediment loads, 13–15 and 20–24 Mt yr^{-1}, respectively (Wheatcroft and Borgeld, 2000; Wheatcroft and Drake, 2003). Off the Eel, a single, tectonically-controlled mid-shelf mud deposit between 50 and 100 m water depth is interpreted to result from episodic flood sedimentation in comparison to the two accumulating depocenters on the Poverty Shelf; differences in shelf morphology clearly play a role in sediment accumulation and preservation, specifically the actively deforming anticlines of the Poverty Shelf. Within the Eel depocenter, the transit time exceeds the dissipation time of all but the thickest layers emplaced on the shelf (Wheatcroft and Drake, 2003; Nittrouer et al., 2007) resulting in few preserved flood layers. Energetic hydrodynamic factors on the Eel Shelf act in concert to destroy much of the physical sedimentary structure emplaced by storm events on the mid-shelf (Crockett and Nittrouer, 2004).

The Columbia River empties into the Pacific Ocean from Washington State, along the same tectonically active margin as the Eel River. Although it's catchment is two orders of magnitude larger than the Eel and Waipaoa (670,000 km^{2}), its yield is two orders of magnitude less than the Waipaoa, 22 t km^{-2} yr^{-1} versus 6800 t km^{-2} yr^{-1} (Nittrouer and Sternberg, 1981, Milliman and Syvitski, 1992). On the shelf adjacent to the Columbia River, physically laminated sediments characterize the inner shelf stratigraphy of the upper 50 cm of seabed and grade into a mid-shelf mud deposit of intermixed mud and sand and bioturbated sediments (Nittrouer and Sternberg, 1981). These patterns are similar to the progression of facies on the Poverty Shelf, and are interpreted to be caused by fluctuations in sediment supply, decreased influence of physical mixing with increased water depth and accumulation rate. Key differences between the Poverty Margin and the Eel and Columbia River margins include the potential physiohydrographic shelter provided by the irregular coastline and the anticlines which may buffer southern swell and currents on the Poverty Shelf and the accommodation created by the local tectonics. Interestingly, the anthropogenic disturbances between the WSS and the Columbia catchment are disparate. The relatively rural WSS has experienced dramatic increases in erosion as a result of modern land-use changes (Wilmshurst, 1997) whereas the modern damming of the Columbia river coupled with crippling increases in water usage have dramatically reduced the Columbia's yield by over 35%.

Located north of the WSS, the Waiapu River, shares the tectonically active setting, but regional-scale differences including bathymetry and wave and current energies cause sediment dispersal on the adjacent continental shelf to be different. The Waiapu River has a similar catchment size, but a much higher total sediment load of 35 t yr^{-1} and one of the world's highest sediment yields (17,800 t km^{-2} yr^{-1}). As a result, it is hypothesized to produce hyperpycnal plumes an order of magnitude more frequently than the Waipaoa (Hicks et al., 2004). Unlike the Poverty Shelf, the Waiapu Shelf is defined by a single locus of deposition, similar to that of the Eel River, and wave and current energy are the primary factors in sediment dispersal off the Waiapu, although strata, from well-laminated to strongly-bioturbated, radiate away from the river mouth (Kniskern et al., this issue), as with the Poverty Shelf.

An obvious first order difference between larger-scale stratigraphy of the Poverty Shelf and that observed on many passive margin shelves (e.g. the Amazon, Mississippi, and Ganges–Brahmaputra Rivers) is the absence of a subaqueous delta clinoform or prograding deposit due to the narrow continental shelf and active hydrodynamic environment. However, the progression of facies across the narrow, tectonically active Poverty Shelf appears to be similar to those of much larger river passive margin shelves, despite the disparate scales of these systems (catchment area, shelf width, sediment load, etc.) and the clear individuality of each system. The passive margin shelf off the

Fig. 10. Sedimentation Patterns on the shelf. a) ^{210}Pb accumulation rates (cm yr^{-1}) overlain with ^{7}Be inventory (dpm cm^{-2}) contours. b) ^{210}Pb accumulation rates (cm yr^{-1}) overlain with average bulk-density (g cm^{3}) contours.

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Amazon River provides an interesting comparison to the Poverty Shelf especially when accounting for the relative importance of scale in strata formation and the distribution of facies on the two shelves.

The Amazon River has a load three orders of magnitude greater than that of the Waipaoa and seismic profiles reveal a classic subaqueous delta clinoform (Kuehl et al., 1986). Meter-thick surface mud layers, unlike anything observed on the Poverty Shelf, are found on the continental shelf off the Amazon and are interpreted to be the result of physical reworking from strong tidal currents (Kuehl et al., 1995). Despite the overarching differences of scale, the main facies types and their spatial progression across-shelf from physically to biologically dominated environments are comparable. Physically stratified sand facies are found nearshore and an interbedded mud and sand facies is described on the Amazon Shelf (Kuehl et al., 1986). Most ILMS cores from Poverty Shelf also show evidence of some bioturbation, while Amazon interbedded mud and sand has little to no bioturbation except at its seaward boundary and beneath the thick surficial layer (Kuehl et al., 1986). This may be due to a more fine-grained composition, overwhelming sediment supply and rapid accumulation of Amazon sediments (Wood and Carter, this issue; Kuehl et al., 1986). No Poverty Shelf analog exists for either the proximal-shelf sandy silt or faintly laminated mud facies described for the Amazon clinoform, likely because of the differences in hydrodynamic operations between the two shelves already mentioned.

Shelf system characteristics are influenced by dynamic variations in sediment supply, transport and tectonic forces on continental shelf environments (Milliman and Syvitski, 1992; Walsh and Nittrouer, 2009). Although transitions from facies across-shelf off of small mountainous and large, passive margin systems may parallel each other due to the ranking of similar processes in their operation on the shelf (sediment supply, wave energy, water depth), as discussed above, the main influences on facies development and their spatial extent may be quite different. It appears that the primary control on accumulation within the morphologically indistinct dual-depocenters of the Poverty Shelf (and difference from other shelves off small mountainous rivers) is the tectonically influenced basin-fill (Gerber et al., this issue) behind the Ariel and Lachlan anticlines. However, as the map of facies indicates, the subsidence associated with the anticlines does not appear to influence the pattern of fine-scale sedimentary strata characteristic of the ILMS, MLM and MM facies — tectonics, appear to be irrelevant to their lateral progression. Rather, the facies are determined by hydrodynamic and biological processes while deposition and accumulation appear to reflect accommodation (tectonic) processes.

6. Conclusions

X-radiographic, radio-isotopic and physical properties analysis of 87 box cores collected in January 2005 aboard the *R/V Kilo Moana* show distinct trends in Waipaoa River sediment dispersal and stratal character on the Poverty Shelf, New Zealand.

1) Three distinct facies are radially distributed across and along-shelf with increasing distance from the Waipaoa River mouth: A) interbedded/laminated muds and sands; B) mixed layers and mottles; and C) mottled muds.
2) ^{7}Be is widespread throughout surface sediments in the study area indicating rapid seaward transport of Waipaoa effluent. ^{7}Be inventories confirm deposition occurs predominantly within two depocenters located landward of the Ariel and Lachlan anticlines.
3) Bulk-density measurements have similar patterns to those of ^{7}Be inventory distributions along- and across-shelf. Accumulation rates from ^{210}Pb analyses of Kasten cores (Miller and Kuehl, this issue), which are highest in the depocenters and on the shelf break, are consistent with this depositional pattern.
4) Characteristic ^{210}Pb activity profiles are distinctly partitioned by facies. Low, uniform activities are found exclusively with the ILMS facies, non-steady-state activity profiles are found in the MLM facies and largely steady-state accumulation is observed in the MM facies.
5) Basin-fill of the two Poverty Shelf depocenters has been shown to be a result of accommodation space associated with active tectonic deformation which distinguishes it from other active and passive margin shelves. Although facies progression across-Poverty Shelf is similar to other active and passive margins, their distribution appears to be independent of accumulation rates.

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