Correlation of fluvial terraces within the Hikurangi Margin, New Zealand: implications for climate and baselevel controls

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Abstract

A correlation of fluvial terraces is presented for eight non-glacial catchments of the eastern North Island, New Zealand, within the actively uplifting Hikurangi Margin. Using a combination of loess and tephra covered stratigraphy, and radiocarbon and OSL dating of fluvial deposits and loess coverbeds, we demonstrate correlation of four fill terraces, T1–T4. The available age constraints suggest T1=15–30 ka, T2=31–50 ka, T3=50–70 ka, and T4=~115 ka, but the association and temporal link with loess deposits suggest correlation with cold periods, and thus the refinement of T2=late MIS 3 (31–40 ka), T3=MIS 4 (55–70 ka), T4=MI Substage 5b (~90 ka), 5d (~110 ka), or MIS 6 (~140–160 ka). The ability to correlate terraces between catchments, plus the lack of independent evidence for tectonic triggering events, indicates terraces have probably formed in response to either climate (terrestrial) or baselevel (sea level) control. Climate control is indicated by the temporal link of post-glacial incision with re-establishment of forest cover, and of LGM aggradation with limited grass and shrub cover and periglacial processes. Aggradation due to increased sediment supply under reduced vegetation is dramatically demonstrated by formation of the Taupo Pumice Alluvium terrace in response to inundation by volcanic deposits (unwelded ignimbrite) following the 1.8 ka Taupo eruption, and the response to post-settlement (<500 yr BP) deforestation. The upstream limit of post-glacial baselevel control is recorded by a post-glacial sediment wedge burying older terraces in six catchments. In one catchment, the inner (landward) edge of the wedge is a mid-Holocene fill terrace, interpreted to have formed in response to the post-glacial sea level highstand, and thus is a baselevel-controlled terrace. Evidence defining the downstream extent of climate control during the LGM (and thus the upstream limit of baselevel-controlled lowstand incision) is now buried beneath the continental shelf, but limited fluvial features on the inner shelf (<20 km offshore), and LGM aggradation despite a range of shelf gradients indicate climate-induced aggradation probably extended at least to the present day inner shelf.

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Keywords: Fluvial terraces; Aggradation; Climate; Baselevel; Tephra; Loess

1. Introduction

A fluvial terrace records the former bed level of a river, and can be classified as either aggradational (fill) or degradational (fill-cut or strath) (e.g., Bull, 1990).
The switch between aggradation and degradation behaviour of the rivers occurs in response to a change in one or more of external controls including climate, total catchment relief, baselevel, bedrock lithology, tectonics, and human activities (Bull, 1991). In recent years the role of climate has received considerable attention (e.g., Antoine, 1994; Fuller et al., 1998; Macklin et al., 2002; Jain and Tandon, 2003; Starkel, 2003; Pan et al., 2003). Blum and Tornqvist (2000) highlight an apparent emerging mismatch between the role of climate versus sea level. For example, in many non-glacial basins, fill terraces appear to have been constructed during glacial periods in response to increased sediment supply (e.g., Zeuner, 1945; Vella, 1963; Milne, 1973a; Yoshikawa et al., 1981; Porter et al., 1992; Sugai, 1993; Fuller et al., 1998; Bridgland, 2000 and references therein), whereas in sequence stratigraphy models glacial periods (i.e. sea level lowstands) are viewed as times of erosion (river incision) and sediment by-passing (e.g., Posamentier and Vail, 1988; Zaitlin et al., 1994; Blum and Price, 1998; Talling, 1998). In reality there is a transition point between the two, which may vary widely for different tectonic and climatic settings (e.g., Merritts et al., 1994; Blum and Tornqvist, 2000).

Fluvial terrace studies in New Zealand have also traditionally been viewed from a climate-controlled (i.e. an upland or geomorphological) perspective (e.g., Pillans, 1991 and references therein), but recently the role of other controls such as sea level (baselevel) and tectonics has started to be addressed (e.g., Leckie, 1994; Browne and Naish, 2003; Berryman et al., 2000, submitted for publication). Most of the fluvial terrace studies to date have also been on an individual river or catchment basis (e.g., Powers, 1962; Vella, 1963; Soons and Gullentops, 1973; Vella et al., 1988; Yoshikawa et al., 1988; Palmer et al., 1988; Eden, 1989; McIntosh et al., 1990; Bull, 1991, chapter 5; Almond, 1996; Berryman et al., 2000), albeit with limited correlations to well preserved terrace flights such as the Rangitikei valley terraces in the lower North Island (Milne, 1973b) and glacial outwash terraces in north Westland, South Island (e.g. Suggate, 1985; Suggate and Waight, 1999). In this study we show that fill terraces in particular can be correlated on a regional scale, throughout the eastern North Island, and thus that terrace formation has been in response to the same external control(s).

A key to correlating terraces, independent of models of the mode of their formation, is dating. An advantage to studying fluvial terraces in the eastern North Island is the ability to use tools such as loess stratigraphy and tephrochronology. Loess and tephra are particularly well preserved as coverbeds on fluvial terraces, and provide minimum ages for the underlying terrace deposits as well as aiding correlation between catchments. Numeric ages are also available by both radiocarbon and luminescence dating. Although generally sparse, organic material is present as wood within the gravel-dominated deposits, and also occurs as peat in terrace cover deposits, and charcoal within tephras. Luminescence dating is being increasingly used in New Zealand to extend age control beyond the limits of radiocarbon dating, and has particularly been used to date loess (e.g., Berger et al., 1992, 2001, 2002; Litchfield and Lian, 2004). The present study is the first to apply Optically Stimulated Luminescence (OSL) dating directly to fluvial deposits in the eastern North Island, although OSL ages of loess coverbeds have been used to estimate the minimum ages of river terrace deposits (Wang, 2001; Formento-Trigilio et al., 2003).

The aims of this paper are thus: (i) to describe and correlate fluvial terraces in the eight major catchments of the eastern North Island, (ii) to summarise and examine age constraints for the terraces, and (iii) to discuss the mechanisms of terrace formation, with particular attention to the relative effects of climate and baselevel control.

2. Regional setting

The eastern North Island comprises a zone of ranges and basins formed in response to tectonics associated with the Hikurangi Subduction Margin between the Australian and Pacific Plates (Fig. 1). The ranges can be subdivided into the axial ranges, which are the basement-cored frontal ridge, or backstop, and the lower elevation coastal ranges, comprising the partially uplifted forearc basin and outer arc high (e.g., Lewis and Pettinga, 1993). The average elevation of the axial ranges is 1300 m, and the maximum is 1752 m near the north end (Mt. Hikurangi, Fig. 2). They form a major drainage divide and topographic barrier.
which forms a rain shadow in the wake of the prevailing westerly wind direction.

The eight major river catchments of the eastern North Island drain 23,800 km², and flow generally east from their headwaters in the axial ranges (Figs. 1 and 2). Trunk rivers are up to seventh or eighth order and range in length from 108 to 237 km, draining catchment areas of 1700–5900 km². Mean annual flow rates in the lower reaches range from 34 to 102 m³ s⁻¹ (Duncan, 1992). The rivers are typically bedrock channels (e.g., Tinkler and Wohl, 1998) in their upper catchments, and gravel or sand bed rivers in the lower reaches. Bedrock is predominantly Triassic to Early Cretaceous greywacke and argillite in the axial ranges, and Cretaceous to Pleistocene sandstone, mudstone, limestone, and conglomerate in the coastal ranges (uplifted forearc) (Field and Uruski, 1997). The majority of units strike northeast–southwest and in the coastal ranges the limestones in particular form strike ridges that locally divert drainage.

The present day climate of the eastern North Island is warm temperate (average annual temperature ~15 °C), with a northwest–southeast rainfall gradient from a maximum of ~6500 mm yr⁻¹ in the crests of the axial ranges to ~800 mm yr⁻¹ in the driest parts of the coastal lowlands, with slightly higher rainfall occurring in winter (NZ Meteorological Service Climate Summary Data, http://www.metservice.co.nz). Prior to deforestation following Maori (~500 yr BP) and European (commencing in the 1820s) settlement, the eastern North Island was almost completely vegetated with podocarp/hardwood (mainly conifer) forest in the lowlands, Nothofagus forest at higher altitudes, and alpine–subalpine shrubland and grasslands on the highest parts of the axial ranges (McGlone, 1988; Wilmshurst, 1997). Except for some very small glaciers
in the southern axial ranges (e.g., Stevens, 1990), the headwaters of the eastern North Island catchments were not glaciated during the glacial periods.

3. Methods

Terrace mapping was undertaken along the trunk rivers of the eight major catchments, selected on the basis of stream order. Due to the large size of catchment 6, it was subdivided into two sub-catchments (6a and 6b, Fig. 2) of which the trunk rivers converge ~11 km upstream from the coast. Field mapping was undertaken at 1:50,000 scale, either to supplement, or to field check, pre-existing data, and focussed primarily on the topographic sequence of aggradational terraces and the stratigraphy of terrace deposits and coverbeds (Figs. 3 and 4). Degradational
Terraces were mapped primarily from aerial photographs. Natural streambank and roadcut exposures were logged, along with hand auger holes on terrace-treads. Two examples of terrace maps are shown in Figs. 5 and 6, and the complete set of maps and stratigraphic sections is contained in Litchfield (2003). It should be noted, however, that a small number of terrace correlations have been reinterpreted since the report of Litchfield (2003) in light of newly acquired OSL ages (Litchfield and Rieser, submitted for publication).

Terrace age control was obtained using loess and tephra stratigraphy, radiocarbon and OSL dating, and the full set of available ages is compiled in Litchfield (2003). Tephra was identified in the field where possible, with additional identification from heavy mineral assemblages and electron microprobe analysis of glass shards. Tephra used for dating fluvial terraces are listed in Table 1. Loess was also subdivided in the field, but is often difficult to distinguish in isolation; instead units are often identified by their association with key tephras (Figs. 3 and 4). Regionally extensive loess units are numbered from youngest to oldest (Loess 1–Loess 3). Radiocarbon ages are given as calibrated ka unless otherwise stated. Radiocarbon ages <20 ka were
Fig. 4. Exposures of fluvial deposits and coverbed deposits of T1, T2, T3, and the Taupo Pumice Alluvium terrace. (A) T1 fluvial deposits (gravel and silt) and tephra cover exposed in catchment 6a. Sample site for WAIU13 is out of view to left at approximately the stratigraphic position where labelled. See Fig. 2 for location. (B) The ~26.5 ka Kawakawa (Kk) Tephra within T1 fluvial silt deposits in catchment 6a. Note the distinctive thin (1–2 cm) white base and primary (shower) bedding. See Fig. 6 for location. (C) The Kawakawa Tephra (Kk) within loess cover on T2 fluvial gravel in catchment 2. See Fig. 6 for location. (D) The Kawakawa Tephra (Kk), ~31 ka Omataroa (Om), and 43–50 ka Rotoehu (Re) tephras within loess cover on T3 fluvial gravel in catchment 6a. See Fig. 6 for location. (E) The Taupo Pumice Alluvium terrace in catchment 5. Note the exposures of white, fluvially reworked ignimbrite (pumice) and the hummocky surface. See Fig. 2 for location.
calibrated using Calib 4.4 (Stuiver et al., 1998) and a southern hemisphere correction curve (McCormac et al., 2002), and for >20 ka, using the formula of Bard (1998). Eighteen new OSL ages were obtained from the Victoria University of Wellington Luminescence Dating Laboratory. Most ages were obtained from polymineral silt samples by the Multiple Aliquot Additive Dose technique with late-light subtraction (Aitken and Xie, 1992), while two ages were obtained from sand sized quartz samples by a Single Aliquot Regenerative (SAR) protocol (Murray and Wintle, 2000). The details are described in Litchfield and Rieser (submitted for publication). The uncertainties for all OSL ages are quoted at 1σ.

4. Description of fill terraces

The terraces mapped in the eastern North Island and their age control are summarised in Table 2. Fig. 3B shows a schematic cross-section summarising the relationship between terrace fluvial deposits, and loess and tephra coverbeds. Both degradational (for brevity hereafter referred to as cut) and aggradational (hereafter referred to as fill) terraces are present in each catchment (e.g., Fig. 3A). Cut terraces (strath or fill-cut) are usually narrow, unpaired across-river, and, where exposed, have thin (usually <3 m) fluvial deposits, typically of sub-rounded, pebble-boulder gravel. Cut terrace fluvial deposits rest on either a
bedrock strath, or older fill deposits (Fig. 3). Anecdotal evidence from limited exposures suggests the cut terrace fluvial deposits are coarser than fill terrace deposits, but this warrants detailed investigation. Fill terraces are comparatively broader, generally paired, and have generally thick (≤30 m, but typically 5–6 m) fluvial deposits of sub-rounded, pebble–cobble gravel (locally cross-bedded), sand, and/or silt, resting on a bedrock strath. Although the strath is not always well exposed, we have not observed any systematic variation in fluvial deposit thickness along the length of the rivers. Terraces generally converge downstream, and are best preserved downstream of the axial ranges (within 25–80 km). In the lower reaches, where the valleys generally widen into broad floodplains, terraces are progressively buried beneath younger marine and alluvial deposits (e.g., Fig. 6).

The highest terraces (T1–T4) are generally fill terraces, and these form the main focus of this study. In each catchment there is one widely preserved fill terrace, T1, which is characterised by little (<1 m) or no loess cover, a tephra cover in the north (e.g., Fig. 4A), and relatively thick gravel and/or silt fluvial deposits resting on a bedrock strath (Fig. 3B). In the south (catchments 1–4), where the rivers drain across broad tectonic basins, the gravel-dominated T1 terraces form large east-draining coalescing alluvial fans that now stand up to 55 m above river level. A range of ages from their coverbeds suggests the age of the terrace/fan-tread is in part diachronous (Litchfield,
2003). In the north, where the valleys are narrower, terraces are less continuous and form small remnants up to 200 m above river level. In addition, in catchments 6–8 the fluvial deposits are silt dominated, reflecting the greater proportion of Miocene silt bedrock there. In eleven locations (Fig. 2) primary and/or reworked ~26.5 ka Kawakawa Tephra occurs within T1 fluvial silt (e.g., Fig. 4B). In the north, the Mangamate (~11.3 ka), Waiohau (~13.7 ka), and/or Rerewhakaaitu (~17.7 ka) tephras rest directly on terrace deposits (Table 2).

Up to three higher fill terraces (T2–T4) are variably preserved in each catchment, generally best preserved in the downstream reaches. From the sparse exposures available, T2–T4 gravels appear to be similar in clast size and thickness to T1 gravels. Loess coverbeds are particularly well preserved in the south, although there is evidence for wind-stripping in the upper reaches of terraces 1, 3, and 4 (e.g., Eden and Hammond, 2003). The Kawakawa Tephra (~26.5 ka) occurs within the uppermost loess (Loess 1) on T2–T4 in catchments 1–7 (Figs. 3B and 4C), but does not appear to have been deposited in catchment 8. In catchments 5–7, the Omataroa Tephra (~31 ka) occurs beneath Loess 1, and the Rotoehu Tephra (~43–50 ka) occurs beneath Loess 2 (also in catchments 3 and 8) (Figs. 3B and 4D; Table 2). Loess thickness varies, the maximum thickness measured is 7 m, but typically they are 1–3 m thick.

Below T1 is a suite of predominantly cut terraces, which have not been traced along the length of the rivers, dated, or attempted to be correlated between catchments. These are collectively called Post-T1 Cut terraces (Fig. 3).

<table>
<thead>
<tr>
<th>Tephra name (including Bullot Formation)</th>
<th>Symbol</th>
<th>Conventional $^{14}C$ age (ka)</th>
<th>Calibrated age (ka)</th>
<th>Tephra age reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taupo</td>
<td>Tp</td>
<td>1.85±0.01</td>
<td>1.7–1.8</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Waimihia</td>
<td>Wm</td>
<td>3.28±0.02</td>
<td>3.5–3.6</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Whakatane</td>
<td>Wk</td>
<td>4.83±0.02</td>
<td>5.5–5.6</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Mamaku</td>
<td>Ma</td>
<td>7.25±0.08</td>
<td>8.0–8.2</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Rotoma</td>
<td>Rm</td>
<td>8.53±0.01</td>
<td>9.5</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Karapiti</td>
<td>Kp</td>
<td>9.82±0.08</td>
<td>10.7–11.5</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Waiohau</td>
<td>Wh</td>
<td>11.85±0.06</td>
<td>13.4–14.1</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Rerewhakaaitu</td>
<td>Rk</td>
<td>14.7±0.11</td>
<td>17.1–18.2</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Kawakawa (including Aokautere Ash)</td>
<td>Kk</td>
<td>22.59±0.23</td>
<td>26.3–26.9</td>
<td>Froggatt and Lowe (1990)</td>
</tr>
<tr>
<td>Omataroa</td>
<td>Om</td>
<td>26.52±0.22</td>
<td>30.8–31.3</td>
<td>Jurado-Chichay and Walker (2000)</td>
</tr>
<tr>
<td>Rotoehu</td>
<td>Re</td>
<td>43–50</td>
<td>50–60</td>
<td>Lian and Shane (2000), Santos et al. (2001)</td>
</tr>
<tr>
<td>MIS 4 tephric paleosol</td>
<td></td>
<td></td>
<td>60–70</td>
<td>A. Palmer pers. comm. 2003</td>
</tr>
<tr>
<td>Fordell Ash</td>
<td></td>
<td></td>
<td>280–300</td>
<td>A. Palmer pers. comm. 2003</td>
</tr>
<tr>
<td>Rangitawa (including Mount Curl Tephra)</td>
<td></td>
<td>345±12</td>
<td></td>
<td>Pillans et al. (1996)</td>
</tr>
</tbody>
</table>

- $^{14}C$ age is after Froggatt and Lowe (1990).
- Tephra age references are after Froggatt and Lowe (1990) unless otherwise noted.
- MIS 4 tephric paleosol is after Lian and Shane (2000), and Santos et al. (2001).
- Fordell Ash age is after A. Palmer pers. comm. 2003.
- Rangitawa age is after Pillans et al. (1996).
Table 2
Summary of fluvial terraces mapped along the trunk rivers in the eight major catchments in the eastern North Island

<table>
<thead>
<tr>
<th>Catchment number</th>
<th>River name</th>
<th>Taupo Pumice Alluv.</th>
<th>Mid-Holocene Fill</th>
<th>Post-T1 Cut</th>
<th>T1 (Fill)</th>
<th>T2 (Fill)</th>
<th>T3 (Fill)</th>
<th>T4 (Fill)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Waiapu</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rk (~17.7 ka) cover</td>
<td>Silt and sand fluvial dep.</td>
<td>OSL ages 16.3±1.5, 17.0±1.5 ka</td>
<td>Re (~43 – 50 ka) cover</td>
</tr>
<tr>
<td>7</td>
<td>Waipaoa</td>
<td>Wood in fluvial dep.</td>
<td></td>
<td></td>
<td>Rk (~17.7 ka) cover</td>
<td>1 loess cover with Kk (~26.5 ka)</td>
<td>Om (~31 ka) cover (beneath loess)</td>
<td>2 loess cover(a)</td>
</tr>
<tr>
<td>6b</td>
<td>Hangaroa</td>
<td>Wood in fluvial dep.</td>
<td></td>
<td></td>
<td>Wh (~13.7 ka) cover</td>
<td>1 loess cover with Kk (~26.5 ka)</td>
<td>Om (~31 ka) cover (beneath loess)</td>
<td>Silt fluvial dep.?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kk in fluvial dep.</td>
<td>Kk in fluvial dep.</td>
<td>Kk (~26.5 ka) in fluvial dep.</td>
<td></td>
</tr>
<tr>
<td>6a</td>
<td>Waiau</td>
<td>Tp fluvial dep. cover</td>
<td></td>
<td></td>
<td>Wh (~13.7 ka) cover</td>
<td>Silt fluvial dep.</td>
<td>OSL age 19.6±2 ka Kk (~26.5 ka) in fluvial dep.</td>
<td>Re (~43 – 50 ka) cover (beneath loess)</td>
</tr>
<tr>
<td>5</td>
<td>Mohaka</td>
<td></td>
<td></td>
<td></td>
<td>Rk (~17.7 ka) cover</td>
<td>1 loess cover with Kk (~26.5 ka)</td>
<td>Om (~31 ka) cover (beneath loess)</td>
<td>2 loess cover</td>
</tr>
<tr>
<td>Location</td>
<td>Notes</td>
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<td></td>
</tr>
<tr>
<td>Ngaruroro</td>
<td>Loess 1 cover</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OSL age 18±1.8</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loess 2 cover</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OSL age 39.7±2.5</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

| Tukituki      | Loess 1 cover                                                       |
|               | OSL age 18±1.8                                                       |
|               | Loess 2 cover                                                       |
|               | OSL age 39.7±2.5                                                    |

| Manawatu      | Loess 1 cover                                                       |
|               | OSL age 18±1.8                                                       |
|               | Loess 2 cover                                                       |
|               | Re (~43–50 ka) cover                                                 |
|               | (beneath loess)                                                     |

| Ruamahanga    | Loess 1 cover                                                       |
|               | OSL age 18±1.8                                                       |
|               | Loess 2 cover                                                       |
|               | OSL age 39.7±2.5                                                    |

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* denotes the presence of terrace, below is listed the key age control. See Table 1 for tephra abbreviations.

- Tentative correlations based on the OSL ages (Litchfield and Rieser, submitted for publication).
- Eden et al. (2001).
- Berryman et al. (2000).
- Begg et al. (2001).
- Palmer et al. (1989).
publication) studied a suite of nine cut terraces in a tributary of the trunk river of catchment 7, where tephra cover and material suitable for radiocarbon dating are preserved within incised meanders. They obtained ages of 0.15–18 ka, indicating they record post-glacial (post-Termination; e.g., Newnham et al., 2003) degradation.

Within the Post-T1 Cut terrace sequences in catchments 5 and 6, two fill terraces are sometimes present. In the lower reaches of catchment 6, a paired, fluvial silt terrace, that progressively buries older terraces (Fig. 6), contains wood (15 m below the terrace surface) radiocarbon dated at ~7.3 ka (Litchfield, 2003). The terrace is thus interpreted as a correlative of the buried 5–7 ka (conventional age) Waipaoa Gravel traced in groundwater bores in the lower reaches of catchment 7 (Brown, 1995). This fill terrace is hereafter referred to as the mid-Holocene fill terrace and its origins are discussed in Section 6.2.1. In catchments 5–6, a set of fill and fill-cut terraces composed of pumice alluvium (e.g., Figs. 4E and 6) has formed by fluvial reworking of 1.8 ka Taupo Ignimbrite (Wilson and Walker, 1985; Segschneider et al., 2002). The uppermost, fill, terrace is characterised by a hummocky surface (e.g., Fig. 4E), and is hereafter referred to as the Taupo Pumice Alluvium terrace (‘tpi’ of Cutten, 1994). Segschneider et al. (2002) estimate the entire sequence of fill and fill-cut terraces were formed within 17 yr of the 1.8 ka eruption. In the lower reaches of catchment 6a, Taupo Pumice Alluvium locally buries the mid-Holocene fill terrace (Fig. 6).

5. Terrace correlations and ages

In this section we propose the correlation of fill terraces T1–T4 between catchments and assign their ages as summarised in Table 3.

T1 has the best age control, and we propose it is the same age (15–30 ka; approximately the Last Glacial Maximum) in each catchment, for the following reasons:

(i) The ~26.5 ka Kawakawa Tephra (Kk) has been identified within T1 fluvial deposits in five catchments (1, 2, 5, 6a, 7) (Fig. 2; Table 2). The stratigraphic position of the tephra within the

<table>
<thead>
<tr>
<th>Terrace name, this study</th>
<th>Terrace age, this study (ka)</th>
<th>MIS Correlation</th>
<th>Rangitikei terrace name&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Rangitikei terrace age (Milne, 1973a,b) (ka)</th>
<th>Rangitikei terrace age (Pillans, 1994) (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-T1 Cut (not differentiated)</td>
<td>&lt;1.8</td>
<td>1</td>
<td>Kakariki</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taupo Pumice Alluvium</td>
<td>1.8</td>
<td>1</td>
<td>Onepuhi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Holocene fill</td>
<td>5.7–7.7</td>
<td>1</td>
<td>Rewa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-T1 Cut (not differentiated)</td>
<td>1.8–18</td>
<td>1</td>
<td>Bulls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>15–30</td>
<td>2</td>
<td>Ohakea 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>31–50</td>
<td>3 (31–40)</td>
<td>Rata</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>50–80</td>
<td>4 (55–70)</td>
<td>Porewa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4?</td>
<td>115</td>
<td>5b (~90?)</td>
<td>Cliff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4?</td>
<td>5d (~110?)</td>
<td></td>
<td>Greatford</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4?</td>
<td>6 (~140–160?)</td>
<td></td>
<td>Marton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T4?</td>
<td></td>
<td></td>
<td>Burnand</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aldworth</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Waituna</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Ages in parenthesis are refined based on correlation with loess and thus with cold periods.

<sup>b</sup> The terrace names of Milne (1973a,b) refer to sets of terraces within 15 m vertical separation, so some include both fill and cut terraces (e.g., Rata) and some are sets of cut terraces (e.g., Bulls and Kakariki).

<sup>c</sup> Terrace-tread ages (i.e., the timing of abandonment of the terrace-tread, not the deposition of the terrace deposits).

<sup>d</sup> Conventional radiocarbon ages.
fluvial deposits varies, but it is generally several metres below the top, indicating that aggradation was occurring simultaneously in these catchments prior to ~26.5 ka. The Kawakawa Tephra has also been described within terrace deposits and fans in other catchments in the eastern North Island (Litchfield, 2003 and references therein) and in the northern South Island (Bull, 1991; Nicol et al., 1994; Little et al., 1998), adding strength to the regional extent of this correlation. The presence of the Kawakawa Tephra and the apparent absence of the ~31 ka Omataroa Tephra provide loose maximum age constraints of ~30 ka.

(ii) Six OSL ages for T1 silt or sand fluvial deposits have been obtained from three catchments (4, 6a, and 8; Table 2; Fig. 7), and range from 15 to 26 ka (at 1σ). A single radiocarbon age of ~26 ka has been obtained from wood within laterally correlative fan deposits from a tributary in catchment 2 (Fig. 7; Hanson, 1998). Although none of these samples were collected from exposures also containing the Kawakawa Tephra, their stratigraphic position within the upper half of the fluvial deposits suggests that aggradation continued for several thousand years after deposition of the Kawakawa Tephra.

(iii) A number of radiocarbon and OSL ages of T1 coverbeds have also been obtained (Table 2; Fig. 7). Radiocarbon ages are from peats within hollows on the terrace-tread, and one sample of charcoal from within the ~13.7 ka Waiohau Tephra (Litchfield, 2003). OSL ages are from thin (<1 m), laterally discontinuous loess deposits. The coverbed ages range from 4 to 18 ka, which only slightly overlaps the youngest fluvial deposit ages (Fig. 7). It should be noted, however, that the coverbed ages as displayed in Fig. 7 are not evenly geographically spread; the majority is from catchment 1.

(iv) The oldest tephra coverbeds resting on fluvial deposits range from 11 to 18 ka (Table 2; Fig. 7). The oldest is the ~17.7 ka Rerewhakaaitu
Tephra, which is present macroscopically only in the far north (catchments 7 and 8), but has been identified microscopically in catchment 5 (Hammond, 1997). The absence of the Rerekawhakaaitu Tephra in the south, plus the lack of fluvial deposit ages in the south and an apparent diachronocity in the fan covered ages, lead us to increase the uncertainty of the terrace-tread age southwards (Fig. 7).

(v) Higher terraces (T2–T4) are overlain by one to three loess coverbeds (Table 2), and in most catchments Loess 1 (the youngest) contains the Kawakawa Tephra. Thus, the presence of the Kawakawa Tephra within both T1 fluvial deposits and loess on older surfaces temporally links the aggradation of T1 and loess deposition, and dates it to the Last Glacial Maximum (e.g., Pillans et al., 1993, discussed further below).

No numerical ages have been obtained for T2 fluvial deposits. The oldest tephra coverbed is the ~31 ka Omataroa Tephra (catchments 5–7), which occurs beneath loess (Table 2). Elsewhere T2 is generally overlain by one loess coverbed, often containing the Kawakawa Tephra within the lower half. OSL ages of 18.5±1.4 and 23.1±1.8 ka have been obtained for loess coverbeds on T2 in catchment 3 (Table 2). Thus, we assign a minimum age of 31 ka for T2. No exposures of tephra within T2 fluvial deposits have been discovered, so the maximum age constraint of 50 ka is loosely based on the terrace deposits post-dating the 43–50 ka Rotoehu Tephra.

T3 generally has two loess coverbeds separated by a paleosol and/or the ~31 ka Omataroa Tephra (north only). In the northern half of the area the 43–50 ka Rotoehu Tephra rests directly on fluvial deposits, beneath Loess 2. One OSL age of 39.7±2.5 ka was obtained for Loess 2 resting on T3 in catchment 4. Three OSL ages ranging from 64 to 81 ka have been obtained from fluvial deposits of terraces initially mapped as T1 or T2 based on height alone (Litchfield, 2003). At least two of these can be reinterpreted as T3, as discussed by Litchfield and Rieser (submitted for publication), and suggest that T3 are more widespread than originally recognised, and that the fill terrace sequence is compressed or expanded in places. Thus, a tentative age for T3 is 50–80 ka, predating the Rotoehu Tephra, and incorporating the OSL ages of fluvial deposits.

T4 is poorly preserved in most catchments. In catchment 7, Berryman et al. (2000) describe three loess coverbeds and the same tephra cover sequence as occurs on T3. We obtained an OSL age of 115.2±11.2 ka from sand terrace deposits originally mapped as T1 (Litchfield, 2003), but the possibility that it is an older terrace cannot be ubiquitously discounted (Litchfield and Rieser, submitted for publication). Berryman et al. (2000) suggested T4 (their Waipaoa 4) formed within Marine Isotope Stage (MIS) 5, at either ~90 (MI Substage 5b) or ~110 ka (MI Substage 5d), and if correct, the ~115 ka OSL age would favour correlation with MI Substage 5d. Another possibility is MIS 6, to which large, well preserved terraces have been correlated in other catchments in the lower North Island (Milne, 1973a,b; Vella et al., 1988; Palmer et al., 1988).

In summary, the ages, and their constraints, for T1–T4 are as follows:

1. T1=15–30 ka, based on coverbed ages of 11–18 ka (tephra) and 4–18 ka (peat, loess), fluvial deposit ages of 15–26 ka, the presence of the ~26.5 ka Kawakawa Tephra, and the absence of the ~31 ka Omataroa Tephra within fluvial deposits.
2. T2=31–50 ka, based on loess coverbed ages of 18–25 ka, one loess coverbed often containing the ~26.5 ka Kawakawa Tephra, which is underlain by the ~31 ka Omataroa Tephra within fluvial deposits.
3. T3=50–80 ka, based on the presence of the ~43–50 ka Rotoehu Tephra beneath two loess coverbeds, a 39.7±2.5 ka OSL age of Loess 2 cover, and 65–81 ka OSL ages of fluvial deposits.
4. T4 is poorly constrained in age. A single OSL age of 115.2±11.2 ka may date this terrace, but requires further investigation. Tentative estimates are ~90, ~110, or ~140–160 ka (MI Substage 5b, MI Substage 5d, MIS 6), based on correlation with other terraces in the lower North Island.

The proposed ages for the fill terraces are similar to those proposed for the Rangitikei valley terraces of...
Milne (1973a,b) and Pillans (1994) (Table 3), with a few notable exceptions. Both these authors gave the age of the T1 equivalent (Ohakea 1), as terrace-tread ages, of 15 (conventional age) and 18 ka, respectively, whereas we assign a terrace age (aggradation duration age) of 15–30 ka. Also, the presence of the Omataroa and Rotoehu tephras at the base of loess coverbeds in the northern half of the eastern North Island constrains the minimum age of T2 and T3 to ~31 and ~50 ka, respectively (Table 3). Finally, in this study only loose maximum age constraints have been provided for T2 and T3, which results in longer age intervals, and is discussed further in Section 6.1.

6. Discussion

We have described a suite of fill and cut terraces in the eastern North Island and shown that fill terraces T1–T4 in particular can be correlated between catchments, based on tephra and loess coverbed stratigraphy, and numerical age control. The correlation suggests that they have formed in response to the same, external control. The eastern North Island is an actively uplifting subduction margin, and the preservation of flights of terraces (i.e., that older terraces are generally not buried by successive aggradation events; Fig. 3), and the spacing between them, is at least in part a function of tectonics. There is, however, no independent evidence for tectonic events triggering the switch between aggradation and degradation. We now explore the relative effects of two other major external controls, climate and baselevel. These controls are not entirely independent, so we make the distinction between terrestrial, or upland, climate-controlled processes, and baselevel-controlled processes related to eustatic sea level fall and rise. We then explore the relative influences of these in different parts of the catchment.

6.1. Climate controls on terrace formation

From the Last Termination (~18 ka) to the present, the eastern North Island rivers have predominantly been incising into bedrock, forming cut terraces. From pollen records, the period ~18 to 13 ka was characterised by an initial rapid spread of podocarp (conifer)-dominated forest, followed by forest stabi-

sation, and then diversification with the introduction of new broadleaf species in the mid-Holocene (McGlone, 1988, 2001; McLea, 1990). McGlone (2001) showed that the rapid spread of podocarp forest during the early post-glacial period was probably closer linked to the decrease in windy conditions (contraction of the glacial westerly system, Shulmeister et al., 2004) than the increase in temperature. Because of the rain shadow effect produced by the interaction of the axial ranges and the westerly winds, a decrease in (westerly) windiness would also have resulted in a relative increase in discharge (stream power) in the eastern North Island, enhancing incision. Thus, there is an association between warmer, wetter climate and river incision (degradation) in the eastern North Island.

The age control presented here for T1 indicates that T1 aggradation was broadly contemporaneous with the Last Glacial Maximum (LGM). Vegetation during the LGM was predominantly scrub and grassland, with only small localised patches of cool-temperate forest (McLea, 1990; McGlone, 2001, 2002). As well as cold temperatures, the vegetation record also indicates that LGM conditions were drier and windier than present (see also Shulmeister et al., 2004), and reworked Tertiary pollen indicates increased erosion (McGlone, 2001). The result of a decreased vegetation (forest) cover on the hillslopes of the eastern North Island is dramatically demonstrated by the response to post-settlement (Maori, ~500 yr BP, and European, ~1820 A.D.) deforestation, best recorded in catchments 8 and 9. Increased shallow landsliding and gully erosion have resulted in aggradation of parts of the riverbed (up to 40 m since measurements began in 1950), and exceptionally high suspended sediment yields (69 Mt yr⁻¹) (Hicks et al., 1996; DeRose et al., 1998; Marutani et al., 1999; Gomez et al., 1999; Page et al., 2001; Reid and Page, 2002).

Besides the reworked pollen, evidence for increased hillslope erosion at the LGM comes from the erosion of tephras erupted during or prior to the LGM, and periglacial features. Roadcut sections and peat bog cores record sequences of Late Glacial and Holocene tephras preserved on the axial ranges, but none older than the ~17.7 ka Rerewhakaaitu Tephra (Vucetich and Pullar, 1969; Yoshikawa et al., 1988; Froggatt and Rogers, 1990; Lowe et al., 1999). In particular, the widespread ~26.5 ka Kawakawa Tephra
is absent above 800 m a.m.s.l. (Pillans et al., 1993), as is the Oruanui Ignimbrite from the same eruption, despite it originally reaching elevations >1000 m (Wilson, 1991). Froggatt and Rogers (1990) also noted that in some of their peat bog sections in the central axial ranges, basal tephra overlies 10–20 cm of angular greywacke fragments, which they attributed to periglacial conditions during the LGM. Similar solifluction deposits have been described for the southern axial ranges by Cotton and Te Punga (1955), Stevens (1957), and Brodie (1957), and Brodie obtained a number of LGM radiocarbon ages of channel deposits within fossil gullies. In lowland areas to the west of the axial ranges deposits below the Rerewhakaaitu Tephra also contain erosion surfaces and less soil development than above (McGlone et al., 1984; Pillans et al., 1993; Kennedy, 1994; Newnham et al., 2003). In summary, there is abundant evidence for periglacial erosion and solifluction during the LGM, which, by analogue with the historic, deforestation-induced hillslope processes resulted in increased sediment supply to the rivers, inducing river aggradation. It should be noted, however, that the modern day gullying and shallow landslide processes are not entirely analogous to the LGM periglacial processes, which Oguchi et al. (2001) describe as sluggish soil movement.

As well as increased sediment supply, the drier conditions during the LGM means discharge (stream power) was decreased. A decrease in discharge would likely promote alluvial fan deposition and increased storage in the upper reaches. Large LGM (T1) alluvial fans are present in the southern catchments, but in the north, gravel fluvial deposits extend to the river mouth, with little evidence of significant downstream fining or thinning (cf. the Late Holocene sediments in catchment 7; Gomez et al., 2001). Thus, discharge decrease was probably less significant for fluvial deposition than sediment supply increase during the LGM in the north.

The strath beneath T1 fluvial deposits is considered to have been cut during a (brief) period of incision (degradation) between the T1 and T2 aggradation events, and is analogous to the post-T1 cut terraces. Where exposed, the strath is generally flat, but in a few places steps can be observed, preserving some of the pre-T1 valley shape (particularly well exposed in the downstream end of catchment 5). A few cut terraces have been mapped above T1, but these are generally poorly preserved and/or exposed, and have not been studied in detail.

The ages of fill terraces T2–T4 are not constrained tightly enough to provide independent evidence of linking with previous cold stadial/glacial periods. However, one of the key features that has lead to North Island fill terraces being linked with cold periods in the past, is their close relationship with loess (e.g., Milne and Smalley, 1979; Palmer et al., 1988; Vella et al., 1988; Pillans, 1991, 1994). That is, successively higher fill terraces have incrementally greater numbers of loess sheets. The deposition of regionally extensive loess sheets has been attributed to the dry, windier conditions of the cold stadial/glacial periods based on palynology, limited dating control of the younger loesses (supported by this study—Table 2), tephrochronology, the presence of paleosols separating loesses, stratigraphic relationship with marine terraces, and the presence of increased detrital quartz in glacial-age deposits in offshore cores (e.g., Milne and Smalley, 1979; Stewart and Neall, 1984; Pillans, 1988; Palmer et al., 1988, 1989; Pillans et al., 1993; Eden and Hammond, 2003 and references therein). In the lower central North Island, Cowie (1964) noted thinning of loess away from rivers, suggesting that aggrading riverbeds provided the main source for loess on higher terraces. The temporal link between fill terraces and correlative loess coverbeds on higher terraces (i.e., T1=Loess 1, T2=Loess 2, etc.) is best constrained for the lower terraces (summarised in Litchfield, 2003), and has been strengthened by the results of this study. In particular, correlations are provided by the presence of the Kawakawa Tephra within both T1 fluvial deposits and Loess 1, and the overlap of T1 fluvial deposits and Loess 1 OSL ages. The single OSL age for Loess 2 also overlaps with the proposed age of T2, although numerical ages for T2 fluvial deposits are lacking. Correlation between fill terraces and cold periods allows the refinement of the ages of T2 and T3, indicating they were probably deposited during the latter, colder part of MIS 3 (31–40 ka), and MIS 4 (~55–70 ka) (Fig. 8). A similar line of reasoning was used by Berryman et al. (2000) for T4 in catchment 7, suggesting correlation with MI Substage 5b, or MI Substage 5d, and we add MIS 6 as a third possibility.
In summary, evidence for post-LGM incision (post-T1 cut terraces), aggradation during the LGM (T1), plus the link between older fill terraces (T2–T4) and cold period loess deposits demonstrates a primary climate control on river aggradation versus degradation. That is, within the non-glacial catchments of the eastern North Island, changes in climate, particularly in wind strength, trigger changes in vegetation, which in turn causes changes in sediment supply. That significant increase in sediment supply results in aggradation is graphically demonstrated by the post-deforestation aggradation in catchments 8 and 9, as well as the deposition of the Taupo Pumice Alluvium terrace in catchments 4, 5, and 6a, following inundation by the Taupo Ignimbrite. Changes in river discharge are likely to be important for controlling the switch to degradation (incision), but only partly important for controlling aggradation.

6.2. Climate versus baselevel (sea level) controls on terrace formation

Thus far we have shown that climate is a major (terrestrial) control for aggradation versus degradation behaviour of the rivers. An important question is how far this influence extends downstream, and where the transition with baselevel control occurs. This transition is not fixed in time and space, and is at least partly concealed beneath sediments on the continental shelf; so we attempt to place constraints on: (1) the upstream limit of baselevel control during sea level highstands, and (2) the downstream limit of climate control during sea level lowstands.

6.2.1. Upstream limit of baselevel control during sea level highstands

Merritts et al. (1994) and Blum and Tornqvist (2000) define the post-glacial upstream limit of baselevel control as the intersection between the modern floodplain and the LGM floodplain surface. In catchments 1–4, 6, and 7, T1 dips beneath, and is buried by, younger alluvial or marine deposits in the downstream reaches (e.g., Fig. 6). Thus, the upstream limit of post-glacial baselevel control is the intersection point of the T1 tread with these younger deposits, which occurs between 8 and 47 km upstream from the coast. Downstream of the intersection point in catchments 4 and 7, T1 fluvial deposits (Matokitoki Gravel and last glacial fluvial and swamp deposits) have been identified in drillholes, and can be traced toward the coast with a seaward dip (Brown, 1995; Dravid and Brown, 1997; Berryman et al., 2000). Above the T1 fluvial deposits is an interfingering wedge of alluvial and marine silts and sands, in which radiocarbon ages of wood and shells range from 400 to 11400 yr BP (conventional ages) (Brown, 1995; Dravid and Brown, 1997). Detailed studies of these deposits demark a prograding post-glacial coastline (Pullar and Penhale, 1970; Brown, 1995; Dravid and Brown, 1997). The seaward dip of T1 fluvial deposits beneath the post-glacial wedge in these catchments is the result of a combination of deposition by rivers grading to the LGM sea level lowstand and/or tectonic subsidence. Holocene rates of tectonic subsidence of 1–6 mm yr⁻¹ have been calculated for catchments 4, 6, and 7 from buried shells within the post-glacial wedge (Ota et al., 1989b; Brown, 1995; Berryman et al., 2000). In contrast, at the downstream ends of catchments 5 and 8, the absence of a post-glacial wedge is interpreted to be the result of uplift and/or coastal erosion. Thus, the added influence of tectonics means that the position of the upstream limit of baselevel control differs between catchments, and likely varies with time (e.g., Merritts et al., 1994).
The inner (landward) edge of the post-glacial wedge in catchment 6 is the mid-Holocene fill terrace. The radiocarbon ages for the mid-Holocene fill terrace indicate it was formed during the post-glacial sea level highstand, ~7.3 ka (Gibb, 1986). Thus, the aggradation is proposed to have occurred in response to the rapid shortening and steepening of the river profile at the sea level highstand, and thus it is a baselevel-controlled terrace. In catchment 6, the terrace is first recognised ~16 km (subcatchment 6a) and ~26 km (catchment 6b) upstream from the coast, and in catchment 7, the correlative, buried Waipaoa Gravel extends from at least 23 km upstream from the coast. Anecdotal evidence suggests that correlative terraces grading to uplifted Early to mid-Holocene estuary deposits (e.g., Ota et al., 1988) are commonly preserved in smaller catchments along the east coast of the North Island, indicating the regional extent of this aggradation event. The poor preservation of Pleistocene marine terraces and MIS 5 fill terraces at the mouths of the eastern North Island rivers means that it is difficult to test whether higher fill terraces grade to previous sea level highstands. We suggest that baselevel-controlled fill terraces such as the mid-Holocene fill terrace are locally restricted near the paleo river mouths, and older terraces have probably been eroded away, or buried in most catchments.

6.2.2. Downstream limit of climate control during sea level lowstands

The downstream limit of climate control during sea level lowstands (and thus the upstream limit of baselevel control) is more difficult to define because it is now buried on the continental shelf. The presence of T1 fluvial deposits exposed at the river mouth in catchment 5, and traced in drillholes at the downstream ends of catchments 4 and 7 (Berryman et al., 2000), indicates that LGM aggradation extended beyond the present coastline. Although not as well exposed and/or constrained in age in drillholes, similar observations can be made for fill terraces T2–T4 (Dravid and Brown, 1997). Offshore, gravel has been sampled in cores within Hawke Bay and Poverty Bay (located in Fig. 2), and some channels imaged seismically offshore of the river mouths of catchments 4, 7, and 8 (e.g., Carter, 1974; Heffer et al., 1976), and the identification of sea level lowstand fluvial deposits and channels on the shelf is the subject of ongoing research.

The presence of LGM age fluvial deposits on the present day continental shelf implies that lowstand baselevel-induced incision was restricted to the middle or outer shelf, but does not entirely rule out baselevel control of at least the nearshore fluvial deposits during falling sea level. For instance, Browne and Naish (2003) show that LGM age fluvial deposits exposed along the Canterbury coast, in the South Island of New Zealand correlates to basinward-thickening, offlapping deposits beneath the present day continental shelf. There the continental shelf has a lower gradient than the coastal plain, and they interpret these deposits as forced regression fluviodeltaic sediments (regressive systems tracts) deposited in the newly created accommodation space during sea level fall (also Leckie, 1994). Regressive systems tract deposits have not been detected offshore of the eastern North Island (P. Barnes, pers. comm., 2004), and furthermore, the geometries of the coastal plain and shelf may preclude them from being deposited. The continental shelf off the eastern North Island is generally narrow and steep, although it locally widens in the vicinity of Hawke Bay embayment and in the southwestern North Island (offshore of catchment 2 river mouth) (Fig. 2). Thus, for many catchments, the shelf was probably too steep to force regression, and besides, the fact that regional-scale LGM aggradation occurred regardless of the coastal plain-shelf geometry implies that aggradation was not the result of baselevel control, and was instead forced by (terrestrial) climate effects, as described in Section 6.1.

In summary, the presence of LGM age fluvial deposits at the present day coast and up to 20 km offshore, implies that baselevel-controlled incision during the LGM was probably restricted to at least the middle, if not the outer shelf. That aggradation during the LGM occurred in all catchments, regardless of the coastal plain–shelf geometries, suggests that forced regression was not the controlling factor for aggradation. Thus, climate control during the sea level lowstands extended downstream at least as far as the present day inner shelf. This has important implications for onshore–offshore correlations, particularly for the interpretation of
seismic horizons as erosional or aggradational. Onshore–offshore correlations is the subject of ongoing work.

7. Conclusions

(i) Fill and cut terraces are widespread in the eastern North Island, and fill terraces in particular can be correlated between catchments. The most widespread (T1) is broadly LGM in age (15–30 ka, ~MIS 2), and is characterised by the presence of the Kawakawa Tephra within fluvial deposits in a few localities, the Rerewhakaaitu Tephra as coverbeds in the north, and everywhere little or no loess cover. Higher terraces can also be correlated primarily from their tephra and loess coverbeds, and available age control constraints suggest T2=31–50 ka and T3=50–80 ka. The association with loess deposits and therefore cool periods place further age constraints, and implies that T2=late MIS 3 (31–40 ka), T3=MIS 4 (55–70 ka), and T4=MI Substage 5b (~90 ka), MI Substage 5d (~110 ka), or possibly MIS 6 (~140–160 ka).

(ii) The correlation of fill terraces indicates that they have formed in response to the same, external control. The preservation of flights of terraces, and the spacing between them, is at least in part a function of tectonics, but there is no independent evidence for tectonic events triggering the switch between aggradation and degradation. The temporal link between post-glacial incision with re-establishment of forest cover and increase in discharge, and between LGM aggradation and limited grass and shrub cover and periglacial processes, demonstrates a primary (terrestrial) climate control.

(iii) We have placed some constraints upon the position of the transition between climate and baselevel controls. The upstream limit of baselevel control during the post-glacial sea level highstand is the intersection point between T1 and the post-glacial wedge, which occurs between 8 and 47 km upstream in catchments 1–4, 6, and 7, but appears to have been eroded away as a result of a combination of coastal erosion and uplift in catchments 5 and 8. In two catchments the inner (landward) edge of the wedge is characterised by a mid-Holocene fill terrace, which is a baselevel-controlled terrace formed in response to the 7.3 ka sea level highstand. The downstream limit of climate control during sea level lowstands is more difficult to define, as it is buried beneath the continental shelf, but the presence of gravel and fluvial channels on the inner shelf indicates (terrestrial) climate control extended at least as far downstream as the inner shelf during the LGM.

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