A Source to Sink Perspective of the Waipaoa River Margin

Steven A. Kuehl^a, Clark R. Alexander^b, Neal E. Blair^{c,k}, Courtney K. Harris^a, Kathleen M. Marsaglia^d, Andrea S. Ogston^e, Alan R. Orpin^f, Joshua J. Roering^g, Aaron J. Bever^h, Eric L. Bilderbackⁱ, Lionel Carter^j, Corina Cerovski-Darriau^g, Laurel B. Childress^k, D. Reide Corbett^l, Richard P. Hale^m, Elana L. Leitholdⁿ, Nicola Litchfield^o, Julia M. Moriarty^a, Mike J. Page^o, Lila E. R. Pierce^a, Phaedra Upton^o, John P. Walsh^l

^a *Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA 23062, USA*

^b *Skidaway Institute of Oceanography, University of Georgia, Savannah, GA 31411, USA*

^c *Department of Civil and Environmental Engineering, Northwestern University, Evanston, IL 60208, USA*

^d *Geological Sciences, California State University Northridge, Northridge, CA 91330, USA*

^e *School of Oceanography, University of Washington, Seattle, WA 98195, USA*

^f *National Institute of Water and Atmospheric Research (NIWA), Private Bag 14-901, Kilbirnie, Wellington, New Zealand*

^g *Department of Geological Sciences, University of Oregon, Eugene, OR 97403, USA*

^h *Anchor QEA, LLC, San Francisco, CA 94102*

ⁱ *Geologic Resources Division, National Park Service, Denver, CO 80225, USA*

^j *Antarctic Research Centre, Victoria University of Wellington, PO Box 600, Wellington, New Zealand*

^k *Department of Earth and Planetary Sciences, Northwestern University, Evanston, IL 60208, USA*

^l *East Carolina University, UNC Coastal Studies Institute, Greenville, NC 27858, USA*

^m *Department of Earth and Environmental Sciences, Vanderbilt University, Nashville, TN 37235, USA*

ⁿ *Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA*

^o *GNS Science, PO Box 30-368, Lower Hutt 5040, New Zealand*

Keywords: Waipaoa River, New Zealand, continental margin, sedimentology, stratigraphy, landscape evolution, sediment transport, carbon cycle

ABSTRACT

A fundamental goal of the Earth Science community is to understand how perturbations on Earth's surface are preserved in the stratigraphic record. Recent Source to Sink (S2S) studies of the Waipaoa Sedimentary System (WSS), New Zealand, are synthesized herein to provide a holistic perspective of the processes that generate, transport and preserve sedimentary strata and organic carbon on the Waipaoa margin in the late Quaternary. Rapid uplift associated with subduction processes and weak sedimentary units have conspired to generate rapid rates of incision and erosion in the Waipaoa catchment since the Last Glacial Maximum (LGM). We show that although much of the sediment exported offshore during this time interval originated from valley excavation, a substantial portion emanated from hillslopes, mostly through deep-seated landslide and earthflow processes that were vigorous during periods of rapid fluvial incision just prior to the Pleistocene-Holocene transition. Lacustrine sediments deposited in naturally-dammed 7-ky-old Lake Tutira provide a record of Holocene environmental controls on upper catchment sedimentation in the WSS, with 1400 storms identified. Storm frequency is modulated by the waxing and waning of atmospheric teleconnections between the tropics and Antarctica. Furthermore, clear long-term changes in sediment yield are evident from the Lake Tutira record following human

settlement as conversion to pasture is accompanied by a 3-fold increase in the long-term lake sediment accumulation rate.

Whereas there is ample evidence that Waipaoa River flood deposits are routinely deposited offshore in the sheltered confines of Poverty Bay, over the longer term, waves and currents subsequently resuspend and transport these deposits both landward (sandy fraction) and seaward (finer fraction). Thus, the timing of sediment supply to areas of net sediment accumulation is more often driven by wave events that are not associated with river flooding. Therefore, we conclude that asynchronicity of river-sediment delivery and of wave resuspension in most instances precludes the direct preservation of flood events in the stratigraphic record of the Waipaoa Shelf. Over the longer term, the sediment package preserved on the shelf and slope since the LGM can be explained in large measure by sequence-stratigraphic models forced by varying sea level and ongoing tectonic deformation of the margin. As sea level rose, sediment supply to the slope was reduced by about a factor of 5 due to shelf trapping. Despite this reduction, turbidites are found at similar frequency throughout the LGM-Present, as the dominant trigger appears to be subduction earthquakes, with large ones having a return interval of about 200 ± 100 years. Sediment-budget exercises that consider both modern (river discharge versus centennial accumulation rates) and post-LGM (terrestrial production versus offshore isopachs) mass balances indicate that about half of the total sediment production from the Waipaoa escapes the study area. Moreover, a coupled sediment transport-hydrodynamic model and observations of textural trends on the shelf indicate that a large fraction of the sediment is carried outside the study area along the shelf to the northeast by the river plume or by combined current/wave activity. Therefore, we conclude that the WSS is an open system with sediment escape from the present day through the LGM.

The organic matter associated with sediment as it moves from upland source to marine sink is a product of particle history, and provides a record of materials that have cycled over timescales of days to millions of years. The ubiquity of fossil Organic Carbon (OC) in both the terrestrial and marine realms of the Waipaoa attests both to the chronic nature of its source, crumbling mudstones further destabilized by landuse, and its biogeochemical recalcitrance. Modern OC persists by virtue of its continual production along the S2S transit, and is buried and preserved within the adjacent marine depocenters. The Waipaoa contrasts with dispersal systems on wide, energetic shelves (e.g., the Amazon and Fly Rivers) where sediment is extensively refluxed in oxygenated overlying water resulting in the biogeochemical incineration of particulate OC. The Waipaoa, like other small mountainous rivers on active margins, exhibits a high riverine OC preservation efficiency (>50%) in its marine depocenters because of the relatively rapid, event-driven accumulation of sediment.

INTRODUCTION

A longstanding goal of the Earth Science community is to provide quantitative explanations and predictions about how perturbations on Earth's surface are reflected in the geologic record preserved within continental-margin sedimentary sequences. Many margins have been studied piecemeal, and mostly from a single-disciplinary perspective, but there are very few studies that have taken a holistic approach to understanding a complete system from mountain Source to ocean Sink (S2S). Such an understanding is necessary if we hope to improve predictions of mass transfer from land to ocean, and the role this transfer (and intermediate storage) plays in the cycling of carbon, in ecosystem change caused by climate change and sea level, and resource management of soils, wetland, groundwater, and hydrocarbons (MARGINS, 2004). Moreover, our fundamental understanding of the stratigraphic record contained within continental margins is predicated on knowing how variations in geological processes and material fluxes are imprinted and preserved through time.

These considerations, among others, contributed to the initiation of the MARGINS S2S program focusing on the Waipaoa Sedimentary System (WSS) in New Zealand. The goal of this cooperative USA-NZ program is to “provide a comprehensive study of linked, terrestrial and marine sediment dispersal systems over the range of time scales for which sedimentary processes operate [with questions that] center around the role of changing tectonics, climate and sea level as forcing functions in the production, transport and storage of sediments and solutes; processes initiating erosion and sediment transfer, and their interactions; and the interplay of sedimentary processes and forcing functions in creating the stratigraphic record” (MARGINS, 2004).

Selection of the WSS as a focus area for the MARGINS S2S program was based on a number of perceived system attributes, including: strong forcing that produces clear sedimentary signals, active material transfer and sedimentation among the S2S environments, a closed sedimentary system, a high-resolution stratigraphic record, advantageous background data and scientific infrastructure, manageable logistics, and societal relevance (Kuehl et al., 2003, 2006). As described in more detail below, the WSS embodies many (but not all) of these attributes and, in particular, allows S2S scientists to build on a comprehensive foundation of understanding about the margin based on decades of prior terrestrial and oceanographic research by the New Zealand research community and collaborators.

The objective of this review is to summarize and integrate the salient results of WSS S2S and related studies. Lacustrine records are presented to establish a benchmark for large-magnitude storms and climate variations (among other environmental factors) that affect sediment delivery in the catchment. The history of landscape evolution during the Late Quaternary highlights the underlying mechanisms of sediment production and their variation in space and time. Stratigraphic sequences on the shelf and slope preserve signals that can be related to changing sediment inputs and environmental controls. Centennial trends in sediment dispersal, and contemporary sediment dynamics and modeling studies allow a mechanistic view of processes that operate to transport and preserve sediments and form fine-scale sedimentary strata. Carbon transport and transformations on a multitude of temporal and spatial scales in the S2S system inform key questions regarding biogeochemical cycling and OC preservation. The integrated results of the studies presented herein are intended to provide a system perspective on the WSS from mountain source to ocean sink and to elucidate the key environmental signals that are generated and preserved within this S2S system.

BACKGROUND

Onshore and Offshore Tectonics, Geology, and Seismology

The modern WSS has developed on a convergent continental margin where the Pacific Plate subducts beneath the Indo-Australian Plate at a rate of 5-6 cm y⁻¹ (Wallace et al., 2004). The oldest rocks in the region, the Mesozoic Torlesse terrane, a forearc accretionary complex (Mortimer, 1994), are overlain by Upper Cretaceous to Paleogene siliciclastic shelf to slope units, followed by Oligocene limestone (Field et al., 1997; Mazengarb and Speden, 2000). In the Oligocene to early Miocene, there was thrust emplacement of a large wedge of deeper-water sedimentary units, the East Coast Allochthon, across a portion of the study area (Rait et al., 1991; Mazengarb and Speden, 2000; Sutherland et al., 2009) followed by Miocene to Pliocene forearc basin sedimentation. Together, these units form a collision margin accretionary prism with its seaward boundary at the Hikurangi Trough. Pleistocene to Holocene uplift and exposure of these Cretaceous to Pliocene marine-sedimentary successions have been credited to underplating along the subduction interface (e.g., Wilson et al., 2007; Sutherland et al., 2009).

The Upper Cretaceous to Pliocene units that crop out within the Waipaoa River drainage basin (Fig. 1) are mostly shale to mudstone, locally calcareous, with some distinct sandstone, limestone and tuffaceous intervals, the latter supplied from the evolving magmatic arc to the west (Mazengarb and Speden, 2000). The friable and easily erodible mudstone lithologies from the sheared and shattered allochthon within the 2150-km² WSS catchment have generated prodigious volumes of largely muddy sediment (De Rose et al., 1998), which is transported by the Waipaoa River as wash load to Poverty Bay (Hicks et al., 2000). Volcaniclastic input to the WSS from the extremely active rhyolitic Taupo Volcanic Zone (TVZ) has resulted in numerous tephra intervals that are useful time markers, not only in the

upper Tertiary forearc successions (Schneider, et al. 2001), but also in the Quaternary fluvial-to-lacustrine units (Eden et al., 2001) and shelf-to-slope facies (Alloway et al., 2005; Gerber et al., 2010).

The Hikurangi Margin is a seismogenic zone capable of generating moderate-to-large earthquakes with magnitudes up to M_w 8 (Doser and Webb, 2003; Dowrick et al., 1995; François-Holden et al., 2008), as well as smaller yet collectively important slow-slip events associated with seamount subduction (Wallace and Beavan, 2010). There is variable uplift and subsidence across the WSS associated with subduction tectonics. For example, onshore, uplift in the upper reaches of the Waipaoa drainage basin is concurrent with differential subsidence that steers the river mouth to the south (Brown, 1995; Wolinsky et al., 2010). Seismic-reflection data show deformed rock units that extend offshore to underlie the Late Quaternary marine sequence. These units are locally exposed along the outer-shelf in uplifted and deformed anticlinal ridges (i.e., Lachlan Ridge and Ariel anticline; Fig. 1), which partition the shelf into discrete mud depocenters (Fig. 2) (Foster and Carter, 1997; Gerber et al., 2010; Lewis, 1980; Lewis and Petinga, 1993). Subducting seamounts on the Pacific Plate have destabilized the frontal wedge of the margin creating large arcuate slope failures (Pedley et al., 2010) including the Poverty indentation/embayment (Fig. 1), which serves as a major canyon-fed slope depocenter (Alexander et al., 2010) ultimately linking the Hikurangi Trough to Poverty Canyon (Figs. 1, 2). Seismic events also generate and transport sediment via subaerial and submarine landslides, with the former creating lake environments that record climatic and tectonic events until landslide dams are breached (Carrasco, 2012; Pere, 2003; Orpin et al., 2010) and the latter creating seismogenic turbidite records in slope basins (Pouderoux et al., 2012b).

Waipaoa River and Discharge

The Waipaoa River drains the southeastern watershed of the steep and rugged Raukumara Ranges. The river has a mean annual flow of $\sim 35 \text{ m}^3 \text{ s}^{-1}$ but is highly ephemeral, with a mean annual flood discharge of $1,320 \text{ m}^3 \text{ s}^{-1}$ (Hicks et al., 2000). Annual gauge-height data from 1932–2002 at Kanakanaia Bridge on the lower reaches of the Waipaoa River show that large floods ($>1,900 \text{ m}^3 \text{ s}^{-1}$) have a 6-year recurrence interval (data modified after Reid, 1999), and that the largest recorded flood, associated with Cyclone Bola in March 1988, reached an estimated peak of $\sim 4,000 \text{ m}^3 \text{ s}^{-1}$. Hicks et al. (2004) have shown that during flood events such as Bola (estimated recurrence interval of 40 years), suspended-sediment concentrations likely exceed the threshold for generation of hyperpycnal river flows to Poverty Bay. Along its 104-km length (Fig. 1), the Waipaoa River changes from a braided system in its uppermost reaches, to a single meandering channel (Gomez et al., 2001). Downstream fining in the modern river is observed by the decrease in size of gravel clasts, many of which are fragments from friable mudstone (Marsaglia et al., 2010; James et al., 2007).

The river is actively aggrading, in part because sediment yield has increased owing to anthropogenic activity that started with Maori deforestation on the East Coast ~ 600 y ago. This culminated with the widespread destruction of native forests by Europeans and conversion to pastureland across the $\sim 2,000\text{-km}^2$ catchment from 1820 to 1920 (Pullar, 1962; Wilmshurst et al., 1999). Kettner et al. (2007) estimate that the sediment discharge increased from ~ 2 to 15 Mt y^{-1} during the Anthropocene, in several pulses: after Polynesian arrival (+140%), after European colonization (+350%) and from deforestation in the upper reaches of the river (+660%). Hydrologic transport models (Upton et al., 2013) suggest that Holocene climate change from 3 to 5.5 ka also affected discharge as a function of rainfall and

of vegetation cover and type (forest versus grassland), with the latter controlled not only by climate but also by tephra distribution during volcanic eruptions.

Landscape Evolution

The form of hillslopes in the Waipaoa catchment is remarkably gentle and low in relief given the rapid pace of tectonic forcing. The maximum altitude of the terrestrial watershed is 1,200 m above sea level, the mean altitude is 300 m, and only 16% of the Waipaoa catchment is over 500 m. Relief is greatest in the northwest portion of the catchment, coincident with allochthonous marine mudstone, sandstone, and limestone units (Mazengarb and Speden, 2000) and with rapid uplift rates (Litchfield and Berryman, 2006).

Landscape denudation mechanisms in the WSS are linked to source-rock properties. For example, Pliocene-Miocene mudstones commonly undergo shallow landsliding (Hicks et al., 2000; Reid and Page, 2002), whereas *mélange* units and sheared Cretaceous mudstones in the allochthon are prone to gullying (De Rose et al., 1998; Marden et al., 2005) with the latter exhibiting higher sediment yields (Reusser and Bierman, 2010; Cerovski-Darriau et al., 2014). Late Pleistocene aggradational-terrace levels in the upper reaches of the river catchment linked to colder climate episodes (Berryman et al., 2010; Marden et al., 2008a) contain higher proportions of sandstone clasts, suggesting that gullying was a less important source of sediment at that time (Marsaglia et al., 2010). During the last glacial period, the river was actively aggrading until ~18 ka (Marden et al., 2008a). Since then, ~16.7 km³ of sediment flux from fluvial incision alone has been estimated (Marden et al., 2014), 40% of which is stored in the flood plain and 60% delivered offshore. More recent reforestation has decreased erosion in the upper catchment (Hicks et al., 2000; Marden et al., 2005; Marden and Rowan, 1993) but the river still has a great suspended-sediment discharge rate at its mouth of 15 Mt y⁻¹ (Hicks et al., 2000), which is significantly increased due to major rain-producing storm events like Cyclone Bola (Page et al., 1999; Foster and Carter, 1997).

Regional Palaeoceanography and Palaeoclimate

Currents and Sea-Surface Temperature (SST) have varied through time off North Island, New Zealand and along the Poverty margin (Alloway et al., 2007). At the peak of the Last Glacial Maximum (LGM), ~20 ka, the margin was dominated by a cold, northeastward-flowing coastal current (Carter et al., 2002; Carter and Manighetti, 2006; Nelson et al., 2000; Weaver et al., 1998). Onshore, the climate was colder (by ~5°C), windier and drier than present, as reflected by the presence of pervasive grasslands and shrub-lands (McGlone, 2001). Deglaciation was heralded by a warming of the deep ocean beginning ~18 ka (Carter et al., 2008) and concomitant warming of the terrestrial climate and expansion of forests (McGlone 2001). Surface-ocean warming, initially erratic (Carter et al., 2008; Marr et al., 2013; McGlone 2001), became established at ~12 ka with SST reaching ~18°C, coincident with the onset of a strong East Cape Current (Carter et al., 2008; Nelson et al., 2000).

From 11 ka to the present day, the upper ocean has been well stratified owing to a weakened wind regime with a peak in SST at ~19°C in the early to middle Holocene. This was followed by a general decline, punctuated by a cold phase (e.g., 7-6 ka), to the present mean annual temperature of 18°C (Pahnke and Sachs 2006; Carter et al., 2008; Marr et al. 2013). Modern sea level was more or less established at 7 ka (Gibb, 1986), and was accompanied by development of the northward flowing Wairarapa Coastal Current. The accompanying terrestrial climate became generally moist and mild, and favored the expansion of forest cover (McGlone 2001). Overprinting these changes were the influences of high-frequency climate modes from the equator (El Niño-Southern Oscillation - ENSO) and Antarctic-Southern Ocean (Southern Annular Mode), whose interactions with one another strongly affected regional winds, precipitation, and storms - a situation that continues

today (Gomez et al., 2012, 2013).

Modern Oceanography

The marine segment of the modern WSS begins at the coast in Poverty Bay (Figs. 1, 2), a small ($\sim 60 \text{ km}^2$) shallow ($< 30 \text{ m}$ deep) coastal embayment that opens to the Poverty Shelf. Tidal currents are weak and diurnal in the Bay (tidal range of 1.5 m), with peak currents of $\sim 0.05 \text{ m/s}$ (Stephens et al., 2001). Wave heights average $\sim 1 \text{ m}$ although maxima during storms can exceed 6 m (Orpin, 2004). There is a local anticlockwise current in Poverty Bay (Stephens et al., 2001) with complex current flow and sediment redistribution patterns that serve to concentrate sand on the beach and export mud to the shelf (Bever et al., 2011). The WSS portion of Poverty shelf is $\sim 60 \text{ km}$ long and $\sim 25 \text{ km}$ wide with water depths generally $< 70 \text{ m}$, bounded to the east by the Lachlan and Ariel anticlines (Brown, 1995). The regional oceanographic flows on the shelf have been not been thoroughly studied, however important circulation patterns include the Wairarapa Coastal Current that flows northward along the shelf (well documented south of Hawke Bay; Chiswell, 2000) and the East Cape Current that flows southward along the shelf edge and slope; both of these currents are affected by winds and coastal gyres (Foster and Carter, 1997; Chiswell and Roemmich, 1998; Healey, 2002; Carter et al., 2002; Chiswell, 2005).

RESULTS OF RECENT STUDIES

The discussion sections that follow summarize and synthesize results from recent studies that span the entire WSS, from the uplands to the deep sea, and for timescales that range from near-instantaneous perturbations (e.g., flood, earthquake) to long-term trends (e.g., sea-level change, margin deformation) occurring over the Late Quaternary.

Upland Source Signals - Lake Tutira

By virtue of the close proximity to the Waipaoa catchment (Fig. 1a, inset), similar steep upland geomorphology and sediment lithologies, the Lake Tutira record provides a window into the catchment responses to climatic, volcanic and tectonic processes, as well as anthropogenic effects that have also influenced the Waipaoa source through time. Like the Waipaoa, at Tutira, the combination of the same vigorous maritime climate and geography have resulted in a suite of distinctive deposits that span both the period of enhanced post-colonization erosion, and prehistoric time with natural forest cover. The lake has an expanded, high-resolution environmental record as a result of: high sediment supply from nearby rugged and easily-erodible slopes; mass-wasting processes that operate during intense rainfall events and earthquakes; and, the lake's closed depositional system that is conducive for the complete capture of sedimentary signals and the creation of well laminated strata.

Lake Tutira has also provided a point of reference to compare with the adjacent marine record on the continental margin. Rainfall modulates the production and delivery of terrigenous sediment by virtue of the fundamental control it exerts on soil moisture and runoff (Gomez et al., 2013). The Lake Tutira storm-sediment record serves as a broad proxy for the regional rainfall in the Waipaoa catchment. Model simulations extend that record back to the mid-Holocene, and suggest that regional changes in rainfall patterns gave rise to wetter and drier periods of centuries or millennia duration, and modulated the suspended-sediment yield (Upton et al., 2013). In the absence of profound disturbances to the vegetation cover, climate exerts the dominant control on the production and delivery of sediment.

Environmental setting - Lake Tutira was formed by hillslope collapse ~7.2 ka, possibly triggered by a large earthquake, which dammed the southern valley outlet (Adams, 1981; Trustrum and Page, 1992; Cochran et al., 2006; Page et al., 2010). This small (1.8 km²) and shallow lake, with a mean depth of 21 m and maximum depth of 42 m (Irwin, 1978), is a sediment and nutrient trap and repository of storm-induced erosion (e.g., Guthrie-Smith, 1999

– first printed in 1921; Adams, 1981; Page et al., 1994a; Eden and Page, 1998; Gomez et al., 2002). The lake has a catchment of 32 km² and is situated ~155 m above sea level (Irwin, 1978) within the Hikurangi Margin forearc (Lewis and Pettinga, 1993). Locally, the geology is dominated by uplifted Tertiary marine sandstones and mudstones, with interlayered calcareous rocks (including limestone) and conglomerates (Lowe, 1987). The southern region surrounding the lake is particularly landslide-prone, featuring a physiography of steep, dissected hills and narrow-infilled valleys (Page et al., 1994a). Most terrestrial sediment entering Lake Tutira is derived from these proximal hillslope sources of similar lithology. The bathymetry of the lake shows a drowned valley morphology of interfingering spurs with steep slopes that descend into a narrow meandering lake floor.

Record of landscape response to environmental change -The central lake bottom is primarily comprised of five sedimentary components that are the result of distinctive inputs: ashfall tephras, organic layers, brown muds emplaced by sediment gravity flows (homogenites), graded storm beds and storm clay layers (Orpin et al., 2010). Tephras constitute only a small proportion of the sediment record. Proportionally, the balance of intra-lake and mixed lithotypes versus deposits formed directly from storm events is 69% and 26%, respectively (Fig. 3). Hence, the preserved event record has formed in response to a number of drivers of varying frequency and magnitude. Lake Tutira is ~100 km downwind of the active TVZ and this close proximity led to the preservation of twelve discrete air-fall tephras in the lake sediments (Orpin et al., 2010; Page et al., 2010), and some form important chronostratigraphic markers in the adjacent marine sequence (e.g., Gomez et al., 2007; Gerber et al., 2010; Pouderoux et al., 2012b). Lake tephra deposits have been used previously, along with other age markers (e.g., pollen, diatoms, radiocarbon and ¹³⁷Cs activity), to establish the late-Holocene sedimentation history (e.g., Page and Trustrum, 1997; Eden and Page, 1998). Tephra deposits also mantled the landscape regionally (e.g., Froggatt

and Lowe, 1990) and were readily eroded from steep hillslopes. Transport via airfall can form thick “instantaneous” lake deposits (e.g., 49.5-cm-thick Waimahia Tephra, 3392 cal. BP) and can be distinguished by their purity and normal grading. Redeposited tephras contain non-volcanic material and occur in both graded and massive beds and laminae (Orpin et al., 2010). The twelve tephras, together with three radiocarbon dates from wood fragments provide the chronology to interpolate linearly the ages of storm events (e.g., Page et al., 2010). This tight temporal control affords Lake Tutira the best chronostratigraphic record spanning the late to mid-Holocene in the WSS.

A major determinant for the scale of landscape response to climatic events or climate shifts has been landscape vegetation. Despite the magnitude of the Taupo eruption (the largest known eruption in the last 5 ky) pollen records of tall forest taxa are recorded after deposition of the tephra at Tutira, suggesting that forests were not completely destroyed and substantial vegetation cover remained (Wilmschurst et al., 1997). The landscape recovered fully within ~200 y of the eruption (Wilmschurst and McGlone, 1996; Gomez et al., 2007). Palynological evidence suggests that human impacts on the landscape around Lake Tutira began ~500 y ago with Polynesian settlement and shortly after the Kaharoa eruption (636 cal. BP). Repeated burning eliminated the indigenous conifer-broadleaved forest and replaced it with fern and bracken scrub (Wilmschurst, 1997). The resulting increase in erosion led to only moderate increases in sediment accumulation rate for this post-Polynesian period, as the valley floors and riparian cover buffered sediment shed from landslide-prone hill slopes (Page and Trustrum, 1997). Sediment thickness for a given rainfall event was about six-times less under pre-settlement forest cover than under pasture (Eden and Page, 1998). European conversion to pasture in the Tutira area began in the late 1870’s (Guthrie-Smith, 1999), and the post-European settlement period shows an order-of-magnitude increase in the lake sediment accumulation rate to >10 mm/y since ~1880 AD (Orpin et al., 2010). Bathymetric

surveys in 1925 and 1963 were used to estimate a sediment flux to the lake of $5.4 \times 10^4 \text{ m}^3 \text{ y}^{-1}$ or $63,000 \text{ t y}^{-1}$ (Page et al., 2004). However, landscape preconditioning may also affect the sediment yield (e.g., Fuller and Marden, 2010), so rainfall might only provide a first-order control on flood-layer thickness (Gomez et al., 2002). The occurrence of thick event deposits within several decades of known pre-historic earthquakes reinforces the role of earthquakes generally in priming the landscape and increasing sediment yields (Orpin et al., 2010; Gomez et al., 2015).

The catchment behaviour through the Holocene has not necessarily been constant or linear (e.g., Gomez and Livingston, 2012). A study in the Waihuka tributary in the headwaters of the Waipaoa River revealed that up to 50% of the post-glacial downcutting was achieved in a short period during 10-8 ka, representing just 10–15% of the post-glacial time (Berryman et al., 2010). A similar period of accelerated fluvial incision during 14-7.9 ka was also identified throughout the WSS (Marden et al., 2014), and this period of significant downcutting presumably led to increased sediment yields.

Storm record – High-intensity rainstorms, some of tropical cyclonic origin, are an essential characteristic of the rainfall regime. During Cyclone Bola in March 1988, 753 mm of rain fell at Tutira in 4 days, with 320 mm and 329 mm on successive days. For comparison, mean annual rainfall at Tutira is 1413 mm (1971-2000 rainfall normal - from NIWA climate summaries). Page et al. (1994b) constructed a sediment budget for the cyclone that provides a template for the catchment response to rainfall events, from hillslope erosion, to sediment transport and lake deposition. Given the close proximity of sediment sources and vigorous maritime climate, sediment deposits resulting from storms occur continuously throughout the lake record, intercalated with the other sediment types. Page et al. (2010) investigated the relationship between frequency and magnitude for 1400 storms identified in the Tutira sediment record, and hindcast from layers of 0.05–20+ cm thickness that correlate linearly to

historical rainfall intensity (Eden and Page, 1998, Orpin et al., 2010). Here, the average frequency of all storm layers is 1-in-5 years with a standard deviation of 14 years. But for storm layers ≥ 1.0 cm thick, the average frequency is every 53 years, with a considerably larger standard deviation of 75 years, testament to the variability of large rainfall events (Page et al., 2010). The historical record was used by Orpin et al. (2010) to hindcast over the 7.1 ky pre-historic period using the relationship of storm-bed thickness and rain intensity, which indicates that ~53 storms occurred similar in magnitude to an event like Cyclone Bola that produced a 21.5-cm-thick storm deposit. A further 7 similarly large pre-historic storm beds (>10 cm thickness) are inferred to reflect extreme, catastrophic rainfall events.

A striking feature of the record is the variability in magnitude and frequency of storms with storm clusters of decadal duration, often with sudden onset and cessation. Page et al. (2010) noted 9 periods with an increased frequency of large storms and intervals of several centuries between them over the ~6 ky of the sediment record (Table 1). Major periods of increased storminess occur on a cycle of several centuries with a prominent storm period of particularly high magnitude and frequency, occurring during 1830-2120 cal. BP, when the recurrence was 1 storm every ~2.9 years. This is identified as a time of major environmental change by several other regional records (Page et al., 2010).

Climatic implications for the Waipaoa Sedimentary System - Storm frequency reflects New Zealand's latitude that spans tropical and polar climatic influences including ENSO, Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM). Over the course of the middle and late Holocene, ENSO and the SAM may have interacted to influence the frequency of large rainfall events that impacted the Waipaoa catchment (Gomez et al., 2012). The largest magnitude storms preserved in the lake strata are a local manifestation of the large-scale climate variability associated with La Niña events and their correlation with the positive phase of SAM. The strength of this interaction between ENSO

and the SAM has waxed and waned at millennial timescales that appear to modulate ENSO at precessional orbital frequencies. Over the last 7 ky, three essential climatic patterns were recognized, with a period of more intense and frequent storms occurring when ENSO and the SAM were in phase between 2–5 ka (Gomez et al., 2012).

To simulate the suspended-sediment discharge of the Waipaoa River since the mid-Holocene, Upton et al. (2013) used a climate-driven hydrologic transport model (HydroTrend, after Kettner and Syvitski, 2008). They constrain the precipitation input with a paleo-rainfall index derived from the high-resolution Lake Tutira storm-sediment record. This was achieved by scaling the number of storms in each centennial pre-human period to the modern rainfall record (1590 mm y^{-1}) (Fig. 4). The major control on sediment flux from the Waipaoa catchment since the mid-Holocene is climate, primarily rainfall, with changes in catchment size moderating the signal. Their HydroTrend simulation was extended to 22 ka using a lower-resolution version of the model, constrained by terrestrial and marine paleoenvironmental indicators (e.g., vegetation and sea-surface temperature) and a simulated model of northeast New Zealand's climate at the LGM. The modeling predicts that a significant catchment disturbance during the LGM would result in approximately double the riverine sediment flux compared to the catchment response during the Holocene, in part resulting from the lack of LGM forest cover. Re-vegetation of the WSS ~17.5 ka reconfigured the catchment, and brought about a balance between the competing drivers of increasing rainfall and decreasing catchment size as sea level rose from the LGM. A similar reconfiguration in catchment behaviour occurred after human settlement and land clearance for pasture (e.g., Gomez et al., 2007).

Landscape Processes and Sediment Production since the LGM

The active tectonic setting and weak geologic substrate of the WSS promoted profound and extensive morphologic change and sediment export since the LGM (Fig. 5). A robust

and comprehensive sediment budget for the terrestrial component of the WSS is required for comparison with the timing and magnitude of downstream sediment dispersal and deposition offshore. Modern sediment fluxes are dominated by gully processes, but landforms in the Waipaoa demonstrate that a range of post-LGM erosional processes were pervasive, including valley excavation and diverse mass wasting processes. Post-LGM incision of the mainstem Waipaoa channel initiated widespread downcutting throughout the tributary network, which in turn triggered a diffuse pattern of landsliding, a significant component of terrestrial sediment production. Characterizing and quantifying hillslope response proved to be an essential but challenging task for establishing the post-LGM sediment budget of the WSS. In this section, we summarize and synthesize findings on the style and pace of sediment production processes in the Waipaoa River system since the LGM. The combination of remote-sensing data, particularly airborne lidar topography and air-photo mapping, with field-based data, including tephrochronology, provides geoscientists with a powerful means to quantify trends in sediment production that can be synthesized with the sediment dispersal and depositional components of this well studied S2S system.

Tectonic context and fluvial history - Post-LGM sediment production in the Waipaoa is facilitated by the combined effects of on-going tectonic forcing along the Hikurangi subduction zone and climate-induced periods of rapid valley aggradation and incision. Rock uplift rates inland of the subduction zone average 1 mm y^{-1} and approach 4 mm y^{-1} in the headwaters of the Waipaoa (Litchfield and Berryman, 2006), likely enhanced by sediment underplating (Eberthart-Phillips, 2005) and possibly the subduction of thickened oceanic crust or seamounts (Davy and Wood, 1994; Lewis et al., 2004; Litchfield et al., 2007). During the LGM (18 to 29 ka; Barrell et al., 2013), intense sediment production associated with dry and cold (and likely periglacial) conditions contributed to extensive valley aggradation (Gage and Black, 1979; Berryman et al., 2000) such that channels were largely

unable to access and incise bedrock in order to keep pace with rock uplift. Thus, in the absence of valley lowering, rock uplift accumulated, increasing the elevation of the valley network relative to the surrounding low-relief hillslopes (e.g., Bilderback et al., 2014).

A major phase of baselevel lowering in the non-glacial Waipaoa catchment commenced after the LGM as low-relief hillslopes and broad valleys inherited from the Pleistocene were transformed by a warm and moist period that promoted incision and the excavation of wide valleys. This response is proposed to reflect a climate-driven decrease in sediment supply and increase in stream power (Gage and Black, 1979; Berryman et al., 2000; Crosby and Whipple, 2006; Marden et al., 2008b; Berryman et al., 2010; Gomez and Livingston, 2012). Importantly, however, this post-LGM baselevel change was neither steady nor uniform. Instead, scattered portions of the landscape (mostly in the headwaters) contain relict ‘Pleistocene’ hillslopes as knickpoints downstream demarcate the up-catchment extent of post-LGM fluvial network adjustment. Based on modeling, fieldwork, and topographic analysis, Crosby and Whipple (2006) determined that the distribution of >200 knickpoints unrelated to lithologic contacts cannot uniquely identify the temporal pattern of knickpoint initiation or migration. In several tributaries, however, fluvial terraces dated with tephrochronology provide sufficient resolution to infer the history of incision (e.g., Marden et al., 2014). Incision commenced within 1 ky following the termination of the LGM, averaging $1\text{--}3\text{ mm y}^{-1}$ except for a period of rapid incision ($7\text{--}10\text{ mm y}^{-1}$) around the Pleistocene-Holocene ($\sim 11.5\text{ ka}$) transition (Berryman et al., 2010; Marden et al., 2014) (Fig. 6A). During this 2-4 ky interval of rapid lowering, a disproportionate fraction (40-60%) of post-LGM incision was accomplished. While the transmission of knickpoints has been implicated as a potential source of this accelerated incision (Berryman et al., 2010), limited tephrochronology data from LGM terraces in two headwater tributaries (specifically, the Mangamaia and Waingaromia; Fig. 1b) indicate that incision at the termination of the LGM

was nearly synchronous between mainstem river and headwater tributaries (Gomez and Livingston, 2012; Bilderback et al., 2014). Similar to rock uplift rates, cumulative post-LGM incision varies systematically in the Waipaoa, approaching 120 m in the headwaters and 55 m at the midpoint of the catchment, while lower sections near the coast experienced deposition driven by subsidence (Berryman et al., 2000).

Sediment production processes - During the LGM, sediment production in the Waipaoa catchment was likely driven by periglacial and mass-wasting processes as evidenced by inactive scree slopes and other characteristic surficial deposits found on low-gradient, relict hillslopes (Gage and Black, 1979; Bilderback et al., 2014). These slopes are typically found above hanging valleys and often grade to the extensive 17.6 ka Waipaoa 1 (W1) terrace. Post-LGM fluvial incision and vegetation change, as well as post-European settlement deforestation, promoted extensive hillslope adjustment via landsliding that continues today. Because the mainstem valley network in the Waipaoa is remarkably wide, perhaps owing to weak sedimentary bedrock that permits rapid lateral migration, post-LGM sediment production via fluvial excavation has been distinguished from that via hillslope processes (Marden et al., 2014). In most active tectonic settings, valley excavation is minor relative to hillslope contributions (e.g., Larsen and Montgomery, 2012), but in the Waipaoa, the contributions of these two mechanisms are of similar magnitude.

Currently, a spectrum of landslide styles can be found in the Waipaoa, including: 1) shallow, soil-dominated landslips that travel rapidly in response to intense rainfall (Fig. 5C); 2) slow-moving, shallow-to-deep earthflows that activate seasonally due to wetting and drying of clay-rich material, but persist for decades to millennia (Fig. 5D); and, 3) deep translational landslides or rotational slumps that fail incrementally to catastrophically due to de-buttressing at the toe (Fig. 5A). Collectively, these landslide styles, and the extensive gully systems that can develop on them (Fig. 5B), account for much of the sediment delivered

to the Waipaoa since the post-LGM climate shift and in response to recent land-use change (Gage and Black, 1979; Marden et al., 2005, 2008b, 2014; Page and Lukovic, 2011; Bilderback et al., 2014). Landslide style tends to correlate with rock-type variations throughout the Waipaoa (O'Byrne, 1967; Gage and Black, 1979; Reid and Page, 2002; Page and Lukovic, 2011; Bilderback et al., 2014) and thus geologic maps have been used to delineate the relative contribution of these different landslide styles. About 86% of the catchment consists of hilly terrain (slopes $>20^\circ$), with the steepest angles occurring in the mid to lower parts of the catchment dominated by Miocene-Pliocene rocks. In those areas, shallow, rainfall-induced landslides and discrete deep-seated landslides and slumps are the dominant sediment production mechanisms (Page and Lukovic, 2011). In mudstone-dominated allochthonous terrain, which comprises much of the upper catchment, hillslopes are highly unstable and frequently exhibit susceptibility to earthflows, slumps, and gully erosion (Gage and Black, 1979; Bilderback et al., 2014). In the lower catchment, the Waipaoa River drains through the Poverty Bay floodplain, a large alluvial plain (comprising ~10% of the catchment) (Page and Lukovic, 2011).

In sub-catchments of the Waipaoa with relatively strong bedrock (typically slightly indurated sandstone and limestone units) and relatively steep ($20\text{--}40^\circ$) slopes, the absence of deep-seated landsliding or earthflow activity promotes shallow landslide erosion (Fig. 5C). These shallow failures initiate within rounded hilltops and ridge-valley sequences as planar failures that remove soil and perhaps a thin layer of weathered bedrock (Page et al, 1999). Most of these failures are <1 m thick and seldom exceed 200 m^2 in area. During historically intense rainfall events (such as Cyclone Bola), sliding generates highly mobile debris flows that evacuate scars and produce a trail of debris downslope (Page et al., 1999; Reid and Page, 2002; Preston, 2008; Page and Lukovic, 2011). Some of these flows deliver sediment to stream channels whereas others terminate where gentle gradients along footslopes or the

valley floor encourage deposition (Preston, 2008; Jones and Preston, 2012). Following evacuation of slide material, exposure of the underlying bedrock encourages rapid weathering through the alteration of clay minerals (Claridge, 1960; Pearce et al., 1981; Trustrum and DeRose, 1988; Crozier and Preston, 1999; DeRose et al., 1998), which may control the frequency of shallow landsliding at a given location.

Most geologic units in the Waipaoa have been subject to extensive tectonic deformation associated with accretion, generating vast swaths of heavily sheared and low-strength materials, and making the terrain susceptible to deep-seated slides and slumps (Fig. 5A). These failures typically exceed 10^5 to 10^6 m² in area and 10 to 100 m in depth and collectively constitute nearly 20% of the modern hilly terrain (Page and Lukovic, 2011; Bilderback et al., 2014), although this value is likely underestimated because the signature of deep-seated failure can fade with time since destabilization. The style of deep-seated failure generally occurs via large slide/flow complexes and discrete slumps with many extending from valley floor to ridgeline (Gage and Black, 1979; Page and Lukovic, 2011; Bilderback et al., 2014), which at times have blocked drainages (Pere, 2003; Taylor, 2011). Their movement varies from slow, relatively continuous deformation to catastrophic failure. In many situations, tephra deposits combined with landslide maps indicate that ridgelines have migrated or lowered up to 100 m since the LGM due to slide activity (Bilderback et al., 2014). Deep failures tend to emerge (or daylight) along the hillslope-valley interface where basal slip surfaces are sometimes visible, suggesting that local base-level lowering facilitates gravitational collapse for the vast majority of features (Gage and Black, 1979; Page and Lukovic, 2011; Bilderback et al., 2014).

In particularly weak geologic units in the Waipaoa (e.g., relict fault zones or *mélange*), slow-moving earthflow complexes reduce slope gradients and imprint flow-like features across the landscape surface (Fig. 5D). These mass movements resemble elongate

(>100 m) sediment ‘glaciers’ and seldom exceed 10 m in depth. Despite modest slope angles (<10°), earthflows translate downslope at rates of 10^0 to 10^1 m y⁻¹. With well-defined lateral margins, these features typically span from ridgeline to valley margin and progressively deliver sediment to the valley network until the source is depleted (Zhang et al., 1991; Mackey et al., 2009; Mackey et al., 2011). In Northern California, similar individual earthflows have been shown to remain active for hundreds to thousands of years before becoming dormant (Mackey et al., 2009). Although earthflow-prone slopes are gentle, sediment production from these locales is vigorous owing to the extremely low residual strength of the materials and persistence of viscous-like failure.

Gully erosion also tends to occur in zones of heavily sheared bedrock, particularly argillite susceptible to acid sulfate weathering (Pearce et al., 1981). Deep, rapidly eroding channels that coalesce to form gully networks initiate and grow when subsurface flowpaths are unable to accommodate rainfall delivered to hillslopes. Once initiated (often atop landslide complexes), hydrologic response in gullied areas becomes dominated by overland flow that entrains sediment and destabilizes slopes leading to headward migration. While some active gullies in the Waipaoa appear to have initiated due to slope instability that exposed underlying bedrock and altered the near-surface hydrologic regime, most gullies arose following deforestation by European settlers (DeRose et al., 1998; Marden et al., 2005; Marden et al., 2008b). Because intense storms are relatively common each year, gully erosion persists in many Waipaoa tributaries despite efforts to reforest hillslopes and re-establish the pre-European hydrologic regime (Fuller and Marden, 2011). Migration and headward erosion of historical gullies is typical, and the likelihood of gully expansion appears to depend on their initial gully area (Marden et al., 2012).

Terrestrial sediment budget and temporal variations in sediment production -The Waipaoa River is 100-200 km downwind of the Taupo Volcanic Zone (TVZ), which frequently

experienced rhyolitic eruptions during the late Pleistocene (Smith et al., 2005; Lowe et al., 2008; Lowe et al., 2013). In the Waipaoa, 15-20 tephra units with relatively distinct geochemical signatures (based on ferromagnesium mineralogy and electron microprobe analysis) spanning from 55 ka to 0.636 ka in age have been used to date terraces, landslides, and other surfaces within the catchment (e.g., Berryman et al., 2000; Eden et al., 2001; Litchfield and Berryman, 2005; Marden et al., 2014; Bilderback et al., 2014; Cerovski-Darriau et al., 2014). On terraces or landslide surfaces, the age assigned to the basal tephra observed in soil pits or hand-auger samples corresponds to the timing of the first eruption since that location was last disturbed by landsliding, approximating the time since stabilization (Preston and Crozier, 1999; Lang et al., 1999; Bilderback et al., 2014). Thus, this technique enables ages to be established to within ~2 ky, or the average recurrence of diagnostic tephra deposits (Marden et al., 2005). The distribution of terraces and landslide deposits has been established in much of the Waipaoa catchment through analysis of air photos, topographic maps, airborne LiDAR data, and field observations (e.g., Gage and Black, 1979; Berryman et al., 2000; Crosby and Whipple, 2006; Page and Lukovic, 2011; Marden et al., 2014; Bilderback et al., 2014; Cerovski-Darriau et al., 2014).

Based on the volume of sediment and bedrock excavated below reconstructed valley surfaces, Marden et al. (2014) calculated the fluvial component of post-LGM sediment production from the Waipaoa River and its major tributaries to be 16.7 km³. Spatial variation in valley excavation is substantial, but systematic, and reflects two primary factors: rock uplift rate and knickpoint location, which may reflect a stream power threshold. The post-18 ka incision depth of the mainstem Waipaoa River increases monotonically upstream (Fig. 7), consistent with the inferred pattern of rock uplift (Berryman et al., 2000; Litchfield and Berryman, 2006). As a result, a disproportionate fraction of sediment production emanates from headwater catchments (Marden et al., 2014). For the major tributaries of the Waipaoa,

the average cross-sectional area of valley excavation is strongly correlated with the average incision rate, except for the mainstem segment of the Waipaoa which exhibits voluminous excavation despite a modest average incision rate (Marden et al., 2014). This results from both the exceptional width of the mainstem valley as well as the along-profile variation in incision (Marden et al., 2014). Bedrock and aggradation gravel constituents account for ~80% and ~20% of the excavated valley volume, respectively. Using representative bulk densities for these constituents, the estimated post-LGM fluvial sediment production in the Waipaoa amounts to 41,000 +/- 7000 Mt, or $\sim 1.9 \text{ Mt y}^{-1}$ (Marden et al., 2014). Consistent with the post-LGM incision-rate time series, rates of fluvial sediment production peak around the Pleistocene-Holocene transition, particularly in sub-catchments with high average incision rates (Marden et al., 2014).

In contrast to the well established fluvial component of post-LGM sediment production, the post-LGM hillslope contribution in the Waipaoa has been ambiguous because landslides are spatially and temporally distributed, and thus challenging to characterize. The role of shallow landslides was assessed in the wake of 1988 Cyclone Bola using air photos (Page et al., 1999), although uncertainty in the frequency of intense rainstorms, sediment-delivery ratios, and the influence of post-colonial deforestation contributed to uncertainty in extrapolating historic landslide rates to the LGM (Jones and Preston, 2012). Regardless, a modern, shallow-landslide sediment-yield estimate of $2.6 \times 10^6 \pm 0.6 \text{ t y}^{-1}$ was proposed by Reid and Page (2002) and used in a sediment budget by Page and Lukovic (2011). This was converted to a post-LGM contribution mass of 8,700 +/- 3,200 Mt by assuming average densities and applying yield reductions for different assumed land cover through the late Pleistocene and Holocene (Bilderback, 2012). For deep-seated landslides and earthflows, the emergence of airborne LiDAR data and high-resolution photogrammetry has enabled researchers to map landslide deposits and reconstruct pre-LGM topography to inventory

sediment production from entire catchments or individual slope failures (Cеровski-Darriau et al., 2014; Bilderback, 2012). Using tephrochronology to establish the minimum age of surfaces disrupted by landsliding, Bilderback (2012) determined that >20% of Waipaoa hillslopes have been affected by landsliding since the LGM and demonstrated that widespread hillslope adjustment occurred 9-13 ka, coincident with the period of rapid incision (Fig. 6A). Furthermore, sediment-production estimates for two heavily studied sub-catchments were extrapolated across the Waipaoa by Bilderback (2012) using a detailed deep-seated landslide inventory (Page and Lukovic, 2011), producing a post-LGM deep-seated landslide sediment production value of 25,000 +23,000/-12,000 Mt.

In addition to landsliding, the contribution of post-LGM overland flow erosion was estimated to be negligible, at 2,200 Mt, while coastal erosion was considered to account for about 13,000 Mt. (Page et al., 2004; Young and Ashford, 2006; Bilderback, 2012). Taken together, post-LGM terrestrial sediment sources total 90,600 +37,000/-26,000 Mt (Bilderback, 2012), which equates to an average denudation rate of 0.8 mm y^{-1} , consistent with the range of rock uplift values observed in the Waipaoa basin (Berryman et al., 2000; Litchfield and Berryman, 2006). However, this value greatly exceeds the mass tallied from the Waipaoa floodplain and marine sediments of the adjacent shelf and slope and (45,000 +/- 10,000 Mt) (Marden et al., 2008a; Gerber et al., 2010; Bilderback, 2012), implying that post-LGM transport out of the study area may be substantial, as discussed in later sections.

Data that quantify temporal variations in hillslope erosion since the LGM are limited. Comparison of a post-LGM landscape erosion analysis for a Waipaoa tributary (Mangataikapua) (Cеровski-Darriau et al., 2014) with fluvial incision rates (Marden et al., 2014) and the initiation of widespread deep-seated landsliding (Bilderback et al., 2014) confirm that peak terrestrial-sediment production occurred around the Pleistocene-Holocene transition (Fig. 6). These observations suggest that slope failure and hillslope-derived

sediment production are tightly coupled with incision and valley excavation. Furthermore, the post-LGM erosion rate of $>1.6 \text{ mm y}^{-1}$ for the 16-km^2 earthflow-dominated Mangataikapua tributary catchment is associated with a narrow band of weak early Cretaceous melange, indicating that variations in rock type can modulate landslide erosion rate by a factor of 2 or more (Bilderback et al., 2014; Cerovski-Darriau et al., 2014).

Historic (post-European settlement) landscape change -With the arrival of European settlers, clearance of indigenous podocarp-hardwood forest in the Waipaoa began in 1894 and was nearly complete by 1914 (Black, 1977). Mass wasting accelerated (Zhang et al., 1991; Marden et al., 2005) and gullies were initiated; notably the largest gully complex (Tarndale) (Fig. 5B) initiated in the winter of 1915 due to vegetation loss on the site of a dormant slump deposit. Many other gullies were initiated during the subsequent winters of 1916, 1917, and 1918 (Gage and Black, 1979; Marden et al., 2005). Although these features constituted a small fraction of the landscape area, they became prodigious producers of sediment, contributing $>50\%$ of the modern average suspended-sediment load of 15 Mt y^{-1} (Hicks et al., 2000; Marden et al., 2005; Marden et al., 2008b). Concentrations of meteoric ^{10}Be in stream sediments vary by more than an order of magnitude across the Waipaoa with low-concentration samples reflecting a 20 times increase in sediment production from heavily gullied catchments (Reusser and Bierman, 2010). In addition, fluvial terrace sediments differ in composition from their modern river counterparts, likely reflecting the historical development of major gullies (Marsaglia et al., 2010).

Late Quaternary Record of the Shelf and Slope

Sediment generated by valley excavation and hillslope failure ultimately is delivered by the Waipaoa River to Poverty Bay and dispersed to the shelf and slope, forming the marine record of the WSS. The post-glacial marine transgression for Poverty margin has resulted in the systematic migration of sediment depocenters on the slope and shelf.

Furthermore, a combination of great sediment supply and tectonic accommodation has preserved a nearly continuous record of environmental change that has included: sea level, tectonics, sediment supply, climate, seismicity, volcanism, regional oceanography and human land-use practices. During the LGM, riverine sediment draining from the Raukumara Range largely bypassed the modern shelf and debouched onto the modern slope through a network of upper-slope gully systems and incised submarine canyons to be captured in slope basins and fans (Lewis et al., 1998; Orpin, 2004; Alexander et al., 2010; Pouderoux et al., 2012a). As the shoreline retreated landward during the ensuing transgression, riverine sediment began to fill newly created accommodation on the shelf (Foster and Carter, 1997; Gerber et al., 2010) as the supply to the slope diminished (Pouderoux et al., 2012a).

The architecture of the Late Quaternary shelf sediment package is consistent with sequence stratigraphic models forced by rising to stable sea level (i.e., transgressive and maximum-flooding surfaces, highstand systems tract) but also shows the strong influence of tectonic deformation with differentially subsiding mid-shelf basins and mid- to outer-shelf anticlines (Fig. 8) (Foster and Carter, 1997; Orpin et al., 2006; Gerber et al., 2010). Several giant piston cores retrieved from the shelf and slope preserve low-frequency signals related to glacio-eustatic sea level, storminess and intensification of ENSO, and historic land-use changes (Figs. 1, 9 and 10) (Wilmshurst, 1997; Carter et al., 2002; Gomez et al., 2004b, 2007; Pierce, 2012). This history of LGM-to-present sediment dispersal and accumulation on the slope and shelf is presented in more detail below. For simplicity and clarity, we refer to the cores in the subsequent discussion according to their geographic locations on the shelf and slope (Fig. 1) as follows: Southern Depocenter (MD3004), Northern Depocenter (MD3001 and 3007), Poverty Gap (MD2122), Outer Shelf Depocenter (MD3006), Paritu Trough (MD3003) and Paritu Basin (MD3002).

LGM – Holocene - During the LGM, sea level was ~120 m lower than present, thus the paleo-coast was nearly at the modern shelf break. Consequently, a more direct riverine input to Poverty Canyon resulted in rapid accumulation in mid-slope basins of alternating hemipelagites and coarse silty-sandy turbidites, as recorded in the 18-ky sedimentary record on the slope (Pouderoux et al., 2012a). Prior to 14 ka, $\delta^{13}\text{C}$ values in Paritu Trough (Fig. 10) suggest a higher proportion of terrestrial organic matter and, along with higher accumulation rates, support the idea of more direct fluvial sediment input during sea-level lowstand. Seventy-six percent of the 18-ky sequence in the giant piston cores is composed of cm-thick turbidites alternating with hemipelagites, tephra and debrites, at an average rate of 5.5 turbidites per meter (Pouderoux et al., 2012b). For example, the Paritu Trough shows a relatively coarse interval (average of 5.5 phi, solid vertical black bar) and high textural variability before ~13 ka (Fig. 10B) reflecting episodic emplacement of coarse turbidites (Pierce, 2012). Synchronous turbidites can be assigned to 5 lithofacies, which collectively register a broad range of debris flows and triggers, including earthquakes and rare hyperpycnites. The synchronicity of inter-basin lithological evidence suggests that earthquakes are the predominant trigger regionally (e.g., Pouderoux et al., 2014). Furthermore, sedimentation patterns have been significantly impacted by the emplacement of a large failure deposit on the mid-slope, the Paritu debris avalanche, produced during 7–8.2 ka. This deposit caused a mid-Holocene switch in the main slope depocenter of the turbidite system from the Paritu Trough to the Paritu Basin (Fig. 11, Pouderoux et al., 2012a).

Two distinct patterns of sedimentation were recognised in concert with post-glacial sea-level rise as sediment dispersal shifted to the shelf with a concomitant 5-fold reduction in slope sediment accumulation rate since the LGM. Despite this landward shift in margin dispersal processes, 26 turbidites occurred during the late Holocene (0–7 ka), and the remaining 41 turbidites occurred during the Early Holocene and Late Pleistocene (7–18 ka)

(Pouderoux et al., 2014). These indicate a relatively consistent mean return time for turbidites of ~240 years, extending back to the LGM. Comparison with other chronostratigraphic records along the northern Hikurangi Margin suggests that large earthquakes ($M_w > 7.3$) are more likely to occur on the northern Hikurangi Margin with an return interval of 200 ± 100 years, while large to great subduction interface earthquakes ($M_w >> 7.5$) might occur every 550 ± 50 years (Pouderoux et al., 2014).

Following the LGM, sea level rose episodically in the Western Pacific (Liu et al., 2004 and references therein) and the Poverty shoreline migrated landward, reducing the direct fluvial input to the slope. The Paritu Basin accumulation rate (water depth 1398 m) was halved after ~14 ka (from 0.14 to 0.06 cm y^{-1}) and remained low through the mid-to-late-Holocene (Fig. 9). In contrast, Pouderoux et al. (2012a) reported accumulation rates in the Paritu Trough (MD3002) that did not show a similar decrease at 14 ka, presumably because of its location farther from the shelf break at a water depth of 2305 m. A marked fining from silt- to clay-size texture is seen in sediments deposited on the slope after about 13 ka, when mean grain size decreases from 5.5 to 7.8 phi in the upper core section (Fig. 10B). A similar but less marked fining of slope sediments also occurs in a slope basin off Hawke Bay (Carter et al., 2002). The likely cause is an abrupt Late Pleistocene (~14 ka) sea-level rise of about 20 m (Stanford et al., 2006), corresponding to the time of Meltwater Pulse 1a. As a result, sea level changed from about 100 m below present sea level (mbsl) to 79 mbsl, which flooded the shelf and encouraged trapping of coarse sediment there (Suggate, 1990; Liu et al., 2004). A similar, yet more gradual, textural shift is observed at the Outer Shelf Depocenter, where sediment fined from an average of 4.8 to 7.8 phi after 12 ka. During the rapid rise in sea level from ~12 ka to the early Holocene (30 mbsl, Fleming et al., 1998), the shoreline would have likely moved landward of the Ariel and Lachlan anticlines, shifting the locus of river sediment deposition from the present-day outer shelf and slope to the inner-middle

shelf. Today, the edges of these anticlines occur at ~50 mbsl (Fig. 1), but were likely 10 m to 20 m deeper at that time, factoring in their rapid tectonic uplift rate of 1-2 mm y⁻¹.

Accumulation rates decreased markedly and remained low in Paritu Basin after 14.5 ka, and remain low at the Outer Shelf Depocenter (0.06 cm y⁻¹ in both locations, Fig. 9A). Bulk sediment $\delta^{13}\text{C}$ for the Paritu Trough and Outer Shelf Depocenter shift toward more positive values at 15 ka and 11 ka, respectively, suggesting an increased contribution of marine organic matter (assuming typical terrestrial values of -25 to -27 ‰ and marine values of -18 to -21 ‰). Terrestrial input to the outer shelf and slope would be expected to decrease with increased nearshore trapping as sea level continued to rise, shifting the depocenter landward to the mid-shelf, and allowing shoreline progradation to begin forming Poverty Flats (Wolinski et al., 2010).

High-resolution seismic-reflection studies on the shelf reveal a distinct unconformity that has been interpreted to represent the erosional surface formed during the LGM (W1; Fig. 8) (Lewis, 1973; Foster and Carter, 1997; Gerber et al., 2010). The W1 surface (see next section) is evident by its strong acoustic return and the presence of steeply dipping and truncated underlying reflectors. W1 crops out on the shelf in the vicinity of the Ariel and Lachlan ridge-anticlines, thought to represent Miocene slope mudstone and the front of accretionary slope deformation (Lewis and Pettinga, 1993; Foster and Carter, 1997). These emergent structures form a seaward barrier to sediment dispersal and flank the two mid-shelf depocenters discussed below (e.g., Gerber et al., 2010).

Shelf Inundation to Maximum Flooding - Subaerial exposure, erosion and shoreline migration across Poverty shelf with sea-level change in the late Pleistocene and early Holocene developed the prominent acoustic reflector and diachronous surface, W1, that now underlies a shelf sediment deposit with an estimated thickness of ~70 m in the southern depocenter (extrapolated from sub-bottom profiles; Gerber et al., 2010). At maximum post-

glacial flooding ~7 ka, the Waipaoa mouth was situated at its farthest inland position, ~12 km landward of the present shoreline, and a large protected embayment occupied the modern Waipaoa River floodplain in an area now known as Poverty Bay flats (Brown, 1995). Subsequently, the shoreline began to advance as sediment supply to Poverty embayment outpaced sea-level rise and subsidence (Wolinsky et al., 2010) and the efficiency of offshore sediment dispersal by waves and currents (Bever, 2010).

The core records from the Outer Shelf, Northern and Southern Depocenters show a consistent progressive fining from 10 ka to ~7 ka (Fig. 10), indicating the increased importance of sea-level rise and coastal trapping of bedload sediment within the quiescent Poverty Bay paleo-embayment, effectively limiting the offshore dispersal of coarser fractions (Pierce, 2012). Wolinsky et al. (2010) estimate ~0.8 Mt y⁻¹ sediment trapping in Poverty embayment at 7 ka onwards (until European landscape changes in the 19th century), representing ~40% of the sediment discharged by the Waipaoa River. Whereas the timing of the maximum transgression and the fining of sediments deposited offshore roughly coincide, maximum fining in the Southern and Northern Depocenters occurred at slightly different times, peaking at 6.7 and 7.8 ka (Fig. 10), respectively, implicating differential tectonic accommodation or infilling of the depocenters. Sediments in both the Southern and Northern Depocenters have $\delta^{13}\text{C}$ signatures suggesting substantial contributions of marine organic matter up to maximum flooding, with the Southern Depocenter consistently displaying a slightly larger marine contribution (Fig. 10 A, D, and E); sediment $\delta^{13}\text{C}$ values suggest increased terrestrial influence after 7 ka (Pierce, 2012; Leithold et al., 2013).

The fining trend in the mid-shelf depocenters reverses after maximum flooding and progressive upward coarsening occurs until ~3.5 ka (Fig. 10D and E). In conjunction with this textural change, a distinctive transition occurs in seismic facies at 7 ka, as observed in CHIRP records (Fig. 8)(Gerber et al., 2010). A largely acoustically transparent facies (with a

few weak, discontinuous reflectors) overlies W1 and persists for the mid-shelf depocenters until the maximum transgression ~7 ka. Above the maximum flooding surface, reflectors are more numerous, stronger and more laterally continuous, corresponding to the period where there was likely increased bypassing of silt and sand to the shelf from Poverty Bay as the embayment infilled (Brown, 1995; Wolinsky et al., 2010) (Fig. 8). Consistent with this scenario, the $\delta^{13}\text{C}$ record from the mid-shelf depocenters (Fig. 10 D and E) suggests a substantial admixture of marine organic carbon (~ -24‰) in the early Holocene sections of the cores before ~7 ka. After that, bulk sediment $\delta^{13}\text{C}$ values become more negative, indicating increased terrestrial input (Pierce, 2012).

Highstand and Regression - Trends in sediment accumulation rates on the shelf vary considerably among the depocenters following the maximum transgression. The Outer Shelf Depocenter shows a four-fold increase in accumulation rate after 7 ka (Fig. 9A) that likely reflects increased riverine supply to the shelf and bypassing of sediment from the mid-shelf depocenters to sites farther offshore. A two- to three-fold increase in accumulation rate (from 0.16 to 0.41 cm y⁻¹) is observed during 7-5.8 ka in the Southern Depocenter, after which rates drop back to 0.12 cm y⁻¹. In contrast, rates for the Northern Depocenter remain steady after 7 ka at 0.28-0.33 cm y⁻¹ until ~4 ka when accumulation rates show a four-fold reduction to 0.07-0.09 cm y⁻¹ (Pierce, 2012).

The contrasting trends in sediment accumulation rates for the three shelf depocenters reflect a combination of factors, including relative sea-level position, as well as spatial and temporal differences in tectonics, accommodation and sediment dispersal patterns (both from Waipaoa and from the Hawke's Bay shelf to the south). The timing of the abrupt increase in accumulation rate after 7 ka in the Outer Shelf Depocenter (Fig. 9) suggests that, during the transgressive phase, sediment trapping on the inner shelf and within Poverty embayment limited the offshore dispersal of Waipaoa sediments, a condition that changed rapidly as the

shoreline trajectory reversed following maximum transgression. Trends for the Northern and Southern Depocenters, however, are more difficult to interpret.

Sequence stratigraphic analysis of the Holocene fill for the mid-shelf depocenters shows contrasting basin-fill architecture related to differential subsidence and infilling (Gerber et al., 2010). Seismic reflectors in the southern depocenter define an underfilled syncline, in contrast to those in the northern depocenter that display a progradational pattern resembling a low-gradient clinoform and suggesting that the accommodation in the north is limited relative to the south. This difference is also evident in the regional structural patterns that show tectonic tilting with coastal uplift increasing alongshore toward the northern depocenter (Berryman, 1993). Moreover, this pattern can be seen in both the modern bathymetry and post-glacial sediment thickness that show deeper water and increasing sediment thickness in the southern depocenter. Based on these regional considerations, we can interpret the Northern Depocenter accumulation rate trend to reflect accommodation limits, where shallower water depths and increased sediment bypassing along and across the shelf effectively control the accumulation rate. The reduction in accumulation rate after 4 ka for the Northern Depocenter could either reflect the completion of the basin infilling, or increased resuspension, perhaps related to the onset of a stronger ENSO and the increasing occurrence of storms (Pierce, 2012).

4 ka to Present – ENSO and Anthropogenic Influences - In the Southern and Northern Depocenters, and Poverty Gap the coarsening trend that began after maximum transgression (~7 ka), abruptly intensifies after ~4 ka with an increase in mean particle size of about 1 phi (Fig. 10). In the Southern Depocenter, this coincides with more positive $\delta^{13}\text{C}$ values, possibly indicating an increasing marine influence or alternatively increased soil input (Leithold et al., 2013), with a peak at ~1 ka, a time that corresponds with a period of reduced storm frequency as recorded the Lake Tutira (Table 1). Studies of terrestrial and marine cores

from Poverty margin and the continental slope off southern Hawke Bay (MD 2121) suggest a link between prominent coarsening after 4 ka and landscape erosion and climate change from the Mid-Holocene due to intensification of the ENSO (Gomez et al., 2004b, 2007).

According to Preston and Crozier (1999), the modern soil mantle in the Waipaoa catchment contains little clay and is not extensively weathered. Therefore, they postulate that increased shallow landsliding liberates a preponderance of heterogeneous silt and sand material relative to other hill-slope erosion processes such as gullying and deep-seated earth-flows (which generate finer material), implicating a climate-enhanced textural coarsening. Paradoxically, there is no observed increase in accumulation rate for the Poverty shelf depocenters corresponding to the onset of the intensification of ENSO and the proposed increase in shallow landsliding. The Southern Depocenter shows steady accumulation rates during this time and the Northern Depocenter shows a four-fold decrease in accumulation rate, commencing at ~4 ka (likely a result of basin infilling, as described above).

While increased landsliding spawned by an intensification of the ENSO could well drive the observed trends in the three mid-shelf cores, another explanation may arise from changes in oceanographic conditions associated with the onset of increased storms and the changing configuration of Poverty Bay over time (Bever, 2010). More energetic wave conditions could drive the observed textural trends through enhanced resuspension and winnowing of fines. One way to test these ideas would be to examine the downcore abundances of tephra, as the coarse fraction in Waipaoa catchment soils is dominated by tephra. A landslide-driven coarsening should be reflected in an increase in tephra abundance; however, such evidence is presently lacking.

A major textural and isotopic excursion is recorded in the Northern and Southern Depocenters in the uppermost sections of MD 3004 and MD 3007 (Fig. 10 D and E). This abrupt fining and reversal to significantly more terrestrially sourced $\delta^{13}\text{C}$ reflects the massive

influx of fine river sediment following changes in landscape erosion and sediment supply linked with human habitation and modification of the Waipaoa watershed (Wilmschurst, 1997; Gomez et al., 2004a). A fining in texture is also seen in the Outer Shelf Depocenter, albeit less dramatic than seen in mid-shelf depocenters (Fig. 10C). An abrupt decrease in radiocarbon ages of charcoal in the youngest (<2 ka) section of the Northern Depocenter has been attributed to widespread burning related both to the Taupo eruption and human habitation (Leithold et al., 2013). A concomitant increase in shelf sediment accumulation rates over the last century is evident (Miller and Kuehl, 2010; Gerber et al., 2010).

Contemporary Shelf and Slope Sediment Dispersal Patterns

The contemporary Waipaoa dispersal system, and the deposits it creates, record the signatures of both natural and anthropogenic activities. As on many active margins, Waipaoa River sediment is discharged directly to the sea; i.e., into Poverty Bay, which has open-marine salinity and regularly receives oceanic swell (Bever et al., 2011). From the bay, sediment is distributed widely and accumulates where accommodation is being created by tectonic activity, so that the sediment record highlights regions of geologic change (Orpin et al., 2006; Gerber et al., 2010). Further, these deposits hold preserved records of both natural (e.g., floods, earthquakes; Rose and Kuehl, 2010; Pouderoux et al., 2012b) and anthropogenic events (i.e., deforestation by early settlers; Pullar 1962; Gomez et al. 1999; McGlone and Wilmschurst, 1999; Wilmschurst et al. 2008), both of which significantly affect the magnitude and timing of sediment input.

The distribution of sediment accumulation rates on centennial timescales integrates the results of sediment delivery, transport and deposition processes on the Waipaoa margin, and highlights dispersal pathways that lead to sediment depocenters that serve as sinks for sediment, carbon and anthropogenic materials (Foster and Carter, 1997; Orpin et al., 2006;

Walsh et al., 2007; Alexander et al., 2010; Brackley et al., 2010; Miller and Kuehl, 2010; Leithold et al., 2013). The following sections detail accumulation-rate trends, sediment budgets and surface texture that generally reflect processes operating during the past century.

Sediment Accumulation Rates and Sediment Budget – Some modern material discharged from the Waipaoa River is accumulating in four depocenters within the study area: the Northern and Southern Depocenters on the mid-shelf, the Outer Shelf Depocenter seaward of the gap between the Lachlan and Ariel anticlines (Poverty Gap), and the upper slope, where shelf-indenting canyons and gullies trap sediment that is escaping the shelf (Figs. 2, 12; Foster and Carter, 1997; Orpin, 2004; Gomez et al., 2007; Walsh et al., 2007; Alexander et al., 2010; Gerber et al., 2010; Miller and Kuehl, 2010). Consequently, ^{210}Pb sediment accumulation rates vary both along-shelf and across-shelf (Miller and Kuehl, 2010).

Accumulation rates on the shallow shelf (30-50 m) are low because vigorous reworking of the seabed in this depth range resuspends material, which is transported northward and southward along shelf (see below in **Sediment Dynamics of the Waipaoa Continental Shelf**). Some of this sediment accumulates in mid-shelf depocenters, located in synclinal basins landward of the Lachlan and Ariel anticlines, or is bypassed through the Poverty Gap to the Outer Shelf Depocenter (Hale et al., 2014; Walsh et al., 2014). All three of these depocenters exhibit similarly high rates of modern sediment accumulation ($0.6\text{--}1.2\text{ g cm}^{-2}\text{ y}^{-1}$; Alexander et al., 2010; Miller and Kuehl, 2010) and exhibit accumulation patterns similar to post-glacial shelf sediment isopachs (Gerber et al., 2010).

Sediment bulk density and sedimentary structures also serve to delineate the boundaries of these three shelf depocenters (Rose and Kuehl, 2010); Whole-core bulk-density measurements in box cores exhibit statistically significant differences between depocenter and non-depocenter regions, with lower than average bulk densities within the depocenters and higher than average bulk densities in non-depocenter regions (Rose and Kuehl, 2010).

The distribution of sedimentary structures along and across the shelf illustrates the transition from stratified sediments on the inner shelf, where physical energy dominates, to mottled muds in depocenters and on the outer shelf, where biological factors dominate strata formation (Rose and Kuehl, 2010; Walsh et al., 2014).

Some of the material reaching the outer shelf is bypassed over the shelf edge, to accumulate in the heads of shelf-indenting gullies and canyons, where modern accumulation rates are of a similar magnitude to those in the shelf depocenters ($\sim 1 \text{ g cm}^{-2} \text{ y}^{-1}$; Walsh et al., 2007; Alexander et al., 2010). These rates decrease downslope, with rates near the mouths of slope gullies ($\sim 0.25 \text{ g cm}^{-2} \text{ y}^{-1}$) greater than rates in similar water depths on the open slope ($\sim 0.15 \text{ g cm}^{-2} \text{ y}^{-1}$) (Alexander et al., 2010). Accumulation rates are slow and similar across the mid-slope plateau, suggesting that these distal areas are also receiving sediment via hemiplegic sedimentation. Rates in the head of Poverty Canyon ($1.2\text{-}1.9 \text{ g cm}^{-2} \text{ y}^{-1}$) are the most rapid rates observed on the Waipaoa margin, exceeding those from the shelf depocenters. This observation implies that the canyon head is infilling and being buried, given the relative lack of significant down-canyon mass movement evident from the most recent deposits (discussed below in *Centennial-Scale Transport to the Deep Sea*) (Walsh et al., 2007).

A centennial-scale budget for Waipaoa sediment illustrates the importance of the four sediment depocenters to the sequestration of modern sediments on the margin, but also indicates that the fate of much of the sediment supply has not yet been identified. Of the $\sim 15 \times 10^6 \text{ t y}^{-1}$ of sediment being discharged by the Waipaoa annually, $\sim 25\%$ is accumulating on the shelf and $\sim 15\%$ is accumulating on the upper slope, dominantly within the four depocenters (Alexander et al., 2010; Miller and Kuehl, 2010), leaving $\sim 60\%$ of the annual discharge unaccounted (Fig. 2). Similar observations, that less than half of a river's sediment discharge can be accounted on the adjacent shelf and slope, have been made on other

physically energetic, active margins (e.g., Eel River margin, California; Alexander and Simoneau, 1999; Waipao River margin, New Zealand; Kniskern, 2007; Santa Clara River margin, California; Alexander and Lee, 2009).

Seasonality of Sediment Supply - Floods can occur throughout the year, but Waipaoa River sediment discharge to the margin peaks in the austral winter (Reid, 1999). Sediment cores reveal the presence of ^7Be , a naturally occurring radionuclide with a short 53-day half-life that typically indicates the presence of river-derived material. ^7Be is present in shelf and slope sediments soon after discharge events during summer, suggesting that Waipaoa River sediment can be rapidly (weeks to months) resuspended and distributed broadly to the mid-shelf, outer shelf and upper slope depocenters (Alexander et al., 2010; Rose and Kuehl, 2010; Kniskern et al., 2014; Walsh et al., 2014). Winter and summer sampling of the outer shelf and slope demonstrates that sediments are dispersed across (and possibly along) the margin throughout the year (Fig. 13 A, B; Alexander et al., 2010). Whereas the likely main source for this sediment is the Waipaoa River (because of its proximity and high input), we cannot rule out the possibility that some fraction of this material originates in the Hawke Bay region and is carried northwest into the study area by coastal circulation (Carter et al., 2010).

Centennial-Scale Transport to the Deep Sea - Sediments accumulating in the head of the Poverty Canyon and along the upper slope (Fig. 2) apparently are not being redistributed to the Hikurangi Trough under current highstand conditions. Sediment accumulation rates rapidly decrease offshore to ~1200 m water depth, where rates in the canyon and outside the canyon on the open slope are comparable ($\sim 0.15\text{--}0.25 \text{ g cm}^{-2} \text{ y}^{-1}$; Alexander et al., 2010). In this same depth range, 200–1200 m, significant evidence for gravity-flow activity has been documented (i.e., non-steady-state ^{210}Pb profiles; shallower-water foram assemblages; stratified zones bracketed by bioturbated zones in cores; Sumner, 2007; Culver et al., 2012),

suggesting that sediment is only making its way down the upper part of the canyon, probably triggered by cyclones or local seismic activity (Pouderoux et al., 2012b).

Although the final 22-km reach of the Poverty Canyon, found in 1,200 m to 3,000 m water depths, exhibits a relatively steep slope of 3–4°, the lower canyon does not exhibit evidence of modern sediment transport. A short piston core from 2,404-m depth in the lower reaches of the canyon contains stiff late Pleistocene mudstone overlain by ~10 cm of unconsolidated mud, with a sharp erosional contact between the units (Orpin, 2004). At the mouth of Poverty Canyon, an area of strong and mottled acoustic backscatter extends eastwards from the canyon confines onto the Hikurangi Trough at ~3,350 m depth. Thus, the lower portion of the main Poverty Canyon channel has been largely inactive during the Holocene. This is inferred from the thin cover of hemipelagic sediment, erosional morphological features, and the lack of a fan at the canyon mouth (Orpin, 2004).

Sediment Character (Texture, Petrology and Microfossils) - The distribution of surficial sediments on the continental shelf and slope represents the integrated response to tectonic, climatic, anthropogenic and physical oceanographic forcing of the WSS at time scales ranging from hourly variations in hydrodynamic processes to millennial eustatic changes in sea level.

Sediments on the Waipaoa shelf exhibit distinct patterns that reflect their transport pathways (Foster and Carter, 1997; Wood, 2006; Culver et al., 2012; Parra et al., 2012; Walsh et al., 2014). The Lachlan and Arial anticlines form a series of northeast aligned zones of exposed Neogene sedimentary rocks and associated aprons of predominantly muddy, sandy gravel. In contrast, the gravel and rocky zones near the coast appear to be extensions of structural promontories that reach onto the inner shelf (e.g., near the mouth of Poverty Bay), except at 38° 35'S where the zone nearly reaches the Arial Anticline (AA) (Fig. 14).

Emanating from the Lachlan Anticline is a northeastward directed tongue of well-sorted sand that grades into a zone of clayey silty sand and finally sandy clayey silt. Both the distribution pattern and northeastward fining of grain size indicate a net northeastward transport of outer to middle shelf sediment. Wood (2006) suggested the main driver was likely to be southerly storms that reinforced the Wairarapa Coastal Current and flood phase of the tide to affect along-shelf transport of bedload and wave-suspended sediment. Interestingly, the bathymetry off the northern extremity of Mahia Peninsula reveals a northward-directed submarine spit with a sediment cover that fines in the same direction (Fig. 13). Such a setting is consistent with the northeastward sediment transport modelled by Moriarty et al. (in review) for the area, and the regional picture where the northern sides of major coastal promontories commonly have growing submarine spits (Herzer, 1981; Carter et al. 1985). Nevertheless, there is also an across-shelf transport of mud that is not immediately clear in the surficial dispersal patterns but is evident in high-resolution seismic profiles (Orpin et al., 2006; Gerber et al. 2010) seaward of Poverty Gap as a substantial deposit on the outermost shelf and upper slope (i.e., Outer Shelf Depocenter). The similarities between millennial scale, post-glacial sediment-accumulation patterns, and modern sediment-accumulation and textural distributions highlights the strong effects that active-margin tectonics has on sediment distribution and accumulation patterns on a variety of timescales.

On the shelf, the finest sediments in the WSS are landward of the anticlinal ridges and associated with seaward transport pathways. Clayey silts and sandy silts occupy areas coincident with the main shelf depocenters as identified from seismic profiles (Foster and Carter 1997; Gerber et al., 2010) and sediment cores (Alexander et al., 2010; Miller and Kuehl, 2010; Rose and Kuehl, 2010). That coincidence of modern sediment patterns with actively deepening depocenters, containing >50 m of post-LGM sediment, dramatically highlights the direct and immediate influence of the tectonic regime. Landward of the

depocenters, clayey silty sand extends almost to shore (i.e. to the 10-m isobath) where it is replaced by sands that continue to the beach. The presence of a significant clayey silt fraction in such shallow depths suggests the dominance of the Waipaoa River discharge and to a lesser extent the protection from the dominant southerly storms afforded by Poverty Bay, the Mahia Peninsula and the outer shelf anticlinal ridges. Alexander et al. (2010) examined surficial sediment patterns on the outer shelf to mid-slope, documenting that sediments continue to fine from mid- and outer-shelf sandy and clayey silts to lower-slope silty clays, indicating that resuspension, transport and sorting occur across the margin.

Sands present in the shallow areas of Poverty Bay are trapped there by hydrodynamic processes (Bever et al., 2011; Bever and Harris, 2014), and presumably originate from the Waipaoa River. However, cliff erosion of Miocene-Pliocene strata with subsequent reworking is apparently a significant contributor of sand (Culver et al., 2012; Parra et al., 2012), particularly outside of Poverty Bay. Analyses of surficial sand roundness and composition (Parra et al., 2012) and microfossils (Culver et al., 2012) reveal that erosion of shoreline cliffs and shelf anticlines notably influence the sediment content across the shelf. For example, more angular sand and reworked forams on the midshelf indicate local sources of these sands (i.e., minimal transport).

Sediment Dynamics of the Waipaoa Continental Shelf

The marine dynamical processes that move sediment from their riverine source to their ultimate sink in the sediment dispersal system are spatially and temporally varied across the Waipaoa margin. Study of these processes provides an opportunity to investigate more deeply the link between active transport processes and the associated depositional signatures that may be preserved and subsequently interpreted in the stratigraphic record. Dispersal processes can be inferred from the deposits on the seabed, but the linkages between the

mechanics of those processes and their attendant signatures must be known to interpret, in more detail, the records obtained on the shelf and slope. In addition, understanding of sediment dynamics provides a means for deciphering geochemical signatures (e.g., variations of organic carbon) in the marine realm. With these motivations, observational and numerical modeling efforts have garnered insights into how sediment transport impacts dispersal and deposition on the Waipaoa continental shelf.

Active shoreline and river-mouth transport processes in the tectonically created Poverty Bay have a major influence on initial sediment dispersal, and the bay itself acts as a temporary deposition zone for flood sediment with reworking and export of muddy sediment from the bay occurring during subsequent wave events (Bever et al., 2011). Thus, the delivery of sediment to the coastal ocean is generally asynchronous with its final deposition on the WSS, except in the case of long-duration, “wet storms” in which high river discharge is accompanied by energetic oceanic waves (Hale et al., 2014; Hale and Ogston, in review). This leads to deposition on event time-scales on the shelf that exhibits a high degree of spatial variability (Kniskern et al., 2014; Walsh et al., 2014; Moriarty et al., in review). Additionally, the observations and models shed light on the role of wave-supported gravity flows, and event-bed preservation potential on the Waipaoa shelf (Hale and Ogston, in review). Here we discuss each of these topics, and contrast sediment dynamics on the WSS with examples of other systems.

Shoreline/river-mouth controls on initial sediment dispersal - Drowning of river valleys during the Holocene transgression changed the morphology of the resulting shoreline and impacted sediment dispersal offshore. Both observations and model results have demonstrated the role of shoreline and river-mouth controls for the Waipaoa River sedimentary system. Analysis of water-column measurements at a 15-m-deep site within Poverty Bay during the austral winter of 2006 demonstrated temporary deposition of fine-

grained sediment within the bay (Fig. 15 f, g). The data showed that multiple factors controlled retention of sediment in the bay during typical wet storms: (1) the shape of the receiving basin shelters the river mouth from larger waves; (2) the configuration of Poverty Bay promotes estuarine circulation; and (3) non-linear wave effects in the nearshore drove shoreward sediment fluxes near the seabed (Bever et al., 2011). In addition to promoting sediment retention in Poverty Bay, these processes also helped separate the sands from finer grain sizes. Divergence of currents in water depths of 10-15 m appeared to transport sand, which is carried near the bed toward shore, while exporting fine-grained sediment, especially the fine silts and clays, seaward (Bever and Harris, 2014). These processes are consistent with the observed progradation of the sandy shoreline, and concomitant export of fine-grained sediment to shelf depocenters (Bever et al., 2011).

Numerical models provided further insights into the role of the embayment in transforming flood signatures prior to dispersal on the continental shelf (Bever and Harris, 2014). Though at times the bay serves as a zone of deposition for fine-grained fluvial sediment, that material mostly leaves the bay via energetic wave resuspension, preserving little evidence of the flood record in shallow nearshore or shelf environments (Fig. 15 f, g). In comparison to other small mountainous river basins, the initial dispersal of sediment into a small embayment of the Waipaoa system increased the time of delivery to the shelf system, and hydrodynamics promoted landward flux of nearbed sediment. In addition, the embayment acted to shelter the river mouth from intense wave activity, further increasing the retention capacity of the bay (Bever and Harris, 2014). There are exceptions to these generalizations, as a flood layer from Cyclone Bola is clearly preserved in the shelf stratigraphic record at a water depth of 23 m (Brackley et al., 2010), indicating that under some conditions major storm/flood sediments are rapidly transported and their deposits preserved offshore.

These conclusions were consistent with characterization of the Waipaoa seabed as physically dominated in the inner shelf (Rose and Kuehl, 2010), and with the presence of terrestrial markers such as ^7Be occasionally found in surface sediment (Walsh et al., 2014; Kniskern et al., 2014). The nearshore and inner shelf of other sedimentary systems have been shown to be important for sediment dispersal, including the Eel Shelf (Curran et al., 2002; Crockett and Nittrouer, 2004), and the Waiapu Shelf (Wadman and McNinch, 2008; Kniskern et al., 2010). However, the morphology of the Waipaoa inner shelf, and particularly the presence of Poverty Bay adds greater capacity for temporary retention on the inner shelf than seen in these other sites.

The geometry of Poverty Bay, and nearshore processes likely influence shoreline advance over geologic timescales, and numerical modeling studies show an inverse relationship between estimated wave energy and shoreline progradation rate. Changes in the bay geometry over the past 7000 years reduced wave sheltering as the shoreline advanced, which increased wave energy impacting the river mouth. In the absence of other drivers, this would increase sediment export from Poverty Bay (Bever, 2010).

Asynchronization of delivery and dispersal processes - Previous discussions of sediment dispersal offshore of small, mountainous river drainages argued that orographic effects on atmospheric frontal systems drove synchronous river flooding and energetic ocean-wave conditions (e.g., Wheatcroft, 2000). Under such concurrent discharge and storm conditions, flood-derived sediment is rapidly dispersed to the continental shelf, and little is retained near the river mouth. This synchronization between storms and floods at the mouths of small-mountainous-river drainage basins cannot be applied universally, however (e.g., Waiapu River, Ma, 2009; some US West Coast rivers, Kniskern et al., 2011).

In the WSS, evidence indicates that flood delivery is not always concurrent with the energetic waves capable of transporting sediment to the shelf. Asynchronization between fluvial supply and marine sediment dispersal was seen in sediment-transport observations and numerical models for Poverty Bay and the shelf. Local winds often blow seaward when storm systems cross the Poverty Bay coastline, which will reduce wave heights during times of peak river discharge (Bever et al. 2011 ; Orpin et al. 2006). In this system, where events of enhanced wave energy can occur year-round (Kniskern et al., 2014; Hale et al., 2014) and the marine wave climatology varies little (Smith, 1988), the largest river discharge events can occur in the absence of energetic waves (Fig. 16). Thus, remobilization from wave-current interactions on the inner shelf drives a secondary dispersal system (Hale et al., 2014) that may be synchronous or may lag behind flood delivery to the inner shelf (Figs. 15, 16). Bever et al. (2011) observed deposition of fine-grained sediment within Poverty Bay that was emplaced during a river discharge pulse, remained for a period of 2-3 weeks, and was subsequently removed by southern swell waves. Consistent with the time scale of this temporary deposit in Poverty Bay, Hale et al. (2014) established that the duration of marine-storm conditions contributes to the resuspension and fate of the nearfield deposited sediment. A relatively predictable delay was seen between flood discharge and observed deposition at a tripod located on the mid-shelf (37 m water depth) that was related to the summed duration of wave-induced bed stresses exceeding a critical threshold following the discharge event (Hale et al., 2014).

A comparison of storm types on the shelf suggests that only wet storms with near synchronous river flood and large waves for multiple days have the potential for immediate (i.e., hours to days) transport to the shelf system (Hale et al., 2014). The shelf response during dry storms depends on sediment availability and shelf currents in Poverty Bay. Model estimates and seabed observations suggest spatially patchy distributions of erosion and net

deposition occur over the shelf, even during single storms (Fig. 15). Net deposition during dry storms increases on the shelf when the bay has been recently supplied with flood sediment and if weak along-shelf currents reduce export from the proximal shelf area (Moriarty et al., in review.).

Transience in dispersal patterns - Time-series sensor deployments and seasonal seabed coring were used to identify event-time-scale deposition of sediment in the Waipaoa coastal ocean, but in some ways these yielded contrasting pictures. Altimetry data from instruments located at one site in Poverty Bay, and three sites on the continental shelf evaluated seabed elevation changes on an hourly basis. Within the bay, Bever et al. (2011) saw ephemeral deposition at 15-m water depth in response to a river discharge event, as described above, but no evidence of longer-term accumulation. The shelf observations of Hale et al. (2014) generally found deposition at the inner shelf station (37 m depth), and erosion at the southern depocenter (50 m depth).

On a seasonal time scale, repeated sediment coring during the 2010 calendar year provided evidence from X-radiography and short-lived radioisotopes (^7Be) of recently deposited sediment, covering a wider spatial area than possible with the water-column instrumentation. Walsh et al. (2014) reported evidence of recent deposition from four different cruises completed over a year (Fig. 17D). This included X-radiographs having characteristics of wave-supported fluid muds at some mid-shelf and shallower sites, and inventories of ^7Be on the surficial deposits (Walsh et al., 2014). Additionally, Kniskern et al. (2014) sampled the seabed in 2010 within two weeks after a large flood and found evidence of recent terrestrial deposition (^7Be) in cores across much of the shelf. For the successive research cruises, the spatial distribution of deposition was variable, but patterns generally depended upon preceding river and ocean conditions (Walsh et al., 2014).

Intriguingly, following a flood in 2010, cores from the southern depocenter contained a layer (~2 cm) of sediment with a terrestrial ^7Be signature (Kniskern et al., 2014), but this corresponded to a time period when the altimetry data did not indicate deposition there (Hale et al., 2014). Viewed over the year sampled, however, both the instrument observations and ^7Be results indicated little or no clear deposition in the southern depocenter (Hale et al., 2014; Walsh et al., 2014). Over the 100-year time scale, however, this region appears to be accumulating in a steady-state manner at a rate $>1 \text{ cm y}^{-1}$ (Miller and Kuehl, 2010). This contrast, and the patchiness seen in repeated core sampling, illustrates that episodes of accumulation on the shelf are very much spatially and temporally variable (Walsh et al., 2014).

Numerical models provide a means toward a better understanding of the shelf-wide dispersal system, especially in light of the high degree of variability in shelf processes on this margin. Results from a coupled sediment-transport/hydrodynamic shelf model indicated that a significant fraction of the sediment budget was carried alongshelf and out of the modeled grid, primarily to the north, within river flood plumes or by currents during periods of energetic waves (Moriarty et al., in review). Export of fluvial sediment from the bay to deeper areas of the shelf depended on sediment and seabed properties, with the use of slower-settling velocities and a spatially varying erodibility parameter significantly increasing these fluxes (Moriarty et al., 2014; in review). Modeled depositional patterns for individual events varied (Fig. 15), however, depending on the winds, waves, and larger-scale currents during specific floods, consistent with the variability seen in sediment cores (Walsh et al., 2014).

Role of Gravity flows – Wave-supported gravity flows have been found to be important for cross-shelf sediment transport on a number of continental shelves, including near the Eel River (Ogston et al., 2000; Traykovski et al., 2000; Harris et al., 2005), and the Po River (Traykovski et al., 2007); see also Wright and Friedrichs (2006). For the WSS, wave-

supported fluid muds appeared infrequently in the one-year observational record of Hale et al. (2014) and were only clearly detected at water depths of 37 m during a wet storm event having synchronous high river discharge and high wave energy (Fig. 17 A). Although infrequent, this type of event can carry a significant portion of the annual sediment budget across the shelf, as has been noted for the Eel Shelf (Traykovski et al., 2000; Harris et al., 2005) and the Po subaqueous delta (Traykovski et al., 2007), and may create thick deposits having potential to be preserved (e.g., Macquaker et al., 2010; Harris et al. 2005). Wave-supported fluid-mud transport and resulting deposition in Poverty Gap was observed between the century-scale shelf depocenters. However this event was not observed with sensors located in the southern depocenter, once again illustrating the spatial heterogeneity of transport processes on the shelf (Hale et al., 2014).

The coupled hydrodynamic-sediment transport modeling of Moriarty et al. (2014) estimated deposition resulting from suspended transport alone that was in relatively shallow water compared to radioisotope observations (see Fig. 17 C and D) of Kniskern et al., (2014) and Walsh et al. (2014). This is likely, in part, because this model neglected gravity flows within the wave boundary layer. To help explain this discrepancy predicted and observed seabed deposition, Hale and Ogston (in review) calculated the potential rate of gravity-flow transport following the method of Scully et al. (2002), which balances the downslope force of gravity acting on a dense nearbed layer with frictional forces (Fig. 17 A, B). This provides a means for evaluating the distance travelled by a gravity flow over the duration of a wave event. Results indicated that an event such as this can carry sediment through Poverty Gap to the slope (Hale and Ogston., in review). Cumulative deposition at the observation site in Poverty Gap during this wave-supported gravity flow event was estimated from the gradient of wave-orbital velocities and shelf slope, after Scully et al. (2002). These results compared

favorably with the temporal depositional pattern observed in the hourly altimetry data of seabed elevation (see Hale and Ogston., in review).

In summary, both observations and model results imply that on the Waipaoa shelf, although they may occur infrequently, gravity flows form a critical part of the transport pathway in routing sediment from the inner shelf to deeper areas, including longer-term depocenters on the outer shelf and slope. In this way, the Waipaoa is similar to the Eel Shelf (Harris et al. 2005) and the Waiapu shelf (Ma et al. 2010, Kniskern et al. 2010), although initial deposition within Poverty Bay has the potential to alter the timing and synchronization with delivery by a river discharge event.

Preservation Potential of Event Beds - Observation of a Cyclone Bola event layer (Brackley et al., 2004) and analysis of seabed facies (Rose and Kuehl, 2010) indicate that portions of the mid-shelf region are conducive to preserving event-bed strata, but study of sediment dynamics in the WSS coastal ocean imply that only the largest flood and wave events have any likelihood of creating preservable event beds. Numerical-model results indicated that during the 2010 field season, waves and currents were sufficiently energetic to induce centimeters of resuspension on the shelf (Moriarty et al., in review). Additionally, numerical models of Poverty Bay imply that moderate discharge pulses are heavily reworked within the bay, while larger floods are routed more directly to the shelf, where flood-bed preservation is more likely (Bever and Harris, 2014). Inner-shelf reworking, and the fact that transport to shelf depocenters usually occurred in multiple stages, makes it unlikely that the stratigraphic record can preserve the physical structure of flood deposits except for very large discharges ($>>2000$ cumecs) on the Waipaoa River (Hale, 2014). Contrasts between the short-term deposition on the shelf and the time-averaged pattern of shelf accumulation highlights the stochastic nature of event-dispersal and continual reworking of ephemeral deposits,

particularly on the inner shelf and in Poverty Bay, that create the longer-term sedimentary strata (Walsh et al., 2014).

Wave-induced bed stresses dominated current-induced bed stresses by an order of magnitude, and the wave-stresses respond strongly to bathymetric controls, being higher in shallow areas (Fig. 18). Over the course of many flood and wave events, sediment likely accumulates to either side of Poverty Bay and in slightly deeper areas where bed stresses are less intense. These areas of low average bed stresses also are co-located with mid-shelf depocenters active over century-to-Holocene timescales (Fig. 2; Miller and Kuehl, 2010; Gerber et al., 2010). In this manner, the bed-stress patterns, inferred from modern wave and current climatology can be related to longer-term depositional patterns (Moriarty et al., in review).

Waipaoa Organic Carbon – S2S

The evolution of organic carbon (OC) in the Waipaoa sedimentary system as particles travel from upland source to marine sink can be viewed from a variety of perspectives. Sedimentary organic geochemistry has long been used as a tool to interpret the geological record (Meyers, 1997). Particulate organic carbon (POC) retains a memory of the particle history, thus interpretation of the organic geochemical record, and especially that from river-dominated continental margins, requires a S2S accounting of this history (Blair et al., 2004). Deciphering the organic geochemical signal provides clues and constraints for models of Waipaoa system evolution in response to tectonic, climatic and anthropogenic forcings.

Predicting the behavior of the carbon biogeochemical cycle and its interaction with climate has become more urgent as we face global-scale changes to the Earth's Critical Zone; that intersection of the geosphere, hydrosphere and atmosphere deemed essential to human

survival (Amundson et al., 2007). Globally, anthropogenic activities have displaced soil and associated OC at rates an order of magnitude greater than previously recorded (Lal, 2003; Syvitski and Kettner, 2011; Syvitski et al., 2005). The Waipaoa is a local example where the conversion of the landscape to pastureland accelerated soil erosion rates by ten-fold (Carter et al., 2010; Foster and Carter, 1997). The fate of the displaced soil C, either from a local or global perspective is a significant uncertainty in C-budgets and models (Scott et al., 2006), because the extent to which the soil C either oxidized to CO₂ or was sequestered in depositional centers is poorly characterized. A S2S accounting of carbon is essential if we are to predict the response of the Critical Zone C-cycle to changing land use and climate.

Small active margin rivers, such as the Waipaoa, occupy distinctive global biogeochemical niches (Blair and Aller, 2012). Sitting atop accretionary prisms in many cases, these rivers export a blend of organic sources ranging from the contemporary to the ancient. Rapid, episodic deposition of sediment on the margins coupled with the recalcitrance of the ancient component contributes to some of the highest OC burial efficiencies observed in the marine environment (Blair and Aller, 2012). Globally these systems represent major sinks of terrestrial OC in the marine environment and are the primary sites for the recycling of ancient (fossil) C (Blair and Aller, 2012; Hedges and Keil, 1995; Lyons et al., 2002; Milliman and Syvitski, 1992).

Sedimentary OC Sources -The rock cycle embedded within accretionary-prism dynamics provides a conveyor belt-like template for organic carbon transformations and transport within the Waipaoa system (Fig. 19). The uplifted forearc marine sedimentary rocks associated with the Hikurangi subduction margin that provide the basement of the watershed (Mazengarb and Speden, 2000) can thus be viewed as a foundational element of the Waipaoa carbon landscape. The OC contents of exhumed sedimentary rocks in the Waipaoa watershed range from ~0.03 weight percent for sandstone to ~0.65% for mudstone (Blair et al., 2010b).

The $\delta^{13}\text{C}$ values (mean $\pm$ SD = $-25.1 \pm 1.3\text{‰}$, Blair et al. 2010b; $-26.0 \pm 1.2\text{‰}$, Gomez et al 2003) of the sedimentary rock OC likely reflect mixtures derived from ancient terrestrial S2S systems astride the accretionary-prism C-cycle.

The ancient OC is intrinsically unreactive given its age and diagenetic history. Even so, exposure of uplifted rock can result in oxidative loss of ancient OC if time is adequate (Petsch et al., 2000). In the Waipaoa watershed the estimated rock OC concentration of riverine suspended sediments ($0.26 \pm 0.09\%$ C dry wt) is sufficiently similar to the mean % OC of outcrop samples ($0.25 \pm 0.19\%$) to indicate that a large fraction of the rock C escapes oxidation (Blair et al., 2010b). The tectonically crushed mudstone is friable and is the major contributor of sediment in the system. Coupled with geologically rapid uplift rates, this limits subaerial exposure time and thus the opportunity for oxidation of the rock OC. Accordingly, the rock C is ubiquitous throughout the Waipaoa S2S system (Blair et al., 2010b; Brackley et al., 2010; Gomez et al., 2010; Gomez et al., 2003).

Soils and vegetation -The soil mantle in the Waipaoa watershed is a complex dynamic source of organic material that has responded to tectonic, climatic and anthropogenic perturbations to the otherwise continual processes involved in the generation of soil OC. In general, soil OC concentrations decrease by an order of magnitude with depth, as a result of inputs from the extant ecosystem at the surface and diagenetic losses down profile (Fig. 20). Subsurface (>50 cm) OC concentrations are $\leq 0.2\%$ in some well-drained soils. OC composition is dominated by fresh plant litter at the surface and transitions to diagenetically altered, aged material at depth. Notably, the soil OC has a considerably younger ^{14}C -age than the co-existing tephra as the result of downward transport of surficial material (Fig. 20). Plant roots, mycorrhizal fungi, burrowing animals and/or leaching could contribute to the displacement of young material to depth. The parent material may also be an important source of OC, especially if developed on an exposed mudstone. The rock OC, given its recalcitrance,

becomes proportionately more important as a source with depth into the regolith and would contribute to an apparent ^{14}C -aging to the soil OC. In contrast, the OC contribution from a tephric parent material is negligible.

The large eruptions from the Taupo and Okataina volcanic centers have periodically blanketed the landscape and the deposited tephras have provided the parent material for developing soils (Eden et al., 2001). Tephra geochronology indicates that soil OC pools as old as ~18 ka exist in the alluvial terraces (Eden et al., 2001). The oldest tephric-soil OC sources are likely to be minor contributors to the C-flux exported from the watershed, because of the low OC concentrations in the deep soil horizons.

In addition to the volcanic eruptions, climate change during the Holocene has altered soil cover and the vegetative C inputs (McGlone and Wilmshurst, 1999; Newnham et al., 2013; Wilmshurst et al., 1999; Wilmshurst et al., 2007). Loess accumulation and river aggradation were prominent during the LGM due to cold, dry conditions (Alloway et al., 2007). The landcover was a shrubland-grassland mosaic with patches of beech (*Nothofagus* species) (Newnham et al., 2013). Lowland portions of the watershed were dominated by podocarp/hardwood forests in the late Holocene (Wilmshurst et al., 1999). The massive Taupo eruption drove a shift from podocarp forests to seral taxa and grasses. It also elevated the quantity of charcoal in soils (Wilmshurst et al., 1999).

The burning of lowland forests by early Maori settlers drove a similar shift from podocarp forests to transitional plant communities as well as augmenting soil charcoal content (Wilmshurst et al., 1999). Large-scale deforestation via Europeans during ~1880-1920, coupled with naturally high erosion rates, led to a loss of much of the tephric soil cover on steep (>25°) upland slopes (Page et al., 2008; Reid and Page, 2002). Bedrock and old subsoils have been exposed, allowing development of new soils (Sparling et al., 2003).

Native podocarp-broadleaved forest and beech forest were replaced with pastures, thus altering the vegetative C inputs to soils (McGlone and Wilmshurst, 1999; Newnham et al., 2013; Wilmshurst et al., 1999; Wilmshurst et al., 2007). Exotic species, and in particular *Pinus radiata* (Monterey pine), have been employed to rapidly reforest erosion-prone hillslopes (Reid and Page, 2002). Mature *P. radiata* is now logged commercially in the watershed, which may in turn promote mass wasting.

Delivery modes of OC to the river channel and lowland integration of upland signals - The mode of sediment generation will influence the concentration and composition of the OC delivered to the river. Sheetwash and rill erosion, which constitute a relatively small fraction of the post-LGM sediment budget, preferentially move plant litter and O-horizon-soil OC. This material will be relatively high in organic content, young and biologically reactive. Gullying and earthflows, on the other hand, excavate into the underlying mudstone of the Waipaoa upland (DeRose et al., 1998), and deliver large volumes of sedimentary-rock debris and its OC to the river. All of these processes respond to low-magnitude high-frequency rain events (DeRose et al., 1998; Trustrum and DeRose, 1988) and are accordingly chronic sources of sediment and OC. These are in contrast to shallow landslides that are initiated by large-magnitude storms that exceed ~120-200 mm rainfall and occur at low frequencies (Hicks et al., 2000; Trustrum et al., 1999). The average soil excavation depth via shallow landsliding caused by large Cyclone Bola-size events is ~75 cm (Page et al., 1999). This would transport both contemporary and aged soil C to the channel (Blair et al., 2010b). Perhaps the most notable aspect of large events is their capability to export significant quantities of woody debris via failures on forested slopes and/or large-scale bank erosion (Hilton et al., 2011; Hovius et al., 2011; West et al., 2011).

Hypothetically, one might expect to see a succession of OC sources delivered to the river in response to the intensity of precipitation and channel flow. In reality, upland OC

signatures of sediment-generating processes are blended by the capture and storage of particulates in lowland features, and differences throughout the hydrograph are attenuated (Blair et al., 2010b; Hilton et al., 2008). The deposition and remobilization of landslide deposits is one mechanism of OC source blending. Over half of shallow landslide debris is retained on the landscape, to be eroded slowly by subsequent events (Page et al., 1999). Vegetation of the debris tail may occur, thus new organics are added to the sediment while original material is decomposed or aged.

Alluvial deposits composed of recycled sedimentary rock and soils from upstream are another source of partially homogenized OC (Blair et al., 2010b; Gomez et al., 2010; Gomez et al., 2004a). Ages of Waipaoa alluvial deposits range from 1 to 10^5 years, with an area-weighted age of 4400 years (Phillips et al., 2007). The modeled mean half-life of alluvium-OC exceeds 300 years (Phillips et al., 2007). The estimated ^{14}C -age of suspended riverine non-rock derived OC is ~ 1000 years ($F_m = 0.87 \pm 0.11$), thus providing an additional constraint on the mean life time of exported non-rock OC and sediment in the watershed (Blair et al., 2010b).

The % OC of the Waipaoa suspended sediments ranges between ~ 0.3 to 1.6% (Blair et al., 2010b; Gomez et al., 2003). These low values imply that shallow sources of OC such as overland flow must be substantially diluted with low OC-bearing sediment derived from sedimentary rock and/or subsurface soils. Carbon isotope (^{12}C , ^{13}C , ^{14}C) mass balance constraints indicate that the sedimentary-rock-derived OC is approximately one third of the total riverine suspended OC pool (Fig. 20) (Blair et al., 2010b). At least 15% and perhaps substantially more of the non-rock component is derived from aged soil C. Pyrolysis GCMS analyses substantiates that subsoil OC dominates over OC from the soil surface (Blair et al., 2010a). When all observations are considered, it appears that bank erosion is an important chronic source to the river.

There have not been sufficient OC measurements reported of suspended load as a function of river flow to identify trends in compositional changes and OC sources. Gomez et al. (2003) report higher POC contents in suspended sediments at low flows ($1.6 \pm 0.6\%$ POC; at $Q/Q_{\text{mean}} < 5$) relative to higher discharges ($0.6 \pm 0.1\%$ POC; at $Q/Q_{\text{mean}} > 5$), but no systematic differences have been observed in $\delta^{13}\text{C}$ or $\Delta^{14}\text{C}$ values (Blair et al., 2010b; Gomez et al., 2003). Hysteresis in the hydrograph may obscure any OC composition-flow relationship that exists.

Evidence for changes in OC composition as a function of river discharge can be found in the floodplain sedimentary record of the Waipaoa (Gomez et al., 2010). A depth profile within a fresh flood deposit ($Q/Q_{\text{mean}} \sim 50 - 100$) revealed no obvious relationship between flow and carbon isotopic ratio or % C, but did show a decrease in radiocarbon and %C as a function of time through the flood event. The $\delta^{13}\text{C}$ values became more positive as a function of time. All trends considered, it appears a young surface source of OC (plant or plant litter) decreased with time through the event, relative to a subsoil or rock C sources. The proposed mechanism is a transition from topsoil erosion to bank failure of alluvium as flood waters subsided (Gomez et al., 2010). Landsliding was not considered to be an important source of sediment in this event because rainfall was focused in the lowlands. This example illustrates the inherent spatial and temporal variability of sediment generating processes and OC signatures in the watershed.

The evolution of POC in the marine sink - In general, the composition of sedimentary OC increases in complexity once in the marine environment. Marine sources contribute to the POC as it transits the Waipaoa margin from Poverty Bay to the Hikurangi trough. Transport processes both mix and separate POC pools while diagenetic reactions can oxidize or alter them. Burial below the surface mixed layer of the seabed significantly slows transformations and essentially locks in elemental, isotopic and molecular compositions of the POC, thus

recording the organic geochemical history of the sediment (Blair and Aller, 2012; Brackley et al., 2010). The integrity of the original terrestrial signature thus depends strongly on how rapidly the POC is buried.

Deposition-resuspension cycles in Poverty Bay hydrodynamically sort sediment and POC (Bever et al., 2011). Sands rich in sedimentary rock OC accumulate nearshore and fines that include contemporary, aged soil, and rock C are transported offshore (Fig. 21) (Bever et al., 2011; Brackley et al., 2010). The rock C-rich sands are evident to water depths of at least 27-36 m on the open shelf, whereas the finer-grained POC fractions dominate at >50 m (Brackley et al., 2010).

Depocenters for recently deposited terrestrial sediments exist north and south of Poverty Bay in ~30-60 m water depth (Fig. 2) (Kniskern et al., 2014). During Jan-Feb 2010, following a large flood (8-y recurrence interval) relatively fresh vascular plant debris was identified by lignin concentrations and lignin phenol acid/aldehyde ratios in the southern depocenter, whereas more degraded material was identified in the northern depocenter (Kniskern et al., 2014). It is not clear how those patterns were created or whether they are a persistent trend, however. Recently produced marine OC is added to the POC pool in the ~30-60-m zone, as indicated by $^{13}\text{C}/^{12}\text{C}$ and $^{14}\text{C}/^{12}\text{C}$ isotopic mass balances (Fig. 21) (Brackley et al., 2010). Diatoms and dinoflagellates contribute to the marine source as indicated by sterol biomarkers (Brackley et al., 2010).

River sediment reaches the outer shelf and upper slope rapidly following its introduction to the coastal ocean, within monthly to seasonal timescales (Figs. 13 and 17; Alexander et al., 2010; Walsh et al., 2014). C-isotope measurements suggest that aged marine C is added to the POC as it transits beyond 50 m water depth and onto the slope (Brackley et al., 2010). The depletion of long-chain ($\text{C}_{22} - \text{C}_{28}$) alcohols on the slope (1428 m) suggests a

change in terrestrial source as well. The presence of recycled pollen from periods predating the time of deposition on the outer shelf and mid-slope provide further evidence for transport of old organics into the Waipaoa marine environment (Mildenhall and Orpin, 2010). A local peak in the abundance of fossil planktonic foraminifera near the Lachlan anticline indicates that reworked sediments from that feature could be a source of old marine C (Culver et al., 2012). In addition, pre-aged POC from adjacent depositional sites is likely transported into the area via the northeastward-flowing Wairarapa Coastal Current on the shelf and/or the southward-flowing East Cape Current (ECC) along the upper slope.

POC dispersal transitions from a flood- and storm-controlled regime on the shelf and upper slope to one that is dominated by large earthquake triggering of turbidity flows on the lower slope (Pierce, 2012; Pouderoux et al., 2012b). Catastrophic floods that form hyperpycnites are less frequent triggering mechanisms, accounting for ~3-4% of the total turbidites in the last 18 ky. The hyperpycnite POC is likely derived from riverine flood material mixed with shelf/slope scour, whereas the bulk of the turbidite POC appears to have originated from upper-slope sediments, as indicated by $\delta^{13}\text{C}$ values (Pouderoux et al., 2012a). Leafy and woody debris are evident throughout the turbidite sequences attesting to the relatively rapid delivery of terrestrial POC to the lower slope (Pouderoux et al., 2012b). Rocks of Miocene to Cretaceous age that underlie the Quaternary sediment sequences, are exposed in gully and canyon walls (Mountjoy and Micallef, 2012), and may contribute to the fossil OC pool of the lower (>1000 m) slope sediments. The turbidite deposits are interlaced with hemipelagic muds that have a more marine POC component (Pouderoux et al., 2012a).

Burial and preservation of POC and the generation of the Waipaoa organic geochemical record - As is apparent from the previous discussion, the composition of sedimentary OC is highly dynamic on the seafloor surface. Transit through and burial below the surface mixed layer isolates the POC pool from new sources and eliminates transport-induced mixing and

sorting. In most muddy environments, burial below the surface mixed layer also limits exposure to O₂, which in turn attenuates the kinetics of OC oxidation (Hartnett et al., 1998). The Waipaoa contrasts with dispersal systems on wide, energetic shelves (e.g., the Amazon and Fly Rivers) where sediment is extensively refluxed in oxygenated overlying water resulting in the biogeochemical incineration of POC (Aller and Blair, 2006; Aller et al., 2008).

Degradation or oxidation studies have not been performed on the Waipaoa margin. However, observations on the neighboring Waiapu shelf provide insights into the relative behaviors of the various POC pools. Stable isotopic and radiocarbon measurements of dissolved inorganic carbon (DIC) from sediment interstitial (pore) water indicate that young OC is preferentially oxidized in the seabed. Evidence for oxidation of terrestrial plant-derived POC is seen only at the shallowest (~60 m) sampling site (Brackley et al., 2010). In contrast, marine OC oxidation dominates in the Waiapu shelf depocenter (80-130 m), where marine productivity is assumed to be more important (Blair et al., 2013; Thompson, 2009). The preferential oxidation of different pools of OC has the potential to bias the preserved signal towards material that is the most unreactive (i.e. aged pools; Blair and Aller, 2012), and this would be pronounced between major events when accumulation rates are slow relative to those of resuspension and redeposition.

Apart from the addition of marine C to sediments as they travel seaward, large floods generate the most distinctive OC signature preserved. Storms that exceed the threshold for shallow landsliding generate sediment rich in woody material. An event layer on the inner Waipaoa shelf (27 m water depth) is attributed to Cyclone Bola (Brackley et al., 2010). A significant increase in vascular plant input can be seen in the >25- μ m-grain-size fraction; this is marked by a nearly 10-fold increase in %C (>3%) over that buried in non-Bola intervals (~0.3%), a 2‰ depletion in $\delta^{13}\text{C}$ (flood layer ~-27‰, non-flood ~-25‰) and a doubling of

C/N ratio from ~10 to 23 (Brackley et al., 2010). The <4 and 4-25 μm POC fractions showed less sensitivity to the flood event. Qualitatively similar signals for landsliding have been noted in mid- to late-Holocene record on the shelf (Leithold et al., 2013) (Fig. 10).

Radiocarbon ages of woody and charcoal debris preserved in the mid-to-late Holocene Northern Depocenter of the Waipaoa shelf reflect variations in the residence time of the OC sources in the watershed (Leithold et al., 2013). Relative to the tephrochronology of the core (MD3007), woody debris was ~500-1500 years older than the expected reservoir age, with the oldest material potentially indicating deeper erosion into soil horizons associated with increased storm frequency and anthropogenic disturbance. Charcoal, on the other hand, had a measured ^{14}C -age of ~13-15 ka for deposition occurring during 2-9 ka. Leakage of charcoal from older soil or terrace deposits may have been the source. After the Taupo eruption in 1717 cal. BP and synchronous with anthropogenic deforestation, charcoal ages dramatically decrease to ~1-7 ka owing to influxes of younger charred material from biomass burning (Leithold et al., 2013).

SUMMARY AND CONCLUSIONS

The source-to-sink concept applied to the Waipaoa sedimentary system is predicated on our ability to characterize and quantify changes in long-term inputs and event signals over the timescale(s) of interest and ultimately to relate these to the stratigraphic record. Weak sedimentary units rapidly uplifted during subduction have conspired to generate high rates of incision and erosion in the Waipaoa basin since the LGM. Although much of the sediment exported offshore during this time interval originated from valley excavation, a substantial portion emanated from hillslopes, mostly through deep-seated landslide and earthflow complexes. Notably, much of the Waipaoa catchment exhibits relatively low-relief, gentle hillslopes that belie the rapid pace of landscape lowering. This demonstrates that given weak

materials, threshold slope processes can ensue even at relatively modest slope angles. The timing of incision and landsliding shows a period of increased activity around the Pleistocene-Holocene transition.

In addition to the long-term trends discerned from studies of landscape evolution, the Lake Tutira record provides a nuanced view of Holocene environmental controls on upper catchment sedimentation in the WSS. The preserved event record was formed in response to a number of drivers, and while the record of storm frequency is directly related to climate variability, the record of storm magnitude is also influenced by earthquakes and inter- and intra-lake geomorphic controls on sediment supply. From the 7200-y Lake Tutira sediment record, 1400 storms are identified, with one storm period (1830–2030 cal. BP) of particularly high magnitude and frequency that persisted for two centuries. Storm frequency is modulated by the waxing and waning of atmospheric teleconnections between the tropics and Antarctica. Consistent with the observational record, storminess depends on the strength and phase of ENSO and the phase of the SAM (Gomez et al., 2012). Severe storms similar to Cyclone Bola in 1988 occurred throughout much of the Holocene at centennial frequencies (53 over 7 ky), but there is also evidence for catastrophic rainfall events at millennial frequencies (7 over 7 ky).

From landscape modeling, along with erodibility and forest cover, projected changes in rainfall associated with wetter and drier periods of centuries to millennia duration drive the sediment-flux variations. During the LGM, conditions were more erosive than during the Holocene, as there was no forest cover and the landscape was vegetated with tussock and grass. The LGM landscape was four-times more erodible than during the Holocene (doubling the sediment yield), and half that of the deforested landscape today. Long-term changes in sediment yield are evident from the lake record following human settlement as conversion to pasture was accompanied by a three-fold increase in the long-term lake sediment

accumulation rate. While some portions of the watershed lie above knickpoints and thus remain insulated from post-LGM landscape adjustment, other locales have experienced a major transformation in historic times, as gullies have cannibalized deep landslide complexes following post-European deforestation. These localized sediment sources, which may be unique to the post-European landscape, have caused downstream aggradation up to 50 m and continue to cause erosion and flood management problems.

The sediment package preserved on the shelf and slope since the LGM can be explained in large measure by sequence-stratigraphic models forced by rising to stable sea level and ongoing tectonic deformation of the margin. As sea level rose since the LGM, sediment supply to the slope was reduced by about a factor of 5 as shelf trapping ensued. Despite this reduction in supply to the slope, turbidites are found at similar frequency from the LGM to Present, as the dominant trigger appears to be earthquakes, with large earthquakes having a return interval of $\sim 200 \pm 100$ years. Textural signals in the shelf basins from giant piston cores clearly demark transgressive and highstand systems tracts. These demonstrate upward-fining followed by upward-coarsening trends, respectively, with the shift occurring near the maximum landward position of the shoreline at ~ 7 ka. The shift to a highstand systems tract is also reflected in $\delta^{13}\text{C}$ trends that generally show more terrestrial signatures since the maximum transgression. Other major textural signals evident in the Holocene shelf record include a period of coarsening with the onset of ENSO and increased storminess, and a dramatic fining coincident with human landscape changes. Human and natural disturbances in the watershed are inferred from radiocarbon ages of wood and charcoal that show dramatically reduced residence times for these organic materials. Accumulation-rate trends for the mid-shelf basins over the late Quaternary are dominantly influenced by tectonic deformation, accommodation and basin filling, with steady rates seen in the Southern

Depocenter (underfilled basin) and decreasing rates in the Northern Depocenter (overfilled basin).

Contemporary sediment-dispersal patterns and sediment-transport dynamics on the Waipaoa shelf and slope reflect both geologic and oceanographic drivers, as well as the dramatically increased supply of fine-grained sediment in response to human modification of the landscape. Key geologic controls include the incompletely filled valley at the river mouth (Poverty Bay) and margin deformation driven by subduction, which has created the mid-shelf depocenters and outer-shelf anticlines. These underpinning and evolving features appear to help modulate both the initial delivery of sediment to the shelf, as well as the sediment-accumulation-rate patterns measured over centennial and longer time scales.

Whereas there is ample evidence that Waipaoa River sediment is deposited in the sheltered confines of Poverty Bay during floods, over subsequent days to months, waves and currents resuspend these deposits: carrying the fines offshore while moving the sands toward the coast. This divergence of transport supports observed sandy shoreline progradation as well as mud deposition offshore, but the timing of sediment supply in both instances seems driven by wave events that are not typically associated with river flooding. Therefore, a key finding is the asynchronicity of sediment delivery by the river and wave resuspension and export from Poverty Bay. In most instances, this precludes the direct preservation of flood events in the stratigraphic record of the Waipaoa Shelf. Exceptions to this norm may occur during rare extreme events when high river discharge occurs in concert with large waves. These conditions typified the passage of Cyclone Bola, when wave-supported gravity flows likely delivered sediment directly to the shelf and slope depocenters.

Four distinct offshore depocenters are found on the Waipaoa margin: two mid-shelf depocenters in the subsiding synclines landward of Lachlan and Arial anticlines; one on the

outer shelf seaward of the gap between the two anticlines; and one on the upper slope. Accumulation rates in all of the depocenters is on the order of $1 \text{ g cm}^{-2} \text{ y}^{-1}$ during the past century. The regular accumulation pattern on the shelf during the past century belies field observations of short-term (event) sedimentation that show a high degree of spatial and temporal variability. Sediment-transport-modeling simulations support the idea that the net dispersal to the depocenters is likely accomplished by episodic strong wave conditions, which ultimately disperse sediment to bathymetric lows, where shear stresses are reduced and deposition occurs. Because the bathymetric lows (centered at the mid-shelf depocenters) are modulated by tectonic subsidence, there appears to be a direct link between the geology and bottom-shear-stress distribution, and therefore the location of shelf depocenters.

Sediment-budget exercises that consider both modern (river discharge versus centennial accumulation rates) and post-LGM (terrestrial production versus offshore isopachs) mass balances indicate that about half of the total sediment produced in the WSS escapes the study area. A coupled sediment-transport/hydrodynamic shelf model indicates that a large fraction of the sediment is carried outside the study area along the shelf to the northeast by the river plume, coastal currents, or combined current/wave activity. Northeast transport is consistent with the regional oceanography that has a persistent northeastward flowing Wairarapa Coastal Current. Furthermore, sediment textural trends support the idea of a net transport along the shelf towards the northeast. Therefore, we can conclude that the WSS is an open system with about as much loss to the northeast as what accumulates in the adjacent nearshore, shelf and slope. This is in stark contrast with the earlier notion of WSS being a closed system (MARGINS, 2004). Moreover, satellite imagery from the region also shows high turbidity in coastal waters extending northward from Hawke Bay onto the Poverty shelf and slope (Carter et al., 2010). Should this contribute significant quantities of material, even greater export from the study area would be required to balance the sediment budget.

The organic matter associated with sediment as it moves from upland source to marine sink is a product of particle history providing a record of materials that have cycled over timescales of days to millions of years. The challenge for interpreting the organic geochemical record of a sedimentary system such as the Waipaoa lies not only in identifying the sources of OC but also understanding how the various pools of OC are integrated. Source flux, proximity and reactivity are all factors that control relative contribution to the total pool. The ubiquity of fossil OC in both the terrestrial and marine realms of the Waipaoa attests both to the chronic nature of its source, crumbling mudstones further destabilized by land use, and its biogeochemical recalcitrance. Modern OC derived from extant ecosystems, though reactive, persists by virtue of its continual production along the S2S transit. The nature of the modern OC changes as new sources are added and upstream sources are lost. Some OC pools are dynamic and others are not.

The Waipaoa, like other small mountainous rivers on active margins, exhibits a high riverine OC preservation efficiency (>50%) in its marine depocenters because of the rapid, event-driven accumulation of sediment (Blair and Aller, 2012). While some of the preservation effectiveness can be attributed to the unreactive nature of the fossil component, even the contemporary terrestrial OC can be well preserved thus demonstrating the conditional nature of OC reactivity. Rapid burial below the dynamic sediment-water interface is protective of otherwise reactive OC. The Waipaoa contrasts with dispersal systems on wide, energetic shelves (e.g., the Amazon and Fly Rivers) where sediment is extensively refluxed and POC undergoes biogeochemical incineration. The absence of significant signal buffering via a large active floodplain such as in the Amazon system is also critical. Organic geochemical signatures of individual events are recorded with greater fidelity on the Waipaoa shelf relative to those on the Amazon or the Fly shelves.

Overall, the S2S study of the Waipaoa margin provides a remarkable perspective on signal generation and preservation in this small mountainous setting. Landscape evolution and lake studies provide clear and detailed records of changes in both long-term sediment production and event frequency. However, it is clear that our ability to recognize these signals in offshore sediment deposits is limited because they are filtered and overprinted by oceanographic processes. Furthermore, these signals are obscured within the major long-term influences of sea-level rise and tectonic deformation that, to first order, drive the development of the offshore sediment sequences. Moreover, a mass balance approach for the study area has been challenging because energetic oceanographic conditions result in the loss of about half of the delivered sediment to the study area. Nonetheless, like the terrestrial record, the offshore record contains a rich history revealing changes in the Waipaoa landscape, regional climate, as well as both natural and human disturbances.

ACKNOWLEDGMENTS

This S2S study was made possible through support from the US National Science Foundation grants: OCE- 0948106, 0841096, 0646760, 0405726, 0646771, 0948319, 0841049, 0504690 0600043; GEO- 0119936, 0503609.

MARGINS S2S was originally supported in New Zealand by the Foundation for Research, Science and Technology contract C09X0213 to Landcare Research, contract C05X0203 to GNS Science, and contracts C01X0203 and C01X0702 to the National Institute of Water and Atmospheric Research (NIWA). More recently, other MARGINS S2S research was supported by the Marine Physical Resources Programme within NIWA's Coasts and Ocean Centre.

The MARGINS S2S study in New Zealand would not have been possible without the inputs from numerous ships' crew, field and laboratory workers, students and post-doctoral research scholars who materially participated in this program, contributing greatly to its ultimate success.

The authors also thank Patricia Wiberg and Chuck Nittrouer for thoughtful and detailed reviews of the manuscript.

REFERENCES

- Adams, J., 1981. Earthquake-dammed lakes in New Zealand. *Geol.*, 9, 215-219.
- Alexander, C.R., Simoneau, A., 1999. Spatial variability in sedimentary processes on the Eel continental slope. *Mar. Geol.*, 154, 243-254.
- Alexander, C.R., Lee, H., 2009. Sediment Accumulation on the Southern California Bight Continental Margin During the Twentieth Century. In: *Earth Science in the Urban Ocean: The Southern California Continental Borderland*, H. Lee and B. Normark (editors), GSA Special Paper 454, Ch. 2.4, p. 69-88.
- Alexander, C.R., Walsh, J.P., Orpin, A.R., 2010. Modern sediment dispersal and accumulation on the outer Poverty continental margin. *Ma. Geol.*, 270, 213-226.
- Aller, R.C., Blair, N.E., 2006. Carbon remineralization in the Amazon-Guianas tropical mobile mudbelt: A sedimentary incinerator. *Cont. Shelf Res.*, 26, 2241-2259.
- Aller, R.C., Blair, N.E., Brunskill, G.J., 2008. Early diagenetic cycling, incineration, and burial of sedimentary organic carbon in the central Gulf of Papua (Papua New Guinea). *J. Geophys. Res.-Earth Surface*, 113(F1): DOI:10.1029/2006jf000689.
- Alloway, B.V., Pillans, B.J., Carter, L., Niash, T.R., Westgate, J.A., 2005. Onshore-offshore correlation of Pleistocene rhyolitic eruptions from New Zealand: implications for TVZ eruptive history and paleoenvironmental reconstruction. *Quat. Sci. Rev.*, 24, 1601-1622.
- Alloway, B.V., Lowe, D.J., Barrell, D.J., Newnham, R.M., Almond, P.C., Augustinius, P.C., Bertler, N.A., Carter, L., Litchfield, N.J., McGlone, M.S., Shumeister, J., Vandergoes,

- M.J., Williams, P.W., NZ-Intimate members, 2007. Towards a climate event stratigraphy for the New Zealand over the past 30 000 years (NZ-INTIMATE project), *J. Quaternary Sci.*, 22, 9-35.
- Amundson, R., Richter, D.D., Humphreys, G.S., Jobbagy, E.G., Gaillardet, J., 2007. Coupling between biota and earth materials in the Critical Zone. *Elements*, 3, 327-332.
- Barrell, D.J.A., Almond, P.C., Vandergoes, M.J., Lowe, D.J., Newnham, R.M., and INTIMATE members, 2013. A composite pollen-based stratotype for inter-regional evaluation of climatic events in New Zealand over the past 30,000 years (NZ-INTIMATE project), *Quat. Sci. Rev.*, 74, 4-20.
- Berryman, K., 1993. Age, height, and deformation of Holocene marine terraces at Mahia Peninsula, Hikurangi Subduction Margin, New Zealand. *Tectonics*, 12, 1347-1364.
- Berryman, K.B., Marden, M., Eden, D., Mazengarb, C., Ota, Y., Moriya, I., 2000. Tectonic and paleoclimatic significance of Quaternary river terraces of the Waipaoa River, east coast, North Island, New Zealand. *The New Zealand Journal of Geology and Geophysics*, 43, 229-245.
- Berryman, K., Marden, M., Palmer, A., Wilson, K., Mazengarb, C., Litchfield, N., 2010. The post-glacial down cutting history in the Waihuka tributary of Waipaoa River, Gisborne district: Implications for tectonics and landscape evolution in the Hikurangi subduction margin, New Zealand. *Mar. Geol.*, 270, 55-71.
- Bever, A.J., 2010. Integrating space- and time-scales of sediment-transport for Poverty Bay, New Zealand. Virginia Institute of Marine Science, College of William & Mary Ph.D. dissertation, 275 pp.
- Bever, A.J., McNinch, J.E. and Harris, C.K., 2011. Hydrodynamics and sediment-transport in the nearshore of Poverty Bay, New Zealand: Observations of nearshore sediment segregation and oceanic storms. *Cont. Shelf Res.*, 31(6), 507-526.
- Bever, A.J., Harris, C.K., 2014. Storm and fair-weather driven sediment-transport within Poverty Bay, New Zealand, evaluated using coupled numerical models. *Cont. Shelf Res.*, 86, 34-51.
- Bilderback, E. L., 2012. Hillslope response to climate-modulated river incision and the role of deep-seated landslides in post-glacial sediment flux: Waipaoa Sedimentary System, New Zealand, PhD. Thesis, University of Canterbury, <http://hdl.handle.net/10092/7439>.
- Bilderback, E. L., Pettinga, J., Litchfield, N. J., Quigley, M., Marden, M. , Roering, J. J., Palmer, A. S., 2014. Hillslope response to climate-modulated river incision in the Waipaoa Catchment, East Coast North Island, New Zealand, *Geol. Soc. of Am.*, doi:10.1130/B31015.1.
- Black, R.D., 1977. Rivers of change; early history of the upper Waipaoa and Mangatu catchments. New Zealand Forest Service, Forest Research Institute: Christchurch, New Zealand. Unpub. Rep.

- Blair, N.E., Leithold, E.L. and Aller, R.C., 2004. From bedrock to burial: the evolution of particulate organic carbon across coupled watershed-continental margin systems. *Marine Chem.*, 92(1-4), 141-156.
- Blair, N.E., Fournillier, K., Leithold, E.L. and Childress, L.B., 2010a. Resolving organic carbon of differing diagenetic/catagenetic states in riverine and marine sediments. *Geochim. Cosmochim. Ac.*, 74(12), A95-A95.
- Blair, N.E., Leithold, E.L., Brackley, H., Trustrum, N., Page, M. and Childress, L., 2010b. Terrestrial sources and export of particulate organic carbon in the Waipaoa sedimentary system: Problems, progress and processes. *Mar. Geol.*, 270(1-4), 108-118.
- Blair, N.E. and Aller, R.C., 2012. The fate of terrestrial organic carbon in the marine environment. *Annu. Rev. Mar. Sci.*, 4, 401-423.
- Blair, N., Ginnane, C., Childress, L., Leithold, L., 2013. The fate of small active margin river POC in the marine environment Goldschmidt Conference, Florence, Italy.
- Brackley, H.L., Blair, N.E., Trustrum, N.A., Carter, L., Leithold, E.L., Canuel, E.A., Johnston, J.H. Tate, K.R., 2010. Dispersal and transformation of organic carbon across an episodic, high sediment discharge continental margin, Waipaoa Sedimentary System, New Zealand. *Mar. Geol.*, 270(1-4), 202-212.
- Brown, L.J., 1995. Holocene shoreline depositional processes at Poverty Bay, a tectonically active area, northeastern North Island, New Zealand: *Quat. Res.*, 26, 21-33.
- Carrasco, J., 2012. Stratigraphy and sedimentology of late-Pleistocene lacustrine to alluvial deposits from the Waipaoa River catchment, North Island, New Zealand. M.S. thesis, California State University Northridge, CA. pp. 109.
- Carter, L., Manighetti, B., Elliot, M., Trustrum, N., Gomez, B., 2002. Source, sea level and circulation effects on the sediment flux to the deep ocean over the past 15 ka off eastern New Zealand. *Global Planet. Change*, 33, 339-355.
- Carter, L., Manighetti, B., 2006. Glacial/interglacial control of terrigenous and biogenic fluxes off a high input, collisional margin; a 139 kyr-record from New Zealand. *Mar. Geol.*, 226, 307-322.
- Carter, L., Manighetti, B., Ganssen, G., Northcote, L., 2008. SW Pacific modulation of abrupt climate change during the Antarctic Cold Reversal-Younger Dryas. *Palaeogeogr., Palaeoclimatol.*, 260, 284-298.
- Carter, L., Orpin, A.R. and Kuehl, S.A., 2010. From mountain source to ocean sink - the passage of sediment across an active margin, Waipaoa Sedimentary System, New Zealand. *Mar. Geol.*, 270(1-4), 1-10.
- Carter, R.M., Carter, L., Williams, J.J., Landis, C.A., 1985. Modern and relict sedimentation on the South Otago continental shelf, New Zealand. *New Zealand Oceanographic Institute Memoir*, 93, pp. 43.

- Cerovski-Darriau, C., Roering, J., Marden, M., Palmer, A., Bilderback, E., 2014. Quantifying temporal variations in landslide-driven sediment production by reconstructing paleolandscapes using tephrochronology and lidar: Waipaoa River, New Zealand. *Geochem. Geophys.*, *Geosy.*, doi: 10.1002/2014GC005467.
- Chiswell, S.M., 2000. The Wairarapa coastal current. *New Zealand Journal of Marine and Freshwater Research* 34, 303–315.
- Chiswell, S.M., 2005. Mean and variability in the Wairarapa and Hikurangi eddies. *New Zealand Journal of Marine and Freshwater Research* 39, 121– 134.
- Chiswell, S.M., Roemmich, D., 1998. The East Cape Current and two eddies: a mechanism for larval retention. *New Zealand Journal of Marine and Freshwater Research* 32, 385-397.
- Claridge, G.G.C., 1960. Clay minerals, accelerated erosion, and sedimentation in the Waipaoa River catchment. *NZ J. Geol. Geophys.*, 3, pp. 184-191.
- Cochran, U., Berryman, K., Zachariassen, J., Mildenhall, D., Hayward, B., Southall, K., Hollis, C., Barker, P., Wallace, L., Alloway, B., 2006. Paleoecological insights into subduction zone earthquake occurrence, eastern North Island, New Zealand. *Geol. Soc. Am.*, 118(9), 1051-1074.
- Crockett, J. S., Nittrouer, C. A., 2004. The sandy inner shelf as a repository for muddy sediment: an example from Northern California." *Cont. Shelf Res.*, 24(1), 55-73.
- Crosby, B., Whipple, K., 2006. Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand, *Geomorph.*, 82(1-2), 16-38.
- Crozier, M., Preston, N., 1999. Modelling changes in terrain resistance as a component of landform evolution in unstable hill country, In: *Process Model. Landf. Evol. Lecture Notes in Earth Sciences* 78 (Ed. by S.Hergarten & H.J.Neugebauer), pp. 267-284.
- Culver, S.J., Camp, R.L., Walsh, J.P., Hayward, B.W., Corbett, D.R. Alexander, C.R., 2012. Distribution of foraminifera of the Poverty continental margin, New Zealand: Implications for sediment transport. *J. Foramin. Res.*, 42(4), 305-326.
- Curran, Kristian J., Paul S. Hill, and Timothy G. Milligan. 2002. Fine-grained suspended sediment dynamics in the Eel River flood plume." *Cont. Shelf Res.*, 22(17), 2537-2550.
- Davy, B., R. Wood, R., 1994. Gravity and magnetic modelling of the Hikurangi Plateau, *Mar. Geol.*, 118, 139-151.
- DeRose, R.C., Gomez, B., Marden, M., Trustrum, N.A., 1998. Gully erosion in Mangatu forest, New Zealand, estimated from digital elevation models. *Earth Surface Proc. Land.*, 23(11), 1045-1053.
- Doser, D.I., Webb, T.H., 2003. Source parameters of large historical (1917-1961) earthquakes, North Island, New Zealand. *Geophys. J. Int.*, 152, 795-832.

- Dowrick, D.J., Rhoades, D.A., Babor, J., Beetham, R.D., 1995. Bulletin of the New Zealand National Society for Earthquake Engineering, 28, 134-145.
- Eberhart-Phillips, D., Reyners, M., Chadwick, M., Chiu, J.-M., 2005. Crustal heterogeneity and subduction processes: 3-D Vp, Vp/Vs and Q in the southern North Island, New Zealand Geophys. J. Int., 162 (1), 270-288.
- Eden, D.N., Page, M.J., 1998. Palaeoclimatic implications of a storm erosion record from late Holocene lake sediments, North Island, New Zealand. Palaeogeogr., Palaeocl., 139, 37-58.
- Eden, D.N., Palmer, A.S., Cronin, S.J., Marden, M., Berryman, K.R., 2001. Dating the culmination of river aggradation at the end of the last glaciation using distal tephra compositions, eastern North Island, New Zealand. Geomorph., 38(1-2), 133-151.
- Field, B.D., Uruski, C.I., Beu, A., Browne, G., Crampton, J., Funnell, R., Killops, S., Laird, M., Mazengarb, C., Morgans, H., Rait, G., Smale, D. and Strong, P., 1997. Cretaceous-Cenozoic geology and petroleum systems of the east coast region, New Zealand. Institute of Geological and Nuclear Sciences, Geological Monograph. 19, 301.
- Fleming, K., Johnston, P., Zwart, D., Yokoyama, Y., Lambeck, K., 1998. Refining the eustatic sea-level curve since the last glacial maximum using far- and intermediate-field sites. Earth Planet. Sci. Lett., 163, 327-342.
- Foster, G., Carter, L., 1997. Mud sedimentation on the continental shelf at an accretionary margin - Poverty Bay, New Zealand. New Zealand J Geol.Geophys., 40(2), 157-173.
- François-Holden, C., Bannister, S., Beavan, J., Cousins, J., Field, B., McCaffrey, R., McVerry, G., Reyners, M., Ristau, J., Samsonov, S., Wallace, L., 2008. The Mw 6.6 Gisborne earthquake of 2007: Preliminary records and general source characterization: Bulletin of the New Zealand Soc. for Earthquake Engineering, 41. 266-277.
- Froggatt, P.C., Lowe, D.J., 1990. A review of Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume and age. New Zealand J. Geol.Geophys., 33, 89-109.
- Fuller, I.C., Marden, M., 2010. Rapid channel response to variability in sediment supply: cutting and filling of the Tarndale Fan, Waipaoa catchment, New Zealand. Mar. Geol., 270, 45-54.
- Fuller, I. C., Marden, M., 2011. Slope-channel coupling in steepland terrain: A field-based conceptual model from the Tarndale gully and fan, Waipaoa catchment, New Zealand. Geomorph., 128, 105-115.
- Gage, M., Black, R. D., 1979. Slope-stability and geological investigations at Mangatu State Forest, New Zeal. For. Serv. Tech. Pap., pp. 66.
- Gerber, T.P., Pratson, L.F., Kuehl, S.A., Walsh, J.P., Alexander, C., Palmer, A., 2010. The Influence of sea level and tectonics on Late Pleistocene through Holocene sediment

- storage along the high-sediment supply Waipaoa continental shelf. *Mar. Geol.*, 270, 139-159.
- Gibb, J.G., 1986. A New Zealand regional Holocene sea level curve and its application to vertical tectonic movements. In: *Proceedings of the international symposium on Recent Crustal Movements*. Bull. Roy. Soc. N.Z., 24, 377-395.
- Gomez, B., Eden, D.N., Hicks, D.M., Trustrum, N.A., Peacock, D.H., Wilmshurst, J.M., 1999. Contribution of floodplain sequestration to the sediment budget of the Waipaoa River, New Zealand. In: Mariott, S.B., Alexander, J. (Eds.), *Floodplains: interdisciplinary approaches*. Geol. Soc. of London Special Publication, 163, 69-88.
- Gomez, B., Rosser, B.J., Peacock, D.H., Hicks, D.M., 2001. Downstream fining in a rapidly aggrading gravel bed river. *Water Res.*, 37, 1813-1823.
- Gomez, B., Page, M.J., Bak, P., Trustrum, N.A., 2002. Self-organized criticality in layered, lacustrine sediments formed by landsliding. *Geol.*, 30, 519-522.
- Gomez, B., Trustrum, N.A., Hicks, D.M., Rogers, K.M., Page, M.J., Tate, K.R., 2003. Production, storage, and output of particulate organic carbon: Waipaoa River basin, New Zealand. *Water Res.*, 39(6).
- Gomez, B., Brackley, H.L., Hicks, D.M., Neff, H., Rogers, K.M., 2004a. Organic carbon in floodplain alluvium: Signature of historic variations in erosion processes associated with deforestation, Waipaoa River basin, New Zealand. *J. of Geophys. Res.-Earth Surface*, 109(F4).
- Gomez, B., Carter, L., Trustrum, N.A., Palmer, A.S., Roberts, A.P., 2004b. El Niño-Southern Oscillation signal associated with middle Holocene climate change in intercorrelated terrestrial and marine sediment cores, North Island, New Zealand. *Geol.*, 32, 653-656.
- Gomez, B., Carter, L., Trustrum, N.A., 2007. A 2400 yr record of natural events and anthropogenic impacts in intercorrelated terrestrial and marine sediment cores: Waipaoa sedimentary system, New Zealand. *Geol. Soc. Am. Bull.*, 119, 1415-1432.
- Gomez, B., Baisden, W.T., Rogers, K.M., 2010. Variable composition of particle-bound organic carbon in steepland river systems. *J. of Geophys. Res.-Earth Surface*, pp. 115.
- Gomez, B., Carter, L., Orpin, A.R., Cobb, K.M., Page, M.J., Trustrum, N.A., Palmer, A.S., 2012. ENSO / SAM interactions during the middle and late Holocene. *The Holocene*, 22, 23-30.
- Gomez, B., Livingston, D. M., 2012. The river it goes right on: Post-glacial landscape evolution in the upper Waipaoa River basin, eastern North Island, New Zealand, *Geomorph.*, 159-160, 73-83.
- Gomez, B., Carter, L., Trustrum, N.A., Page, M.J., Orpin, A.R., 2013. Coherent rainfall response to middle- and late-Holocene climate variability across the mid-latitude South Pacific. *The Holocene*, 23, 1000-1005.

- Gomez, B., Corral, A., Orpin, A.R., Page, M.J., Pouderoux, H., Upton, P., 2015. Lake Tutira paleoseismic record confirms random, moderate to great Hawke's Bay earthquakes. *Geology*, 43, 103-106.
- Guthrie-Smith, H., 1999. Tutira: the story of a New Zealand sheep station. (Reprinted) University of Washington Press, Seattle, pp. 464.
- Hale, R.P., 2014. Investigating sediment transport on the Waipaoa margin: linking *in situ* observations with preserved deposits. University of Washington Ph.D. dissertation, 132 pp.
- Hale, R.P., Ogston, A.S., Walsh, J.P., Orpin, A.R., 2014. Sediment transport and event deposition on the Waipaoa River Shelf, New Zealand. *Cont. Shelf Res.*, 86, 52-65.
- Hale, R.P., Ogston, A.S. In Review. In-situ observations of wave-supported fluid-mud generation on an active continental margin. *JGR- Earth Surface*.
- Harris, C.K., Traykovski, P., Geyer, W.R., 2005. Flood dispersal and deposition by near-bed gravitational sediment flows and oceanographic transport: A numerical modeling study of the Eel River shelf, northern California. *J. Geophys. Res.*, 110(C09025): doi: 10.1029 / 2004JC002727.
- Hartnett, H.E., Keil, R.G., Hedges, J.I., Devol, A.H., 1998. Influence of oxygen exposure time on organic carbon preservation in continental margin sediments. *Nature*, 391(6667), 572-574.
- Healey, T., 2002. Muddy coasts of mid-latitude oceanic islands on an active plate margin - New Zealand: in Healey, T.R., Wang, Y., and Healey, J.-A., 2002, *Muddy Coasts of the World-Processed, Deposits and Function*, Elsevier, Chapter 14, p. 347-374.
- Hedges, J.I., Keil, R.G., 1995. Sedimentary Organic-Matter Preservation - an Assessment and Speculative Synthesis. *Mar. Chem.*, 49(2-3), 81-115.
- Herzer, R.H., 1981. Late Quaternary stratigraphy and sedimentation of the Canterbury continental shelf, New Zealand. *N. Z. Oceanogr. Inst. Memoir*, 89, pp. 71.
- Hicks, D.M., Gomez, B., Trustrum, N.A., 2000. Erosion thresholds and suspended sediment yields, Waipaoa River Basin, New Zealand. *Water Res.*, 36(4), 1129-1142.
- Hicks, D.M., Gomez, B., Trustrum, N.A., 2004. Event suspended sediment characteristics and the generation of hyperpycnal plumes at river mouths: East Coast Continental Margin, North Island, New Zealand. *J. Geol.*, 112(4), 471-485.
- Hilton, R.G., Galy, A., Hovius, N., 2008. Riverine particulate organic carbon from an active mountain belt: Importance of landslides. *Global Biogeochem. Cy.*, 22(1).
- Hilton, R.G., Meunier, P., Hovius, N., Bellingham, P.J., Galy, A., 2011. Landslide impact on organic carbon cycling in a temperate montane forest. *Earth Surface Proc. Land.*, 36(12), 1670-1679.

- Hovius, N., Galy, A., Hilton, R.G., Sparkes, R., Smith, J., Shuh-Ji, K., Hongey, C., In-Tian, L., West, A.J., 2011. Erosion-driven drawdown of atmospheric carbon dioxide: The organic pathway. *App. Geochem.*, 26, S285-S287.
- Irwin, J., 1978. Lakes Tutira: Waikapiro: Orakai Bathymetry 1:5,000. New Zealand. Oceanogr. Inst. Chart, Lake Series.
- James, D.E., DeVaughn, A.M., Marsaglia, K.M., 2007. Sand and gravel provenance in the Waipaoa River System: Sedimentary recycling in an actively deforming forearc basin, North Island, New Zealand: *Special Paper Geological Society of America* v. 420, Sedimentary provenance and petrogenesis: Perspectives from petrography and geochemistry: J. Arribas et al., eds., pp. 253-276.
- Jones, K.E., Preston, N.J., 2012. Spatial and temporal patterns of off-slope sediment delivery for small catchments subject to shallow landslides within the Waipaoa catchment, New Zealand. *Geomorph.*, 141-142, 150-159.
- Kettner, A.J., Gomez, B., Syvitski, P.M., 2007. Modeling suspended sediment discharge from the Waipaoa River system, New Zealand: The last 3000 years: *Water Res.*, 43, 1-15.
- Kettner, A.J., Syvitski, J.P.M., 2008. HydroTrend v.3.0: A climate-driven hydrological transport model that simulates discharge and sediment load leaving a river system. *Computers and Geosciences*, 34, 1170-1183.
- Kniskern, T.A., 2007. Shelf sediment dispersal mechanisms and deposition on the Waiapu river shelf, New Zealand. Dissertation, School of Marine Science: The College of William and Mary.
- Kniskern, T.A., Kuehl, S.A., Harris, C.K., Carter, L., 2010. Sediment accumulation patterns and fine-scale strata formation on the Waiapu River shelf, New Zealand. *Mar. Geol.*, 270(1-4), 188-201.
- Kniskern, T.A., Warrick, J.A., Farnsworth, K.L., Wheatcroft, R.A., Goni, M.A., 2011. Coherence of river and ocean conditions along the US West Coast during storms. *Cont. Shelf Res*, 31(7), 789-805.
- Kniskern, T.A., Mitra, S., Orpin, A.R., Harris, C.K., Walsh, J.P., Corbett, D.R., 2014. Characterization of a flood-associated deposit on the Waipaoa River shelf using radioisotopes and terrigenous organic matter abundance and composition, *Cont. Shelf Res*, <http://dx.doi.org/10.1016/j.csr.2014.04.012>.
- Kuehl, S.A., Carter, L., Gomez, B., Trustrum, N., 2003. Holistic approach offers potential to quantify mass fluxes across continental margins, *AGU Eos*, 84:379/388.
- Kuehl, S.A., Alexander, C., Carter, L., Gerald, L., Gerber, T., Harris, C., McNinch J., Orpin A., Pratson, L., Syvitski, J., Walsh, J.P., 2006. Understanding sediment transfer from land to ocean, *AGU Eos Feature Article*, 87, No. 29, 281/286.
- Lal, R., 2003. Soil erosion and the global carbon budget. *Environ. Int.*, 29(4), 437-450.

- Lang, A., Moya, J., Corominas, J., Schrott, L., Dikau, R., 1999. Classic and new dating methods for assessing the temporal occurrence of mass movements, *Geomorph.*, 30(1-2), 33-52.
- Larsen, I. J., Montgomery, D. R., 2012. Landslide erosion coupled to tectonics and river incision: *Nature Geosci.*, 5(7), 468-473.
- Leithold, E.L., Blair, N.E., Childress, L.B., Brulet, B.R., Marden, M., Orpin, A.R., Kuehl, S.A., Alexander, C.R., 2013. Signals of watershed change preserved in organic carbon buried on the continental margin seaward of the Waipaoa River, New Zealand. *Mar. Geol.*, 346, 355-365.
- Lewis, K.B., 1973. Erosion and deposition on a tilting continental shelf during Quaternary oscillations of sea level. *New Zealand J. Geol. Geophys.*, 16, 281-301.
- Lewis, K.B., 1980. Quaternary sedimentation on the Hikurangi oblique-subduction and transform margin: In *Sedimentation in a Oblique-Slip Mobile Zones Vol. 4.*, P.F. Balance and H.G. Reading Eds., International Association of Sedimentologists, Special Publication. pp. 171-189.
- Lewis, K.B., Collot, J-Y., Lallemand, S.E., 1998. The dammed Hikurangi Trough: a channel-fed trench blocked by subducting seamounts and their wake avalanches (New Zealand-France GeodyNZ Project): *Basin Research*, 10, 441-468.
- Lewis, K.B., Pettinga, J.R., 1993. The emerging, imbricate frontal wedge of the Hikurangi Margin. In: Ballance, P.F. (Ed.), *South Pacific Sedimentary Basins: Sedimentary Basins of the World*. Elsevier Science Publishers B.V., Amsterdam, pp. 225-250.
- Lewis, K.B., Lallemand, S.E., Carter, L., 2004. Collapse in a Quaternary shelf basin off East Cape, New Zealand: evidence for passage of a subducted seamount inboard of the Ruatoria giant avalanche. *New Zealand J. Geol. Geophys.*, 47, 415-429.
- Litchfield, N. J., Berryman, K. R., 2005. Correlation of fluvial terraces within the Hikurangi Margin, New Zealand: implications for climate and baselevel controls, *Geomorph.*, 68(3-4), 291-313.
- Litchfield, N., Berryman, K., 2006. Relations between postglacial fluvial incision rates and uplift rates in the North Island, New Zealand, *J. Geophys. Res.*, 111(F2), F02007, doi:10.1029/2005JF000374.
- Litchfield, N., Ellis, S., Berryman, K., Nicol, A., 2007. Insights into subduction-related uplift along the Hikurangi Margin, New Zealand, using numerical modeling, *J. Geophys. Res.*, 112(F2), F02021, doi:10.1029/2006JF000535.
- Liu, J.P., Milliman, J.D., Gao, S., Cheng, P., 2004. Development of the Yellow River's subaqueous delta, North Yellow Sea. *Marine Geology*, 209, 45-67.
- Lowe, D.A., 1987. The geology and landslides of the Lake Tutira-Waikoau area, northern Central Hawke's Bay. Unpublished M.Sc. thesis, Victoria University of Wellington, Wellington, New Zealand.

- Lowe, D. J., Shane, P.A.R., Alloway, B.V., Newnham, R. M., 2008. Fingerprints and age models for widespread New Zealand tephra marker beds erupted since 30,000 years ago: a framework for NZ-INTIMATE, *Quat. Sci. Rev.*, 27(1-2), 95-126.
- Lowe, D., Blaauw, M., Hogg, A.G., Newnham, R.M., 2013. Ages of 24 widespread tephras erupted since 30,000 years ago in New Zealand, with re-evaluation of the timing and palaeoclimatic implications of the Lateglacial cool, *Quat. Sci. Rev.*, 74, 170-194.
- Lyons, W.B., Nezarat, C.A., Carey, A.E. and Hicks, D.M., 2002. Organic carbon fluxes to the ocean from high-standing islands. *Geol.*, 30(5), 443-446.
- Ma, Y., 2009. Continental shelf sediment transport and depositional processes on an energetic, active margin: the Waiapu River shelf, New Zealand. Virginia Institute of Marine Science, College of William & Mary Ph.D. dissertation, 216 pp.
- Ma, Y., Wright, L.D., Friedrichs, C.T., 2008. Observations of sediment transport on the continental shelf off the mouth of the Waiapu River, New Zealand: evidence for current-supported gravity flows. *Cont. Shelf Res.*, 28(4), 516-532.
- Ma, Y., Harris, C.K., Friedrichs, C.T., Harris, C.K., Wright, L.D., 2010. Deposition by seasonal wave- and current-supported sediment gravity flows interacting with spatially varying bathymetry: Waiapu shelf, New Zealand. *Mar. Geol.*, 275, 199-211.
- Mackey, B. H., Roering, J.J., McKean, J.A., 2009. Long-term kinematics and sediment flux of an active earthflow, Eel River, California, *Geol.*, 37(9), 803-806.
- Mackey, B. H., Roering, J.J., 2011. Sediment yield, spatial characteristics, and the long-term evolution of active earthflows determined from airborne LiDAR and historical aerial photographs, Eel River, California, *Geol. Soc. Am. Bull.*, 123(7-8), 1560-1576.
- Macquaker, J.H.S., Bentley, S. J., Bohacs, K.M., 2010. Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: Reappraising sediment transport processes operation in ancient mudstone successions. *Geol.*, 38 (10), 947-950. doi:10.1130/G31093.1
- Marden, M, Rowan, D., 1993. Protective value of vegetation on tertiary terrain before and during Cyclone Bola, East Coast, North Island, New Zealand. *N. Z. J. For. Sci.*, 23, 255-63.
- Marden, M., Arnold, G., Gomez, B., Rowan, D., 2005. Pre- and post-reforestation gully development in Mangatu Forest, East Coast, North Island, New Zealand, *River Res. Appl.*, 21(7), 757-771.
- Marden, M., Mazengarb, C., Palmer, A., Berryman, K., Rowan, D., 2008a. Last glacial aggradation and postglacial sediment production from the non-glacial Waipaoa and Waimata catchments, Hikurangi Margin, North Island, New Zealand, *Geomorph.*, 99(1-4), 404-419.

- Marden, M., Betts, H., Arnold, G., 2008b. Gully erosion and sediment load: Waipaoa, Waipapu and Uawa rivers, eastern North Island, New Zealand, IAHS-AISH Publ., (December), 2008.
- Marden, M., Arnold, G., Seymour, A., Hambling, R., 2012. History and distribution of steepland gullies in response to land use change, East Coast Region, North Island, New Zealand. *Geomorph.*, 153, 81-90.
- Marden, M., Betts, H., Palmer, A., Taylor, R., Bilderback, E., Litchfield, N., 2014. Post-Last Glacial Maximum fluvial incision and sediment generation in the unglaciated Waipaoa catchment, North Island, New Zealand, *Geomorph.*, doi:10.1016/j.geomorph.2014.02.012.
- MARGINS, 2004. NSF MARGINS Program Science Plans 2004. Margins Office, Lamont-Doherty Earth Observatory. 170 pp. http://www.nsf-margins.org/Publications/SciencePlans/MARGINS_SciencePlans2004.pdf
- Marr, J. P., Carter, L., Bostock, H.C., Smith, E., Bolton, A., 2013. Southwest Pacific Ocean response to a warming world: using Mg/Ca, Zn/Ca and Mn/Ca in foraminifera to track surface ocean water masses during the last deglaciation. *Paleoceanography*, 28, 1-16.
- Marsaglia, K.M., DeVaughn, A.M., James, D.E., and Marden, M., 2010. Provenance of fluvial terrace sediments within the Waipaoa sedimentary system and their importance to New Zealand source-to-sink studies: *Mar. Geol.*, 270, 84-93.
- Mazengarb, C. and Speden, I.G., 2000. Geology of the Raukumara Area, Institute of Geological & Nuclear Sciences 1: 250,000 geological map 6. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand.
- McGlone, M. 2001. A late Quaternary pollen record from marine core P69, southeastern North Island, New Zealand, *New Zeal. J. Geol. Geophys.*, 44, 69-77.
- McGlone, M.S., Wilmshurst, J.M., 1999. Dating initial Maori environmental impacts in New Zealand. *Quat. Int.* 59, 5-16.
- Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. *Organic Geochem.*, 27(5-6), 213-250.
- Mildenhall, D.C., Orpin, A.R., 2010. Terrestrial palynology from marine cores as an indicator of environmental change for the Waipaoa Sedimentary System and north-eastern New Zealand. *Mar. Geol.*, 270(1-4), 227-234.
- Miller, A.J., Kuehl, S.A., 2010. Shelf sedimentation on a tectonically active margin: a modern sediment budget for Poverty continental shelf, New Zealand. *Mar. Geol.*, 270(1), 175-187.
- Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic tectonic control of sediment discharge to the ocean - The importance of small mountainous rivers. *J. Geol.*, 100(5), 525-544.

- Moriarty, J.M., Harris, C.K., Hadfield, M.G., 2014. A hydrodynamic and sediment transport model for the Waipaoa Shelf, New Zealand: Sensitivity of fluxes to spatially-varying erodibility and model nesting. *J. Mar. Sci. Eng.*, 2(2), 336-369.
- Moriarty, J.M., Harris, C.K., Hadfield, M.G., In Review. Event-to-seasonal sediment dispersal on the Waipaoa River shelf, New Zealand: a numerical modeling study. Submitted to *Cont. Shelf Res.*, August, 2014.
- Mortimer, N., 1994, Origin of the Torlesse Terrane and coeval rocks, North island, New Zealand: *Int. Geol. Rev.*, 7, 891-910.
- Mountjoy, J.J., Micallef, A., 2012. Polyphase Emplacement of a 30 km(3) Blocky Debris Avalanche and Its Role in Slope-Gully Development. *Submarine Mass Movements and Their Consequences*, 31, 213-222.
- Nelson, C.S., Hendy, I.L., Neil, H.L., Hendy, C.H., Weaver, P.P.E., 2000. Late glacial jetting of cold waters through the Subtropical Convergence zone in the Southwest Pacific off eastern New Zealand, and some geological implications. *Palaeogeogr., Palaeocl.*, 156, 103-121.
- Newnham, R., McGlone, M., Moar, N., Wilmshurst, J. and Vandergoes, M., 2013. The vegetation cover of New Zealand at the Last Glacial Maximum. *Quat. Sci. Rev.*, 74(0), 202-214.
- O'Byrne, T.N. 1967. A correlation of rock types with soils, topography and erosion in the Gisborne-East Cape region. *NZ J. Geol. Geophys.*, 10, 217-231.
- Ogston, A.S., Cacchione, D.A., Sternberg, R.W., Kineke, G.C., 2000. Observations of storm and river flood-driven sediment transport on the northern California continental shelf. *Cont. Shelf Res.*, 20(16), 2141-2162.
- Orpin, A.R., 2004. Holocene sediment deposition on the Poverty-slope margin by the muddy Waipaoa River, East Coast New Zealand. *Marine Geology*, 209, 69- 90.
- Orpin, A.R., Alexander, C., Carter, L., Kuehl, S., Walsh, J.P., 2006. Temporal and spatial complexity in post-glacial sedimentation on the tectonically active, Poverty Bay continental margin of New Zealand. *Cont. Shelf Res.*, 26, 2205-2224.
- Orpin, A.R., Carter, L., Page, M.J., Cochran, U.A., Trustrum, N.A., Gomez, B., Palmer, A.S., Mildenhall, D.C., Rogers, K.M., Brackley, H.L., Northcote, L. 2010. Holocene sedimentary record from Lake Tutira: a template for upland watershed erosion proximal to the Waipaoa Sedimentary System, northeastern New Zealand. *Mar. Geol.*, 270, 11-29.
- Page, M.J., Trustrum, N.A., De Rose, R.C., 1994a. A high resolution record of storm-induced erosion from lake sediments, New Zealand. *J. Paleolimn.*, 11, 333-348.
- Page, M.J., Trustrum, N.A., Dymond, J.R. 1994b: Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorph.*, 9, 169-188.

- Page, M.J., Trustrum, N.A., 1997. A late Holocene lake sediment record of the erosional response to land use change in a steep-land catchment, New Zealand. *Zeitschrift für Geomorphologie N.F.*, 413, 369-392.
- Page, M.J., Reid, L.M., Lynn, I.H., 1999. Sediment production from Cyclone Bola landslides, Waipaoa catchment. *J. Hydrol.*, 38, 289-308.
- Page, M.J., Trustrum, N.A., Brackley, H.L., Baisden, W.T., 2004. Erosion-related soil carbon fluxes in a pastoral steep-land catchment, New Zealand. *Agr. Ecosyst. Environ.*, 103(3), 561-579.
- Page, M., Marden, M., Kasai, M., Gomez, B., Peacock, D., Betts, H., Parkner, T., Marutani, T. and Trustrum, N., 2008. Changes in basin-scale sediment supply and transfer in a rapidly transformed New Zealand landscape. In: H. Habersack, H. Piegay and M. Rinaldi (Editors), *Gravel-Bed Rivers VI: From Process Understanding to River Restoration*. *Earth Surf. Processes*, pp. 337-358.
- Page, M.J., Trustrum, N., Orpin, A.R., Carter, L., Gomez, B., Cochran, U.A., Mildenhall, D.C., Rogers, K.M., Brackley, H.L., Palmer, A.S., Northcote, L. 2010. Storm frequency and magnitude in response to Holocene climate variability, Lake Tutira, North-Eastern New Zealand. *Mar. Geol.*, 270, 30-34.
- Page, M., Lukovic, B., 2011. An inventory of deep-seated landslides in the Waipaoa and Waimata catchments, Lower Hutt.
- Pahnke, K., Sachs, J.P., 2006. Sea surface temperatures of southern midlatitudes 0-160 kyr BP. *Paleoceanog.* 21, PA2003, doi:10.1029/2005PA001191, 2006
- Parra, J.G., Marsaglia, K.M., Rivera, K.S., Dawson, S.T., Walsh, J.P., 2012. Provenance of sand on the Poverty Bay shelf, the link between source and sink sectors of the Waipaoa River sedimentary system. *Sediment. Geol.*, 280, 208-233.
- Pearce, A.J., Black, R.D., Nelson, C.S., 1981. Lithologic and weathering influences on slope form and process, eastern Raukumara Range, New Zealand. *Int. Assoc. Hydrol. Sci. Publ.*, 132, 95-122.
- Pedley, K.L., Barnes, P.M., Pettinga, J.R., Lewis, K.B., 2010. Seafloor structural geomorphic evolution of the accretionary frontal wedge in response to seamount subduction, Poverty Indentation, New Zealand, *Mar. Geol.*, 270(1-4), 119-138.
- Pere, V.H., 2003. Formation and consequences of the Totangi landslide dam in the Ngatapa Valley, Gisborne, New Zealand, M.Sc. thesis, Canterbury University, Christchurch, New Zealand, pp. 180.
- Petsch, S.T., Berner, R.A., Eglinton, T.I., 2000. A field study of the chemical weathering of ancient sedimentary organic matter. *Organic Geochem.*, 31(5), 475-487.
- Phillips, J.D., Gomez, B., 2007. Controls on sediment export from the Waipaoa River basin, New Zealand. *Basin Res.*, 19, 241-252.

- Phillips, J.D., Marden, M., Gomez, B., 2007. Residence time of alluvium in an aggrading fluvial system. *Earth Surface Proc. Land.*, 32(2), 307-316.
- Pierce, L.E.R., 2012. Poverty Shelf, New Zealand from the Holocene to present: stratigraphic development and event layer preservation in response to sediment supply, tectonics and climate. College of William and Mary, Ph.D. Dissertation, 274 pp.
- Pouderoux, H., Lamarche, G., Proust, J.N., 2012a. Building an 18 000-year-long paleo-earthquake record from detailed deep-sea turbidite characterisation in Poverty Bay, New Zealand. *Nat. Hazard Earth Sys.*, 12(6), 2077-2101.
- Pouderoux, H., Proust, J.N., Lamarche, G., Orpin, A., Neil, H., 2012b. Postglacial (after 18 ka) deep-sea sedimentation along the Hikurangi subduction margin (New Zealand): Characterisation, timing and origin of turbidites. *Mar. Geol.*, 295, 51-76.
- Pouderoux, H., Proust, J.-N., Lamarche, G., 2014. Submarine paleoseismology of the northern Hikurangi subduction margin of New Zealand as deduced from Turbidite record since 16 ka. *Quat. Sci. Rev.*, 84, 116-131.
- Preston, N., Crozier, M., 1999. Resistance to shallow landslide failure through root-derived cohesion in east coast hill country soils, North Island, New Zealand, *Earth Surf. Process. Landforms*, 675, 665-675.
- Preston, N.J. 2008. Off-slope sediment delivery from landsliding during a storm, Muriwai Hills, North Island, New Zealand. In: Schmidt, J., Cochrane, T., Phillips, C., Elliott, Davies, T., Basher, L., *Sediment dynamics in changing environments*. IAHS Publication, 325, 237-241.
- Pullar, W.A., 1962. Soils and agriculture of the Gisborne Plains. *Bull.* 20, N.Z. Soil Bureau, Wellington, pp. 92.
- Rait, G., Chanier, F., Waters, D.W. 1991. Landward- and seaward-directed thrusting accompanying the onset of subduction beneath New Zealand, *Geol.*, 19(3), 230-233.
- Reid, L. M., Page, M.J., 2002. Magnitude and frequency of landsliding in a large New Zealand catchment, *Geomorph.*, 49, 71-88.
- Reid, C., 1999. Waipaoa River at Kanakanaia: a review of flood data. Unpublished report to the Gisborne District Council, New Zealand, 52.
- Reusser, L.J., Bierman, P.R., 2010. Using meteoric ^{10}Be to track fluvial sand through the Waipaoa River basin New Zealand, *Geol.*, 38, 47-50.
- Rose, L.E. and Kuehl, S.A., 2010. Recent sedimentation patterns and facies distribution on the Poverty Shelf, New Zealand. *Mar. Geol.*, 270, 160-174
- Schneider, J.-L., Le Ruyet, A., Chanier, F., Buret, C., Ferriere, J.-N., and Rosseel, J.-B., 2001. Primary or secondary distal volcanoclastic turbidites: Ho to make the distinction? An example from the Miocene of New Zealand (Mahia Peninsula, North Island): *Sedimentary Geol.*, 145, 1-22.

- Scott, D.T., Baisden, W.T., Davies-Colley, R., Gomez, B., Hicks, D.M., Page, M.J., Preston, N.J., Trustrum, N.A., Tate, K.R. and Woods, R.A., 2006. Localized erosion affects national carbon budget. *Geophys. Res. Letters*, 33(1).
- Scully, M.E., Friedrichs, C.T., Wright, L.D., 2002. Application of an analytical model of critically stratified gravity-driven sediment transport and deposition to observations from the Eel River continental shelf, northern California. *Cont. Shelf Res*, 22(14), 1951-1974.
- Smith, R. K., 1988. Poverty Bay, New Zealand: A case of coastal accretion. *New Zealand Journal of Marine and Freshwater Research*, 22 (1), 135-142.
- Smith, V., Shane, P., Nairn, I., 2005. Trends in rhyolite geochemistry, mineralogy, and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, 148, 372-406.
- Sparling, G., Ross, D., Trustrum, N., Arnold, G., West, A., Speir, T. and Schipper, L., 2003. Recovery of topsoil characteristics after landslip erosion in dry hill country of New Zealand, and a test of the space-for-time hypothesis. *Soil Biol. Biochem.*, 35(12), 1575-1586.
- Stanford, J.D., Rohling, E.J., Hunter, S.E., Roberts, A.P., Rasmussen, S.O., Bard, E., McManus, J., Fairbanks, R.G., 2006. Timing of meltwater pulse 1a and climate responses to meltwater injections. *Paleoceanography*, 21, DOI: 10.1029/2006PA00134
- Stephens, S. A., Bell, R. G., Black, K.P., 2001. Complex circulation in a coastal embayment: Shelf-current, wind, and density-driven circulation in Poverty Bay, New Zealand. *J. Coastal Res.*, Special Issue 34: 45-59.
- Suggate, R.P., 1990. Late Pliocene and Quaternary Glaciations of New Zealand. *Quat. Sci. Rev.*, 9, 175-197.
- Sumner, B.W., 2007. Sedimentation and Morphology on the Outer Shelf/Upper Slope Transition, Waipaoa River Margin, New Zealand. M.S. Thesis, East Carolina University, 129 p.
- Sutherland, R., Stagpole, V., Uruski, C., Kennedy, C., Bassett, D., Henrys, S., Schwerwath, M., Kopp, H., Field, B., Goumlin, S., Barker, C., Bannister, S., Davey, F., Stern, T., and Flueh, E., 2009. Reactivation of tectonics, crustal underplating, and uplift after 60 Myr of passive subsidence, Raukumara Basin, Hikurangi-Kermadec fore arc, New Zealand : implications for global growth and recycling of continents. *Tectonics*, 28: TC5017, doi:10.1029/2008TC002356
- Syvitski, J.P.M., Vorosmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, 308(5720), 376-380.
- Syvitski, J.P.M., Kettner, A., 2011. Sediment flux and the Anthropocene. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 369(1938), 957-975.

- Taylor, R.J., 2011. Catchment sediment dynamics and the role of deep-seated landslide-dams; Waipaoa catchment, Raukumara Peninsula, New Zealand. Unpublished MSc Thesis, Victoria University of Wellington, pp. 223.
- Thompson, C.E., 2009. Tracking Organic Matter from Source to Sink in the Waiapu River Watershed, New Zealand: A Geochemical Perspective, North Carolina State University, Ph.D. Dissertation, 356 pp.
- Tolman, H.L., Balasubramanian, B., Burroughs, L.D., Chalikov, D.V., Chao, Y.Y., Chen, H.S., Gerald, V.M., 2002. Development and implementation of wind-generated ocean surface wave models at NCEP*. *Weather Forecast*, 17, 311–333.
- Traykovski, P., Geyer, W.R., Irish, J.D., Lynch, J.F., 2000. The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. *Cont. Shelf Res*, 20(16), 2113–2140.
- Traykovski, P., Wiberg, P.L., Geyer, W.R., 2007. Observations and modeling of wave-supported sediment gravity flows on the Po prodelta and comparison to prior observations from the Eel shelf. *Cont. Shelf Res*, 27(3), 375–399.
- Trustrum, N.A., DeRose, R.C., 1988. Soil depth-age relationship of landslides on deforested hillslopes, Taranaki, New Zealand. *Geomorph.*, 1, 143–160.
- Trustrum, N.A., Page, M. J., 1992. The long-term erosion history of Lake Tutira watershed: implications for sustainable land use management. In: *Proceedings of International Conference on Sustainable Land Management*. Napier, New Zealand (pp. 212–215).
- Trustrum, N.A., Gomez, B., Reid, L.M., Page, M.J., Hicks, D.M., 1999. Sediment production, storage and output: the relative role of large magnitude events in steepland catchments, *Zeitschrift für Geomorphologie*, Supplement Band 115, 71–86.
- Upton, P., Kettner, A.J., Gomez, B., Orpin, A.R., Litchfield, N., Page, M.J., 2013. Simulating post-LGM riverine fluxes to the coastal zone, The Waipaoa River System, New Zealand: *Comput. Geosci.*, 53, 48–57.
- Wadman, H.M., McNinch, J.E., 2008. Stratigraphic spatial variation on the inner shelf of a high-yield river, Waiapu River, New Zealand: implications for fine-sediment dispersal and preservation. *Cont. Shelf Res*, 28(7), 865–886.
- Wallace, L.M., Beavan, J., McCaffrey, R., Darby, D., 2004. Subduction zone coupling and tectonic block rotation in the North Island, New Zealand, *J. Geophys. Res.*, 109, doi:10.1029/2004JB003241.
- Wallace, L. M., Beavan, J., 2010. Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, *J. Geophys. Res.*, 115(B12402), doi:10.1029/2010JB007717.
- Walsh, J. P., Alexander, C. R., Gerber, T., Orpin, A.R., Sumners, B.W., 2007. Demise of a submarine canyon? Evidence for highstand infilling on the Waipaoa River continental margin, New Zealand. *Geophys. Res. Letters*, vol. 34, L20606, doi:10.1029/2007gl031142.

- Walsh, J.P., Corbett, D.R., Kiker, J., Orpin, A., Hale, R., Ogston, A., 2014. Spatial and temporal variability in sediment deposition and seabed character on the Waipaoa River margin, New Zealand. *Cont. Shelf Res.* 86, 85-102.
- Weaver, P.P.E., Carter, L., Neil, H., 1998. Response of surface water masses and circulation to late Quaternary climate change, east of New Zealand. *Paleoceanography* 13, 70-83.
- West, A.J., Lin, C.W., Lin, T.C., Hilton, R.G., Liu, S.H., Chang, C.T., Lin, K.C., Galy, A., Sparkes, R.B. and Hovius, N., 2011. Mobilization and transport of coarse woody debris to the oceans triggered by an extreme tropical storm. *Limnol. Oceanogr.*, 56(1), 77-85.
- Wheatcroft, R.A. 2000. Oceanic flood sedimentation: a new perspective. *Cont. Shelf Res.* 20(16), 2059-2066.
- Wilmshurst, J.M., McGlone, M.S. 1996. Forest disturbance in the central North Island, New Zealand following the 1850 BP Taupo eruption. *The Holocene*, 6, 399-411.
- Wilmshurst, J.M., 1997. The impact of human settlement on vegetation and soil stability in Hawke's Bay, New Zealand. *New Zealand J. Botany*, 35, 97-111.
- Wilmshurst, J.M., McGlone, M.S., Partridge, T.R., 1997. A late Holocene history of natural disturbance in lowland podocarp/hardwood forest, Hawke's Bay, New Zealand. *New Zealand J. Botany*, 35, 79-96.
- Wilmshurst, J.M., Eden, D.N., Froggatt, P.C., 1999. Late Holocene forest disturbance in Gisborne, New Zealand: a comparison of terrestrial and marine pollen records. *New Zealand J. Botany*, 37(3), 523-540.
- Wilmshurst, J.M., McGlone, M.S., Leathwick, J.R. and Newnham, R.M., 2007. A pre-deforestation pollen-climate calibration model for New Zealand and quantitative temperature reconstructions for the past 18 000 years BP. *J. Quat. Sci.*, 22(5), 535-547.
- Wilmshurst, J.M., Anderson, A.J., Higham, T.F.G, Worthy, T.H., 2008. Dating the late prehistoric dispersal of Polynesians to New Zealand using the commensal Pacific rat. *Proceedings of the National Academy of Sciences*, doi/10.1073/pnas.0801507105.
- Wilson, K., Berryman, K., Cochran, U., and Little, T., 2007. Holocene coastal evolution and uplift mechanisms of the northeastern Raukumara Peninsula, North Island, New Zealand. *Quat. Sci. Rev.*, 26, 1106-1128.
- Wolinsky, M.A., Swenson, J.B., Litchfield, N., McNinch, J.E., 2010. Coastal progradation and sediment partitioning in the Holocene Waipaoa Sedimentary System, New Zealand. *Mar. Geol.*, 270, 94-107.
- Wood, M.P., 2006. Sedimentation on a high input continental shelf at the active Hikurangi Margin, Poverty Bay, New Zealand. Unpublished MSc thesis 200pp. Lodged Library, Victoria University of Wellington, New Zealand.

- Wright, L.D., Friedrichs, C.T., 2006. Gravity-driven sediment transport on continental shelves: A status report. *Cont. Shelf Res*, 26(17), 2092-2107.
- Young, A.P., Ashford, S.A., 2006. Application of Airborne LIDAR for Seacliff Volumetric Change and Beach-Sediment Budget Contributions. *J. Coastal Res.*, 22, 307–318.
- Zhang, X., Phillips, C., Marden, M. 1991. Internal deformation of a fast-moving earthflow, Raukumara Peninsula, New Zealand. *Geomorph.*, 4(2), 145-154.

Table and Figure Captions

Table 1 - Storm periods (cal. BP) based on variations in frequency and thickness of storm sediment layers in Lake Tutira, North Island, New Zealand (modified after Page et al., 2010; Gomez et al., 2012).

Figure 1 - Maps of Waipaoa Sedimentary System (WSS) showing: a) entire WSS including drainage basin (cream shade) and offshore bathymetry (in meters) with the plate boundary shown as a bold black line with triangles; b) geology and major features of drainage basin, including key sub-study areas within the basin (outlined in black) and sampling sites (orange triangles); and, c) shelf and upper slope detail showing locations of Marion Dufresne giant piston cores (red circles).

Figure 2 – Cartoon schematic showing the major marine sediment depocenters and transport pathways on the shelf and slope. The main Depocenters (numbered yellow shapes) include: 1) Southern; 2) Northern; 3) Outer Shelf, and 4) Upper Slope. Sediment-budget exercises both on centennial and Late Quaternary timescales show that most of the Waipaoa River sediment supplied to the ocean escapes the study area, predominantly along the shelf to the north.

Figure 3 - Cartoon summary of sediment deposition based on a core from the centre of Lake Tutira. The relative proportion of the major lithotypes are shown in blue circles based on the total measured thicknesses of the sediments preserved in the core. The modes of deposition are portrayed schematically and assigned to watershed, lake, or volcanic airfall sources. The

inferred underlying drivers are shown below in the yellow bar (Figure after Orpin et al., 2010).

Figure 4 - (A) Scaled rainfall derived from the storm record preserved in Lake Tutira. (B): Simulated suspended-sediment discharge from the Waipaoa over the past 5.5 ka based on scaled rainfall (in A). Figures in the adjacent grey column (right) represent the average sediment flux for the same time periods as sediment accumulation rates (after Phillips and Gomez, 2007). Numbers in parentheses are from a simulation without floodplain storage. (C) Modelled suspended-sediment discharge from the Waipaoa over the past 5.5 ka using climate derived from the SST record of MD97-2121 (using data from Carter et al., 2002). Average suspended-sediment discharges are shown for the same periods as in B and C. (Figure after Upton et al., 2013).

Figure 5 - Photos of common sediment production processes in the Waipaoa River watershed. A) Deep-seated landslides often displace pre-LGM surfaces and deliver sediment to channels, photo by A. Booth, B) Many gullies, like the well known Tarndale Slip, became common after European settlement, and expanded in area leading to downstream aggradation and high sediment yields, photo by Ministry for Primary Industries, New Zealand, C) Shallow landslides like these triggered by the 1988 Cyclone Bola mobilize the soil mantle, photo by M. Page, and D) Slow-moving earthflows impart a fluid-like appearance to hillslopes and generate rapid slope relaxation in response to incision, photo by J. Roering.

Figure 6 - Post-LGM temporal variation in rates of landscape change. A) Average fluvial incision rate (gray boxes) and volumetric valley excavation rate (filled black circles) peak

around the Pleistocene-Holocene transition (9-13ka) before declining through the Holocene. Shaded box width and horizontal error bars represent the temporal sampling interval defined by tephra deposits used to establish terrace ages. Shaded box height and vertical error bars represent one standard deviation of the incision rate. Modified from Marden et al., 2014. B) Average post-LGM erosion rate for two catchments in the upper Waipaoa (labeled EB, dashed dark gray line, Bilderback, 2012) overlap with the average uplift rate estimated by Berryman et al. (2000) and Litchfield and Berryman (2006). Variation of erosion rate (labeled CCD, filled black circles) for the earthflow-dominated, Mangataikapua catchment, (Cerovsk-Darriau et al., 2014). Note that high erosion rates coincide with rapid incision before declining through the Holocene and approaching the uplift rate. In the late Holocene, erosion increases, partly due to the anthropogenic role in slope destabilization. Modern erosion rates (filled gray diamond) estimated by suspended-sediment data (Hicks et al., 2000) exceed uplift and average erosion rates by nearly a factor of 4.

Figure 7 - A) Longitudinal profile for the modern Waipaoa (thin black line), LGM Waipaoa as defined by the Waipaoa 1 terrace (thick gray line), and intermediate profiles (between 2ka and 18ka). Distance defined as valley distance, rather than river distance. Modified from Marden et al., 2014. B) Longitudinal variation in post-LGM incision (thick gray dashed line), rock uplift rate (filled black circles, Berryman et al., 2000), and erosion rates for two landslide-dominated catchments (Mangamaia, thick, light gray line, Bilderback, 2012) and one earthflow-dominated catchment (Mangataikapua, thick, dark gray line, Cerovski-Darriau et al., 2014). The horizontal width of the landslide lines denotes the distance the study catchments span along the Waipaoa River. Note that while post-LGM incision rates increase upstream and approach 8 mm y^{-1} in the headwaters, uplift and erosion rates tend to cluster from 0.5 to 1.5 mm y^{-1} .

Figure 8 – High-resolution CHIRP strike profiles (A-C) along the Poverty mid- to outer-shelf showing the post-glacial sediment cover overlying the transgressive surface (W1). Vertical bars represent approximate depth scales through conversion of two-way travel times (TWT) to distance assuming a sound velocity of 1500 m s^{-1} . Map inset shows track lines overlain on bathymetry for the CHIRP profiles and locations of key Marion Dufresne piston cores (from Gerber et al., 2010).

Figure 9 - A) Slope (MD 3003) and Shelf Break (MD 3006) age model accumulation rates (AR) with major slope changes indicated (black lines) and trendline ARs with 95% confidence intervals associated with the rates (in cm y^{-1}) labeled. B) Southern Depocenter (MD 3004) age model as above. C) Northern Depocenter (MD 3001, MD 3007) age model as above. Line color key same as for Figure 10.

Figure 10 – $\delta^{13}\text{C}$ and grain-size versus age plots for giant piston cores collected from the shelf and slope off Waipaoa River (data from Pierce, 2012): A) All $\delta^{13}\text{C}$ results. B) Slope, MD 3003, $\delta^{13}\text{C}$ and grain size. Vertical lines represent mean grain size for respective intervals. C) Shelf Break Depocenter, MD 3006, $\delta^{13}\text{C}$ and grain size. D) Southern Depocenter, MD 3004, $\delta^{13}\text{C}$ and grain size. E) Northern Depocenter, MD 3007, $\delta^{13}\text{C}$; and MD 3007 and MD 3001, $\delta^{13}\text{C}$ and grain size.

Figure 11 – Cartoon showing how slope-sediment dispersal patterns have been significantly impacted by the emplacement of a large failure deposit on the mid-slope, the Paritu debris

avalanche, produced 7-8.2 ka. This deposit caused a mid-Holocene switch in the main-slope depocenter of the turbidite system from the Paritu Trough to the Lower Paritu Basin (from Pouderoux et al., 2012a).

Figure 12 - Distribution of sediment accumulation rates (in units of mass flux) on the Waipaoa continental margin. The most rapid rates are observed in the two mid-shelf depocenters, in the outer-shelf depocenter and in the head of the Poverty Canyon. Although rates are rapid in the upper Poverty canyon and in upper-slope gullies, accumulation rates are uniformly slow across the base of the upper slope, indicating little transport beyond the upper slope under highstand conditions. Slow sediment accumulation identifies a shelf zone of bypassing between the Ariel and Lachlan anticlines. Data from Alexander et al. (2010) and Miller and Kuehl (2010).

Figure 13 - Surficial distribution of ^7Be , a short-lived radionuclide with a 53-d half-life, on the Waipaoa outer shelf and slope. The widespread presence of ^7Be on the margin in both summer (A) and winter (B) suggests that terrestrially derived sediment is reaching the shelf and slope throughout the year.

Figure 14 – Grain size of surficial sediment and rock cover of the Waipaoa continental shelf from Wood (2006). LA = Lachlan anticline, AA = Aerial anticline, DEP = Depocenter. Note finer sediments are associated with sediment depocenters, and modern sediment dispersal pathways (c.f. Fig. 2).

Figure 15 – Model estimates of cumulative deposition (positive) and erosion (negative) for individual high-discharge events (left column) and subsequent time periods: (a) January 30 – February 14, 2010; (b) March 4 – 13, 2010; (c) July 4-22, 2010; (d) August 29 – September 8, 2010; (e) January, 2010 – February, 2011; (f) April 28 – May 9, 2006; (g) May 9 – September 8, 2006. Panels (a – e) after Moriarty et al. (in review). Panels (f – g) after Bever et al. (2014). Shading shown when changes in seabed height exceed 1 mm; Panel (g) shows erosional areas as white.

Figure 16 - (A) Waipaoa River sediment concentration and cumulative sediment discharge, and (B) offshore wave height over 18 months of record (Sept 2009 – March 2011). Times of sampling cruises are shown with black hatched boxes. C) Time series of wave height and river discharge for selected periods illustrating dry and wet storms, and D) the resulting SSC and bed-elevation changes at the seabed measured at the inner shelf site (see Fig. 15 for location). Figure modified from Walsh et al. (2014) and Hale (2014).

Figure 17- A) Nearbed suspended-sediment concentration during a wave-supported gravity flow that coincided with the July, 2010 flood. B) Estimated across-shelf speed of the wave-supported gravity flow. C) Modeled seabed erosion/deposition (color) and sediment flux (vectors) for July, 2010 after Moriarty et al. (in review). D) Circles represent estimated layer thickness from Walsh et al. (2014) using ^7Be for the same time period. Triangle in (D) approximates location of tripod observations in (A – B), and the box identifies area shown in (C).

Figure 18 – Average bed shear stress (Pa) over thirteen months, from January 2010 – February 2011, estimated using wave estimates from NZWAVE, an implementation of NOAA Wave Watch III model (Tolman et al., 2002), and current velocity estimates from the ROMS model as described in Moriarty et al. (2014). Figure modified from Moriarty et al. (in review).

Figure 19 - The nested carbon cycles of the Waipaoa Sedimentary System. The longest-termed C-cycle results from the subduction of C and its eventual volatilization through the volcanic network. Formation of the accretionary prism with uplift of sedimentary rock creates a ubiquitous source of generally unreactive ancient OC to the system. Terrestrial and marine primary production generate younger sources of OC. Turnover and/or aging of the biogenic OC occur throughout the S2S network. Figure modified from Lowe (2010).

Figure 20 – Soil profiles of organic carbon (OC) attributes and tephra ages in the Waipaoa River watershed (locations shown in Fig. 1b). The primary source of OC to soils is surface vegetation though mixing with underlying parent material C (variously from colluvium, alluvium or sedimentary rock). OC concentrations decrease with depth as a result of diagenesis (left panel; Blair et al., 2010b). The quality of the OC, as indicated by pyrolytic release of n-alkanes, also decreases as a result of diagenesis (right panel; Blair et al, 2010a). The $\delta^{13}\text{C}$ values reflect the various plant sources to the soils (middle panel). Depth variations reflect changes in sources (including mixing ratios between surface inputs and parent materials) and diagenetic processing. The apparent ^{14}C -age of the soil OC is younger than co-existing tephras as a result of downward migration of surface material (right panel).

Figure 21 - The evolution of organic carbon (OC) in the Waipaoa Sedimentary System.

Relative contributions of the three general OC types – sedimentary rock, terrestrial (vegetation- derived), and marine OC – were estimated using C-isotope (^{12}C , ^{13}C , ^{14}C) mass balances (Blair et al., 2010b). The terrestrial and marine components are themselves unresolved mixtures of contemporary and aged materials. Exact estimates of the various components vary as a function of assumed end-member isotopic composition, however the basic patterns are robust. Rock-derived C is evident seaward to the slope (2000 m). Winnowing of sediments nearshore selectively transports younger C offshore, and the source of marine C changes as one moves offshore.

Storm period	Mid-point $\pm$ 2 σ of storm periods	Duration (yr)	Return period (yr)		Southern hemisphere climate teleconnection
			Layers $\geq 0.4\text{cm}$	Layers $\geq 1.0\text{cm}$	
1988–1895AD^a		93	4	7	► Antarctic (SAM) climate dominates
500–680	590 $\pm$ 85	180	18	30	► Fewer storms at Tutira
1120–1270	1195 $\pm$ 48	150	19	21	
1830–2120	1975 $\pm$ 61	290	6	14	
2860–3180	3020 $\pm$ 103	320	16	40	► ENSO and SAM in phase
3600–3990	3795 $\pm$ 72	390	24	35	► More storms at Tutira
4310–4480	4395 $\pm$ 173	170	12	19 ^b	
4720–4950	4835 $\pm$ 208	230	7	18 ^b	
5700–5910^c	5805 $\pm$ 126	210	11	30	► Tropical (ENSO) climate dominates ► Few storms at Tutira

^aEuropean impact

^bHigh storm frequencies may be due to uncertainties in identification of Hinemaiaia Tephra

^cPrior to ~6 ka there are fewer laminated beds and the record is predominantly thick, poorly graded deposits which may indicate a change in catchment conditions.