The Waipaoa Sedimentary System: research review and future directions

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Abstract The Waipaoa Sedimentary System is an ideal natural laboratory for determining the processes that affect sediment delivery and deposition across a high sediment input, active continental margin. As such it was chosen as one of two focus sites for the NSF- and FRST-supported MARGINS Source-to-Sink Initiative. Key research outcomes-to-date are described here, and can be broadly grouped into four themes: (i) long-term (≤100 ka) fluvial processes; (ii) post-18 ka sediment budgets; (iii) contemporary sedimentary processes; and (iv) the response to major events including the impacts of human colonisation. Research gaps include quantification of post-18 ka hillslope erosion, hillslope-channel linkages, and the landscape response to rapid changes in climate and large earthquakes. A new research programme is summarised which aims to fill some of these gaps in the terrestrial part of the Waipaoa SS, to extend understanding of sedimentary systems through numerical modelling, and to appraise the likely changes in sediment delivery through various mitigation strategies.

Key words sedimentary system; erosion; sediment budget; Waipaoa; New Zealand

INTRODUCTION

The Waipaoa Sedimentary System (Waipaoa SS) in the Gisborne Region, New Zealand (Fig. 1), is an ideal natural laboratory for understanding sediment dispersal across an active continental margin and associated societal impacts. Factors such as its relatively small size, with well-defined and documented sedimentary basins (Fig. 1(b)), and its location in a dynamic tectonic and climatic setting with volcanic ash input (Fig. 1(a)), and have combined with rapid rates of dissection and high natural sediment yield to produce large, readily measured signals. In addition, the natural system is overprinted by the impact of recent (past approx. 700 years) human activity, providing the opportunity to compare human *vs* natural impacts. Because of these factors, the Waipaoa SS was chosen as one of two focus sites for the NSF- and FRST-supported MARGINS Source-to-Sink Initiative, which aims to develop a quantitative understanding of margin sediment delivery systems and associated stratigraphy (Kuehl *et al.*, 2003). In this paper we summarise some key findings of Waipaoa SS research to date and highlight what we consider to be research gaps. We then describe the aims and objectives of a new research programme, which will fill some of these gaps and continue to advance knowledge of the Waipaoa SS through numerical modelling.

Tectonic and climatic setting

The Waipaoa SS is situated in the northern part of the Hikurangi Subduction Margin in the northeastern North Island, New Zealand (Fig. 1). The terrestrial part of the Waipaoa SS, the Waipaoa River catchment (approx. 2200 km^2), is situated upon mudstone-dominated Miocene-Pliocene forearc sediments (Mazengarb & Speden, 2000), which are undergoing regional-scale uplift (1–3 mm/year) in response to deep-seated subduction processes such as sediment underplating (Walcott, 1987; Litchfield *et al.*, 2007). The offshore part of the system, the Poverty Bay shelf and slope, is situated on the upper part of the accretionary prism, and is characterised by reverse faulting and folding which have created sedimentary basins that are rapidly infilled due to a high input of terrigenous sediment (Foster & Carter, 1997; Orpin *et al.*, 2006) (Fig. 1).

The Waipaoa SS is characterised by a temperate maritime climate, with a relatively large number of sunshine hours and low wind speeds, but is punctuated by tropical cyclones (Hessell,

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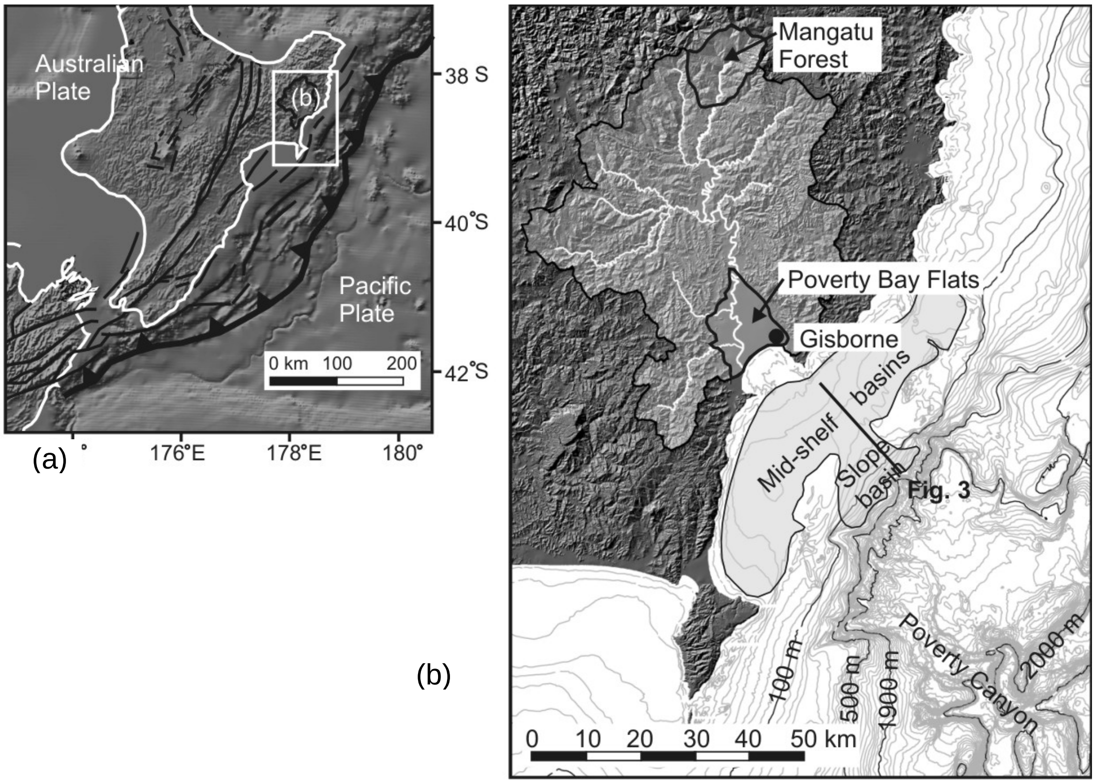

Fig. 1 Location maps of the Waipaoa SS. (a) Plate tectonic setting (black lines are the major active faults), (b) Waipaoa River catchment and offshore basins (from Orpin *et al.*, 2006).

1980). The predominantly westerly winds result in orographic mean annual rainfall varying from 1000 mm at the coast to 3000 mm in the headwaters, with the greatest rainfall occurring in winter (Hessell, 1980). The paleoclimate record is patchy, but pollen records indicate that the early Holocene was wetter and warmer than present (Mildenhall & Brown, 1987), and that fully developed forest existed in the Gisborne region during all but coldest parts of the glacial periods, when it is likely that grass or shrublands characterised (non-glaciated) hillslopes undergoing freeze-thaw processes (McGlone *et al.*, 1984).

Key findings to date

MARGINS S2S research to date in the Waipaoa SS can be broadly grouped into four main topics: (i) long-term (≤ 100 ka) fluvial processes; (ii) post-18 ka sediment budgets; (iii) contemporary sedimentary processes; and (iv) the response to prominent events including human colonisation and changing land use (deforestation).

Long-term fluvial processes

River terraces in the middle and upper parts of the Waipaoa River catchment (Fig. 2(a)) record a history of alternating cycles of aggradation and incision over the last approx. 100 ka, which is primarily driven by climate (Berryman *et al.*, 2000). A second-order control is tectonic uplift, which modulates incision and is manifest as the spacing between aggradation terraces (Berryman *et al.*, 2000; Litchfield & Berryman, 2006). In the lower catchment, subsidence has resulted in stacking of fluvial deposits beneath the Poverty Bay Flats, which are interfingered with estuarine and beach deposits recording marine incursions during sea level highstands (Brown, 1995). The well-documented record of initial marine transgression and subsequent progradation of the shoreline across the Poverty Bay Flats over the last 10 ka (Pullar & Penhale, 1970; Brown, 1995) highlights the influence of sea level in the lower reaches (Wolinsky *et al.*, 2009).

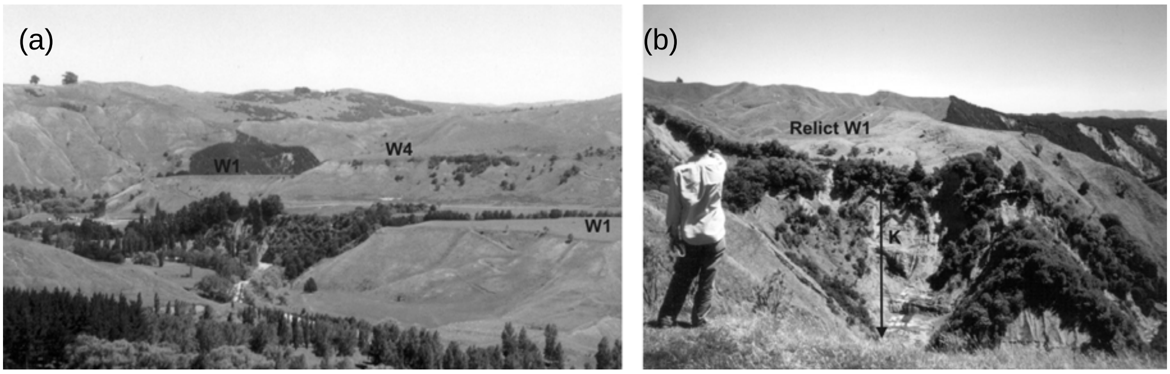

Fig. 2 (a) Fluvial terraces in the Waipaoa SS. The surface age of W1 is c. 18 ka, W4 is approx. 90 or 110 ka. (b) Knickpoint (K) in the upper catchment, separating relict (W1) topography (upstream) from an incised channel (downstream).

In the middle and upper catchment, river behaviour during the post-glacial (<18 ka) period has been dominated by incision. In the headwater reaches, the presence of large steps in the bedrock riverbeds, separating areas of relict topography (i.e., minimal incision below the 18 ka aggradation terrace, W1) from deeply incised (≤120 m) channels (Fig. 2(b)), suggests that knickpoint retreat is an important river incision mechanism (Crosby, 2006; Crosby & Whipple, 2006). Knickpoint retreat has been interpreted as the spike in the rate of post-glacial incision recorded by a series of degradation terraces in the Waihuka tributary (Berryman *et al.*, 2009).

Post-18 ka sediment budgets

In order to assess long-term sedimentary processes, sediment budgets have been compared for different parts of the Waipaoa SS for the period since the end of the Last Glacial Maximum (approx. 18 ka). Onshore, this is marked by the surface of a prominent aggradation terrace, W1 (Fig. 2(a)), which is overlain by the approx. 17.7 cal. Ka Rerewhakaaitu Tephra (Berryman *et al.*, 2000; Eden *et al.*, 2001). Thus, by reconstructing the former extent of the W1 terrace surface in a Geographical Information System (GIS) and then subtracting the modern day channel surface, Marden *et al.* (2008) have calculated the erosion beneath W1 to be 9.5 km^3, with an additional 2.6 km^3 from the adjacent Waimata catchment. Using water well logs, Marden *et al.* (2008) also calculated that 6.6 km^3 of the sediment eroded is currently stored beneath the Poverty Bay Flats flood plain, resulting in only 5.5 km^3 passing to the ocean.

Offshore, a prominent reflector in seismic profiles (also called W1, Fig. 3) is interpreted to be the erosional surface formed at the peak and soon after the Last Glacial Maximum (approx. 18 ka) (Foster & Carter, 1997) for which there is some age control from overlying tephras in drill cores (e.g. Gomez *et al.*, 2004a; Gerber *et al.*, 2009). From the thickness of sediments preserved above the W1 surface, Foster & Carter (1997) estimated a shelf sediment budget of approx. 20 km^3, which was subsequently refined to 15 km^3 in the mid-shelf basins and 3 km^3 in an upper slope basin (Fig. 1(b)) by Orpin *et al.* (2006).

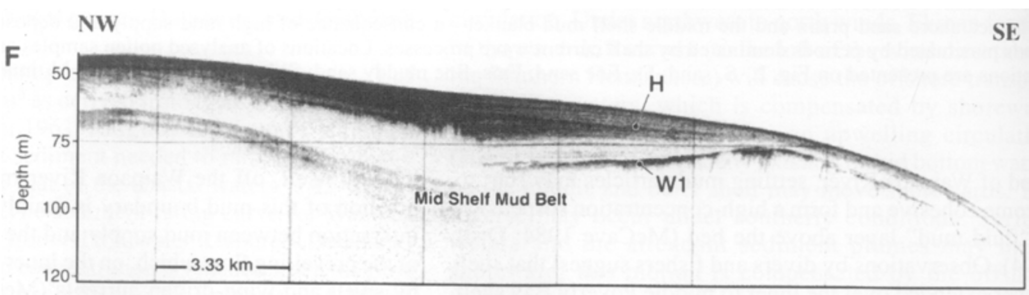

Fig. 3 Seismic profile 3.5 kHz across the Poverty Bay shelf, located in Fig. 1(b). From Foster & Carter (1997).

Contemporary sedimentary processes

Considerable work has been undertaken on contemporary (historical, post AD 1830) hillslope erosion processes and their sediment contribution to the Waipaoa SS, particularly by comparison of aerial photographs, rainfall, and suspended sediment records. Gully erosion (relatively deep and rapidly eroding channels) presently provides the majority (>50%) of the annual sediment load, and mainly occurs during high-frequency, low-magnitude rain events (Hicks *et al.*, 2000, 2004). The largest, amphitheatre-type, gullies such as Tarndale Gully (Fig. 4(a)) are particularly prevalent on the weak, crushed, Cretaceous argillites in the headwaters (DeRose *et al.*, 1998; Marden *et al.*, 2005). In contrast, shallow (typically ≤1 m) landslides, which mainly occur on the soft Tertiary mudstones, contribute 10–20% of the annual sediment load, but are generally triggered during lower-frequency, higher-magnitude storm events (Trustrum *et al.*, 1999; Hicks *et al.*, 2000, 2004; Reid & Page, 2002). For example, during Cyclone Bola in 1988, shallow landslides (Fig. 4(b)) contributed approx. 64% of the sediment load at the river mouth (Page *et al.*, 1999). The remainder of the hillslope erosion processes operating in the Waipaoa SS include earthflows (Zhang *et al.*, 1993), large deep-seated landslides, streambank, sheet and tunnel gully erosion (Page *et al.*, 2000).

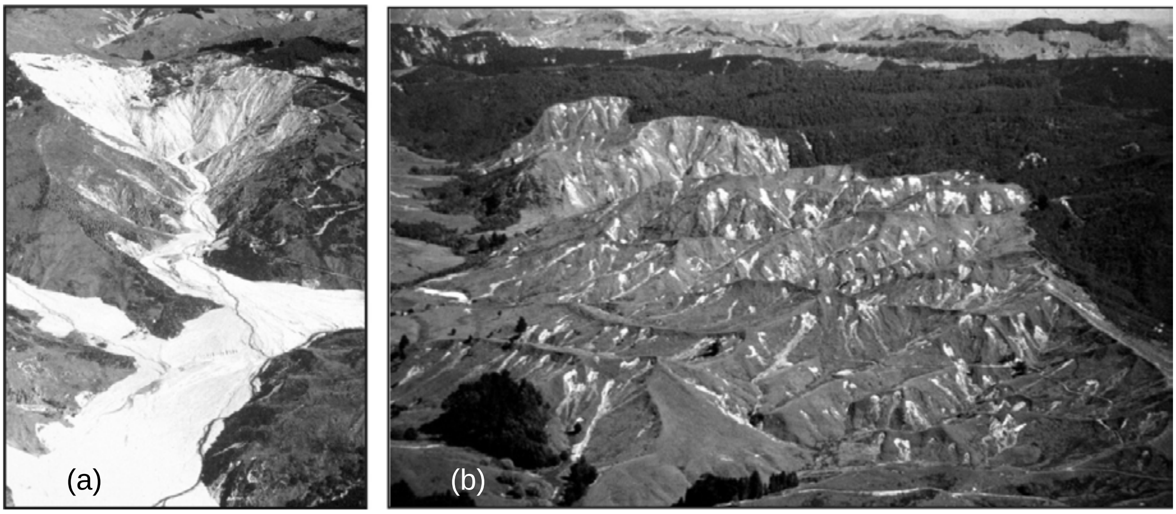

Fig. 4 (a) Tarndale Gully and fan. (b) Shallow landslides formed after Cyclone Bola in 1988. Note the difference between the density on the pasture *vs* exotic forest. Photos taken by N. Trustrum.

In the river channels, Marutani *et al.* (1999) and Kasai *et al.* (2001) showed that sediment generated from the hillslopes during storms is temporarily stored in aggradation terraces in small tributary channels and that sediment delivery ratios (the proportion of sediment eroded from gullies delivered to the mainstem) increase with increasing catchment area for a given gully area and channel slope. Gomez *et al.* (1998, 1999) examined sediment cores from the lower flood plain and showed that the average rate of flood plain accretion is approx. 60 mm/year, but that most occurs episodically during floods at rates of 14–18 mm/h. They also calculated that during 1979–1990 flood plain storage accounted for 5% of the total suspended sediment load and 16% of the suspended sediment load transported during events that exceeded bankfull stage.

Offshore sedimentary processes are currently being investigated. Geophysical and sedimentary evaluation of surficial sediments, together with satellite observations of mud plumes, reveal that the high sediment delivered mainly by the Waipaoa River (15 Mt/year suspended load), is dispersed both along and across the shelf under calm and storm weather regimes (Wood, 2007; Carter *et al.*, 2009). This material, together with sediment introduced from south of the Waipaoa margin, accumulates in two actively subsiding basins on the middle shelf, and a depocentre at the shelf edge (Fig. 1(b)) (Orpin *et al.*, 2006). One of the exciting topics is the delivery of sediment by seabed-hugging, dense sediment plumes or hyperpycnal flows. Hicks *et al.* (2004) proposed that hyperpycnal flows could occur when sediment concentrations in flood discharges exceed approx. 40 000 mg/L, at a return period of approx. 40 years. On the basis of anecdotal evidence, Foster & Carter (1997) suggested that Cyclone Bola (1988) produced a hyperpycnal flow that extended at least onto the middle shelf, and Brackley (2006) used sediment and particulate organic carbon characteristics to identify the Cyclone Bola flood layer and two older layers (1970 and 1941) in cores from the inner and middle shelf.

The response to natural and human impacts (deforestation)

Terrestrial and marine records for the last 2400 years reveal changes in sediment sources at different temporal and spatial scales, in response to natural and anthropogenic forcing. Such events leave textural and geochemical signals that represent the landscape response to vegetation and land-use change, short-term fluctuations in climate, and short-duration, large magnitude storms with a $>10^2$-year recurrence interval, together with other large, infrequent coseismic and volcanic events (Gomez *et al.*, 2007). Of these perturbations, human colonisation had the most profound impact on the depositional record. Like many other sedimentary systems, the Waipaoa SS shows a dramatic response to land-use changes, in particular the deforestation of the hillslopes associated with their conversion to pasture. Deforestation commenced approx. 700 years ago during early Maori settlement (Wilmshurst *et al.*, 1999), but increased dramatically following European settlement in the 1830s (MacKay, 1982) with major clearance in the headwaters occurring in the period 1880–1920 (Henderson & Ongley, 1920; Mackay, 1982).

One of the most dramatic effects of European deforestation was an increase in the number and size of gullies (Allsop, 1973; Marden *et al.*, 2005). Because this increase largely pre-dates aerial photography, the studies of gully erosion have generally focused on the effects of reforestation, particularly in the Mangatu Forest, an exotic *Pinus radiata* forest where planting began in 1960 (DeRose *et al.*, 1998; Gomez *et al.*, 2003; Marden *et al.*, 2005). For example, comparison of sets of aerial photographs dating back to 1939 have shown that the area affected by gully erosion has decreased from 4% in 1939–1960 to 1.5% in 1970–1988, and that sediment production has decreased from 17% to 8% of the Waipaoa River's annual suspended sediment load in the same periods (Marden *et al.*, 2005).

Another dramatic record of the impact of deforestation is the comparison of the density of shallow landslides on pasture *vs* forested terrain following major storms (Hicks, 1991; Marden & Rowan, 1993) (Fig. 3(b)). For example, Marden & Rowan (1993) showed that Cyclone Bola in 1988 resulted in a significant increase in shallow landsliding on all terrain types, but that the increase on pasture (0.383 landslides/ha) or exotic pine forest <6 years old (0.292 landslides/ha) was far greater than on areas of indigenous forest (0.025 landslides/ha) or exotic pine forest >8 years old (0.018 landslides/ha).

Much of the sediment generated as a result of deforestation is still stored in the tributary channels (Kasai *et al.*, 2001; Gomez *et al.*, 2003) (Fig. 3(a)), but there are a number of records that show the impacts have extended throughout the Waipaoa SS. These records include: (i) decreases in bedload size (Gomez *et al.*, 2001), bankfull width, and cross-sectional channel area (Gomez *et al.*, 1998, 2006) in the lower mainstem channel; (ii) increases in the percentage of particulate organic carbon in lower flood plain sediments (Gomez *et al.*, 2004b; Gomez & Trustrum, 2005); (iii) a 25% increase in the volume of material accreted to beaches either side of the river mouth (Smith, 1988); and (iv) changes in sediment properties and increases in sedimentation rate in the flood plain (300%), on the shelf (200–300%), and on the slope (100–200%) (Orpin *et al.*, 2006; Gomez *et al.*, 2007).

IMPLICATIONS FOR SEDIMENTARY SYSTEM BEHAVIOUR

The above findings for the Waipaoa SS have contributed to the following general observations regarding sedimentary system behaviour:

– Climate provides the first-order control on long-term (tens to hundreds of thousands of years) river behaviour, although locally tectonics and sea-level control can dominate.
– Knickpoint retreat is an important mechanism of long-term (tens to hundreds of thousands of years) river incision.
– Sediment delivery through a sedimentary system is modulated by temporary storage in river terraces, flood plains, and sedimentary basins, on time scales of years to tens of thousands of years.
– Sediment delivered as a result of sudden events such as storms, earthquakes, volcanic eruptions, or deforestation can substantially overwhelm annual rates, perturbing a sedimentary system for years to hundreds of years. Deforestation has had the most profound impact on the Waipaoa SS in the Late Holocene.
– Replanting with exotic forest (e.g. *Pinus radiata*) can be as, or even more effective than, reforestation with indigenous forest at slowing sediment delivery.
– Hyperpycnal flows are an important mechanism of delivery of fluvial sediment to the continental shelf and beyond.

Research gaps

A key research gap in Waipaoa SS research is quantification of long-term rates of hillslope erosion, which is attributed to contributing the remainder of the sediment between the post-18 ka sediment budgets calculated for the Waipaoa shelf and slope (18 km^3), and that delivered to the ocean by channel erosion (5.5 km^3) (Marden *et al.*, 2008). As described above, a considerable amount of knowledge has been gained about contemporary hillslope processes, but projecting these back in time is challenging because: (i) of the overwhelming impacts of deforestation, and (ii) by their nature, hillslope erosion removes evidence of prior processes. To some extent these challenges can be overcome by projecting back the magnitude and frequency relationships calculated for contemporary processes under native forest cover, which may be representative of much of the Holocene. But a remaining gap is the contribution from hillslope processes that are either not operating today, or occur at rates too slow to have been sampled during the relatively short written historical period (post-1830). For example, large, deep-seated, bedrock paleo-landslides have been documented in the Waipaoa SS (Pere, 2003) and because of their large volume, could potentially provide a very large contribution to the hillslope erosion sediment budget.

To evaluate the contribution of long-term hillslope processes the amount of sediment being transferred from the hillslopes to the river channels needs to be estimated, as does the timeframes over which that occurs. The delivery of sediment from gully erosion has been quantified, but only limited knowledge has been gained about the delivery from other processes such as shallow and large landsliding. For example, large landslides could provide large volumes of sediment to the river channels and over long timeframes, depending on their rate of movement. Large landslides also have the potential to impact or impede river channels, over potentially long time frames.

Another research gap is the impact of sudden changes or perturbations in some of the drivers of the Waipaoa SS. The impact of events such as volcanic eruptions (Wilmshurst *et al.*, 1999; Gomez *et al.*, 2007; Kettner *et al.*, 2007) and human-induced deforestation (described above) are well documented, but the impacts of rapid climate change and large earthquakes are comparatively less well understood. For the latter, there are several large (M7-8) earthquake sources within and surrounding the Waipaoa SS (Fig. 1(a)), including the subduction interface (Cochran *et al.*, 2006), and historical earthquakes of that size have produced significant landsliding in similar terrain to the north and south (Henderson & Ongley, 1920; Ongley *et al.*, 1937; Hancox *et al.*, 2002).

New research programme

A new research programme led by GNS Science, entitled “Terrestrial Landscape Change: MARGINS Source-to-Sink New Zealand”, will address some of the research gaps in the terrestrial part of the Waipaoa SS and continue to advance understanding through numerical modelling. The 4-year FRST-funded programme has an overall aim to “develop a quantitative understanding of how landscapes respond to ever-changing global environmental drivers and human intervention". The research will be undertaken by a multi-disciplinary team from GNS Science (New Zealand), Landcare Research (New Zealand), NIWA (New Zealand), University of Canterbury (New Zealand), Victoria University of Wellington (New Zealand), Massey University (New Zealand), Indiana State University (USA), and University of Colorado (USA).

The research is divided into three inter-related objectives: (i) Numerical models of landscape functioning in response to environmental change; (ii) Magnitude and frequency of environmental change; (iii) Transfer of sediment from source-to-sink. Objective (i) will be undertaken in conjunction with the "Community Surface Dynamics Modelling System" (http://csdms.colorado.edu/wiki/) and will initially assess and adapt existing hydrological and landscape evolution models. These will include Hydrotrend and CHILD, which have already been applied to aspects of the Waipaoa SS (Crosby *et al.*, 2007; Kettner *et al.*, 2007). Important model adaptations will include integration with tectonic models to include large earthquake events and the hillslope erosion contribution from large landslides. Models developed for the Waipaoa SS will be compared with those for other systems such as the Waitaki SS in the southern South Island.

Numerical models will be constructed and verified by data collected from objectives (ii) and (iii). Objective (ii) will largely involve compilation of existing records of tectonics (large earthquakes), climate, volcanic ash deposition, and sea-level changes in the Waipaoa SS over the last approx. 18 ka. For the tectonics record, paleo-earthquake data are only available for a few faults (Berryman & Marden, unpubl.; Berryman, 1993), so analysis will involve using fault scaling ratios to calculate shaking intensities and recurrence intervals for known active faults and the subduction interface. Likewise for the climate record, only a few Holocene records are available from within the Waipaoa SS (described above), so it is likely these will be supplemented with records from nearby sites such as Kaipo Bog (Newnham & Lowe, 2000), Lake Waikaremoana (Newnham *et al.*, 1998), Lake Tutira (Eden & Page, 1998) and offshore Hawke Bay (Carter *et al.*, 2002, 2008; Carter & Manighetti, 2006). Some of the other records have already been developed, as described above, although the volcanic ash deposition record will need to be expanded across much of the hillslope areas.

Objective (iii) will provide the understanding of how the landscape responds to the environmental changes identified in objective (ii). One major component of this objective will be analysis of large landslides. This will include quantifying distribution, age, and volumes of paleolandslides in the Waipaoa SS, assessing relationships between ground shaking and landslide susceptibility, and detailed analysis of mechanisms, behaviour, and delivery of sediment for selected landslides. Another component is hillslope-channel linkages, particularly the sediment delivery ratios from shallow landslides. This will mainly focus on contemporary shallow landslides, but will develop rates for different land covers as a proxy for rates during different periods of the landscape's history. Research will also continue on post-glacial river channel behaviour.

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