The post-glacial downcutting history in the Waihuka tributary of Waipaoa River, Gisborne district, and implications for tectonics and landscape evolution in the Hikurangi subduction margin of New Zealand

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Abstract

Determining the spatial and temporal delivery of sediment from the Waipaoa River catchment in the post-glacial period is a major goal of integrated source-to-sink landscape evolution studies in the region. In a 2.2 km long section of the Waihuka tributary (217 km$^2$) of the Waipaoa River (2150 km$^2$) in eastern North Island, New Zealand, a sequence of at least ten fluvial terraces and abandoned meanders up to 45 m above the present river record rates and times of post-glacial downcutting. Dateable organic and tephra horizons in the terrace and meander infill stratigraphy indicate that downcutting at this location on the Waihuka tributary was dominated by a short-lived event in the early Holocene from 10-8 ka BP, when as much as half of the downcutting was accomplished in only 10-15\% of post-glacial time. The large downcutting event is interpreted to record the passing of a succession of major knickpoints or a knickzone through this tributary, following the end of MIS 2 age aggradation in the Waipaoa catchment and a switch to post-glacial incision. Based on the timing of rapid downcutting in the Waipaoa River mainstem, where the major knickpoint is now near the headwaters, we estimate the rate of knickpoint retreat along the Waihika tributary was about 2 km/kyr. In the period before and after rapid
downcutting in the Waihuka tributary, modest incision rates, averaging 1-2 mm/yr, probably represent the regional tectonic uplift rate.

**Keywords:** New Zealand, river terraces, post-glacial, knickpoint retreat, tectonics, landscape evolution, Waipaoa catchment, Hikurangi subduction margin

1. **Introduction**

The Waipaoa River catchment (2150 km²), the onshore portion of the Waipaoa source-to-sink sedimentary system, of the east coast of the North Island of New Zealand is a tremendously data-rich study area for obtaining insights into the form and function of fluvial systems in a temperate, tectonically active setting (e.g. Berryman et al., 2000; Eden et al., 2001; Crosby and Whipple, 2006; Marden et al., 2007) (Fig. 1). Landscape change processes in the Waipaoa catchment are rapid as a consequence of easily eroded bedrock, major changes to vegetative cover through glacial-interglacial climate fluctuations, temperate contemporary climate, and tectonism. These combine to produce large perturbations with corresponding large landscape responses. This paper examines aspects of the response of the fluvial system brought about by the switch from sediment over-supply (valley filling/aggradation) during Marine Isotope Stage 2 (MIS 2) in the Waipaoa catchment (Berryman et al., 2000; Eden et al., 2001) to sediment under-supply (valley cutting/degradation) in late MIS 2 and MIS 1. This fluvial response is also influenced in down-valley portions by the c. 100 m of sea-level rise that accompanied the transition to MIS 1, and tectonic uplift in the Hikurangi subduction margin (Litchfield and Berryman, 2005; Wilson et al., 2007a; Litchfield et al., 2007). Here, we present rare field data that constrains the temporal variation in rate of fluvial incision where Quaternary climate fluctuation is a prime agent of change (similar to situations described by Howard and Kerby, 1983; Whipple et al., 2000; Hancock and Anderson, 2002). We are also able to isolate the role of tectonic uplift in driving fluvial incision from the role of sediment supply and runoff.

Berryman et al. (2000), Eden et al. (2001), and Marden et al. (2007) have documented the extent and age of the widespread MIS 2 aggradation terrace throughout the Waipaoa catchment, and the general form of incision that swept through the
catchment following reduction in sediment supply and probably increase in precipitation at about 17-20 cal. ka near the end of the glacial period. Brown (1995), identified the MIS 2 gravel unit beneath the present Poverty Bay lowland, now covered by reworked gravel units, marine and marginal marine deposits accumulated during the post-glacial marine transgression that culminated in New Zealand at c. 7 cal ka. Marden et al. (2007) derived a value for the total sediment volume excavated by fluvial incision in the upland part of the catchment since abandonment of the MIS 2 aggradation level and in part accumulated in the lowland floodplain. Crosby and Whipple (2006) analysed the location of present-day knickpoints in the whole Waipaoa catchment and explored models of knickpoint formation and migration that could account for their current location. They assessed a model in which knickpoint retreat is a power function of drainage area and found a reasonable fit to data considering variability introduced by lithology variations, differences between excavation of alluvial infill versus downcutting through bedrock. They also recognized that incision rate should more properly be examined as a function of sediment load, discharge, and slope, rather than simply drainage area. Crosby and Whipple (2006) also assessed a knickpoint evolution model premised on the idea that knickpoints can develop high in the drainage network as a consequence of threshold drainage area conditions, or at tributary junctions. This model also performed quite well in matching the present-day knickpoint dataset, perhaps because we are judging the models against a long-evolved (c. 18 ka duration) drainage basin perturbation.

The location, and models of migration, of knickpoints through the Waipaoa River catchment are consistent with what drives alternating aggradation and degradation phases in fluvial systems, which was coined Huntington’s Principle by Fairbridge (1968). Huntington (1914) proposed that increasing aridity should lead to a loss of vegetation cover, resulting in channel aggradation due to an increase in the sediment flux from side slopes. Incision would occur during more humid periods, when vegetation stabilizes the hillslopes, reducing runoff, and diminishing sediment supply. Tucker and Slingerland (1997) showed that cyclic changes in runoff intensity produce aggradational-degradational cycles that resemble those observed in the field. Cyclic variations in runoff also lead to highly punctuated denudation rates, with denudation concentrated during periods of increasing runoff intensity and/or decreasing vegetation cover. The sediment
yield from threshold dominated basins may therefore exhibit significant variability in
response to relatively subtle environmental changes, a finding which underscores the
need for caution in interpreting modern sediment-yield data.

To quantify the sediment flux from the catchment in the post-glacial, the timing
and rate of knickpoint retreat in all parts of the catchment are required (Whipple and
Tucker, 1999; Whipple et al., 2000; Howard et al., 1994; Tucker and Slingerland, 1996;
Paola, 2000; Bishop et al., 2005). Crosby and Whipple (2006) developed theoretical
models of how knickpoints may migrate through the Waipaoa catchment, but there is
little or no data to independently verify the timing or amplitude of incision through the
period of landscape perturbation. Here, based on detailed mapping and dating of a suite
of degradational terraces and meander channels along a short, 2.2 km long, section of the
Waihuka tributary of the Waipaoa River, about 17 km above the confluence of the
Waihuka and the mainstem Waipaoa, we determine the characteristics of fluvial incision
below the MIS 2 aggradation level (Figs. 1 & 2). We have concentrated our work on this
short section of the Waihuka River because abandoned meander channels (where dateable
deposits are more usually preserved) are more common at this locality than elsewhere
along this river or the mainstem Waipaoa. Although the study area is quite restricted we
expect that some of the findings may provide insights into landscape evolution on a
regional basis.

2. Regional Setting

The Waipaoa catchment, including the Waihuka tributary, is situated within the
active forearc of the Hikurangi subduction margin (Fig. 1). In the northern sector of the
Hikurangi margin, approximately northward of Mahia Peninsula (Fig. 1), there is tectonic
erosion at the subduction front, a narrow zone of contraction (Berryman, 1993a; Wilson
et al., 2006), and widespread uplift and consequent normal faulting occurs (Berryman,
1988; Lewis and Pettinga, 1993; Litchfield et al., 2007; Wilson et al., 2007b). The
subduction interface is located at a depth of c. 15 km beneath Gisborne and 25 km below
the headwaters of the Waihuka tributary (Ansell and Bannister, 1996). Late Quaternary
vertical deformation, involving uplift and subsidence, have been described in coastal
areas near Gisborne (Ota et al., 1991, 1992; Brown, 1995; Berryman et al., 2000; Wilson
et al., 2006). However, most of the coastal areas in Raukumara Peninsula are undergoing
uplift, (Yoshikawa et al., 1980; Pillans, 1986; Ota et al., 1992; Wilson et al., 2007b),
driven in the offshore area by upper plate reverse faults (Berryman, 1993b; Litchfield et
al., submitted), by sediment underplating (Eberhart-Phillips et al., 2005), by subduction
of over-thick oceanic crust (Davy and Wood, 1994), and possible effects of seamount
subduction (Lewis et al., 2004; Litchfield et al., 2007). Maximum uplift rates are
approximately along the crest of the Raukumara Range (Yoshikawa, 1988; Wilson et al.,
2007a).

3. Methods
The fluvial terrace distribution on the Waihuka River in the Otoko-Gold Creek
area was initially mapped from 1:500 scale, color aerial photographs and then mapped in
detail in the field (Fig. 3). Auger and cored drillholes were taken from selected terraces
and meanders (Figs. 3, 4, & 5), and samples collected for radiocarbon dating and tephra
identification. Radiocarbon samples of wood, peat, and organic rich silt were processed at
the Rafter Radiocarbon Laboratory of GNS Science (numbers with NZA prefix in Table
1) and Waikato University (numbers with Wk prefix in Table 1). Tephras were analyzed
as described below (Table 2, Fig. 6), and compared with tephras previously identified in
the region whose ages are well-established (Table 3). Terrace elevations were recorded
by either Differential or Real Time Kinematic GPS methods, and we expect that all
altitudes are correct to less than ± 0.5 m and horizontal position is correct to about ± 0.1
m (although note that Fig 3 was drawn using non-rectified large scale aerial photographs
and positions may only be accurate to ± 20 m). We generally report all elevations to the
nearest meter (e.g. Fig. 3), but expect that the data are better than this.

Tephra identification was by a combination of ferromagnesian mineralogy and
electron microprobe analysis of glass shards. The ferromagnesian minerals were
separated and percentages determined by grain counts (Table 2). Volcanic glass samples
were analysed by the JEOL 733 Electron Microprobe at the Analytical Facility of
Victoria University. A 10 micron beam diameter and 8.5 nA beam current were used for
all analyses. Most published data for New Zealand tephras cite use of a 20 micron beam,
but some distal tephras, very vesicular pumices, and tuffs are difficult to analyse with a
coarse defocused beam. The 10 micron beam results in higher analyses for Na, and slightly lower values for Si than samples on the database. Therefore the analyst (AP) has re-analysed tephras from type localities and other known sites to construct a new comparative database (Fig. 6). At least ten glass shards were analysed for each sample (e.g. Fig. 6). Only major oxides and chlorine consistently above the detection limit were analysed.

4. **Fluvial Geomorphology in the Waihuka Valley**

Late Pleistocene and Holocene terraces and meanders that are up to 50 m above the modern river at Otoko the post-glacial downcutting history. The sequence is below the prominent aggradation terrace that we correlate to the Waipaoa 1 (W1) terrace (c. 18-19 cal. ka) in the Waipaoa catchment (Fig. 2) that formed during MIS 2 (Berryman et al., 2000; Eden et al., 2001; Marden et al., 2007). The preservation, albeit discontinuous, of many degradational terraces and abandoned meanders, substantial downcutting, and dateable organic and tephra horizons (see Table 3 for details of the nine potential glacial to post-glacial tephra deposited in the study area) in the terrace and meander infill stratigraphy, provide a large magnitude, and high resolution, interpretation of the timing and processes driving fluvial dissection in this region.

In the c. 2.2 km long section of the Waihuka valley from Otoko downstream to near Gold Creek, at river distance 50-52 km from the coast, there are many terrace levels and abandoned meanders (Figs. 3 and 4). We acknowledge that the river in its downcutting phase will have developed terraces in slip-off style. Therefore, even along this 2.2 km long section of the river, there may not be continuous terrace surfaces, and terrace slopes may be steeper than the river gradient at the time. However, at any point in time the river would have been running in an active channel comprising sinuous, bedrock channel sections, and wider terrace-edged sections, just as it is today. Therefore, remnants of terraces and meanders comprise a discontinuous record of past time lines.

The present river channel has an average down-valley gradient of 20.5 m/km, and a sinuosity of 1.43 (Fig. 7). However, there are significant variations in the gradient over the 2.2 km study area with two very uniform reaches with gradient of 15 m/km separated by two short, steep sections corresponding to the two largest meanders where the down-
valley gradient approaches 45 m/km. In detail, the straightened river profile has two very uniform reaches with gradient of 14 m/km, separated by a c. 2 m “step” in the c. 100 m long section between the 147-149 m elevation points. This reach does not correspond to the prominent meanders. Bare bedrock surfaces comprise approximately 50% of the channel bed in the 2.2 km long reach, and along the remainder there are thin (<2 m) sequences of alluvial deposits ranging from sand to coarse gravel. There is no evidence of any appreciable accumulation of recent sediment resulting from deforestation or human occupation, as there is in some upper Waipaoa River tributaries (e.g. Marutani et al., 1999). The Miocene bedrock has significant variability, comprising calcareous mudstone with intercalating beds of fine-grained sandstone and conglomerate (Mazengarb and Speden, 2000), and short steep sections in the riverbed probably reflect this variability in lithology. Elsewhere, the even gradient may reflect very uniform bedrock. The steep down-valley sections correspond to small knickpoints retreating upstream in modern times. Overall we may classify the present channel as an incising, exceedingly steep, moderately meandering, single thread stream.

Remnants of the Waipaoa 1 (W1) terrace occur at c. 217 m elevation at Otoko, decreasing down-valley to 177 m at Gold Creek (Fig. 4). Thus, through this section of the river the aggradation terrace has a slope of c. 15 m/km, about the same as the present-day down-channel profile. These high gradients of both the present-day river profile and the aggradation terrace occur elsewhere in the Waipaoa catchment. For example, the main stem of Waipaoa River has a riverbed gradient of 10 m/km at the same distance of c. 50 km from the river mouth, and the W1 terrace at that distance has a down-valley gradient of c. 9 m/km. Tributary valleys tend to have higher gradients at the same river distance than the main valley (Fig. 3).

Remnants of at least ten abandoned meanders occur in the 2.2 km stretch of the Waihuka from Otoko to Gold Creek (Fig. 4). Airfall tephra and radiocarbon ages obtained from the base of stratigraphic units from terraces and meanders are interpreted to be immediately younger than the abandonment of that level by the river. Meanders represent the former single thread channel of the river which usually contained no deposits. Therefore basal fine-grained infill sediment or airfall tephra can only accumulate when the river has abandoned the meander and switched to a lower level.
Terraces often contain alluvial deposits, and the abandonment of the terrace level is usually marked by the first occurrence of airfall tephra or colluvial deposits, frequently containing the lowermost organic deposits observed in the terrace coverbed stratigraphy. All of these meanders have been cored and samples of organic material and/or tephra have been obtained from seven of those levels (Figs. 4 and 7; Tables 2 and 3). Dating control is also available from two of the alluvial terraces (Figs. 4 and 7). Therefore, we can establish the river level at 9 different times during the 45-50 m of downcutting since about 18 cal. ka. We use the notation Waihuka 1-9, for these levels, with the Waihuka 1 terrace mapped as synonymous with the Waipaoa 1 terrace of Berryman et al. (2000). The Waihuka terrace notation does not include all of the possible post-glacial terrace levels, only those for which there is some age control.

Because of the steep river gradients of the present day river and the terraces, elevation alone cannot be used for correlation or establishing the age of a terrace. In Fig. 8 we have compiled all of our data on terrace and abandoned meander locations and their elevations, and projected them to a single, middle of the valley, profile. On this we have added the available age data at the appropriate elevations, and, taking into account the down-valley slope of all terraces, extrapolated individual levels up and down river. A composite sequence, at location 1600 m of Fig. 8, with assigned “extrapolated elevations”, for each of the nine levels is presented in Table 4. Because terraces and meanders have been extrapolated some distance up and down river there is significant uncertainty in the elevation of some of the terrace levels in this composite sequence. However, there are sufficient terraces and sufficient dating to be reasonably confident about the overall pattern, and we will attempt to be cautious in drawing conclusions because of these uncertainties.

4.1 Terrace Descriptions and Stratigraphy

A single prominent terrace remnant labeled Bailey on Fig. 3 (after the landowner) has a surface that is about 8 m higher in elevation than the adjacent terrace surface correlated with W1. This terrace level projects above the correlated remnants of the W1 terrace on the down-valley projection (Fig. 4). No definitive age control has been obtained from this terrace remnant, but on the opposite side of the valley at c. 204 m
elevation there are outcrops of tephra of 26-30 cal. ka age Mangaone tephra group. These are significantly older, but only slightly higher than the elevation that represents the culmination of the c. 18 ka W1 aggradational infill. Therefore, we infer the Bailey terrace remnant is a discontinuous remnant of the older W2 aggradation episode documented in the Waipaoa River catchment by Berryman et al. (2000) and Marden et al. (2007).

The Waihuka 1 aggradation terrace is mapped in the Waihuka valley on the basis of geomorphic and stratigraphic criteria including down-valley continuity, the presence of fining-upward alluvial gravel above a terrace strath, and across-valley elevation matching of remnants of the terrace surface (Figs. 3 and 4). Remnants of this terrace extend a further 17 km down-valley to merge with the furthest down-valley extent of the terrace mapped in the Waipaoa valley near Te Karaka by Berryman et al., (2000) and Marden et al. (2007) (Fig. 2). In the Waipaoa River valley, the lowermost tephra observed in coverbeds of the W1 terrace is Rerewhakaaitu Tephra (Eden et al., 2001) dated at 17.6 cal ka (we report calendar ages throughout the text, calibrations are presented in Tables 1 and 3). This suggests an age of c. 18-19 cal. ka for the cessation of aggradation (neither Okareka nor Kawakawa tephras (21 and 26.6 cal. ka, respectively) occur in the coverbeds of the W1 terrace).

In this study one cored drillhole (see Fig. 5 – Waihuka 1 drillhole) extended 6+ meters through the coverbeds of the W1 terrace and into the upper part of the aggradation fill. This drillhole encountered a sequence of airfall tephra and hillslope colluvial deposits, including Rotoma tephra (9.5 cal. ka) at about 4 m depth. At 4.7 m coarse alluvial gravel is interpreted to mark the top of the aggradation fill (Fig. 5), and at 5.16 m a thin remnant of the 22.6 cal. ka Kawakawa tephra has been identified. The drillhole extended a further meter or so in alternating stratigraphy of alluvial sand and gravel. The drillhole terminated in sandy gravel where clast sizes increased to beyond the capacity of the drilling operation. In terrace edge exposures nearby, the alluvial gravel becomes coarser with depth, and is up to 15 m thick. Encountering the 26.6 cal. ka Kawakawa tephra (Table 3), in the aggradation deposits provides excellent confirmation of the MIS 2 age for the aggradation phase in the Waihuka valley, as observed elsewhere throughout New Zealand (e.g. Palmer, 1982; Pillans et al., 1993; Litchfield and Berryman, 2005; Clement and Fuller, 2007).
The next dated level, Waihuka 2 (W2), is about 3 m below the W1 terrace. The 3.5 m long drillcore extended through 2.5 m of cover deposits and 1.0 m of alluvial sediment (Fig. 5). Whakatane tephra (5.5 cal. ka – Table 3) occurred at 0.65 m depth, and at the base of the section in alluvial deposits was a sand unit derived from Rerewhakaaitu tephra. Thus, for some time after Rerewhakaaitu tephra (17.6 cal. ka) the river was running at this level. We cannot put an exact age on the abandonment, but estimate c. 16 cal ka, in order to make some estimates of the downcutting rate.

Two undated alluvial terraces have been mapped between the W2 level at 184 m and an extensively dated meander channel at 178 m, which we call W3 (Fig. 5). Numerous drillholes in the W3 meander channel indicate a strath, sometimes overlain by thin alluvial deposits, but frequently (as in the section presented in Fig. 5) only infilled with either back-water clay and silt or airfall and re-worked (probably derived from adjacent slopes) tephra units. We accept the basal radiocarbon age of 9.2 cal. ka (Table 1) as dating the abandonment of this meander channel, but note the identification of Rotoma tephra (9.5 cal. ka), from apparent airfall about 1 m higher in the stratigraphy. We conclude that the tephra, although essentially pure, is a reworked slope-derived deposit. The basal radiocarbon age is from disseminated organics in silt, and the radiocarbon age from the same horizon as the tephra is 9.2 cal ka. Even with the slight uncertainty of the correct age of the basal deposits in this meander channel, it is clear that it is about 9.5 cal ka, about 6.5-7 kyr younger than the W2 level that is 6 m higher in elevation.

There is a difference in elevation of about 7 m below the W3 level to the next identified paleo-elevation of the river, identified as an abandoned meander channel we call W4 (Figs. 2 and 4). About 3 m of tephric sand, silt, and apparent airfall tephra, units were identified in several drillholes at this level. We obtained ages at two horizons in the drillhole shown in Fig. 5. An age of c. 8.8 cal ka was obtained from disseminated organics in the basal silt horizon, and we accept this as the abandonment age by the river of this level. Therefore, the 7 m of downcutting occurred in very quick time, no more than about 500 yrs and perhaps even less.

We identify another meander channel (W5) that is a further 6 m below W3. From the 2.2 m thick infill stratigraphy we obtained from a drillhole at this level many age determinations (Fig. 5; Tables 1 and 2). The basal age of 9.05 cal. ka was from
disseminated organics in the basal silty clay unit, but about 0.2 m higher in the
stratigraphy an apparent airfall tephra was identified as Rotoma tephra (9.5 cal. ka). We
are confident the basal radiocarbon sample is valid, and therefore the tephra must be
reworked, probably as a slope-wash deposit from the hillslopes above the meander
channel. It should also be noted that the glass chemistry for Rotoma tephra is not alone
distinctive, but does have a distinctive ferromagnesian mineral assemblage, including
cummingtonite. This mineral is only present in much older tephras, Rotoma tephra and
the younger Whakatane tephra, which has been positively identified higher in the core.
Therefore the tephra is almost certainly Rotoma. Because the tephra shows no evidence
of mixing we expect it was re-deposited soon after primary deposition, therefore when we
calibrate our radiocarbon ages to interpret the calendar years between events we account
for this stratigraphic observation. The age difference between the W5 and W4, and indeed
W3 levels is clearly short, indicating continued rapid downcutting that started at or soon
after 9.5 cal ka).

About 1 km upstream of where the four levels below W1 discussed above are
located, is another abandoned meander that we call W6 (Figs. 3 and 4). Although the W6
meander is higher in elevation than all of the meanders downstream, we infer that this
meander corresponds to a younger position of the river because of the younger basal age
of c. 8.1 cal ka obtained from the infill stratigraphy (Fig. 5). We considered the
possibility that W6 is an upstream correlative of W5 but, the 2σ calibrated ages of the
respective basal radiocarbon samples do not overlap, hence we favor the interpretation of
different terrace levels. We adopt a 3 m elevation difference between W5 and W6, and an
age difference of 0.4-1.0 kyr.

An abandoned meander located midway between where locations of the W6 and
W5 levels is identified as W7 (Figs. 3 and 4). Few other levels appear to correlate with
this level (Fig. 8), but it is valuable, because although 7 m lower in elevation it appears to
be significantly younger than the next higher level. The stratigraphy in a drillhole from
this level (Fig. 5) revealed 2.9 m of infill comprising tephric sands, apparent airfall
tephra, buried soils, and frequent fragments of woody material scattered throughout. The
age obtained from wood fragments near the base of the infill was 4.07 cal. ka. About 2.0
m stratigraphically above we obtained results from apparent airfall Waimihia tephra
indicating a 3.5 cal. ka age, and there are two weak intervening paleosols. Because our radiocarbon sample is from sizeable wood fragments we cannot be certain they are not fragments of roots growing down from a higher level. Equally, we have observed instances where apparently airfall-bedded tephra are pure, but reworked units. Therefore, we suspect the radiocarbon age may be too young for the stratigraphic horizon.

The next lower level, W8, is at 144 m elevation, 11 m lower than W7 (Figs. 3, 4, and 8). Two radiocarbon ages on disseminated organics in silt units from the basal part of the infill stratigraphy are 1.55 cal. ka and 1.56 cal. ka. The date of 1.55 cal ka is therefore accepted as the age of abandonment of the river at this level.

The lowest level we have mapped in the Otoko locality is only 3.5 m above present-day river level, and is still occupied in high flood (Figs. 3, 4, and 8). The drillhole (Fig. 5) revealed 2.5 m of infill material including a 400 mm thick topsoil above the bedrock strath. No tephra units were observed and a radiocarbon age of 0.15 cal. ka was obtained from 2.0 m depth in the drillhole. This age calibrates in the 0-300 cal. yr range, meaning that at 2σ age uncertainty we cannot be sure the age is not modern, although the thick topsoil argues against this.

4.2 Timing, rates and mechanisms of river downcutting

Elevation and age data from the nine levels discussed above provide sufficient information to construct a downcutting curve for the 2.2 km long section of the Waihuka valley near Otoko (Fig. 9 and Table 4). Although there is uncertainty in the exact timing of abandonment of each level, and the tephra and radiocarbon results do not always match, it is clear that at this location in the Waihuka valley the post-glacial downcutting history is dominated by a short but very rapid event between about 8-10 cal. ka. This is similar to approximate downcutting curves presented by Bull (1991) from the Buller and Charwell rivers in northern South Island. For the rest of the period the fluvial incision rate has probably been in the range of 1-4 mm/yr. The maximum rate of downcutting in the short early Holocene interval is poorly constrained but must average at least 10 mm/yr.

The 1-4 mm/yr incision rate in the late Pleistocene and then mid-late Holocene is similar to that observed elsewhere in the Hikurangi margin (Pillans, 1986; Berryman et
We suggest the driving mechanism for this downcutting to be broad regional uplift driven by deep-seated processes in the subduction margin discussed by Litchfield et al. (2007). There is no evidence for widespread, upper plate active faulting or folding to drive the uplift.

The most likely explanation for the early Holocene episode of extremely rapid downcutting is post-glacial knickpoint retreat advancing up this tributary of the Waipaoa valley at this time. Eden et al., (2001) documented a c. 17 cal. ka initiation of rapid downcutting in the mainstem of the Waipaoa at a site close to the confluence of the Waikohu (which the Waihuka joins about 8 km downstream of Otoko) and Waipaoa following the culmination of the W1 aggradation, but at Otoko, 17 km up-valley from the confluence with the Waipaoa, the initiation of rapid downcutting was about 8 kyr later. We can therefore calculate an average knickpoint migration rate up the Waikohu and Waihuka to Otoko of about 2 km/kyr.

Even within the short 2.2 km long study area at Otoko we see, in the vertically exaggerated profile presented in Fig. 8, some suggestion of a knickpoint retreat geometry. Whereas terrace levels immediately below the W1 level seem to be parallel with it, and similarly, low-level terraces close to the present river appear to be parallel to it, those in between seem to have a steeper downstream gradient. Knickpoint retreat would be manifest as a short-term episode of high gradient terrace remnants. We represent this diagrammatically as an inset in Fig. 8. No major river knickpoints exist in the upstream 10-12 km from the Otoko locality today, suggesting this channel has fully responded to the post-glacial downcutting signal (Crosby and Whipple, 2006), although there are modern knickpoints in most small tributaries of the Waihuka River (Crosby, 2006).

Crosby and Whipple (2006) proposed that the presence of a suite of degradation terraces is indicative of a series of knickpoint retreat episodes, and that the knickpoint itself would not be manifest as a terrace level (their fig. 2). Our interpretation of the terrace and meander sequence preserved at Otoko, based on excellent age control of the timing and amount of downcutting, is that during the major incision episode there were short periods of relative stability when terraces and meanders formed, to be abandoned frequently because of a rapid succession of upstream migrating knickpoints. Each degradational terrace or meander probably represents the migration of a single or multiple
knickpoints through the fluvial system. The overall impression from the terrace suite remaining from this major phase of incision is that of the migration of a knickzone (terminology of Crosby and Whipple, 2006) that achieved as much as 50% of the downcutting in this short section of the Waihuka tributary in only 10-15% of the time period. This period was preceded and followed by smaller incision events that have also left a record of terraces and meander loops, but they do not have the same very steep downstream gradient, and tend to be sub-parallel to the gradients of the aggradation terrace above, and the present river below.

4.3 **Volumes of erosive material**

Based on the GPS survey we have constructed three valley cross-sections in the study area. In each case we have identified the W1 terrace on at least one end of each profile (Fig. 10), and can therefore calculate the volume of material removed since formation of the W1 terrace at about 18-19 cal. ka. The three estimates of the cross-sectional area are 7.28, 9.81, and 9.96x10³ m², or an average of 9.02x10³ m², with a tendency for larger volume downstream. This study therefore indicates for the middle reaches of the Waihuka valley the excavated volume per kilometer length of the river is about 9x10⁶ m³.

Using our knowledge of the age of the river at different elevations we can plot the rate of sediment delivery for different time periods associated with excavation of this section of river (Fig. 11). We make several assumptions in constructing Fig. 11A, notably that lateral planation was taking place throughout downcutting appropriate to the present valley dimension. We also assume the valley floor was flat. Fig. 11B is very similar in shape to the downcutting rate plot shown in Fig. 9. The similarity in shape indicates that the downcutting is not an artifact of valley shape, and that even though the v-shaped valley cross-section can be expected to have some effect on downcutting, the cross-sectional area excavated in the early Holocene event shows through very clearly, and we expect this signal is much larger than the uncertainties acknowledged above.
5. **Landscape evolution in the Waipaoa catchment**

This study of a small section of the Waihuka tributary of the Waipaoa River has revealed a downcutting history rather different in time, but similar in magnitude, to that presented by Eden et al. (2001) for a site on the mainstem of the Waipaoa. The culmination of the sediment fill cycle correlated with MIS 2 was approximately synchronous across the catchment, but initiation of downcutting that followed varies considerably, most probably in response to headward retreat of an eroding knickpoint in the river system (Crosby and Whipple, 2006). Thus, tributary downcutting, and a wider landscape response cannot be initiated until knickpoint retreat passes upstream of the confluence of the tributary and the mainstem. Therefore, every site along the mainstem and all of its tributaries will have a unique downcutting history (and sediment delivery). Integrating all sites provides a continuum of process. Downstream parts of the Waipaoa catchment landscape may have completed its response to river downcutting many thousands of years ago. However, there are upstream parts of the catchment, particularly in the smaller tributaries with lower stream power and slower knickpoint retreat rates, which are essentially relict landscapes, little modified from their late glacial condition (Crosby and Whipple, 2006; Marden et al., 2007).

Integrating sediment flux in space and time for the mainstem of the Waipaoa and all of its tributaries, either by tributary specific study or by modeling based on knickpoint migration rates, is required to determine the sediment delivery rate to sediment sequestering sites in the lower valley onshore, and the offshore Poverty basin. In addition, to the excavated volume from the river channel there are an important additional sediment sources (perhaps even the largest components) in landslides and slope erosion that are of post-glacial age, but higher in elevation than the W1 terrace, that deliver sediment down through the landscape into the fluvial drainages (Marden et al., 2007).

Except for the Bailey Terrace, aggradation terraces older than W1 have not been mapped in the Waihuka valley in this study, and the method of estimating uplift from pairs of aggradation terraces presented by Berryman et al. (2000) from the Waipaoa terrace sequence cannot therefore be employed. However, if rapid downcutting in the Waihuka valley is primarily documenting the timing and procession of knickpoint retreat, then it may be that modest downcutting with parallel geometry pre- and post-dating
knickpoint retreat may be an indication of regional uplift affecting the region. Table 4 indicates incision rates (= uplift rates?) in the range of 1-4 mm/yr for the period pre- and post-dating the rapid incision phase. These rates are similar to those derived from the Waipaoa mainstem (Berryman et al., 2000), and elsewhere in Raukumara peninsula catchments (Litchfield and Berryman, 2006).

In Fig. 9 we see no evidence at Otoko for any difference in the incision rate before and after human occupancy of this area, coincident with widespread forest clearance. Also, the present river channel is indicative of continuing incision, with many bare bedrock strath reaches. Significant volumes of unconsolidated sediment from the Whakatane and Waimihia tephras, aged 5.5 and 3.5 cal. ka respectively, were deposited in the Waihuka tributary but did not apparently change the character of the fluvial system. Elsewhere in the East Coast prominent aggradation terraces composed of tephric alluvium (e.g. Segschneider et al., 2002) have formed. In the Waihuka valley we found no fill terraces corresponding to these tephra ages, probably because the very steep gradients of Waipaoa River tributaries such as the Waihuka (c. 20 m/km) remain supply-limited, even when exposed to significant environmental change. This suggests that environmental changes that resulted in widespread aggradation during MIS 2 had a combined effect that was more substantial than late Holocene volcanic ash deposition or human occupancy of the landscape.

The timing of the major phase of downcutting at Otoko in the Waihuka tributary strongly supports the landscape change model where knickpoint retreat in a tributary cannot begin until knickpoint in the mainstem moves upstream of the confluence with the tributary (Crosby and Whipple, 2006). The long-term rate of knickpoint retreat estimated for the Waihuka tributary at c. 2 km/kyr is very consistent with contemporary measures in similar lithologies (Crosby, 2006). In a study of fluvial response to downcutting in eastern Scotland, Bishop et al. (2005) concluded that catchment area was more important than stream gradient in governing rates of knickpoint retreat. Our study endorses that observation. Both in the mainstem Waipaoa and its tributaries the stream gradients are very high by world standards (c. 10 m/km and 20 m/km, respectively – Milliman and Syvitski, 1992). However, Crosby and Whipple (2006) noted that knickpoints have eroded further headward, and initiated earlier, in the mainstem Waipaoa and larger
tributaries, than the steep tributaries. If slope were a major determinant of knickpoint
retreat we could expect very rapid rates of knickpoint retreat in the steepland tributaries.

6. Conclusions

The detailed study of a 2.2 km long section of the Waihuka tributary of the
Waipaoa River has provided a number of insights into the form and function of fluvial
deposition and erosion pertinent to the catchment. We have identified a fill terrace of late
MIS 2 age in the Waihuka tributary that has a similar age as in the mainstem of the
Waipaoa, demonstrating a basin-wide response to past climate. At the Otoko site located
17 km up-valley from the Waipaoa we have identified a markedly different downcutting
history from the mainstem Waipaoa. The downcutting history at the Otoko locality is
dominated by a short-lived event in the early Holocene when as much as half of the
downcutting was accomplished in only 10-15% of available time. The large downcutting
event is probably a manifestation of major knickzone retreat in this catchment following
the end of glacial-age aggradation in the Waipaoa catchment and a switch to post-glacial
incision. The rate of knickzone retreat up this tributary of the Waipaoa River is about 2
km/kyr.

The Waihuka River study provides some insight into the possible functioning and
landscape age of the whole catchment. Relatively downstream parts of the Waipaoa
system may have finished responding to post-glacial downcutting many thousands of
years ago, while in upstream parts of the catchment the landscape response may not have
even started yet. Landscape age within the catchment, with respect to its response to base-
level change, and climate driven aggradation and degradation episodes (and consequently
sediment transport), is therefore extremely variable.

In the period before and after rapid downcutting in Waihuka catchment, modest
incision rates averaging 1-2 mm/yr, and achieved by retreating knickpoints of modest
scale, probably represent the regional tectonic uplift rate. In the vicinity of the Otoko
locality on the Waihuka tributary other landscape change factors such as large volumes of
volcanic ash arriving in the catchment at 5.5, & 3.5 cal ka have not apparently resulted in
any apparent reduction in the incision rate or temporary switch to aggradation if the river
became over-supplied with sediment, nor in the period since Maori occupation in the last
millennium (Fig. 9). Incision rates in the late Holocene period are comparable to the late glacial period prior to the arrival of the upstream propagating wave of incision.

Acknowledgements
The research presented here was primarily funded by the Foundation for Research Science & Technology under contract C09X0213 to Landcare Research. The authors wish to thank the farming families in the Waihuka valley for their interest and access to the terrace sequence. The expertise of Ted Pinkney (Landcare Research) in obtaining cores with a truck mounted and mobile drill is also greatly appreciated. We appreciate the review comments on the manuscript from Noel Trustrum and John Begg. Janet Arnst digitized the terrace map.

References


Huntington, E., 1914. The climatic factor as illustrated in arid America, Publ. 192, Carnegie Inst., Washington, D. C.


### Table 1.
Radiocarbon dating results

<table>
<thead>
<tr>
<th>Sample no and depth</th>
<th>Loc (NZMS 260 X17)</th>
<th>$\delta^{13}$C (‰)</th>
<th>Lab Code</th>
<th>$^{14}$C age (yrs B.P.)</th>
<th>Calibrated age (2σ cal. yrs B.P.)</th>
<th>Ave. cal. age (cal. ka)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3b – 2.6 m</td>
<td>173933</td>
<td>-26.6</td>
<td>NZA 11054</td>
<td>8183 ± 65</td>
<td>9002-9396</td>
<td>9.20</td>
<td>Sample was small wood fragments. Strath at 3.4 m.</td>
</tr>
<tr>
<td>W3c – 3.4 m</td>
<td>173933</td>
<td>-26.5</td>
<td>NZA 11088</td>
<td>8319 ± 65</td>
<td>9124-9485</td>
<td>9.30</td>
<td>Sample was reddish brown wood. Strath at 3.4 m.</td>
</tr>
<tr>
<td>W4b – 2.9 m</td>
<td>-26.2</td>
<td>NZA 15066</td>
<td>7982 ± 65</td>
<td>8603-9022</td>
<td>8.81</td>
<td></td>
<td>Organic rich silt. Strath at 3.02 m</td>
</tr>
<tr>
<td>W5d – 1.75 m</td>
<td>172933</td>
<td>-28.9</td>
<td>WK 5406</td>
<td>7720 ± 70</td>
<td>8385-8631</td>
<td>8.51</td>
<td>Wood fragments. Strath at 2.2 m.</td>
</tr>
<tr>
<td>W5f – 2.2 m</td>
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<td>-26.3</td>
<td>NZA 7600</td>
<td>8142 ± 73</td>
<td>8742-9348</td>
<td>9.05</td>
<td>Wood fragments. Strath at 2.2 m.</td>
</tr>
<tr>
<td>W6a – 3.3 m</td>
<td>-27.7</td>
<td>NZA 15068</td>
<td>7299 ± 75</td>
<td>7954-8292</td>
<td>8.12</td>
<td></td>
<td>Peat/Wood. Strath at &gt; 3.6 m</td>
</tr>
<tr>
<td>W7c – 2.5 m</td>
<td>163938</td>
<td>-25.6</td>
<td>NZA 11055</td>
<td>3728 ± 60</td>
<td>3898-4247</td>
<td>4.07</td>
<td>Sample consisted of 3 substantial pieces of soft grey wood with thin brown bark. Strath at 2.9 m.</td>
</tr>
<tr>
<td>W8a – 2.0 m</td>
<td>-27.8</td>
<td>NZA 15067</td>
<td>1629 ± 55</td>
<td>1404-1688</td>
<td>1.55</td>
<td></td>
<td>Peat/Wood. Strath at 2.23 m</td>
</tr>
<tr>
<td>W8b – 2.4 m</td>
<td>165937</td>
<td>-28.8</td>
<td>NZA 11164</td>
<td>1662 ± 50</td>
<td>1417-1698</td>
<td>1.56</td>
<td>Sample consisted of fine organics – seed pods, grasses, small wood fragments &amp; twigs. Sample from silt immediately above fine gravel.</td>
</tr>
<tr>
<td>W9a – 2.0 m</td>
<td>168936</td>
<td>-23.9</td>
<td>NZA 11056</td>
<td>141 ± 65</td>
<td>5-304</td>
<td>0.15</td>
<td>Sample was soft cream colored wood. Strath at 2.5 m</td>
</tr>
</tbody>
</table>

Radiocarbon ages were calibrated based on Stuiver and Reimer (1993) using the Southern Hemisphere curve of McCormac et al. (2002), and 2σ calibrated ages are used unless specified. Ave. = average, cal. = calibrated. Bold numbers are ages that constrain the age of terrace abandonment.
Table 2. Tephra mineralogy and chemistry

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Depth (m)</th>
<th>Mineral Assemblage</th>
<th>Opx %</th>
<th>Cpx %</th>
<th>Hbl %</th>
<th>Cmgt</th>
<th>Biotite</th>
<th>Other</th>
<th>Opaques</th>
<th>FeO*</th>
<th>K2O*</th>
<th>n</th>
<th>Tephra</th>
</tr>
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<tbody>
<tr>
<td>W1a</td>
<td>4.15-4.2</td>
<td>6 - 7</td>
<td>47.3</td>
<td>0.6</td>
<td>-</td>
<td>39</td>
<td>0.91</td>
<td>3.30</td>
<td>11 Rotoma</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1b</td>
<td>5.16-5.18</td>
<td>59.6 2.6 6.3 0.3</td>
<td>-</td>
<td>31</td>
<td>1.15</td>
<td>2.84</td>
<td>Kawakawa</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>W2a</td>
<td>0.65-0.7</td>
<td>33.7 2.3 4.0 37.7</td>
<td>-</td>
<td>22.3</td>
<td>0.95</td>
<td>3.19</td>
<td>Whakatane</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>W2b</td>
<td>3.16-3.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.91</td>
<td>3.34</td>
<td>Rerewhakaaitu</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>W3a</td>
<td>2.5-2.6</td>
<td>17.3 2.0 11.0 36.0</td>
<td>0.3</td>
<td>0.3</td>
<td>33.0</td>
<td>0.85</td>
<td>3.30</td>
<td>13 Rotoma</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>W4a</td>
<td>0.81-0.86</td>
<td>8.0 - 2.6 58.0 0.3</td>
<td>0.3</td>
<td>30.6</td>
<td>0.96</td>
<td>3.78</td>
<td>Whakatane</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5a</td>
<td>0.9</td>
<td>Opx + Hbl + Cpx</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Waimihia</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>W5b</td>
<td>1.2</td>
<td>Cmgt + Hbl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Whakatane</td>
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</tr>
<tr>
<td>W5c</td>
<td>1.6</td>
<td></td>
<td></td>
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<td></td>
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<td>0.94</td>
<td>3.36</td>
<td>11 Mamaku</td>
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<td></td>
<td></td>
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<tr>
<td>W5e</td>
<td>1.95</td>
<td>Cmgt + Opx + Hbl</td>
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<td>0.93</td>
<td>3.48</td>
<td>10 Rotoma</td>
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<td>W7a</td>
<td>0.6-0.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.94</td>
<td>2.77</td>
<td>10 Taupo</td>
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<td>W7b</td>
<td>0.85-0.89</td>
<td></td>
<td></td>
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<td>1.82</td>
<td>2.83</td>
<td>10 Waimihia</td>
<td></td>
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<td></td>
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</table>

Note: * recalculated to 100%. Figure in brackets is the standard deviation, n = number of analyses.
Table 3. Tephra Radiocarbon age cal. age (ka) References

<table>
<thead>
<tr>
<th>Tephra</th>
<th>Radiocarbon age</th>
<th>cal. age (ka)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taupo</td>
<td>1850 ± 10</td>
<td>1.8</td>
<td>Froggatt and Lowe, 1990, Wilson, 1993</td>
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<tr>
<td>Waimihia</td>
<td>3280 ± 20</td>
<td>3.5</td>
<td>Froggatt and Lowe, 1990</td>
</tr>
<tr>
<td>Whakatane</td>
<td>4830 ± 20</td>
<td>5.5</td>
<td>Froggatt and Lowe, 1990</td>
</tr>
<tr>
<td>Mamaku</td>
<td>7250 ± 20</td>
<td>8.1</td>
<td>Froggatt and Lowe, 1990</td>
</tr>
<tr>
<td>Rotoma</td>
<td>8530 ± 10</td>
<td>9.5</td>
<td>Froggatt and Lowe, 1990</td>
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<tr>
<td>Waiohau</td>
<td>11,850 ± 60</td>
<td>13.8</td>
<td>Froggatt and Lowe, 1990</td>
</tr>
<tr>
<td>Rerewhakaaitu</td>
<td>14,700 ± 110</td>
<td>17.6</td>
<td>Froggatt and Lowe, 1990, Newnham et al., 2003</td>
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<tr>
<td>Okareka</td>
<td>c. 18,000</td>
<td>c. 21</td>
<td>Froggatt and Lowe, 1990</td>
</tr>
<tr>
<td>Kawakawa</td>
<td>22,590 ± 230</td>
<td>26.5</td>
<td>Wilson, 2001</td>
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Table 4.
## Calculation of downcutting rates

<table>
<thead>
<tr>
<th>Terrace level</th>
<th>Corrected elevation collar height (m)</th>
<th>Age (Cal. yrs B.P.)</th>
<th>Stratigraphic thickness (m)</th>
<th>Downcutting from adjacent level including sediment thickness (m)</th>
<th>Age difference (kyr)</th>
<th>Interval downcutting rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>187</td>
<td>18,000-19,000?</td>
<td>aggradation -</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>W2</td>
<td>184</td>
<td>c. 16,000?</td>
<td>2.5</td>
<td>5.5</td>
<td>?2.0-3.0</td>
<td>?1.8-2.8</td>
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<tr>
<td>W3</td>
<td>178</td>
<td>9124-9485</td>
<td>3.4</td>
<td>7.1</td>
<td>6.5-6.9</td>
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<td>W4</td>
<td>171</td>
<td>8603-9022</td>
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<td>6.6</td>
<td>0.1-0.8</td>
<td>8.2-66.0</td>
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<td>W5</td>
<td>165</td>
<td>8742-9348</td>
<td>2.2</td>
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<td>&lt;0.5?</td>
<td>&gt;10</td>
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<tr>
<td>W6</td>
<td>162</td>
<td>7954-8292</td>
<td>3.4</td>
<td>4.2</td>
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<td>3.0-10.5</td>
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<tr>
<td>W7</td>
<td>155</td>
<td>&gt;3898-4247</td>
<td>2.9</td>
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<td>&lt;3.7-4.3</td>
<td>&gt;1.5-1.8</td>
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<td>W8</td>
<td>144</td>
<td>1404-1698</td>
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<td>10.3</td>
<td>&gt;2.2-2.8</td>
<td>&lt;3.7-4.7</td>
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<tr>
<td>W9</td>
<td>141</td>
<td>0-300</td>
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<td>1.1-1.7</td>
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<tr>
<td>River</td>
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<td></td>
<td>0.5</td>
<td>0.3</td>
<td>&lt;1.6</td>
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</table>
Figures

Fig. 1. A New Zealand Australian - Pacific plate boundary setting. B Tectonic setting of Raukumara Peninsula. C Geology of the Waipaoa catchment showing the location of the Otoko - Gold Creek river section of the Waihuka River.

Fig. 2. Longitudinal profiles of the Waihuka and Waipaoa Rivers and the last glacial maximum age Waipaoa 1 and Waihuka 1 river terraces.

Fig. 3. Waihuka river terraces, abandoned meanders and alluvial fans in the Otoko – Gold Creek area. Map coordinates are in New Zealand Map Grid projection, and elevations are representative spot heights from RTK GPS transects. The present-day river and meanders are projected to a valley centerline and consequently have steep apparent reaches in meanders.

Fig. 4. Detailed terrace profile showing auger and drillcore locations (arrows), and radiocarbon ages (in cal. ka). Tephra ages (cal. ka) are underlined. All river (filled circles) and terrace (crosses) elevations were measured with RTK GPS. Solid lines delineate terraces or meander channels on the true right of the Waihuka, and dashed lines are terraces or meander channels on the true left.

Fig. 5. Stratigraphic columns of auger and drillcores W1-9. All ages are radiocarbon ages, given as cal. ka. Sample ages are marked with a filled black circle and tephra ages are marked with an asterisk and are underlined.

Fig. 6. FeO - 1/3 K\textsubscript{2}O plot of electron microprobe analyses of glass shards of tephra samples obtained from river meander and terrace core. Ellipses for the tephras listed in Table 1 are also shown.

Fig. 7. Present-day profiles of the Waihuka River in the Otoko – Gold Creek area (i) projected to a valley centerline, and (ii) following the channel. The latter shows an average down-valley gradient of 20.5 m/km and many apparently steeper reaches, while the straightened profile (i) averages 14 m/km, and shows only a single steeper section.

Fig. 8. A Terrace profile with interpretation of terrace correlations and abandonment age. Shaded area represents the episode of knickpoint retreat. B Schematic, vertically exaggerated representation of terrace architecture illustrating initial terrace-parallel downcutting, a steeper middle episode of rapid erosion as knickpoint
retreat passed this locality in the valley, and then a more recent return to terrace-
parallel downcutting.

Fig. 9. Downcutting rates versus time for the Waihuka River in the Otoko – Gold Creek
section. Arrows indicate whether the calculated downcutting rate is maximum or
minimum, while the shaded part of the box represents the uncertainty based on
accepted values. Note the break in age between 15 and 10 ka on the age-axis.

Fig. 10. Cross-sections across the Waihuka Valley showing the geometry excavated below
Waihuka 1 terrace. See Fig. 3 for section locations. amsl = above mean sea level.

Fig. 11. A Cross-valley section B showing the elevations of terraces W1-9 for calculation
of excavation volumes. amsl = above mean sea level. B Valley excavation rates
plotted with respect to time.
Miocene to Quaternary melange
Pliocene sandstone, mudstone
Miocene limestone, sandstone, mudstone, and conglomerate
Late Cretaceous to early Tertiary mudstone and sandstone
Quaternary gravel, sand, mud, tephra

Berryman et al. Figure 1
Berryman et al. Figure 2
Alluvial fans
Waihuka 1 terrace
Abandoned meanders
River terraces

GPS elevation measurement (m)
X-section location (Fig. 10)

Other topographic features (risers, ridges)
Alluvial fans
Abandoned meanders
River terraces
Waihuka 1 terrace

Berryman et al. Figure 3
Medium-coarse sand, sparse pebbles - reworked tephra sample

W2(b) = Rerewhakaaitu

Very firm, green-grey clean fine sand, with iron concentration bands

Topsoil

Bioturbated topsoil + Waimihia Tephra

Mixed subsoil & pale grey-green tephra

Creamy white, mottled tephra

White tephra, sample W2(a) = Whakatane

Green-grey slightly mottled tephric sand with manganese nodules

Green-grey fine tephric sand

Pale green-grey tephric sand, moderately mottled, minor manganese staining

Heavily mottled tephric sand, firm, orange-white, with manganese nodules

Coarse sand and fine pebbly gravel, brown, firm

Firm, massive, green-grey Tephric fine sand

Firm, green-grey tephric fine sand, lightly mottled at top, increasing to base, manganese nodules increase to base

Concentrated horizon of iron/manganese nodules in sand

Medium grained sand, sparse pebbles - reworked tephra sample W1(b) = Karetaihaka

Very firm, green-grey clean fine sand, with iron concentration bands

Fine sandy gravel

Organic topsoil with Taupo lapilli

Bioturbated, mixed horizon of topsoil and tephra

Creamy white sandy tephra, coarse near top, fining to base

Firm, green, tephric silty sand, mottled with manganese nodules

Compacted, creamy-white, fining upward (coarse-medium sand) tephra

Green-grey clayey silt & fine sand, with strong manganese concentration at top, mottled, and with many organic fragments

Coarse tephra with fine base and abundant wood fragments

Blue-grey medium sand, highly tephric throughout, some lapilli to 1 mm, tephric lamellae in discrete horizontal

Coarse white tephra, large wood fragments, samples W3(a) and W3(b) = Rotoma

Green-grey clay with organics

Alternating blue-grey silty fine sand & brown organic sticky silt

Brown organic sticky silt, sample W3(c) from base of section

Mudstone bedrock

Berryman et al. Figure 5A
W8 149 m

0.20 meters
Yellow-brown flood silt with reworked tephra

0.36 meters
Buried, organic rich brown topsoil

0.51 meters
Yellow-brown, massive tephric silt

0.62 meters
Grey-brown, slightly organic, iron stained silt

0.69 meters
Organic grey-brown silt

0.84 meters
Yellow-orange, sandy tephra (possibly reworked) with organics

0.93 meters
Brown organic silt with large wood fragments

1.16 meters
Green-brown clayey silt with large wood fragments

1.31 meters
Blue-green fine tephric sand with disseminated organic fragments

1.51 meters
Massive, blue-green fine sand with large wood fragments

1.54 meters
Pale brown, compact organic silt with disseminated organics, sample W8(a)

1.94 meters
Green-brown alternating organic-rich and clay-rich clayey silt, sample W8(b)

2.33 meters
Blue-grey sandstone bedrock

W9 156 m

0.44 meters
Grey-black topsoil

0.55 meters
Coarse yellow-brown sand

0.60 meters
Dark grey sandy paleosol

0.65 meters
Thin yellow-brown silt

1.30 meters
Coarse yellow-orange, sand with finely disseminated organics

1.55 cal. ka

0.15 cal. ka

2.00 meters
Blue-green fine to medium sand with organic fragments, sample W9(a)

2.50 meters
Blue-grey sandstone bedrock
Berryman et al. Figure 6
sinuosity = 1.43
average gradient = 20.5 m/km

Berryman et al. Figure 7
Berryman et al. Figure 9
Berryman et al. Figure 10
Berryman et al. Figure 11