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Last glacial aggradation and postglacial sediment production from the non-glacial Waipaoa and Waimata catchments, Hikurangi Margin, North Island, New Zealand

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Abstract

The sediment flux generated by postglacial channel incision has been calculated for the 2150 km^2, non-glacial, Waipaoa catchment located on the tectonically active Hikurangi Margin, eastern North Island, New Zealand. Sediment production both at a sub-catchment scale and for the Waipaoa catchment as a whole was calculated by first using the tensioned spline method within ARC MAP to create an approximation of the aggradational Waipaoa-1 surface (contemporaneous with the Last Glacial Maximum), and second using grid calculator functions in the GIS to subtract the modern day surface from the Waipaoa-1 surface. The Waipaoa-1 surface was mapped using stereo aerial photography, and global positioning technology fixed the position of individual terrace remnants in the landscape. The recent discovery of Kawakawa Tephra within Waipaoa-1 aggradation gravels in this catchment demonstrates that aggradation was coincidental with or began before the deposition of this 22 600 ^{14}C-year-old tephra and, using the stratigraphic relationship of Rerewhakaaitu Tephra, the end of aggradation is dated at ca 15 000 ^{14}C years (ca 18 000 cal. years BP). The construction of the Waipaoa-1 terrace is considered to be synchronous and broadly correlated with aggradation elsewhere in the North Island and northern South Island, indicating that aggradation ended at the same time over a wide area. Subsequent downcutting, a manifestation of base-level lowering following a switch to postglacial incision at the end of glacial-age aggradation, points to a significant Southern Hemisphere climatic warming occurring soon after ca 15 000 ^{14}C years (ca 18 000 cal. years BP) during the Older Dryas interval. Elevation differences between the Waipaoa-1 (c.15 ka) terrace and the level of maximum channel incision (i.e. before aggradation since the turn of the 20th century) suggest about 50% of the topographic relief within headwater reaches of the Waipaoa catchment has been formed in postglacial times. The postglacial sediment flux generated by channel incision from Waipaoa catchment is of the order of 9.5 km^3, of which ~6.6 km^3 is stored within the confines of the Poverty Bay floodplain. Thus, although the postglacial period represented a time of high terrigenous sediment generation and delivery, only ~30% of the sediment generated by channel incision from Waipaoa catchment probably reached the marine shelf and slope of the Hikurangi Margin during this time. The smaller adjacent Waimata catchment probably contributed an additional 2.6 km^3 to the same depocentre to give a total postglacial sediment contribution to the shelf and beyond of ~5.5 km^3. Sediment generated by postglacial channel incision represents only ~25% of the total sediment yield from this landscape with ~75% of the estimated volume of the postglacial storage offshore probably derived from hillslope erosion processes following base-level fall at times when sediment yield from these catchments exceeded storage.

Keywords: Sediment flux; Postglacial; Fluvial terraces; Tephra; Waipaoa River; Hikurangi Margin

1. Introduction

Estimating the flux and fate of fluvial sediments discharged globally to the ocean from small, steep catchments located on tectonically active margins has proved to be difficult (Milliman &

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Syvitski, 1992; Walling & Fang, 2003). The Waipaoa River ($2150\ km^2$), together with the smaller ($\sim 370\ km^2$) neighbouring Waimata River which also drains into Poverty Bay, are positioned on the tectonically active northern Hikurangi Margin, and are two of several high sediment yield systems that drain the steep and unstable terrain of the Raukumara Ranges on the East Coast, North Island, New Zealand (Fig. 1).

To date, several studies in this catchment have focussed on the effects of post-European deforestation on sediment generation and transport (Gomez et al., 1999; Marutani et al., 1999; Marden et al., 2005) and delivery to the ocean (Hicks et al., 2000); however, little is known about sediment generation and delivery from this catchment during the late Quaternary and Holocene.

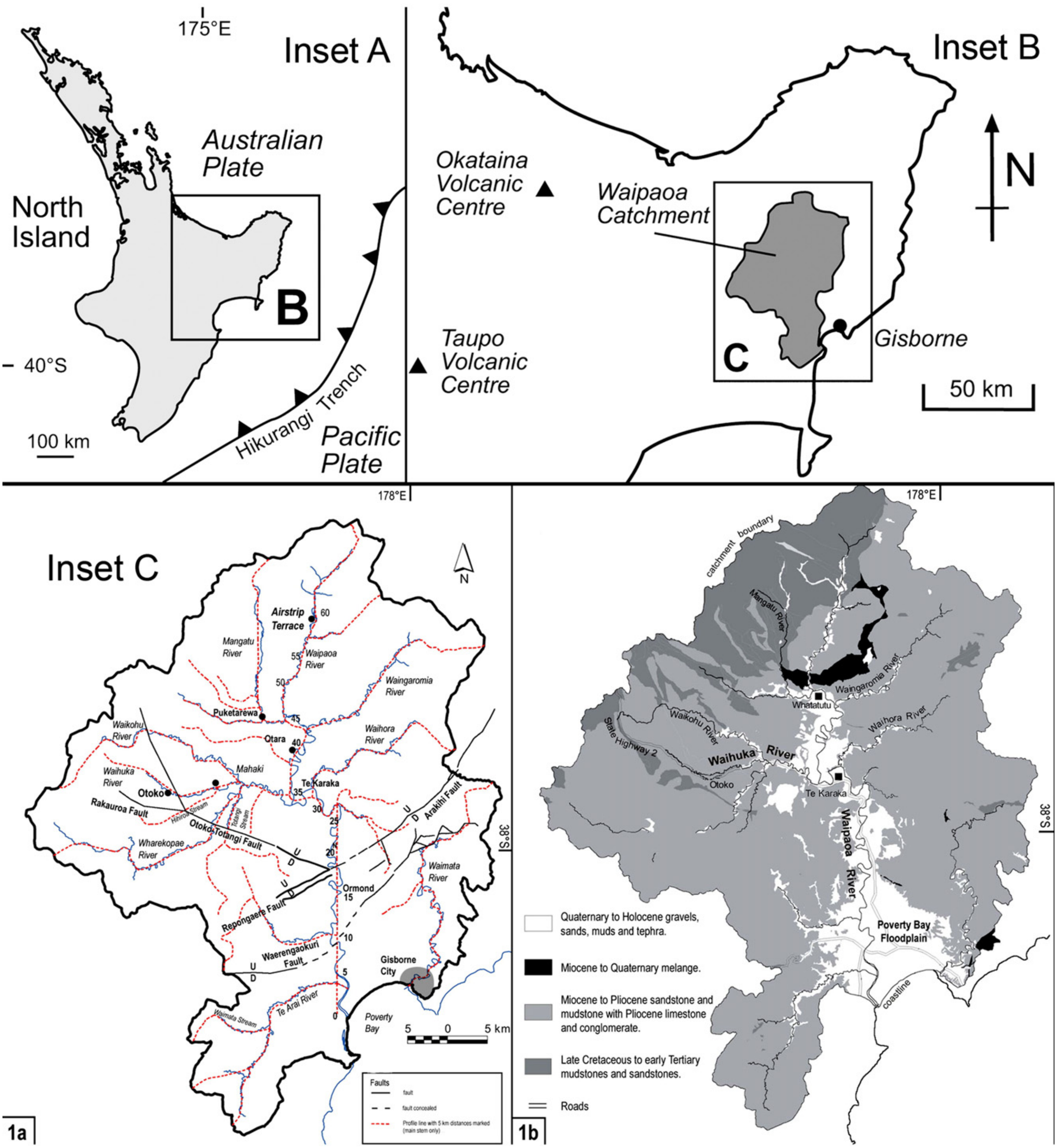

Fig. 1. Inset A: Regional tectonic setting of the eastern North Island, New Zealand (adapted from Lewis and Pettinga, 1993). Inset B: Geographic location of Waipaoa Catchment in relation to Okataina and Taupo Volcanic Centres (adapted from figure supplied by A. Palmer). Inset C: (1a) Details of drainage network, profile lines onto which terrace heights were projected to generate longitudinal river and terrace profiles (see also Fig. 5) and structural elements of Waipaoa and Waimata catchments (adapted from Berryman et al., 2000). (1b) Generalised geology of Waipaoa and Waimata catchments (adapted from Mazengarb and Speden, 2000).

Because of the proximity of the Waipaoa catchment to the central North Island volcanoes (Fig. 1), it has the potential to provide possibly the best chronology for environmental change across the glacial–postglacial transition within the North Island. In recent years, remnants of four Quaternary-aged fluvial terraces have been identified in the middle and upper reaches of the main stem of the Waipaoa River (Berryman et al., 2000). Each represents a former floodplain correlated with cold/cool climate episodes and now isolated or buried as a result of later climatic, tectonic, and erosion processes. The youngest of the aggradation levels, the Waipaoa-1 terrace, is the most extensive and has the ca. 14 700 ^{14}C-year-old (ca. 17 700 cal. years BP) (Froggatt & Lowe, 1990) Rerewhakaaitu Tephra as the oldest part of the coverbed sequence, indicating cessation of aggradation about 15 000 ^{14}C years ago (ca. 18 000 cal. years BP). This provides the best estimate so far for the end of the last glacial aggradation event in North Island, New Zealand (Eden et al., 2001). Following the culmination of glacial-age aggradation there was a switch to postglacial incision, representing a major change in climate, river dynamics, and upper catchment erosion rates. Downcutting produced a sequence of fluvial terraces the chronology of which, in principle, can be correlated regionally (Litchfield & Berryman, 2005; Clement & Fuller, 2007). Notwithstanding, while downcutting in the headwater reach of the Waipaoa River has been ~120 m since 15 000^{14}C years BP (Berryman et al., 2000), it has been shown that downcutting histories vary between tributaries (Berryman et al., 2000; Eden et al., 2001) and depend on the location of their confluence within the greater Waipaoa River catchment, on the average gradient of the tributary, and on the tributary catchment area (Berryman et al., in press). The postglacial period thus represents a time of major sediment flux from the Waipaoa and Waimata Rivers to offshore Poverty Bay and beyond to the Hikurangi Margin (Orpin et al., 2002). With the presence of particularly well-preserved tephras as coverbeds on fluvial terraces and within the resultant sediment currently stored onshore beneath the Poverty Bay Flats and offshore as slope and shelf deposits, the compact Waipaoa River sedimentary system affords a rare opportunity to correlate terrestrial with marine sequences and to balance the sediment budget for a small-scale (<10 000 km^2) (Milliman & Syvitski, 1992) river basin.

Using seismic profiles and cores, offshore postglacial sedimentation was investigated by Foster and Carter (1997). While their study noted the significant capture of Holocene terrigenous sediment on the shelf, Orpin (2004) quantified rates of hemipelagic sedimentation in two mid-slope basins. Thus, while attempts have been made to quantify the offshore storage component of this postglacial flux, the amount generated from the catchment itself and the onshore storage component comprising Poverty Bay Flats, is less well known. Determination of this flux in space and time for the postglacial Waipaoa catchment requires an understanding of the geographic position and elevation of the Waipaoa-1 aggradational terrace (Last Glacial Maximum). To date, this is known only for the main stem of the Waipaoa River (Berryman et al., 2000; Eden et al., 2001) and a 2 km reach of a tributary, the Waihuka River (Berryman et al., in press).

In this paper we present a catchment-wide representation of the Waipaoa-1 aggradation terrace, and based on this we attempt for each major tributary of the Waipaoa catchment and for the Waimata catchment (Fig. 1) a first-order calculation of the postglacial sediment flux generated by channel incision. Although a separate catchment, we include the Waimata catchment because it also flows into Poverty Bay, and at times sediment discharged from it probably contributed to the same postglacial wedge of sediment located on the shelf offshore of Poverty Bay. We briefly discuss uncertainties in attempting to quantify this postglacial sediment flux, assess the importance of Poverty Bay Flats as a sediment sink, and attempt to reconcile differences between estimated volumes of onshore sediment generation and storage versus offshore shelf accumulation.

2. Study area

2.1. Tectonic setting

New Zealand lies across the boundary between the Australian and Pacific crustal plates (Fig. 1, inset A) in a dynamic landscape underscored by tectonic processes and sculptured by the fluctuating climates of the Quaternary (Newnham et al., 1999).

The Waipaoa River, one of the major rivers draining the Raukumara Peninsula, is situated within the active forearc margin of the Hikurangi subduction trench where the occurrence of late Miocene–Recent normal faulting is widespread (Mazengarb et al., 1991).

Late Quaternary vertical movements involving both uplift and subsidence have been described by Ota et al. (1991, 1992) and by Brown (1995). Most of the coastal areas in the Raukumara Peninsula are recognised as undergoing uplift with rates of 2–4 m ka^{-1} occurring in the vicinity of Gisborne City (Ota et al., 1988; Brown, 1995). In contrast, part of the Poverty Bay Flats is an area of net subsidence of ~2 m ka^{-1} adjacent to the Waipaoa River mouth (Brown, 1995). Based on relief and a study of summit accordance, greatest uplift is likely at the crest of the Raukumara Range (Yoshikawa, 1988). However, within a 10 km distance of the Waipaoa catchment divide, where there are uplift and downcutting data, downcutting is about four times faster than tectonic uplift (see Fig. 8B in Berryman et al., 2000). Thus, climate fluctuations are interpreted to be the primary control on the formation of fluvial terrace landscapes in the region (Berryman et al., 2000; Eden et al., 2001). Analysis of river terrace sequences suggest tectonic deformation takes the form of broad regional uplift in the range of 0.5 to 1.1 mm yr^{-1} (Berryman et al., 2000, in press), probably driven by subduction processes in the middle part of the catchment and by a combination of deep-seated subduction processes and local deformation associated with active faults and folds in the lower valley area.

2.2. Catchment geology and landscape morphology

The slope and shelf sediments offshore of the Waipaoa catchment range in age from late Cretaceous to Recent and have been derived from three main lithologic units (Fig. 1b). In the

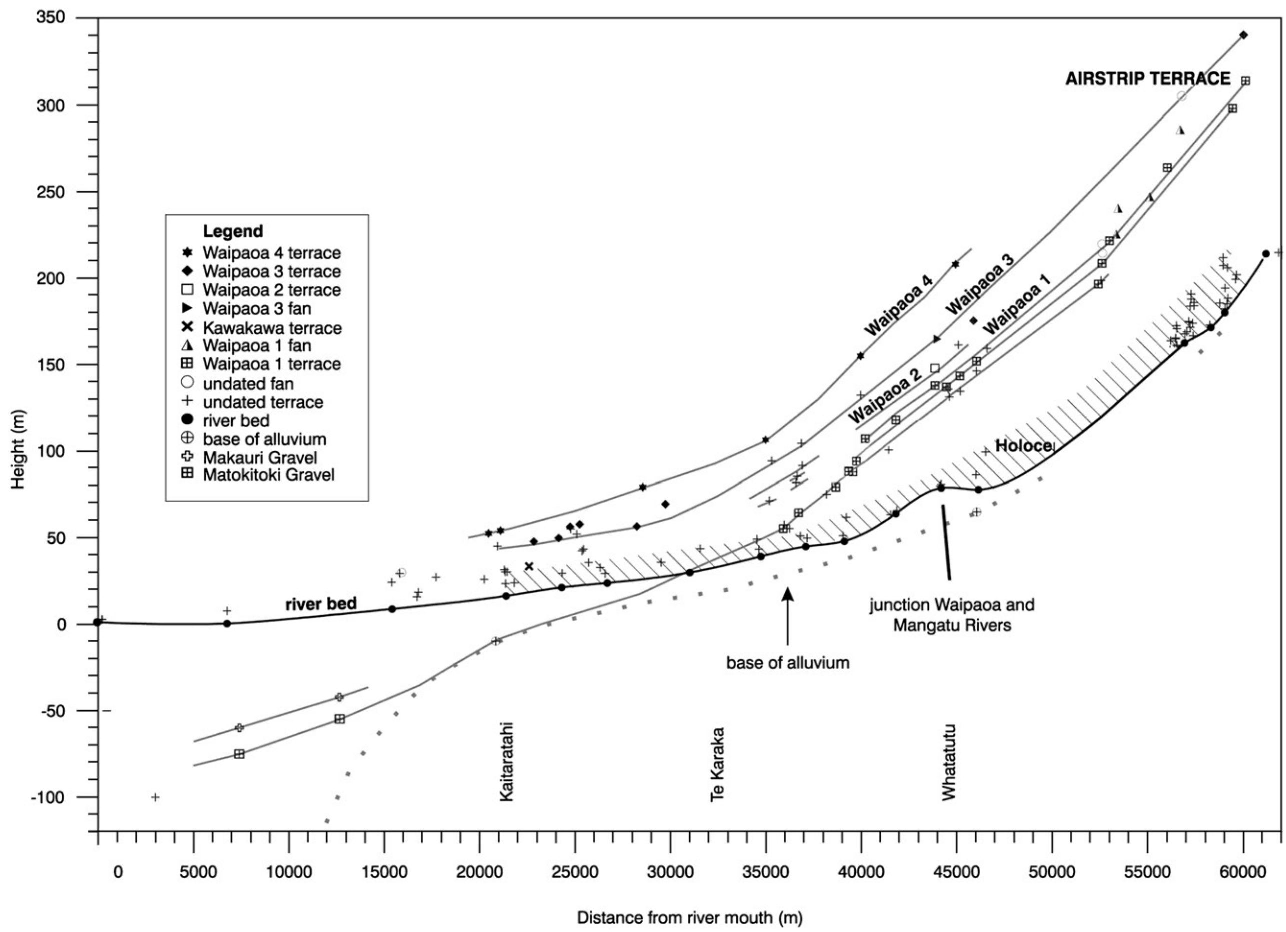

Fig. 2. Profiles of terraces, riverbed and aquifer for the main Waipaoa River from the coast upstream to "Airstrip terrace" (adapted from Berryman et al. (2000) by extending the W-3 terrace upstream to the 60 km mark). Distance from the coast is calculated by projecting the terrace locations onto the generalised profile line shown in Fig. 1. The elevation range of the suite of Holocene terraces is shown by cross-hatching.

headwaters of the Mangatu and Waipaoa Rivers a structurally complex sedimentary suite of Cretaceous and early Tertiary strongly jointed sandstone/argillite, siliceous argillite, smectitic mudstone, marl, and limestone occupies ~8% of the total Waipaoa catchment area. The combination of strong jointing and the presence of smectitic clays result in extensive and highly unstable landforms including earthflows, slumps, and gully erosion that have been a major source of sediment generation throughout the Quaternary (Gage and Black, 1979). The "Airstrip terrace" locality (Fig. 2) is a remnant of the Waipaoa-1 aggradational terrace preserved on this older suite of rocks and located at the upstream extent of the terrace sequence in the main stem of the Waipaoa River.

The second suite, occupying ~92% of Waipaoa and all of Waimata catchment, comprises Miocene to Pliocene interbedded sandstone/mudstone and mudstone with lesser amounts of sandstone and limestone. The rock types in this suite are more competent, support steeper slopes and, unless faulted, are less susceptible to mass movement than the previous suite. Most of the alluvial terraces throughout the wider Waipaoa catchment and within Waimata catchment are developed on this suite of rocks.

The third and spatially least extensive suite is mid-Quaternary sediment, consisting of lacustrine, fluvial, and lagoonal deposits that occur in the middle and lower reaches of the Waipaoa River (largely between Te Karaka and Gisborne City; Fig. 1b).

The Gisborne region lies 100–200 km downwind and to the east of the central North Island volcanoes (Fig. 1, inset B) and has received frequent deposits of airfall tephra throughout the Quaternary (Eden et al., 2001). Volcanism has therefore had a major influence on landscape development, with much of the Waipaoa catchment being mantled with several metres of primary airfall tephra. Tephra layers thus form widespread isochrons and are the key to identifying old and stable landscapes unaffected by postglacial downcutting, dating episodes of landscape instability and elucidating the alluvial terrace history.

The climatic regime varies from years of droughts to wet years that often result from intense cyclonic storms (cf. Eden & Page, 1998), which cause catastrophic erosion and flooding (Page et al., 1994; Trustrum et al., 1999). There are currently very high rates of erosion and sedimentation, and the region's rivers have some of the highest suspended sediment loads in New Zealand (Griffiths, 1982; Gomez et al., 1999). The present day annual average suspended yield to the Pacific Ocean from the Waipaoa catchment is 15×10^6 t and annual bedload yields are ~1% of suspended sediment yields (Hicks et al., 2000). Eastern New Zealand is estimated to account for about 1% of the sediment input into the world's oceans (Carter et al., 1996).

The combination of active tectonics, erodible lithologies and climate regime conditions the dynamics of this catchment.

2.3. Waipaoa-1 aggradation terrace

2.4. Distribution and morphology

The Waipaoa-1 aggradation terrace (Figs. 2, 3 and 4) is the most widespread of the four glacial-aged surfaces identified in the Waipaoa catchment (Fig. 2). In the main stem this terrace becomes emergent above the modern floodplain a few kilometres upstream of Te Karaka and rapidly increases in elevation from the modern floodplain farther upstream, where at the "Airstrip terrace" (Figs. 1 and 2) it is 120 m above the modern river level. The emergent part of the Waipaoa-1 terrace is recognised as aggradational in origin on the basis of its widespread distribution and the thickness of associated material overlying a strath cut into the underlying bedrock. Downstream from Te Karaka, this terrace surface dips beneath the present floodplain where the alluvium has been traced through subsurface borehole and well records (Brown, 1995).

The more expansive remnants of the Waipaoa-1 terrace appear flat but have a gentle down-valley gradient of around 2 to 15 m/km and consist of three treads (Fig. 2) separated vertically by between 2 and 15 m. Typically, the uppermost tread is the repository for Holocene and modern fan deposits. The distal parts of these fans are often truncated, suggesting they were deposited on the surface before the onset of postglacial downcutting, and thus are generally of late glacial to early Holocene age. For extensive parts of the Waipaoa catchment, where the Waipaoa-1 aggradation terrace is intact, valley slopes above the terrace have remained relatively stable for the past 15 000 years, during which rainfall increased and forest cover became established (McGlone et al., 1984). Elsewhere, the absence of the Waipaoa-1 and younger terraces is due to hillslope adjustment processes, including mass movement and gullying, in response to postglacial lowering of stream base-level.

Braided drainage patterns are not seen on these surfaces because they have been masked by the presence of tephra coverbeds. Erosion channels are rare and found only as discontinuous remnants at terrace edges. There are no oxbows present on the Waipaoa-1 terrace and the coverbeds are devoid of dateable organic material.

2.5. Previous investigations of coverbed stratigraphy

Kawakawa Tephra (22 600 ^{14}C years) (Froggatt & Lowe, 1990) is not included in the coverbeds of the Waipaoa-1 terrace, but does occur on older terraces and on hillslopes with greater elevation than the Waipaoa-1 terrace. The recent discovery of Kawakawa tephra within Waipaoa-1 aggradation gravel (Berryman et al., in press) and at Mahaki (this paper) (Fig. 1a) provides the best evidence to date that this period of aggradation within Waipaoa catchment occurred before, during and after the deposition of the Kawakawa Tephra. Its purity and texture suggest it is primary airfall, while its location within this sequence, a metre above the bedrock strath, indicates aggradation started at least 22 600 ^{14}C years ago and ceased before 15 ka in the construction of the Waipaoa-1 terrace. Kawakawa Tephra has previously been found within aggradation gravels at 13 other localities in predominantly eastern North Island catchments (Litchfield, 2003; Litchfield & Berryman, 2005).

The coverbed stratigraphy (finer sediments resting on the gravel surface or tread) and tephra identification of the Waipaoa-1 terrace have previously been investigated at four geographic locations in the main stem of Waipaoa River (Eden et al. 2001) and within a 2.2 km section of the Waihuka tributary, near Otoko (Fig. 1a) (Berryman et al., in press).

3. Methods

3.1. Terrace mapping and dating

Waipaoa-1 terraces were identified stereoscopically from 1:25 000 scale, non-orthorectified, aerial photography, mapped as closed polygons, then transferred onto topographic transparencies from which they were subsequently digitised in ARC INFO (Fig. 3). For age control, samples of tephra were collected from augered and cored sites and from natural river and road embankments for identification. Tephra identification was by a combination of ferromagnesian mineralogy and electron microprobe analysis of glass shards. Samples were analysed by the JEOL 733 Electron Microprobe. A 10 μm beam diameter and 8.5 nA beam current were used for all analyses.

Tephra provided the primary means of establishing the timing of the Waipaoa-1 aggradation phase and to the cessation of the Waipaoa-1 aggradational terrace. Key tephra sample sites are shown in Fig. 3. Tephra critical to the timing of the cessation of the Waipaoa-1 aggradation are listed in Table 1.

Where age control of terraces remains limited (i.e. in most tributary streams), we use terrace heights obtained by GPS (Global Positioning System) technology to extrapolate between terrace remnants. The architecture of the GPS system was a base station located at Te Karaka (Fig. 1a), within 40 km of the periphery of all parts of the catchment. We are confident that all GPS-derived positions and heights have an uncertainty of no greater than ±0.3 m and report all elevations to the nearest metre, but expect that the data are better than this.

Using GPS and nickpoint heights we have attempted to extrapolate and interpolate from dated terrace remnants to other surfaces of uncertain age but similar position in the landscape, to create a long-section profile of the Waipaoa-1 terrace for each tributary (Fig. 5). Terrace and river longitudinal profiles were compiled by projecting GPS locations and elevations to a single, middle of the valley profile line as shown for the main stem of the Waipaoa River (Fig. 1a).

Nickpoints at or near the Waipaoa-1 aggradational level were mapped from aerial photography and used as a surrogate where remnants of the Waipaoa-1 terrace were absent or far apart. Elevations were measured at the base and top of nickpoints using GPS. The position of the nickpoint in the main stem of each of the major tributary streams is shown in Figs. 3 and 5.

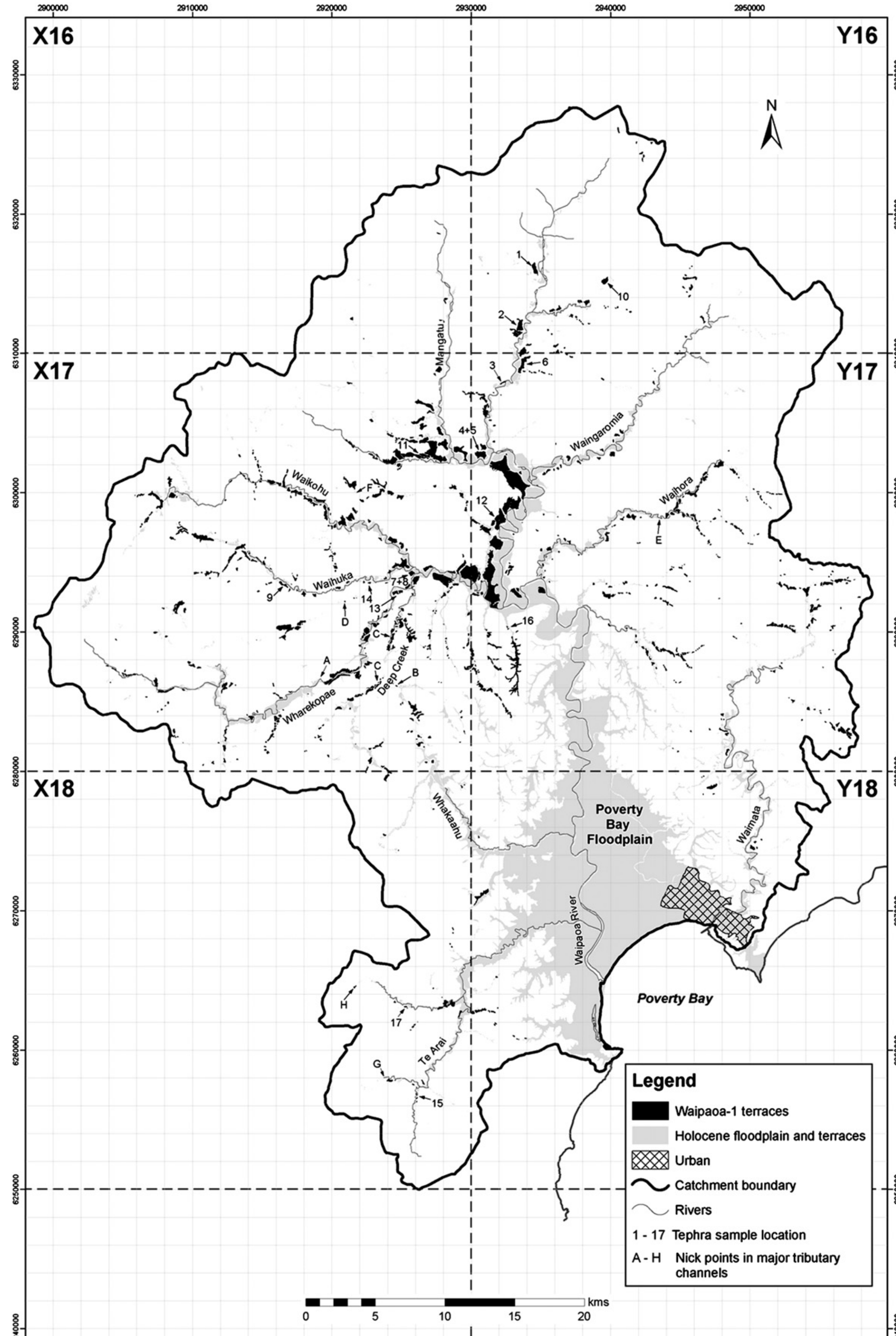

Fig. 3. Catchment-wide distribution of the Waipaoa-1 (Last Glacial Maximum) aggradation terrace within the Waipaoa and Waimata catchments. Key tephra sample locations are numbered 1 to 17. Tephra identifications are presented in Table 1. Locations of nickpoints for major tributaries are numbered A to H. Dashed lines represent NZMS 260 map sheet boundaries.

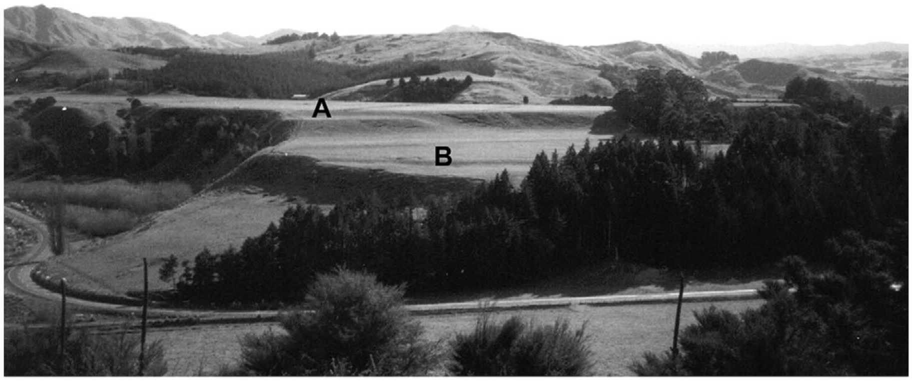

Fig. 4. View of the Waipaoa-1 terrace at Puketarewa (location shown on Fig. 1a), facing northwest. Puketarewa (A) sample site is on the highest terrace and sample site (B) is on the lower terrace 15 m below. The Rerewhakaaitu Tephra (14 700 ^{14}C years BP) (Lowe et al., 1999) overlies alluvial gravel on both surfaces, indicating that 15 m of downcutting occurred, probably within decades, of the cessation of the Waipaoa-1 aggradational phase ~15 000 ^{14}C years BP. (Photo: Mike Marden).

3.2. Calculation of postglacial sediment flux

Based on these terrace and nickpoint heights we used a surface modelling routine, the tensioned spline method within ARC MAP, to create an approximation of the Waipaoa-1 surface for each sub-catchment (Fig. 6).

The spline method was chosen because it honours all data points and extrapolates beyond known data points using the gradient at the point of extrapolation. By using grid calculator functions in the GIS, the modern day surface is subtracted from the Waipaoa-1 surface (where the latter is higher than the former) to derive the amount of erosion at each cell (vertical component) and generate a first-order approximation of the total volume of postglacial sediment generated at a sub-catchment scale and for the Waipaoa catchment as a whole (Fig. 7). Based on the relative elevations of the four (Waipaoa-1 to 4) Late Quaternary alluvial terraces (see also Fig. 2), Fig. 8 is a schematic representation of landscape evolution in the Waipaoa catchment showing the cross-sectional area excavated by channel incision since the Last Glacial Maximum and from which postglacial sediment volumes were calculated.

An estimate of the volume of postglacial material stored in the Poverty Bay floodplain is based on the thickness of deposits overlying the Matokitoki gravel aquifer (Fig. 2) as determined from water well data (Brown, 1995). Unfortunately, these wells are not evenly distributed across the floodplain and many were too shallow to intersect this gravel, thus its subsurface configuration, particularly in the subsiding southeastern part of the Poverty Bay Flats, is not well constrained. The mass of eroded material was computed using a dry bulk density of 1900 kg m^{-3}. This is based on a dry bulk density determination of 2000 kg m^{-3} for debris flow material (Phillips, 1988) and 1840 kg m^{-3} for fan material (DeRose et al., 1998), both originating from Tarndale Gully in the headwater reach of the Waipaoa catchment. The volume estimate for unconsolidated sediments stored on the Poverty Bay Flats was calculated using an average dry bulk density of 1400 kg m^{-3} based on determinations for overbank silts of 1300 kg m^{-3} (Gomez et al., 1999) and 1500 kg m^{-3} for stony alluvial soils (C-horizon) (Wilde & Ross, 1996).

4. Results and discussion

4.1. Distribution and age of the Waipaoa-1 terrace

The analysis of coverbed tephra confirms the presence of remnants of the Waipaoa-1 aggradational terrace in all the major tributary catchments of the Waipaoa catchment (Table 1) and also in the Waimata catchment. Within the Waipaoa catchment, 1200 remnants of this terrace totalling ~3000 ha (<2% of catchment area) have been identified, and in Waimata catchment there are 128 remnants of this aggradation terrace totalling 180 ha (<1% of catchment area).

The age of the Waipaoa-1 terrace is critical to elucidate rates of downcutting, tectonic uplift and to determine rates of erosional output from the valley since the last glaciation. The switch from aggradation, which formed the highest Waipaoa-1 terrace, to downcutting represents a major change in river dynamics and the dating of this would better link this response to environmental change in this region. Previous studies of the extensive last glacial aggradation terrace (Ohakea-1 terrace) in the North Island (e.g., Milne, 1973; Marden & Neall, 1990) have provided estimates for its age, and hence for the completion of river aggradation, but none of the terraces studied had sufficient tephra cover to provide reliable dating and other dateable materials are rare. To provide a minimum age for the cessation of aggradation of the Waipaoa-1 terrace, the identity of the basal tephra in the terrace tephra cover beds needs to be known. Two Okataina-sourced tephra; the ca. 21 000 cal. years BP Okareka (Sandiford et al., 2002) and the ca. 17 000 cal. years BP Rerewhakaaitu (Froggatt & Lowe, 1990) tephras are possible candidates and both are found in the Gisborne landscape (Vucetich & Pullar, 1969; Darragh et al., 2006). Eden et al. (2001) applied discriminant function analysis (DFA) to conclude that the basal tephra was the Rerewhakaaitu. At the time DFA was considered powerful enough to discriminate between tephras erupted from Okataina Volcanic Centre over the last 30 000 years. Recent geochemical and mineralogical work (Newnham et al., 2003; Smith et al., 2005; Dr Phil Shane,

Table 1
Waipaoa-1 terrace locations where Rerewhakaaitu (ca. 14 700 ^{14}C years BP) (Froggatt & Lowe, 1990) and/or Okareka (ca. 18 000 cal. years BP) (Sandiford et al., 2002) tephra are possible candidates for basal airfall on the Waipaoa-1 aggradation surface, Waipaoa catchment[a]

Site no.	Site name[b]	NZMS grid reference[c]	Catchment	Tephra name	Method of identification	Reference
1	Airstrip Terrace	Y16 344160	Main stem Waipaoa	Rerewhakaaitu	Mineralogy, Glass chemistry	Eden et al. 2001
2	Wheterau Stud	Y16 337117	Main stem Waipaoa	Rerewhakaaitu/ Okareka?	Mineralogy	This paper
3	Waikakariki	Y16 313064	Main stem Waipaoa	Rerewhakaaitu	Mineralogy, Glass chemistry	Eden et al. 2001
4	Puketarewa main	Y17 306029	Main stem Waipaoa	Rerewhakaaitu	Mineralogy, Glass chemistry	Eden et al. 2001
5	Puketarewa– 15 m degradational level	Y17 312026	Main stem Waipaoa	Rerewhakaaitu	Mineralogy, Glass chemistry	Eden et al. 2001
6	Makahakaha main	Y17 335089	Main stem Waipaoa	Rerewhakaaitu/ Okareka?	Mineralogy	This paper
7	Quilters	X17 255934	Wharekopae	Rerewhakaaitu/ Okareka?	Mineralogy	This paper
8	Quilters Silage	X17 258941	Waihuka	Rerewhakaaitu/ Okareka?	Mineralogy	This paper
9	Otoko 2	X17 173934	Waihuka	Rerewhakaaitu	Mineralogy, Glass chemistry	Berryman et al. (in press)
10	Claridge Road	Y16 396150	Mangaorongo	Rerewhakaaitu/ Okareka?	Mineralogy	This paper
11	Omapere main	X17 266038	Mangatu	Rerewhakaaitu/ Okareka?	Mineralogy	This paper
12	Otara Quarry	Y17 319974	Main stem Waipaoa	Rerewhakaaitu/ Okareka?	Mineralogy, Glass chemistry	Eden et al. 2001
	Waikohu Station	X17245928	Wharekopae	Rerewhakaaitu	Glass chemistry	This paper
14	Otoko walkway	X17225936	Waihuka	Rerewhakaaitu	Glass chemistry	This paper
15	Gisborne Waterworks	X18262565	Te Arai	Rerewhakaaitu	Glass chemistry	This paper
16	Dymock Road	Y17329896	Maungatarehu	Rerewhakaaitu	Glass chemistry	This paper
17	Waimata Stream	X18288633	Te Arai	Rerewhakaaitu	Glass chemistry	This paper

[a] The Rerewhakaaitu and Okareka tephras have very similar glass chemistry and mineralogy (Smith et al., 2005). In every case the Rerewhakaaitu is the most likely tephra since two separate tephras with similar chemistry do not occur together at any one site.
[b] Site locations shown on Fig. 3.
[c] The map references are for the NZMS 260 1:50 000 New Zealand metric map series.

University of Auckland, pers. comm., 2006) shows that the Rerewhakaaitu and Okareka tephras are compositionally heterogeneous because the eruptive episodes involved multiple magmas. Their major element glass chemistry and mineralogy completely overlap so that it is now difficult to be confident which one is the basal tephra on the Waipaoa-1 terrace. Since only one of these tephra is present on the Waipaoa-1 terrace and given the good preservation potential for tephra on river terraces similarly positioned in the landscape (accurately established using GPS), together with the large number of sites examined, it is logical to conclude that the basal tephra is the younger Rerewhakaaitu Tephra, rather than the older Okareka Tephra.

The presence of the ca. 14 700 ^{14}C-year-old (ca 17 700 cal. years BP; Lowe et al., 1999) Rerewhakaaitu Tephra in the lower part of cover beds on Waipaoa-1 terrace indicates the aggradation that formed this terrace ceased some time before 14 700 ^{14}C years ago. There was clearly an undefined period of time when the river remained close to the terrace since there are often 2 m or more of overbank silts and stream alluvium underlying this tephra. Furthermore, the presence of a paleosol underlying the Rerewhakaaitu Tephra and evidence for an increase in weathering, through the presence of more clay, in the top 0.1 m of the aggradation gravel, suggest the age of the Waipaoa-1 terrace is probably within the range of 15 000–15 500 ^{14}C years BP (18 000–18 500 cal. years BP) (Eden et al., 2001).

These stratigraphic and age relationships provide a confident basis for correlating the Waipaoa-1 terraces with similarly aged surfaces in southern North Island (Palmer, 1982; Marden & Neall, 1990; Pillans et al., 1993). It would appear therefore that the cessation of the last glacial aggradation at around 15 000 ^{14}C years BP was a regional event throughout eastern and southern North Island (Litchfield, 2003) and we conclude that the formation of the most extensive of the Waipaoa-1 terrace treads, within the Waipaoa catchment, was a synchronous event. We illustrate this period of aggradation in relation to the isotopic record of Shackleton (1987) in Fig. 8.

4.2. Mechanism for downcutting

Berryman et al. (2000) calculated that only about one quarter of the downcutting could have been accomplished as a result of tectonic uplift. The cessation of aggradation that formed the highest Waipaoa-1 tread, followed by downcutting, reflects a major change in river dynamics within the Waipaoa catchment around 15 000 ^{14}C years ago (ca. 18 000 cal. years BP). Geomorphic evidence indicating an absence of extensive terraces below the Waipaoa-1 set in the main stem (Berryman

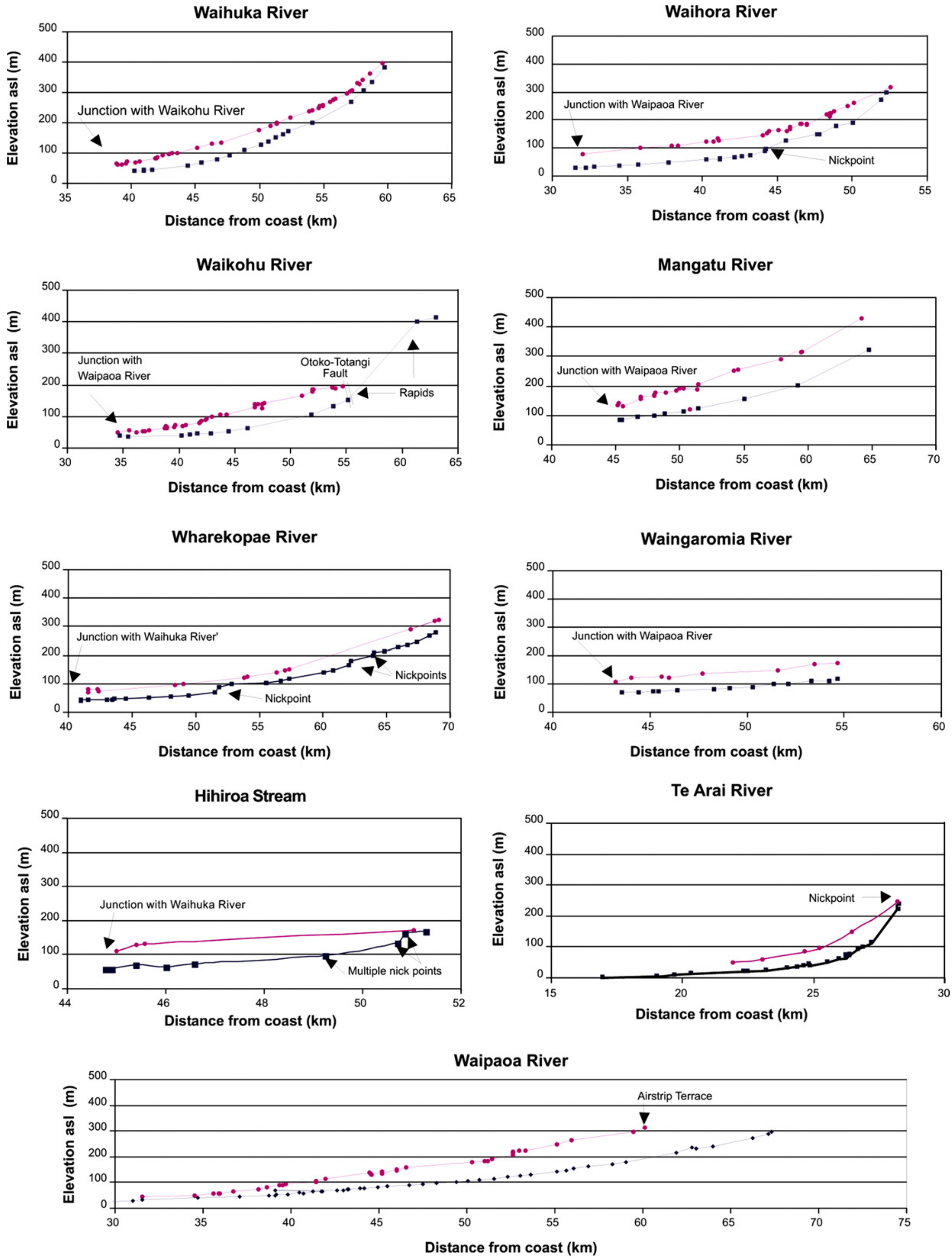

Fig. 5. River and Waipaoa-1 terrace profiles for the main stem and selected tributaries in Waipaoa catchment. Profiles for upper parts of Mangatu, Waipaoa, and Waingaromia rivers are incomplete owing in part to inaccessibility and to the poor preservation of terraces as a result of mass wasting.

et al., 2000) suggests that once degradation had started it was sustained until historic times when anthropogenic aggradation occurred. Therefore, the many metres of downcutting was more likely driven by a combination of (i) stabilisation of the upper catchment landscape by a reduction in the severity of physical weathering and an increase in vegetation cover, and (ii) an increase in discharge that increased the capacity of the river to incise (Bull, 1988; Berryman et al., 2000). A similar

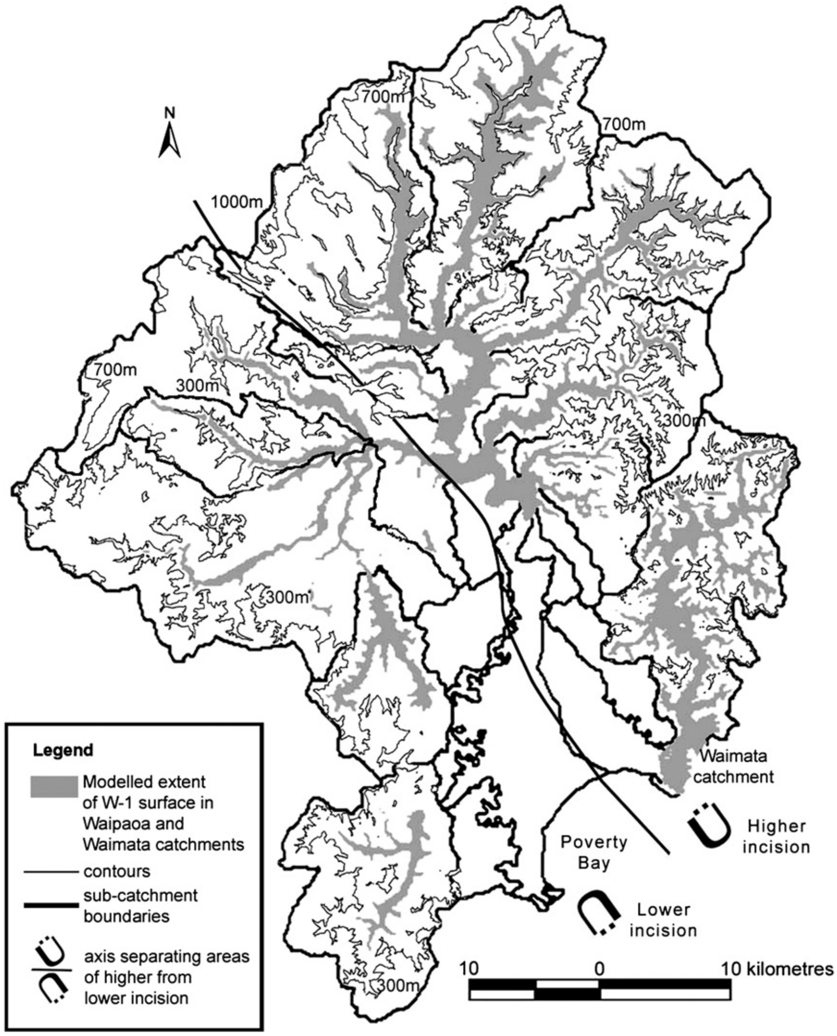

Fig. 6. The modelled Waipaoa-1 terrace surface within Waipaoa and Waimata catchments. The axis of separation between sub-catchments of greater incision (in the north and east) from those of lesser incision (to the south and west) is shown. Waipaoa catchment, in the north and west, reaches an elevation at the divide of ~1000 m a.s.l.

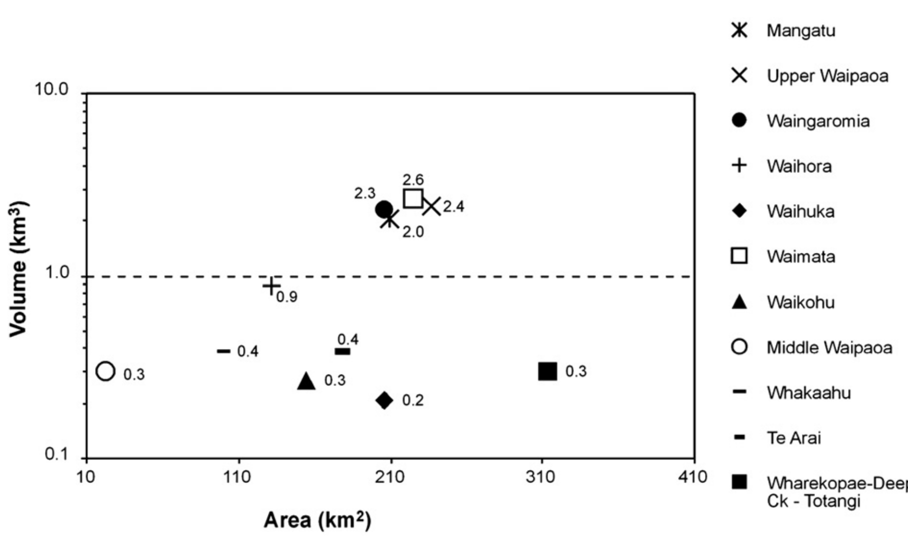

Fig. 7. Volume of sediment excavated from sub-catchments of the Waipaoa and Waimata Rivers since the culmination of aggradation to form the Waipaoa-1 (Last Glacial Maximum) terrace.

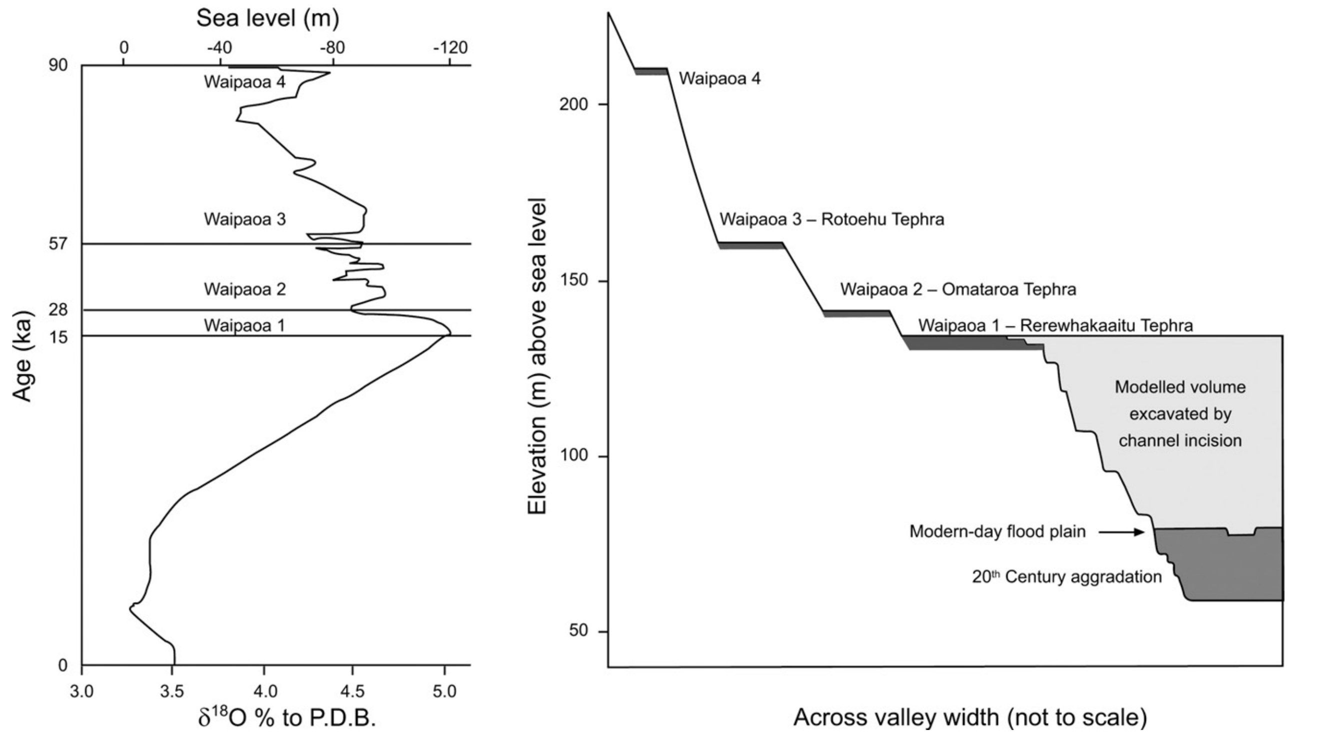

Fig. 8. Schematic representation of landscape evolution in the Waipaoa Catchment showing the age of major aggradation terraces in relation to the oxygen isotope curve (adapted from Shackleton, 1987) and tephra ages (adapted from Berryman et al., 2000). This information brackets the position of inferred aggradation episodes corresponding to Waipaoa 1–4 terraces. Also shown is the cross-sectional channel area excavated since the Last Glacial Maximum and from which sediment volumes generated by downcutting were calculated. Terrace and river heights are based on GPS readings near Whatatutu (Fig. 1b). No horizontal scale intended.

stabilisation of an alpine landscape during warmer climatic periods was described from the central North Island (Vella, 1963; Milne, 1973; Pillans et al., 1993; Newnham et al., 1999).

The similar ages for the uppermost and lowermost Waipaoa-1 terraces (15 m apart vertically) suggest the early part of the downcutting cycle was rapid and may have been in response to an abrupt climate shift rather than to incremental change. Sudden climate transitions that took place over decades rather than centuries or millennia have been recognised increasingly in ice cores (e.g., Adams et al., 1999; Severinghaus & Brook, 1999; Dansgaard et al., 1989). Furthermore, pollen evidence from the Chilean Lake District (Moreno et al., 1999) indicates abrupt withdrawal of ice at around 14 600 ^{14}C years BP (ca. 17 600 cal. Years BP). This is very similar to our evidence for the nature and timing of climate change at the end of the last glaciation in North Island, New Zealand. These evidences (see also Denton et al., 1999) point to significant Southern Hemisphere climatic warming occurring soon after ca. 15 000 ^{14}C years BP (ca. 18 000 cal. years BP) during the Older Dryas interval.

4.3. Hillslope adjustment in response to postglacial downcutting

In places where the Waipaoa-1 aggradation terrace has been preserved, postglacial hillslope adjustments have largely been confined to slopes below the level of this terrace. Mass wasting, in the form of earth flows, rotational slumping and gullies predominates. In contrast, valley slopes above this terrace have remained relatively stable for the past 15 000 years, during which rainfall increased and forest cover became established (McGlone et al., 1984). On these latter slopes, the presence of coverbed materials that include the Kawakawa Tephra (Taupo Volcanic Centre) and/or the older Omataroa (~28 ka years BP) (Jurado-Chichay & Walker, 2000) and Rotoehu (~55–57 ka years BP) (Berryman, 1992) Tephras (Okataina Volcanic Centre) suggests the postglacial incision process has not influenced parts of this catchment's landscape. These same slopes do, however, show evidence of slope adjustment that pre-dates the postglacial incision period and, probably formed in response to earlier periods of river incision, climate change or earthquake triggering.

Our findings suggest postglacial hillslope adjustment is more strongly correlated with the depth of river incision than with lithology. Catchments within which postglacial slope adjustment has been minimal include those that drain Tertiary lithologies where postglacial river incision is typically of the order of 25–50 m below the Waipaoa-1 terrace (e.g., Wharekopae, Waihuka, Waikohu Rivers) (Fig. 5). These valleys are typically narrow and steep-sided — a reflection of the inherent strength of the decimetre-bedded lithologies — and here the preservation of remnants of the Waipaoa-1 terrace decouples slopes from the channel for much of the river's length. As a consequence, and since postglacial incision began, these channels have become progressively narrower. Importantly, the contribution of sediment derived from slope adjustment in response to postglacial base-level fall in these tributary catchments is low. This is because a significant proportion of these catchments lie upstream of a major nickpoint where slope adjustment has yet to occur. In contrast, hillslope adjustment is widespread in deeply incised catchments, particularly those that drain older and tectonically more disrupted lithologies of late Cretaceous–early Tertiary age (e.g., Mangatu River and upper reaches of the Waipaoa River), and in catchments within areas of Tertiary lithologies dominated by mudstone with its greater propensity for mass wasting (e.g., Waingaromia River). In these catchments the net postglacial incision is more typically 80–100 m, nickpoints have retreated to the catchment divide, and hillslope adjustment is widespread. In addition, hillslopes are more often coupled with channels and postglacial adjustment is by earthflow, slump and gully processes that often extend from valley floor to the watershed divide. The result is poor terrace preservation and wider valleys with gentle 15–35° side slopes. Notwithstanding, within the Waipaoa catchment the highest volumes of sediment released during the postglacial period were from these latter tributaries valleys (Fig. 7). On average, the thickness of aggradational terrace deposits upon the Waipaoa-1 surface is ~20% of the total depth of postglacial incision, with ~80% of incision being within bedrock. Areally, Cretaceous lithologies occupy only ~8% of the total Waipaoa catchment area. The volume and composition of sediment eroded during the postglacial period is therefore dominated by material derived from the remaining ~92% of this catchment where Tertiary mudstone and sandstone are the dominant lithologies. Here, and over the longer term, slope-derived sediment inputs would be diluted and masked by bedrock-derived sediment. In the shorter term, however, evidence for the episodic stripping of surficial slope materials (colluvium and tephric beds) and/or increased sediment input as a consequence of mass slope failure (e.g., rotational slumping), in response to climatic and tectonic perturbations, is often preserved as valley fill at downstream sites.

Berryman et al. (in press) estimated that at Otoko in the Waihuka River (Fig. 1a), 17 km upstream from the confluence with the Waipaoa River and 50 km from the coast, rapid incision did not occur until ~8000 ^{14}C years ago. They suggest that for the reach upstream of the Waihuka/Waipaoa junction (Fig. 1) the average nickpoint retreat rate was ~2 km ka^{-1}. The main stems of the Waipaoa River and the Waihuka River are both incised into the same lithological units. We therefore contend that nickpoint retreat occurred in both rivers at a similar rate to reach Puketarewa (Fig. 1a) (in the main stem of the Waipaoa River) and some unknown point immediately downstream of Otoko (in the Waihuka), a similar distance upstream from the coast, at about the same time. Also, while nickpoint retreat in the main stem was unimpeded and continued upstream of Puketarewa, at Otoko it stalled for ~8000 ^{14}C years BP. The cause of this delay is unknown. The most likely explanation is that the rate of nickpoint retreat in the Waihuka slowed in response to a loss in stream power when the nickpoint passed upstream of the Wharekopae and Waikohu River junctions, respectively. Other possible explanations include (i) the presence of a localised and more resistant lithology in the gorge-like reach downstream of Otoko, and (ii) a barrier caused by bedrock displacement on the Otoko/Totangi fault where it traverses Waihuka River, downstream of the Otoko study site (Fig. 1a), although no surface displacement has been observed at this locality. In addition, we find that postglacial river incision and nickpoint retreat also stalled in each of the Wharekopae, Totangi, Taumatapoupou, Hihiroa, Waihora, and Te Arai Rivers and in the Waimata Stream (a tributary of Te Arai River). In these rivers the nickpoint is a near-vertical waterfall. In Table 2 we present minimum rates of nickpoint retreat, since the culmination of maximum aggradation at ca. 15 000 ^{14}C years BP, based on the river distance from the current coastline to the first nickpoint encountered.

We found that nickpoint retreat in tributaries nearer the coast (e.g., Te Arai River) occurred at about half the rate (~1.2–1.4 km ka^{-1}) of that in tributaries draining the mid-reaches of the Waipaoa catchment (~2.5–2.9 km ka^{-1}). The rate of nickpoint retreat for the main stem of the Waipaoa River is considered a minimum rate because there is no nickpoint present in the main channel and the assumption is that it has

Table 2
Minimum rates of nickpoint retreat since the culmination of Waipaoa-1 aggradation (ca. 18 000 cal. years BP) (Berryman et al., 2000) for the reach downstream of each nickpoint

Site no.	Site name [a]	Nickpoint NZMS grid reference [b]	Feature	Height of nickpoint (m)	Distance from the coast (km)	Min rate of nickpoint retreat since the culmination of maximum aggradation (ca 18 ka cal. yrs BP) [c]
A	Wharekopae	X17201866	Waterfall	15	51.5	2.86 km ka^{-1}
B	Totangi	X17247862	Waterfall	2	50.5	2.80 km ka^{-1}
C	Taumatapoupou	X17229860	Waterfall	3	50.2	2.78 km ka^{-1}
D	Hihiroa	X17177904	Rapids and waterfall	21	51	2.83 km ka^{-1}
E	Waihora	Y17446986	Waterfall	12	45.2	2.51 km ka^{-1}
F	Wheo	X17211007	Waterfall	6	52.8	2.93 km ka^{-1}
G	Te Arai	X18288577	Waterfall	15	26	1.44 km ka^{-1}
H	Waimata Stream (a tributary of the Te Arai River)	X18215646	Waterfall	18	22	1.22 km ka^{-1}

[a] Site locations shown on Fig. 3.
[b] The map references are for the NZMS 260 1:50 000 New Zealand metric map series.
[c] Minimum rate of nickpoint retreat is based on river distance from the current coastline divided by the time (years) since the culmination of aggradation ~15 000 ^{14}C years ago (18 000 cal. years BP). These are minimum rates because at times of lower sea level the coastline would have been an unknown distance seaward of its current position.

retreated the full length of this river system. Differences in catchment area and a reduction in stream power as nickpoints retreated upstream of tributary confluences would account for some of the inter-tributary variability in these rates. In rivers where a nickpoint is present, the reach upstream is considerably less well-incised than the downstream reach, and hillslope adjustment often has yet to occur.

4.4. Postglacial sediment flux

Comparisons of longitudinal stream and terrace profiles (Fig. 5) show stream incision and the consequent production of sediment to have been greatest in tributary catchments in the north and east of the Waipaoa catchment (Mangatu River, upper reaches of main stem of the Waipaoa River, Waingaromia River, and Waihora River), and in the Waimata catchment, and least in those tributary catchments in the southwest (Waihuka River, Waikohu River, Wharekopae River, and Te Arai River). In terms of identifying likely source areas and the timing of sediment flux to the Poverty Bay shelf, sub-catchments in the area of greatest tectonic uplift would be expected to display more rapid responses and to generate higher sediment volumes in response to base-level fall. Our model confirms this to be the case with differences in sediment production likely to be due to uplift occurring in the north and east and subsidence in the south and west (Fig. 6). The positioning of the NW–SE-trending axis, separating areas of uplift from subsidence, corresponds closely with rates determined from drillhole data on the Poverty Bay floodplain (see Fig. 2 in Berryman et al., 2000) and is consistent with known rates of uplift and downcutting derived from terrace profiles (Berryman et al., 2000, in press). From our terrace and river profiles (Fig. 5), elevation differences between the Waipaoa-4 terrace (90–110 ka), the Waipaoa-1 terrace (c.15 ka) and the level of maximum incision in modern times (i.e. before aggradation since the turn of the 20th century) suggest up to 50% of the topographic relief within headwater reaches of the Waipaoa River has formed since the Last Glacial Maximum, that is in 15% of the time since the earliest aggradation episode (Waipaoa-4) recorded in this catchment.

For the configuration of sub-catchments presented here a multiple regression analysis of the relationship of catchment area to sediment volume appears not to be significant ($F_{1,\ 9}=1.45$, $p=0.26$), thereby supporting the contention that tectonic regime (uplift/subsidence) at the tributary catchment level has probably been more influential than catchment area in determining the volume and rate of postglacial sediment generation from the Waipaoa and Waimata catchments (Fig. 7). Against this background of tectonic forcing, variations in rock type between tributary catchments appear to be of lesser importance.

Our estimate of the total postglacial sediment volume eroded by channel incision from Waipaoa catchment is ~9.5 km^3 and ~2.6 km^3 from Waimata catchment (Fig. 7). By comparison, Foster and Carter (1997) estimated that 20 km^3 of mud has been deposited on the Poverty Bay shelf since 18 000 cal. years BP, of which 8 km^3 accumulated since 8000 cal. years BP, and Orpin (2004) concluded that during the mid- to late Holocene a further 3 km^3 lobe of postglacial hemipelagic sediment accumulated in mid-slope basins.

These estimates of shelf and slope sediment accumulation are based on the existence of two major seismic reflectors: one (assumed to be last glacial in age) defines the unconformity between unconsolidated postglacial mud and the underlying deformed and indurated Neogene strata; the other, a conformable reflector in the top 15 m of the prism, has been assumed to be early Holocene in age (~8–10 000 ^{14}C years BP) after Pantin (1966). The presence of Tuhua tephra (6970 cal. years BP) at 14.13 m depth in the *Calypso* core MD97-2122 (Gomez et al., 2001) from the Poverty Bay mid-shelf basin, is considered to confirm that the underlying reflector is early Holocene in age (Orpin, 2004). The offshore sediment storage pattern appears to support the contention of an early (before ~8000 ^{14}C years BP) and rapid phase of onshore downcutting that potentially produced ~12 km^3 of offshore sedimentation, followed by a period of slower downcutting during which ~8–11 km^3 of offshore sediment accumulation occurred in the last 8000 years of the Holocene period. We estimate the combined volume of postglacial terrestrial sediment generated from the Waipaoa and Waimata catchments (12.1 km^3) to be about half that estimated to be stored on the Poverty Bay shelf (23 km^3). In addition, our estimate of the volume of unconsolidated postglacial material stored within the confines of the Poverty Bay floodplain is 6.6 km^3. That is, of the total eroded postglacial sediment volume derived from the Waipaoa catchment (9.5 km^3), ~70% has been trapped onshore. The initial trapping of this sediment was probably enhanced during times of marine incursion ~9000–7000 ^{14}C years BP (Brown, 1995) and subsequently by the presence of a lowland forest cover and unrestricted flood flow across this extensive floodplain. If we then assume that just 2.9 km^3 of the sediment eroded from Waipaoa catchment was discharged beyond the Poverty Bay floodplain to the shelf and that all the sediment eroded from the Waimata catchment (2.6 km^3) reached the same depocentre, (the Waimata River does not have a coastal floodplain and, at times in the past, likely drained directly into Poverty Bay), total postglacial sediment contribution to the shelf and beyond amounted to ~5.5 km^3. Accordingly, there appears to be a ~4-fold difference between our estimate of postglacial sediment generated by channel incision onshore and that stored offshore.

Potential sources of error in the methodology used to calculate the volume of sediment generated include, first, a paucity of GPS height control in the upper reaches of most sub-catchments where, in some instances, nickpoints and dummy points were used to constrain the Waipaoa-1 surface. Thus, volume estimates for the main channels, where there was superior height control on the Waipaoa-1 surface, will be more accurate than for tributary channels where volumes have probably been underestimated. Second, due to historical aggradation since the turn of the 20th century, the maximum depth of channel incision in some sub-catchments is unknown and once again our volume calculation will have been underestimated. Most importantly, our volume calculation only accounts for sediment removed from within the vicinity of river channels as a consequence of postglacial fluvial incision and does not therefore account for the significant throughput of sediment generated as a consequence of slope adjustment. That is ~75% of the estimated volume of the postglacial sediment in storage offshore was probably derived from hillslope erosion processes following base-level fall and at times when sediment yield from these catchments exceeded storage.

A refinement of the estimates of onshore sediment production and storage will require a) a better understanding of variations in the rate of incision during the postglacial period, b) a greater accuracy in defining the extent of glacial-aged versus postglacial hillslope adjustment and of the Waipaoa-1 aggradational terrace itself (particularly at sub-catchment scale), c) the determination of rates of hillslope adjustment by mass movement (predominantly rotational slumping and earthslide), and d) greater stratigraphic detail from additional and deeper drillholes and seismic profiling of the Poverty Bay floodplain and of aggraded channels. Refinement of the offshore postglacial sediment storage component is also required, particularly for the early Holocene, through better age control.

5. Conclusions

Identification of the Rerewhakaaitu Tephra (ca. 14700 ^{14}C years or ca. 17700 cal. years BP) as the basal tephra layer on remnants of the Waipaoa-1 aggradational terrace throughout the Waipaoa catchment provides the best date so far for the cessation of last glacial aggradation in North Island, New Zealand.

In the period before and after rapid incision, downcutting rates averaging 1 m ka^{-1} may represent the regional tectonic uplift rate. However, Rerewhakaaitu Tephra is also present at the base of the coverbeds on a Waipaoa-1 terrace that is ca. 15 m lower than the main surface. This suggests downcutting from the highest to the lowest Waipaoa-1 terrace treads was rapid in the main stem. Where we have both downcutting and uplift data for the postglacial incision phase we find downcutting rates of up to 7 m ka^{-1} in upper reaches of the river where uplift accounts for only ~1 m ka^{-1}. In the middle reaches of the main stem downcutting is about four times faster than tectonic uplift. Thus, climatically driven changes in river dynamics and upper catchment erosion rates are interpreted to be the primary control on the formation of fluvial terrace landscapes in the region and mark the transition to the postglacial in eastern North Island.

While this change in river dynamics was significant and triggered an episode of channel incision that was rapid (probably decades rather than centuries) in the main stem, within the Waihuka sub-catchment, at a similar distance upstream to that in the main stem, incision did not occur until ~10000–8000 years ago. Each tributary of the Waipaoa River therefore has its own postglacial history of downcutting and sediment flux in response to base-level fall, with tectonic regime (uplift/subsidence) probably being more influential than catchment area in determining the volume and rate of postglacial sediment generation.

Our estimate of the postglacial sediment flux derived by channel incision for Waipaoa catchment is in the order of 9.5 km^3, of which 6.6 km^3 is stored within the confines of the Poverty Bay floodplain. With just 2.9 km^3 of the postglacial sediment derived from Waipaoa catchment and 2.6 km^3 from the Waimata catchment reaching the same offshore depocentre, total postglacial sediment contribution to the shelf and beyond amounted to ~5.5 km^3. Thus, sediment generated by postglacial channel incision represents only ~25% of the total sediment yield from this landscape with ~75% of the estimated volume of the postglacial storage offshore (23 km^3) likely derived from hillslope erosion processes following base-level fall at times when sediment yield from these catchments exceeded storage.

Further refinements of onshore sediment production and storage are needed and, for individual tributaries, will require an understanding of rates of postglacial downcutting, definition of the extent of postglacial hillslope adjustment and of the Waipaoa-1 aggradation terrace itself, measurement of rates of hillslope mass movement processes, and the acquisition of additional and deeper drillhole data together with seismic profiling of aggraded river channels and of the Poverty Bay floodplain. Refinement of the offshore postglacial sediment storage component through better age control is also required.

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