Hillslope response to climate-modulated river incision in the Waipaoa catchment, East Coast North Island, New Zealand

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ABSTRACT

Quantifying how hillslopes respond to river incision and climate change is fundamental to understanding the evolution of uplifting landscapes during glacial-interglacial cycles. We investigated the interplay among uplift, river incision, and hillslope response in the nonglacial Waipaoa River catchment located in the exhumed inner forearc of an active subduction margin on the East Coast of the North Island of New Zealand. New high-resolution topographic data sets (light detection and ranging [lidar] and photogrammetry) combined with field mapping and tephrochronology indicate that hillslopes adjusted to rapid latest Pleistocene and Holocene river incision through the initiation and reactivation of deep-seated landslides. In the erodible marine sedimentary rocks of the Waipaoa sedimentary system, postincision deep-seated landslides can occupy over 30% of the surface area. The ages of tephra cover beds identified by electron microprobe analysis on 80 tephra samples from 173 soil test pits and 64 soil auger sites show that 4000–5000 yr after the initiation of river incision, widespread hillslope adjustment started between the deposition of the ca. 14,000 cal. yr B.P. Waiohau Tephra and the ca. 9420 cal. yr B.P. Rotoma Tephra. Tephrochronology and geomorphic mapping analysis indicate that river incision and deep-seated landslide slope adjustment were synchronous between main-stem rivers and headwater tributaries. Hillslope response in the catchment can include the entire slope, measured from river to ridgeline, and, in some cases, the interfluves between incising subcatchments have been dramatically modified through ridgeline retreat and/or lowering. Using the results of our landform tephrochronology and geomorphic mapping, we derive a conceptual time series of hillslope response to uplift and climate change–induced river incision over the last glacial-interglacial cycle.

INTRODUCTION

Characterization of hillslope erosion in response to river incision driven by uplift and climate change over glacial-interglacial cycles is fundamental to our understanding of landscape evolution in the vast majority of the world's mountain belts (Milliman and Farnsworth, 2011; von Blanckenburg et al., 2005; Booth et al., 2013). Hillslope processes deliver sediment to streams and rivers, making the sediment discharge from sensitive, small mountainous catchments globally significant (Milliman and Syvitski, 1992; Koppes and Montgomery, 2009). However, sediment-yield studies seldom address glacial-interglacial climate change, and this makes it challenging to integrate fluxes through time and interpret the geological record (Bull, 1991; Schaller and Ehlers, 2006; Fuller et al., 2009; DeVecchio et al., 2012). The ways in which active margin landscapes respond to changes in climate and stream erosive power are important not only to help explain landform development and the mechanisms by which sediment is transferred across landscapes, but also to inform how future land use and climate change may affect landscapes and ecological systems inhabited by people (e.g., Whipple and Tucker, 2002; Milner et al., 2007).

The Waipaoa sedimentary system on the East Coast of the North Island of New Zealand (Fig. 1) is a temperate maritime mountainous river system typical of areas supporting large populations and intensive land-use activities. Poorly indurated and highly fractured sedimentary rocks underlying much of the Waipaoa sedimentary system have contributed to some of the highest sediment yields ever recorded (e.g., Griffiths, 1982; Walling and Webb, 1996; Hicks et al., 1996) and help accentuate the signal of erosion, landscape evolution, and sediment transfer. Sensitivity to external forcing, such as changing storm frequency and deforestation (Gage and Black, 1979; Page and Trustrum, 1997; Page et al., 1999; Wilmshurst et al., 1999), played a role in the selection of this system as part of a larger international initiative investigating terrestrial to marine sediment response and transfer, called the MARGINS Source-to-Sink (Gomez et al., 2001; Kuehl et al., 2003, 2006; Carter et al., 2010). The sensitive and responsive Waipaoa sedimentary system is an ideal location in which to investigate the response of hillslopes to large-scale (glacial-interglacial) climate change and ongoing tectonic uplift on an active margin.

To study the modes and timing of hillslope response to river incision, we chose two geologically and geomorphologically distinct study areas to represent the ~2500 km^2 terrestrial Waipaoa sedimentary system. Two major rivers, the Waipaoa and Waimata Rivers, drain the terrestrial Waipaoa sedimentary system (Figs. 1 and 2). The representative study areas encompass terrain ranging from the lower reaches of two of the three main upper tributary subcatchments of the Waipaoa River catchment to first-order basins. These areas include remnants of the aggradation terrace from the last glacial coldest period (LGCP; ca. 28,000–18,000 cal. yr B.P.; Berryman et al., 2000; Marden et al.,

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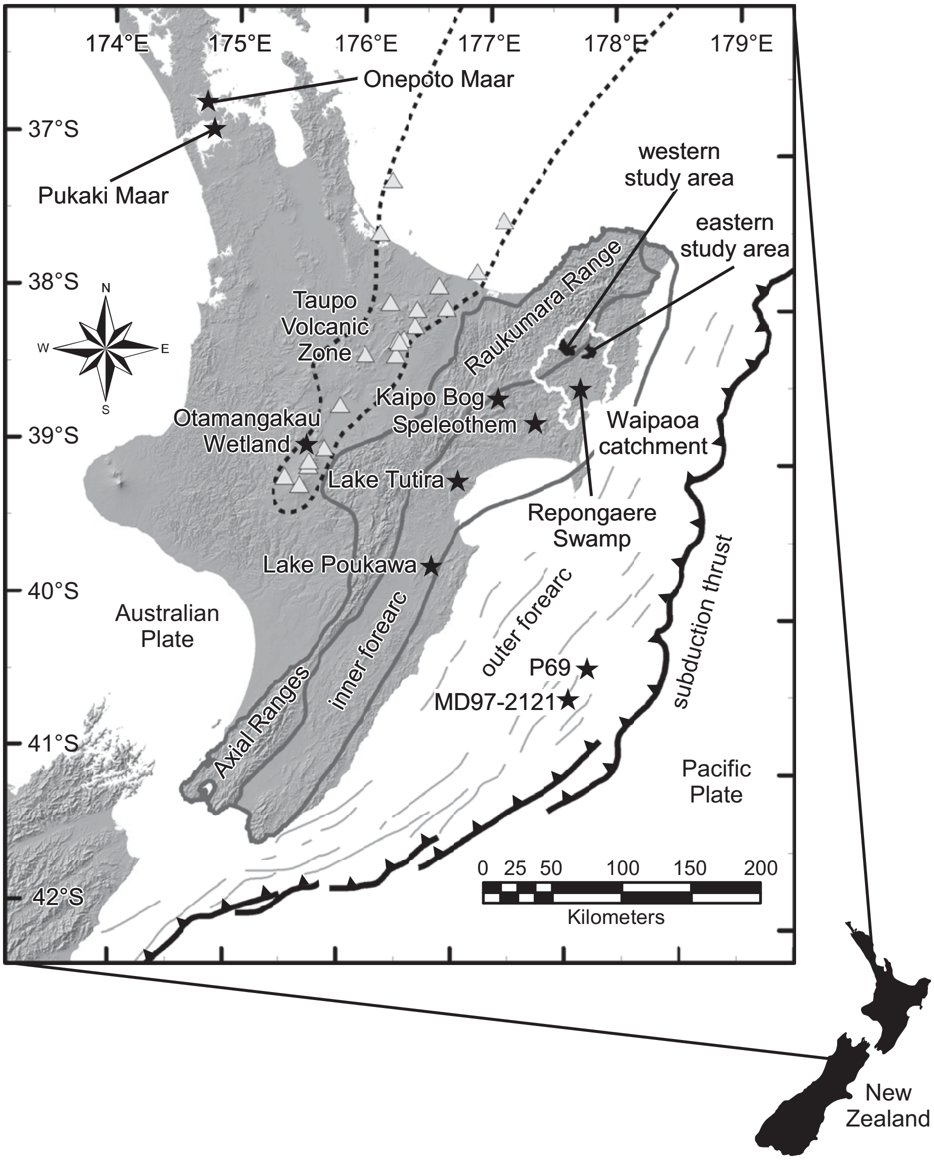

Figure 1. Location and regional tectonic setting of the Waipaoa catchment (white outline) and the two representative study areas on the Hikurangi subduction margin, east coast of the North Island of New Zealand. Triangles are locations of volcanoes in the Taupo volcanic zone. Also shown are the locations (stars) of relevant paleoclimate studies referred to in the text. Figure is modified from Litchfield et al. (2007).

2008), numerous lithologic and nonlithologic knickpoints (Crosby and Whipple, 2006), and a variety of bedrock geology underlying the Waipaoa sedimentary system (Fig. 2). The remnant aggradation terraces are markers of previous river levels and are benchmarks that we can use to measure change.

We used geomorphic mapping based on field investigation, air photo interpretation, and new photogrammetric and light detection and ranging (lidar) topography in the two study areas to investigate deep-seated landslides that postdate river incision. Slope activity in response to the last episode of incision is differentiated from older activity based on landform tephra cover and crosscutting relationships with last glacial aggradation terraces. In the last ~26,000 yr, the Waipaoa sedimentary system has received ash fall from up to 19 major volcanic eruptions from the Taupo and Okataina volcanic centers (e.g., Lowe et al., 1999, 2008; Shane et al., 2003), which are located west of, and upwind of, the Waipaoa sedimentary system. During deposition, these tephra deposits blanket the landscape (Gage and Black, 1979; Pearce and Black, 1981); subsequent mass movement activity modifies this cover by disrupting stratigraphic coherence and/or partially to completely stripping tephra from the landscape. The tephra cover has enabled us to assign minimum stabilization ages to some landslides in a landscape largely devoid of sufficient quartz for cosmogenic exposure ages and radiocarbon material for dating of landslide deposits. In addition, by investigating a population of landslide stabilization ages, we can infer the timing of hillslope response to river incision.

In this study, we: (1) correlate deep-seated landslide–related hillslope erosion to post-LGCP river incision in the tectonically active and climatically sensitive Waipaoa sedimentary system; (2) investigate the geomorphic evolution of Waipaoa sedimentary system valley walls and interfluves from the LGCP to present; (3) present a chronology of slope response based on tephra cover; and (4) present a conceptual model for catchment evolution in the context of river incision and tectonic uplift over the last glacial-interglacial cycle.

TECTONIC, GEOLOGIC, AND CLIMATIC SETTING

The change from the last LGCP to the modern interglacial climate increased temperature and, possibly, annual precipitation and reduced seasonality over much of New Zealand (e.g., Shulmeister et al., 2004; Drost et al., 2007; Newnham et al., 2013). In North Island river catchments, this change led to increased annual discharge but a decrease in the erodibility of upland slopes due to the rapid spread of podocarp forest (Newnham and Lowe, 2000; McGlone, 2001, 2002; Litchfield and Berryman, 2005, 2006; Alloway et al., 2007; Barrell et al., 2013; Newnham et al., 2013). In the terrestrial Waipaoa sedimentary system, the changing climate resulted in an incision of as much as 120 m in trunk and tributary channels (Berryman et al., 2000; Eden et al., 2001; Marden et al., 2008). The incision dramatically increased tributary relief and oversteepened valley walls. This incision occurred in all of the eastern North Island catchments studied by Litchfield and Berryman (2005), and small-scale incision-induced gravitational instability has been observed in East Coast catchments other than the Waipaoa (e.g., Pettinga and Bell, 1992; Lacoste et al., 2009). Underlain by weak marine sedimentary rocks prone to disintegration through wetting and drying cycles, hillslopes in the terrestrial Waipaoa sedimentary system are susceptible to deep-seated mass movement (Gage and Black, 1979; Pearce and Black, 1981; Gomez and Livingston, 2012). Understanding the interplay between hillslope processes, such as deep-seated land-

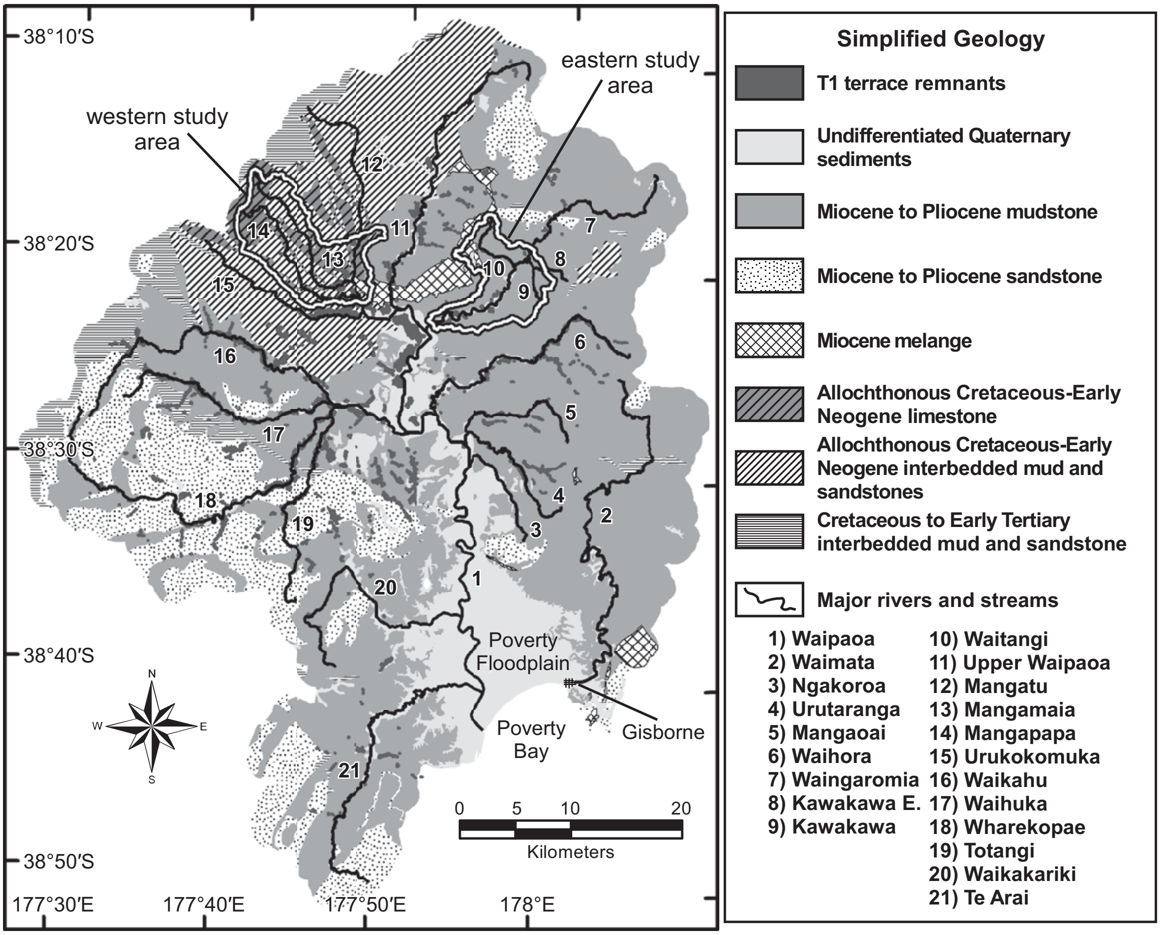

Figure 2. Simplified geologic map of the Waipaoa and Waimata catchments. Major tributaries are named and the study areas are outlined. Geologic map is modified from Mazengarb and Speden (2000).

slides, and episodes of river incision and aggradation can shape a broader understanding of landscape evolution. The temperate maritime Waipaoa sedimentary system, typical of many high-human-use areas, can inform a broader understanding of the interactions among climate change, geomorphic change, and sediment transfer from onshore source to offshore sink.

Tectonic Setting

The Waipaoa sedimentary system straddles the active inner forearc of the Hikurangi subduction margin, with its headwaters in the actively uplifting axial ranges of the North Island (Raukumara Range; Fig. 1). The majority of the terrestrial Waipaoa sedimentary system is drained by the Waipaoa and Waimata River catchments (~2500 km^2 out of 3200 km^2). Other small coastal catchments contribute to a common Waipaoa sedimentary system marine sediment depocenter. For consistency with other studies (e.g., Kuehl et al., 2006; Marden et al., 2008), we define the Waipaoa catchment as the ~2500 km^2 region that includes both the Waipaoa and Waimata Rivers (Fig. 1). The Waimata River is included because this river flows into the same marine depocenter and was likely a tributary to the Waipaoa during sea-level lowstands. Located west of the Raukumara Range divide, the active Taupo volcanic zone is a continental rift that has been one of the most active rhyolitic eruptive systems in the world during the latest Pleistocene and Holocene (Fig. 1; Smith et al., 2005). The Raukumara Peninsula is cut by active normal, reverse, and strike-slip faults. Ruptures on these faults, as well as on the subduction interface, could cause significant ground motions in the Waipaoa sedimentary system exceeding modified Mercalli intensity 8 (Litchfield et al., 2009). Uplift is variable across the Waipaoa sedimentary system and is discussed later.

Geology and Rock Properties

The inner forearc sequence underlying the terrestrial Waipaoa sedimentary system is mostly composed of imbricate-thrust Miocene–Pliocene marine mud and sandstones (e.g., Lewis and Pettinga, 1993; Mazengarb and Speden, 2000). Diapirically emplaced, chaotic mélange that probably originated from Miocene undercompacted shales underlies the north central and coastal eastern areas of the Waipaoa catchment (Fig. 2; Neef and Bottrill, 1992; Mazengarb and Speden, 2000). A highly deformed allochthonous sequence of Cretaceous to Lower Neogene marine mudstones, sandstones, and limestones underlies ~15% of the terrestrial Waipaoa sedimentary system, mostly in the northwest (Fig. 2). Swelling smectite clays are present in the mudstones of the region (Gage and Black, 1979; Pearce and Black, 1981; Pettinga and Bell, 1992; Lacoste et al., 2009). These tectonically crushed, compacted, but poorly cemented, interbedded marine sediments of the North Island East Coast forearc sequence are prone to disintegration through wetting and drying cycles and can weather to thick (~5–15 m in convergent areas) clay-rich residual soil (Gage and Black, 1979).

Unweathered mudstone and sandstone outcrops in the terrestrial Waipaoa sedimentary system exhibit a Hoek and Brown (1997) geological strength index (GSI) of 15–35. GSI in this range for these lithologies generally relates to rock with friction angles less than ~33° and low uniaxial compressive strength, between 5 and 35 MPa (Hoek and Brown, 1997). This is corroborated by uniaxial compression tests undertaken on sandstone and siltstone samples from the East Coast of the North Island (Pettinga and Bell, 1992; Lacoste et al., 2009).

Morphology

The overall form of the Waipaoa catchment is highly concave, with tributaries eroding radially back into uplands from the main-stem Waipaoa River. The maximum altitude of the terrestrial Waipaoa sedimentary system is 1200 m above sea level (a.s.l.). Mean altitude is ~300 m, and ~16% of the Waipaoa catchment is over 500 m. Relief is highest in the northwest of the catchment, approaching 600 m from valley bottom to ridge top. Areas underlain by allochthonous marine mudstone, sandstone, and limestone correspond to the areas of highest relief (Fig. 2; Mazengarb and Speden, 2000). Limestone ridges in this area exhibit the steepest slopes (up to 60°), while the Miocene lithologies incorporated into tectonic mélange exhibit the lowest relief and gentlest slopes of any of the pre-Quaternary geologic units. Most of the rest of the catchment has maximum hillslope relief of ~300 m.

The Waipaoa sedimentary system exhibits a variety of landforms, including deep-seated landslides, aggradation (fill) terraces, fill-cut terraces, strath terraces, and knickpoints. For the purposes of this study, we define deep-seated landsides as typically involving organic and inorganic soils, including regolith and colluvial cover, and varying amounts of weathered or unweathered bedrock. In many cases, this can be generalized as landslides failing at depths of more than ~3 m. Deep-seated landslides of many sizes and types, which are described in detail in the following sections, are pervasive in the terrestrial Waipaoa sedimentary system (e.g., Gage and Black, 1979; Pearce and Black, 1981; Page and Lukovic, 2011). Small, discrete aggradation and degradation terrace remnants are preserved above many tributaries and are described in more detail herein. The landslides and the repeated cycles of aggradation and incision give the terrestrial Waipaoa sedimentary system hillslopes a distinctly hummocky morphology, indicative of landslides, separated by discrete areas of stepped topography at river terraces. In addition, knickpoints related to river incision or lithology are present throughout the catchment and indicate a landscape in transition (Crosby and Whipple, 2006).

Four generations of river aggradation are preserved as remnant terraces in the terrestrial Waipaoa sedimentary system (Berryman et al., 2000; Marden et al., 2008). Because of clear regional correlation of the timing of these terraces across different river catchments around the eastern North Island (Litchfield and Berryman, 2005), we adopt the terminology of T1 to T4 for these terraces from Litchfield and Berryman (2005). This is different from local Waipaoa terminology, Waipaoa-1 (W-1) to Waipaoa-4 (W-4) of Berryman et al. (2000), Eden et al. (2001), and Marden et al. (2008). The LGCP T1 terrace is by far the best preserved aggradation (fill) terrace and is present in many tributaries above the Poverty Bay floodplain where the T1 terrace has been buried by more recent terrestrial aggradation and marine transgression (Fig. 2; Berryman et al., 2000; Marden et al., 2008). The T1 terrace consists of an ~3–20-m-thick package of alluvial sands and gravels covered by overbank silts and ash fall. The thickness of the T1 gravel is generally less than 20% of the total post-T1 river incision (Marden et al., 2008). T1 aggradation began between the deposition of the Omataroa Tephra and the Kawakawa Tephra, ca. 33,000–25,500 cal. yr B.P., and ceased between the deposition of the Okareka Tephra and the Rerewhakaaitu Tephra, ca. 22,000–17,500 cal. yr B.P. (Berryman et al., 2000; Eden et al., 2001; Litchfield and Berryman, 2005; Marden et al., 2008, 2014). Marden et al. (2008, 2014) noted that the cessation of aggradation was followed by a period of incision that cut up to two degradation (fill-cut) terraces that are preserved in a small number of locations along major tributaries before the deposition of the Rerewhakaaitu Tephra (ca. 17,496 cal. yr B.P.).

Uplift

Regional-scale uplift of the Raukumara Range is primarily driven by deep-seated subduction processes, including oceanic plateau subduction, seamount subduction, tectonic erosion, and sediment underplating (Walcott, 1987; Reyners et al., 1999; Upton et al., 2003; Litchfield et al., 2007). Local Quaternary uplift is nonuniform across the catchment, with parts of the lower catchment around the southern Poverty Bay floodplain undergoing tectonic subsidence, while uplift of the headwaters approaches 4 mm yr^{-1} (Brown, 1995; Litchfield and Berryman, 2006). Uplift rates for the upper Waipaoa catchment have been estimated by comparing the elevations of two generations of aggradation terraces, T3 and T1, that are correlated to high $\delta^{18}O$ cool marine isotope stages 4 and 2 and with periods of glacial advance in the South Island (Berryman et al., 2000; Litchfield and Berryman, 2005, 2006). Aggradation terraces T3 and T1 are dated at ca. 55,000 and 18,000 cal. yr B.P., respectively, using tephrochronology techniques similar to those described in the Methodology section (Litchfield and Berryman, 2005). Assuming that the current difference in elevation between these two terraces is due to tectonic uplift, late Pleistocene uplift rates for the middle of the catchment in both field areas are estimated at between 1 and 2 mm yr^{-1} (Litchfield and Berryman, 2006, their fig. 10).

Climate

Modern climate in the Waipaoa sedimentary system is temperate maritime, with mean annual temperatures of 12.5 °C to 15 °C at the coast and lowlands and 7.5 °C to 12.5 °C in the uplands (Leathwick et al., 2002). The mean annual minimum temperature ranges from 2.5 °C to 5 °C and 0 °C to 2.5 °C, and the mean annual maximum temperature ranges from 20 °C to 22.5 °C and 17.5 °C to 20 °C in the lowlands and uplands, respectively. The Raukumara Range shadows the Poverty Bay floodplain from westerly winds, producing mean annual precipitation of less than 1000 mm in Poverty Bay floodplain (Leathwick et al., 2002). Mean annual precipitation in the midelevations ranges from 1000 to 1500 mm and 1500 to 2500 mm in the headwaters of the Waipaoa sedimentary system (Leathwick et al., 2002). High-intensity rainstorms and cyclones occur frequently in the Waipaoa sedimentary system, averaging approximately one every 5 yr throughout the Holocene (Page et al., 2010), and play a significant role in the Waipaoa sedimentary system, as evidenced by the widespread landsliding, flooding, and sedimentation from Cyclone Bola in 1988 (Page et al., 1994a, 1994b).

Broad paleoclimatic conditions in the Waipaoa sedimentary system can be inferred from a number of paleoclimate studies using proxy data such as pollen assemblages, changes in sedimentation, and stable isotope ratios from sites around the North Island East Coast and the North Island in general (Fig. 1). Holocene records include speleothems from the Hawke Bay region (Lorrey et al., 2008), sediment cores from Lake Tutira (Page et al., 2010; Orpin et al., 2010; Gomez et al., 2011), and a sediment core from Repongaere Swamp within the Waipaoa catchment (Wilmshurst et al., 1999). Latest Pleistocene to Holocene paleoclimate proxy data from around the East Coast are derived from sediments from Kaipo Bog (Hajdas et al., 2006; Newnham and Lowe, 2000; Lowe et al., 1999), Lake Poukawa (McGlone, 2002), and marine cores P69 (McGlone, 2001) and MD97–2121 (Carter et al., 2002; Gomez et al., 2004). To assess the regional nature of the climate signal and to draw on other proxy records that span the last glacial-interglacial transition, these records can be compared with other North Island latest Pleistocene to Holocene records, including those from the Onepoto and Pukaki maars in the Auckland region (Augustinus et al., 2011; Sandiford et al., 2003) and Otamangakau wetland (McGlone et al., 2005) on the central North Island. The closest terrestrial long record of environmental change and tephra deposition for this study is Kaipo Bog, located ~70 km west of the Waipaoa field areas at an elevation of 980 m a.s.l. (Fig. 1). This record exhibits high preservation of tephra and pollen with excellent age control and geochemically identified tephras (Lowe et al., 1999; Newnham and Lowe, 2000; Hajdas et al., 2006; Barrell et al., 2013).

Many of these high-resolution paleoclimate records are summarized in Alloway et al. (2007) and Barrell et al. (2013), who produced composite climate event stratigraphies for New Zealand. There is a high degree of correlation for paleoclimatic events between these records. At the nadir of the LGCP, Newnham et al. (2013) estimated a mean annual temperature depression of 6.5 ± 2.0 °C below modern for the southern North Island, including the Hikurangi margin, using pollen-climate modeling. This temperature depression estimate is in broad agreement with central North Island LGCP paleoglacier studies and reconstruction of sea-surface temperatures (McArthur and Shepherd, 1990; Pillans and Moffat, 1991; Pelejero et al., 2006; Barrows et al., 2007). The transition from the LGCP to Holocene interglacial conditions was from ca. 18,000 cal. yr B.P. to ca. 11,800 cal. yr B.P. and included a late-glacial climate reversal between ca. 13,700 and 11,800 cal. yr B.P. The current Holocene interglacial period has had two phases of greatest warmth between ca. 11,600 and 10,800 cal. yr B.P. and from ca. 6800 to 6500 cal. yr B.P. (Alloway et al., 2007).

Vegetation

Vegetation cover on the hillslopes of the terrestrial Waipaoa sedimentary system has varied dramatically during the LGCP, transitional, and Holocene climate phases and due to the short-lived impacts (50–200 yr) of multiple volcanic eruptions in the Taupo volcanic zone (Newnham and Lowe, 2000; Carter et al., 2002). During the LGCP, pollen assemblages in the basal sandy mud of the Kaipo Bog are dominated by grasses, other herbs, and subalpine shrubs with relatively little large tree pollen (Newnham and Lowe, 2000). A data set of 66 pollen site records around New Zealand shows vegetation in the Waipaoa sedimentary system was likely a shrubland-grassland mosaic with patches of beech and rare conifers (McGlone et al., 2010; Newnham et al., 2013).

The modern tree line in the central North Island is at ~1400 m (Leathwick et al., 2003). Temperature depression estimates and paleoglacier reconstructions suggest a tree-line depression of ~800 m during the LGCP (e.g., McArthur and Shepherd, 1990; McGlone et al., 2010). This would have exposed the upland area of the Waipaoa sedimentary system to alpine and subalpine conditions. A hypothesis of alpine and subalpine conditions in the uplands of the Waipaoa sedimentary system is supported by ancient scree found buried beneath the latest Pleistocene tephras at elevations above ~500 m a.s.l. in the western field area and the upper Waipaoa sedimentary system (Fig. 3B; Gage and Black, 1979). In addition, a nondepositional nature and widespread instability of upland surfaces throughout the central North Island during the LGCP are interpreted from the lack of preserved LGCP-aged tephras above ~500 m a.s.l. (Pillans et al., 1993; Alloway et al., 2007). The presence of ancient scree deposits, which may be related to periglacial processes, and the lack of preserved LGCP tephras in the uplands suggest that, at these upper elevations, very little vegetation cover existed, and physical weathering processes dominated, perhaps an analogous environment to that shown in Figure 3C.

After ca. 18,000 cal. yr B.P., mixed podocarp-angiosperm-beech forests expanded, reaching a pre–late-glacial reversal maximum at ca. 15,500 cal. yr B.P. (Newnham and Lowe, 2000). However, the ratio of lowland-montane podocarp pollen to upland grass pollen at Kaipo Bog prior to the late-glacial reversal is still less than half that of the ratio after ca. 11,800 cal. yr B.P., indicating that full Holocene forest conditions were not reached until after ca. 11,800 cal. yr B.P. This record of a full Holocene forest expansion and increasingly mild and wet conditions after ca 11,800 cal. yr B.P. is consistent with the Auckland maar records (Augustinus et al., 2011; Sandiford et al., 2003). Based on the Kaipo Bog and Auckland records, it appears that the climatic optimum for podocarp-angiosperm forests (Fig. 3A) at mid- to high elevations was not reached until after the late-glacial climate reversal at ca. 11,800 cal. yr B.P.

Modern vegetation in the terrestrial Waipaoa sedimentary system consists mainly of pasture land and exotic forest plantations. Fire may have been used as a forest clearance tool by early Polynesian (Maori) settlers, but major deforestation began in the mid-nineteenth century by European settlers with wholesale conversion to pasture by the mid-twentieth century (e.g., Pullar, 1962; Wilmshurst et al., 1999; Dymond et al., 1999).

METHODOLOGY

Two study areas of contrasting lithology and structural setting were chosen as representative of the post-LGCP river incision and hillslope processes that characterize the upper Waipaoa sedimentary system. The 57 km^2 eastern study area in the lower Waingaromia River catchment includes several complete tributary basins and is underlain by Miocene–Pliocene marine mudstones and diapiric mélange (Fig. 2). The 84 km^2 western study area stretches from the lower Mangatu River to the catchment divide, includes two large tributaries to the Mangatu, and is underlain mostly by allochthonous Cretaceous–Lower Neogene marine mudstone, sandstone, and limestone (Fig. 2).

Geomorphic Mapping

We accomplished geomorphic mapping in both study areas by using a combination of field investigation, air photo interpretation, and interpretation of high-resolution topography. The high-resolution topographic data sets used include: (1) eastern area: 2.5 m vertical accuracy photogrammetric topography from predominantly clear-ground (deforested) photography acquired in the late 1970s and early 1980s. Contours in this area are processed to a 5 m grid using ESRI ArcGIS® software; (2) western area: submeter airborne lidar topography acquired during the 2010 Australasian autumn by NZ Aerial Mapping Limited. We processed bare earth lidar return data to a 2 m grid using free software tools available through the National Science Foundation (NSF) Open Topography Portal (http://www.opentopography.org/). Field mapping of geomorphic features such as landslides, terraces, and knickpoints complemented and verified mapping and stream profile analysis based on photography and high-resolution topography. We field verified most mapped features (e.g., 60% of the mapped landslides) during field campaigns in 2009 and 2010. All features mapped were digitized into a geographic information system (GIS) for analysis using ESRI ArcGIS®.

Tephrochronology and Age Control

We determined first-order age control for landslides active since the LGCP by mapping slides that crosscut the T1 LGCP aggradation surface (Marden et al., 2008). Based on this crosscutting relationship, these landslides must have experienced at least some movement since the initiation of river incision. Datable organic material entrained in landslides was found to be limited. Only three suitable samples were

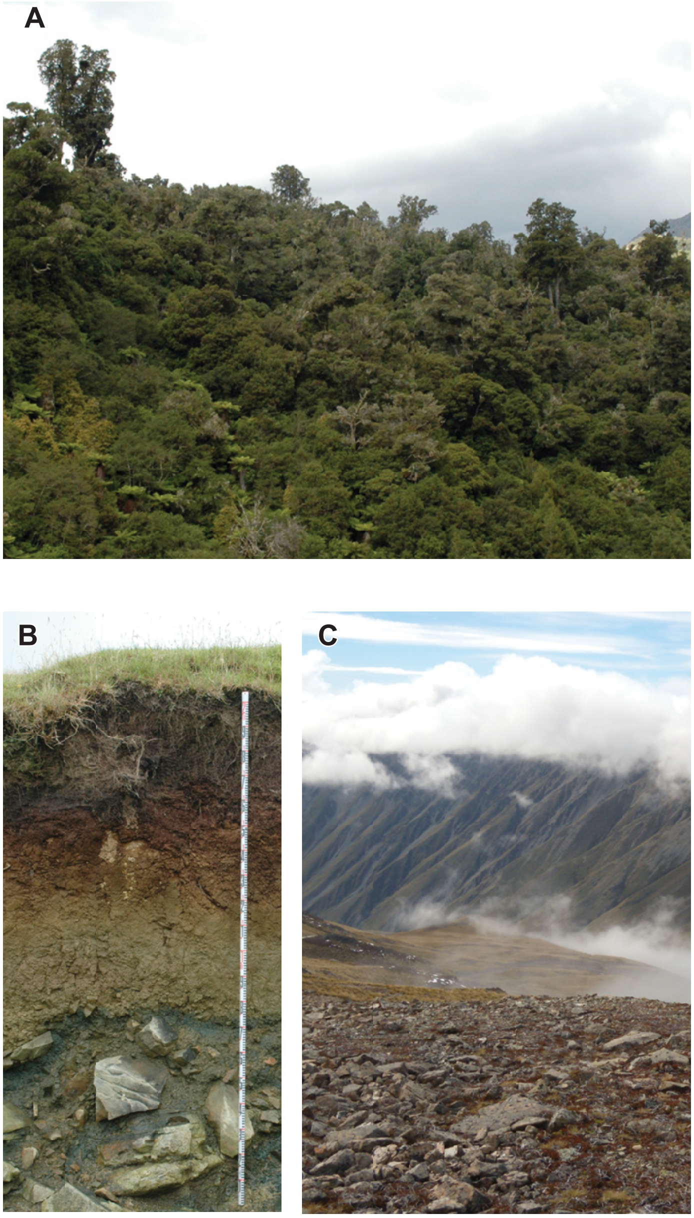

Figure 3. (A) Current native podocarp-angiosperm forest completely covering hillslopes around the Waipaoa sedimentary system (WSS) at ~650 m above sea level. (B) Soil profile showing last glacial coldest period (LGCP) scree buried below tephric soils at 630 m a.s.l. in the upper Waipaoa sedimentary system, western study area. The measuring tape is 2 m long. The basal tephra above the ancient scree is the 17,496 ± 462 cal. yr B.P. Rerewhakaaitu Tephra identified by electron probe microanalysis. (C) Modern scree above tree line in the central South Island, New Zealand, as a visual analog for upland conditions in the LGCP Waipaoa sedimentary system.

collected: one angiosperm and two podocarp logs. In this landscape, lacking sufficient quartz for cosmogenic exposure ages and radiocarbon in landslide deposits, finer-resolution age control of geomorphic features is possible through tephrochronology. At the high-preservation depositional environment of Kaipo Bog, 16 tephra deposits younger than 18,000 cal. yr B.P. have been identified. Time between depositional events in this record range from 100 cal. yr to 2200 cal. yr (Lowe et al., 1999, 2008, 2013; Newnham and Lowe, 2000; Hajdas et al., 2006). Older tephras are also present in the region; these enable the classification of more stable older surfaces (Litchfield and Berryman, 2005). In practice, not all of the tephras present in the high-preservation environment of Kaipo Bog have been described as macroscopic layers in soil profiles on landforms in the terrestrial Waipaoa sedimentary system (10 described tephras; Table 1). However, enough of the tephras are macroscopically present that tephrochronology in the Waipaoa sedimentary system is an effective dating technique for LGCP to present landforms (Table 1; Gage and Black, 1979; Wilmshurst et al., 1999; Berryman et al., 2000, 2010; Eden et al., 2001; Marden et al., 2008).

Tephrochronology of landform activity in the terrestrial Waipaoa sedimentary system is based on four main assumptions: (1) tephra erupted by Taupo volcanic zone volcanoes blankets the landscape of the Waipaoa sedimentary system immediately after deposition; (2) tephras are chemically or visually distinguishable; (3) shallow erosion processes, such as sheetwash, shallow landslide, or soil diffusion, do not completely remove all tephra from landforms; and (4) deep-seated slope failures significantly disrupt or completely entrain the surficial tephra cover. If all of the assumptions are satisfied, the age of the oldest tephra on a landform is a minimum stabilization age for that landform (Lang et al., 1999). The last three of these assumptions can be tested by detailed investigation of tephra cover. To test these assumptions and to sample tephras for identification, we collected 80 tephra samples from 173 soil test pits and 64 soil auger sites across the two study areas. We located test pits and auger sites on the largest expanse of low-slope ground available on a sampled landform (e.g., terrace, landslide body, ridge) to obtain samples from areas with the best tephra preservation potential. Test pit samples were discrete, consisting of no more than 4-cm-thick slices, and auger samples averaged no more than 10 cm thick. All of the sites were logged and located by differential global positioning systems (DGPS).

Tephra Identification

Tephra identification is difficult in the field because paleo-O and paleo-A horizons are absent from tephra soil profiles in all but the most ideal depositional environments, many of the tephras are not visually distinct, and tephras are altered to different extents (Fig. 4). The absence of paleo-O and paleo-A horizons is probably due to secondary alteration, as there was enough time between deposition of individual tephras for organic soils to develop (~500–4000 yr between major eruptions; Table 1).

TABLE 1. SIGNIFICANT TEPHRA DEPOSITS IDENTIFIED IN THE WAIPAOA CATCHMENT BY PREVIOUS STUDIES*

Tephra name	Midpoint of 2σ age range (cal. yr B.P.)	TVZ volcanic center**
Kaharoa	636 ± 12†	Okataina
Taupo	1718 ± 10†	Taupo
Whakaipo, Unit V	2800 ± 60†	Taupo
Waimihia	3401 ± 108†	Taupo
Whakatane	5526 ± 145†	Okataina
Mamaku	7940 ± 275†	Okataina
Rotoma	9423 ± 120†	Okataina
Waiohau	14,009 ± 155†	Okataina
Rotorua	15,635 ± 412†	Okataina
Rerewhakaaitu	17,496 ± 462†	Okataina
Okareka	21,858 ± 290†	Okataina
Kawakawa/Oruanui	25,360 ± 160§	Taupo
Omataroa	32,755 ± 1415#	Okataina
Mangaone	32,285 ± 755#	Okataina
Rotoehu	ca. 55,000#	Okataina

*Previous studies that have identified tephras in the Waipaoa catchment are: Gage and Black (1979); Wilmshurst et al. (1999); Berryman et al. (2000); Eden et al. (2001); Marden et al. (2008); Berryman et al. (2010).
†Age dates from Lowe et al. (2013).
§Age date from Vandergoes et al. (2013).
#Age dates from Smith et al. (2005).
**TVZ—Taupo volcanic zone.

In many profiles of the slightly acidic tephra soils in the oxidizing environments of the East Coast North Island, organic carbon decreases dramatically, until it is almost completely absent below ~50 cm, and secondary clay mineral content increases with depth (Bakker et al., 1996; Alloway, et al., 2007). Additionally, iron-manganese nodules, a product of mineral dissolution, are present lower in the profiles, indicating weathering and alteration. The differing degree of alteration can change the color and to a lesser degree the texture of the tephra from location to location. Because of the difficulty of field identification, tephras are positively identified primarily by electron probe microanalysis (EMPA) of major-oxide glass chemistry, assisted by stratigraphy and ferromagnesian mineralogy.

EMPA was conducted using the JEOL JXA-8230 SuperProbe Electron Probe Microanalyser at Victoria University of Wellington. Wavelength-dispersive X-ray spectrometry was used for all samples. Basic procedures for sample preparation and EMPA followed Lowe (2011). Analysis was calibrated on natural and synthetic glass standards, VG-568 and ATHO-G (Jarosewich et al., 1980; Jochum et al., 2006), and standards were analyzed between all samples to track calibration. Multiple glass shards from each sample were analyzed with a defocused 20-µm-diameter beam of 8.0 nA at 15 kV accelerating voltage. Sixty-seven unknown samples from 56 sites were analyzed, along with 16 previously identified latest Pleistocene and Holocene tephras collected from type sections (Vucetich and Pullar, 1964, 1969). The previously identified tephras include all of the tephras listed in Table 1 except for the Rotoehu, Whakatane, and Whakaipo tephras, for which appropriate type section samples were not available. For these three tephras, samples were compared with published glass chemistry results (Smith et al., 2005, 2006; Lowe et al., 2008).

EMPA results from unknown field-collected samples were compared with results from previously identified samples and results from literature on major-oxide biplots. All results were normalized to 100% to minimize the effects of secondary hydration. For Taupo and Okataina volcanic center rhyolitic tephras, K_2O, CaO, and FeO appear to be the most diagnostic of the major oxides (Smith et al., 2005, 2006; Lowe et al., 2008). Okataina tephras from this age range are distinctively higher in K_2O and lower in CaO than Taupo tephras. For three of the Okataina center tephras (Rotoma, Mamaku, and Whakatane) that have significant glass chemistry and ferromagnesian assemblage overlap (Smith et al., 2006), stratigraphy, field texture, and glass chemistry biplot patterns were used to identify individual tephras.

RESULTS

Geomorphic Mapping

We identified 236 deep-seated landslides that have been active since the end of the LGCP in the two study areas (Fig. 5). The landslides are not limited to one mode of movement, and there are numerous examples of complex failure combining rotational, translational, and earthflow deep-seated mass movement mechanisms. The identified deep-seated landslides range in size from 2760 m^2 to 1,745,660 m^2 and can have widely varying length-to-width aspect ratios, ranging from 0.3 to 12.8. Many of the landslides show evidence of multiple generations of movement in the form of internal changes in vegetation recovery, morphology, and internal discrete shear zones. Even though many deep-seated landslides show evidence of multiple "nested" failures and landslide reactivation, we have concentrated on mapping the larger features with clearly defined scarps. In our inventory, we have included 23 of the largest and most prominent reactivation features that are inside the mapped boundaries of larger landslides, where these features illustrate multiple generations of movement on a hillslope (Fig. 5). Only six of the mapped landslides clearly lie upstream of any LGCP river incision (Fig. 5).

Landslides make up 35% of the three-dimensional surface area of the lower-relief Miocene–Pliocene mudstone terrain of the eastern study area. The higher-relief, older, limestone- and mudstone-dominated western study area, by contrast, has only 13% of its surface area affected by post-LGCP landslides. The vast majority of mapped landslides toe-out into streams, a relationship that directly couples them to the fluvial system. This indicates significant sediment delivery to the Waipaoa sedimentary system (Bilderback, 2012). Most also have large portions of their mass movement bodies located under the projected elevation of the T1 LGCP aggradation surface (Fig. 5).

Landslide aspect is not closely linked with bedding structure. Only ~25% of landslides could be considered dip-slope landslides, shown by bedding attitude measurements obtained from bedrock within a half kilometer of 123 landslides (Mazengarb and Speden, 2000). Sliding surfaces for landslides are generally not exposed; however, based on morphology and two exposures, sliding surfaces slope toward and intersect with incising streams. The two exposures of sliding surfaces at streambeds show weathered deformed material over relatively unweathered bedrock material with slickensides indicating downslope movement. This is consistent with other observations of landslide surfaces in New Zealand Tertiary marine sedimentary rocks (Trotter, 1993) and indicates that weathering depth plays a role in landslide activity (Gage and Black, 1979; Booth and Roering, 2011).

Twenty-five T1 aggradation terrace remnants were mapped, many of which were originally identified by Marden et al. (2008). Terrace remnants are found above modern tributaries from the main stems to headwater areas (Fig. 5). Terrace remnants, including portions of paleo–alluvial fans grading to the T1 aggradation surface, range in size from 274 m^2 to 180,645 m^2 and range in height above the modern fluvial system from 12 m to 116 m.

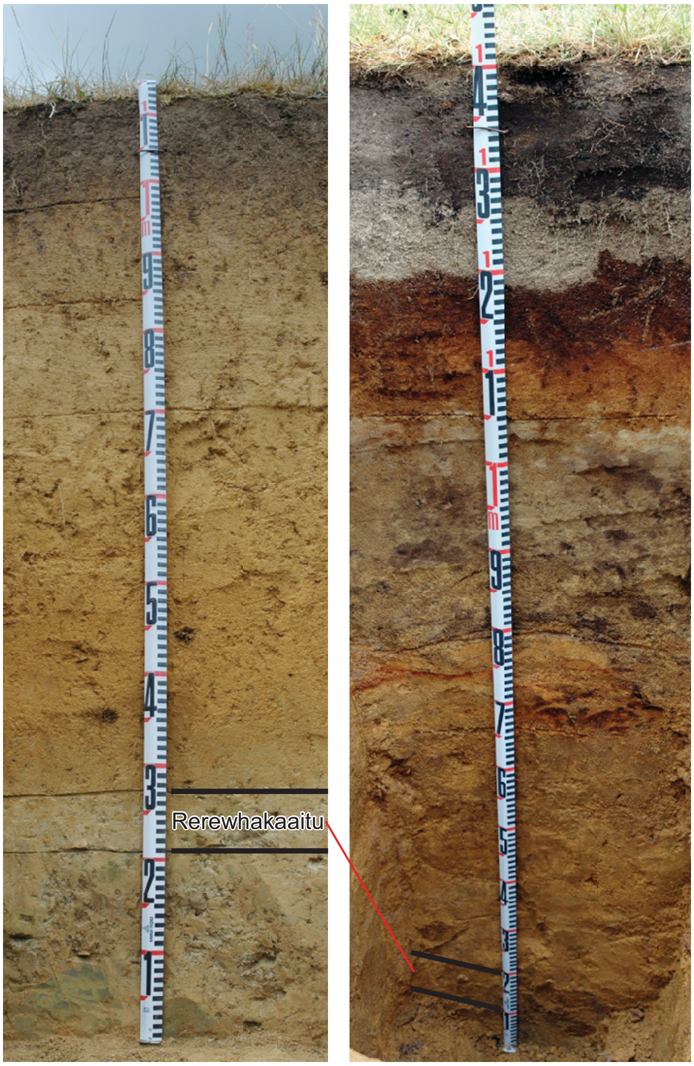

Figure 4. Examples of tephra profiles. Profiles are located in the western study area on last glacial coldest period aggradation terraces and bottom in gravels. The numbers on the measuring rod show 10 cm increments. Electron probe microanalysis results from both sites indicate that the basal tephra is the 17,496 ± 462 cal. yr B.P. Rerewhakaaitu Tephra. The sites are located less than 5 km apart and at less than 150 m elevation difference. All tephras from the Rerewhakaaitu Tephra to the Kaharoa Tephra listed in Table 1 are probably present in these profiles. Color and, to some extent, textural difference are due to secondary alteration. There are no paleo-O or paleo-A horizons in the profiles, making visual differentiation of individual tephras difficult.

Fifty-eight nonlithologic post-LGCP river incision knickpoints were mapped and used to define the LGCP aggradation surface (Fig. 5). Nonlithologic knickpoints are located in the low-order (low drainage area) portion of the tributary system, as noted by Crosby and Whipple (2006). Contrary to theory of detachment-limited channels responding to increased uplift through knickpoint retreat, where knickpoints remain at similar elevations (a.s.l.; Whipple and Tucker, 1999; Niemann et al., 2001), knickpoints in the study area are not located at similar elevations. In just the eastern study area, for example, the difference in elevations between the 47 knickpoints on different tributaries is over 50% that of the total elevation difference of the stream network. The knickpoints in the study areas are located between ~55 and 75 km from the Waipaoa River mouth, and there are two orders of magnitude difference between the areas of the largest and smallest drainage basins upstream of a knickpoint. These observations are consistent with results from Crosby and Whipple (2006), who described 236 Waipaoa sedimentary system knickpoints.

Tephra Stratigraphy

Of the sixty-seven tephra samples analyzed using EMPA, the majority were useful for stratigraphy and chronology. Only two samples appeared to be very mixed, containing shards from multiple tephras out of stratigraphic sequence. These two samples were from landslide bodies. Many of the additional samples included a small percentage of shards from generally overlying and younger tephras, but this did not preclude the identification of the major tephra in the sample (Fig. 6).

The absence of paleo-O and paleo-A horizons and the differing degree of color/texture of postdepositional alteration make tephra identification based on site characteristics alone difficult at best. However, EMPA results showed that field observations of EMPA site tephra texture-thickness relationships and the number of color/texture horizons present at a site strongly indicate the oldest tephra (basal tephra) deposited at a given site. We used these relationships to assign a probable oldest tephra to located and logged sites that were not chemically analyzed.

The EMPA results confirmed that for test pits dug in all localities except sag ponds, Taupo (ca. 1720 cal. yr B.P.) and Kaharoa (ca. 640 cal. yr B.P.) tephras are present only as lapilli or shards dispersed in the soil O or A horizons. In this case, the O and A horizons combined are not thicker than 15 cm.

All of the sites that have a concentrated tephra comprising the inorganic portion of the A horizon show a layer of gray to dark-brown coarse lapilli-rich tephra as much as 10–50 cm thick. In all locations where 10 cm or less of this horizon is present, EMPA results indicated the presence of the Whakaipo (ca. 2800 cal. yr B.P.) or the Waimihia (ca. 3400 cal. yr B.P.) Tephra. In all locations where this coarse layer is more than 10 cm thick, basal sample EMPA results indicated the presence of the Whakatane (ca. 5530 cal. yr B.P.) Tephra.

Where a tephric B horizon is present below the coarse horizon, it is a fine to medium, light gray to pinkish white, generally stiff tephra. EMPA results indicate that where this horizon is less than 30 cm thick, it contains the Mamaku (ca. 7940 cal. yr B.P.) or the Rotoma (ca. 9420 cal. yr B.P.) Tephras, and where it is

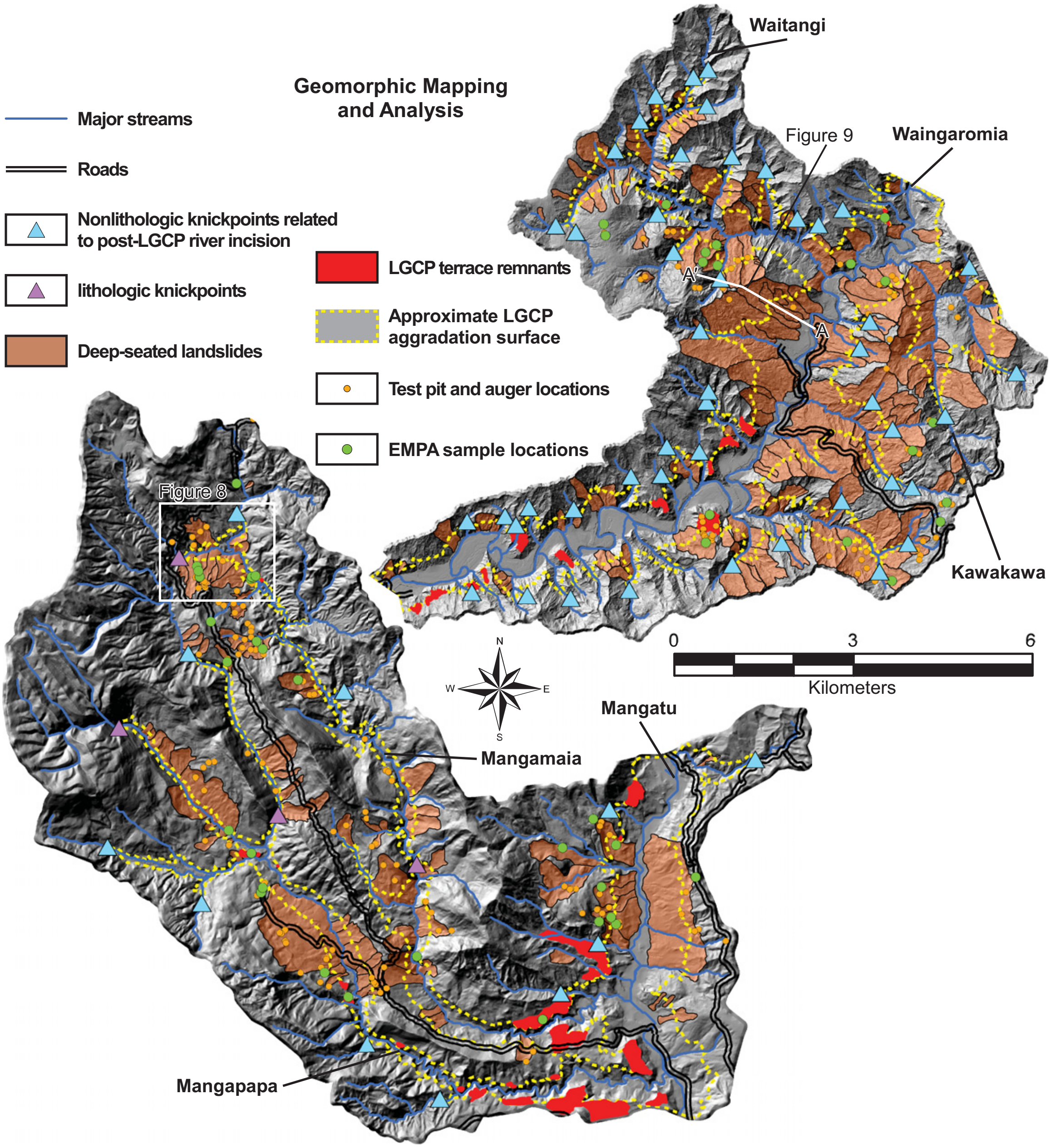

Figure 5. Geomorphic mapping and analysis for the western study area and the eastern study area. Shown are deep-seated landslides, T1 aggradation terrace remnants, knickpoints, and the approximate outline of the last glacial coldest period (LGCP) aggradation surface based on terrace remnants and knickpoints in the two study areas. Also shown are test pit and auger boring locations, tephra sample sites analyzed by electron probe microanalysis (EMPA), the location of the area presented in Figure 8, and the location of the cross sections shown in Figure 9. Major stream names are indicated.

more than 30 cm thick, it most likely contains the Waiohau Tephra (ca. 14,010 cal. yr B.P.) or the Rerewhakaaitu Tephra (ca. 17,500 cal. yr B.P.). Profiles containing the Waiohau or the Rerewhakaaitu Tephras also often show some other color/texture changes at depth. Biotite can commonly be seen in the Rerewhakaaitu Tephra with a hand lens. Profiles that have the Kawakawa (ca. 25,400 cal. yr B.P.) Tephra or older tephras are often well over 1 m thick. The Omataroa Tephra (ca. 32,800 cal. yr B.P.) is readily distinguishable in the field because it is always more than a meter deep in a soil profile and consists of coarse yellowish lapilli ≥50 cm thick.

From these relationships and from the EMPA results, we produced six stabilization categories in the two study areas (Table 2). These categories were used to make stabilization age estimates for landslides that had been investigated by test pit or soil auger but did not have EMPA results.

Landform Tephrochronology

Field and EMPA assessment of 141 of the 236 (60%) mapped post-LGCP deep-seated landslides indicates that no tephra older than the

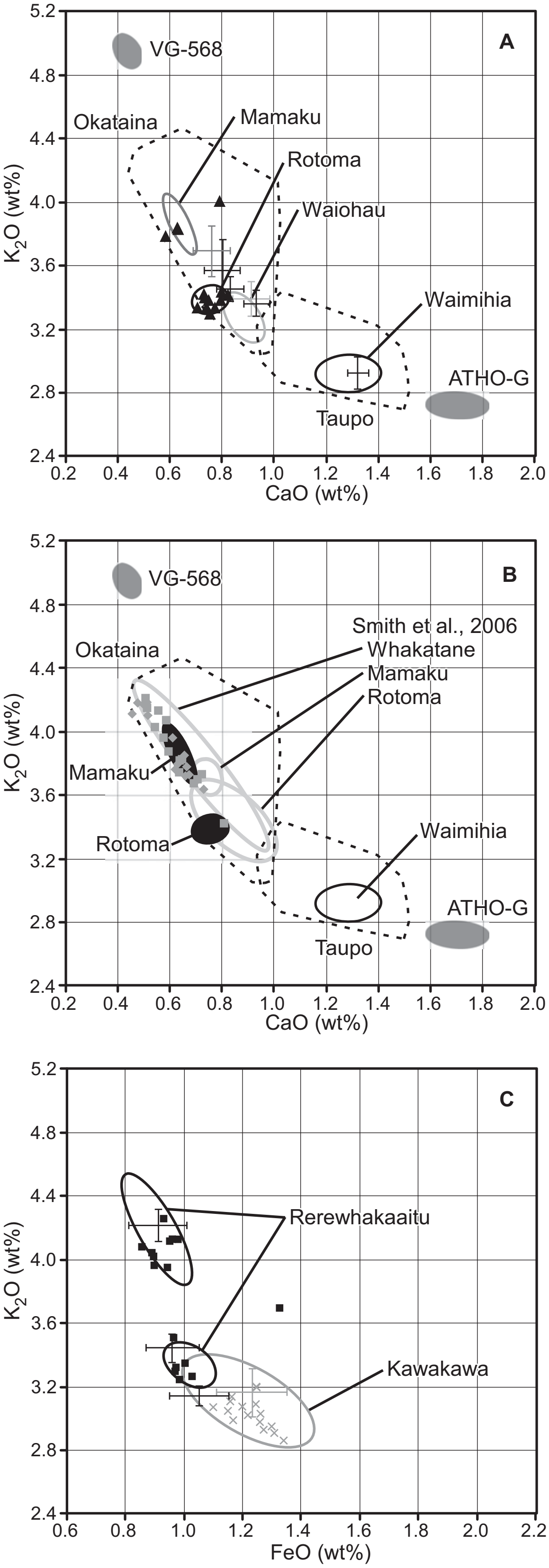

Figure 6. Bivariant plots of select electron probe microanalysis (EMPA) results. Dashed polygons are convex hulls of all the known Okataina and Taupo volcanic center results used in this study, except for the distinctly bimodal Rotorua tephra. Ovals are 95% confidence ellipses from EMPA analysis of known tephras (*n* > 10). Crosses are 2σ error bar results for the same tephras from a different instrument (Lowe et al., 2008). VG-568 and ATHO-G are glass standards used for calibration. (A) Unknown sample (black triangles) interpreted to be the Rotoma Tephra based on the tight cluster overlapping the Rotoma 95% ellipse. (B) Sample unknowns (gray squares and diamonds) interpreted to be Whakatane Tephra on the basis of similar glass chemistry pattern of Smith et al. (2006) (gray 95% ellipses), field stratigraphic relationships, and clear Okataina source. (C) Unknown samples represented by black squares and gray crosses interpreted to be the bimodal Rerewhakaaitu Tephra and the Kawakawa Tephra, respectively.

Rotoma (ca. 9420 cal. yr B.P.) is present on the bodies of these slide masses (Fig. 7). Furthermore, 70% of these 141 landslides have accumulated only the Taupo (ca. 1720 cal. yr B.P.) and the Kaharoa (ca. 640 cal. yr B.P.) Tephra, the Kaharoa only, or no tephra. There is no discernible spatial pattern to the oldest tephra observed on any of the landslide masses investigated (Fig. 7). For example, landslides located at both high and low elevations in the fluvial drainage network have the Mamaku (ca. 7940 cal. yr B.P.) or Rotoma (ca. 9420 cal. yr B.P.) as the oldest tephra on the slide mass (Fig. 7).

With the exception of one sample of the Waiohau Tephra (ca. 14,010 cal. yr B.P.), the Rerewhakaaitu Tephra (ca. 17,500 cal. yr B.P.) is the basal tephra cover bed on all the prospective T1 terrace remnants analyzed. In the western study area, the observation that three terrace treads all have Rerewhakaaitu as the basal tephra (Marden et al., 2008) can be extended up to the headwaters of the catchment above a prominent lithologic knickpoint. The uppermost of these three treads is the T1 LGCP aggradation terrace sensu stricto, and the two, up to 13 m thick, lower terraces are interpreted to be degradation terraces (fill-cut terraces; after Bull, 1991) cut into the T1 surface.

Stable landforms such as terrace remnants, broad ridge tops, or catchments upstream of knickpoints related to post-LGCP river incision (EMPA results from 31 sites) are all overlain by thick tephra sequences with a basal tephra of Rerewhakaaitu (ca. 17,500 cal. yr B.P.) or older. The Rerewhakaaitu Tephra overlies ancient scree deposits that can be found in other locations in the headwaters of the Waipaoa sedimentary system (Fig. 3B; Gage and Black, 1979). These thick older tephra sequences can be preserved on very steep (≥30°) slopes.

Many interfluves flanked on both sides by landslides exhibit an extremely truncated tephra profile characterized by either no tephra or a thin sequence of post-Waimihia tephras (ca. 3400 cal. yr B.P.). Notably, some truncated interfluve profiles exist in close proximity with multiple other sites overlain by the entire Rerewhakaaitu Tephra (ca. 17,500 cal. yr B.P.) to present sequence. The lack of tephras in areas where a full sequence is expected is most prominent in the eastern study area.

DISCUSSION

Hillslope Instability

Mapping of post-LGCP, large, deep-seated landslides shows that slope instability has affected large areas of the upper Waipaoa sedimentary system, with many slides extending

TABLE 2. TEXTURE-DEPTH RELATIONSHIPS FOR ESTIMATING PROBABLE BASAL TEPHRA FOR HILLLSLOPES

Soil profile observation	Typical total profile depth range (cm)	Probable oldest tephra	Estimated landform stabilization age range (cal. yr B.P.)
No tephra observed	3 to 10	No tephra	Younger than 636
Lapilli scattered in the O and A horizon	5 to 15	Taupo and/or Kaharoa	2800 to 636
Thin coarse lapilli-rich A horizon tephra	12 to 20	Waimihia and/or Whakaipo	5526 to 2800
Thick coarse lapilli-rich A horizon tephra	30 to 60	Whakatane	7940 to 5526
Thin fine to medium B horizon tephra	40 to 65	Mamaku and/or Rotoma	14,009 to 7940
Thick fine to medium B horizon tephra	60 to 130	Waiohau and/or Rerewhakaaitu	Older than 14,009
More than three distinct tephra layers with a total thickness of over a meter	100+	Older than Waiohau	Older than 14,009

from valley floor to ridge crest (Fig. 5). Analysis of tephra cover stratigraphy indicates that some of the interfluves that are flanked on either or both sides by landslides are also recently stabilized landforms, suggesting that many of the ridgelines have been lowered or have retreated through mass movement on both sides of drainage divides.

Landslides are generally not bedding controlled, and where observable, slide planes are visible at incised streams. This means that before river incision, the current slide planes

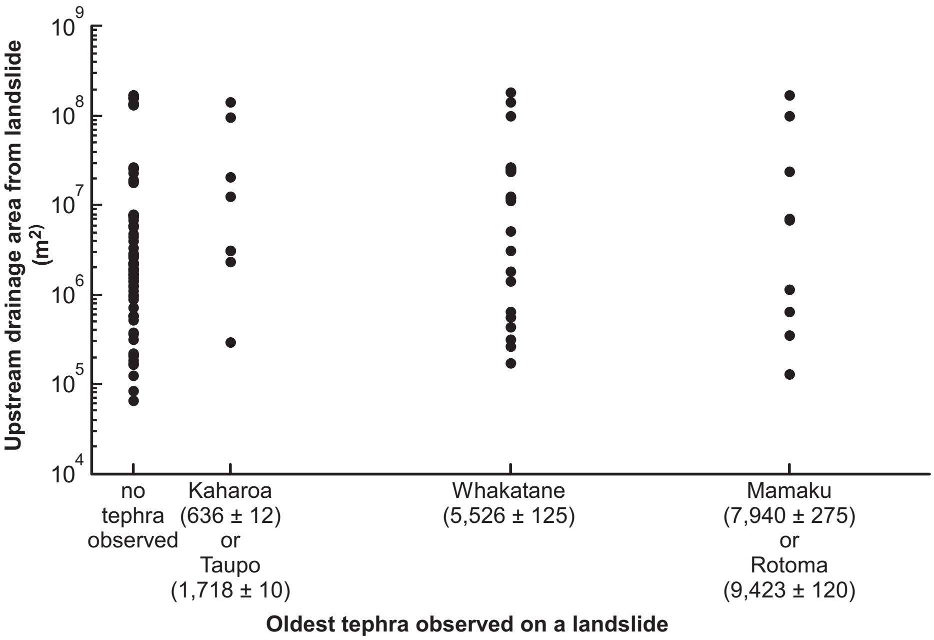

Figure 7. The oldest tephra identified on a landslide body plotted against the upstream location of the landslide. Tephra eruption ages in parenthesis are in cal. yr B.P. Landslides with no tephra observed are interpreted to have been active since 636 ± 12 cal. yr B.P. The *y*-axis, log drainage area above the point where the landslide toe intersects the stream, locates the landslide in the drainage basin. Landslides located at a point above which there is considerable drainage basin area (greater than 9.0 × 10^7) are located on main-stem rivers, and landslides at lower drainage basin areas are located further up the drainage basin on progressively smaller tributaries. Spacing on the *x*-axis is proportional to the time between tephras. The Waimihia Tephra was only confirmed as the oldest basal tephra on one landslide and is not included in the figure. There is no clear pattern showing a decrease in the stabilization age of upstream landslides located at smaller drainage areas; if this were the case, a line with a positive slope could be fit to the data. In fact, it appears that position in the drainage network has very little to do with the stabilization age of the landslide.

for many of the mapped deep-seated landslides would have been many meters beneath intact bedrock without any free, unbuttressed surface to facilitate sliding. In addition, the accommodation space for the sliding mass did not exist before river incision. We therefore conclude that slopes underlain by low-strength and highly sheared bedrock were debuttressed by river incision and responded by gravitational collapse. This is illustrated by the example in Figure 8, where the headscarp height and the amount of river incision are approximately the same (~25 m), indicating that river incision was the primary cause of deep-seated landsliding.

Our observations are consistent with theories for threshold hillslopes where vertical river incision into bedrock oversteepens hillslopes to gradients near threshold angles, leading to increasing relief until gravitational stress exceeds mountain-scale material strength, and deep-seated bedrock landsliding ensues (e.g., Pettinga, 1980; Pettinga and Bell, 1992; Schmidt and Montgomery, 1995; Burbank et al., 1996; Montgomery, 2001; Montgomery and Brandon, 2002; Binnie et al., 2007; Larsen and Montgomery, 2012). Deep-seated landslides in the Waipaoa sedimentary system may have been triggered by intense or long-duration precipitation events common to the Waipaoa sedimentary system (Page et al., 2010; Gomez et al., 2013) or by seismic events (Litchfield et al., 2009; Orpin et al., 2010), but the underlying causes for the observed widespread landsliding are river incision and low bedrock mass strength.

Timing of Hillslope Response

Minimal tephra was found on the bodies of landslides, while thick sequences of multiple tephras are preserved on other stable landforms (e.g., terraces). Incomplete tephra stratigraphy was found on about a third of the landslides analyzed (Fig. 7), indicating that at least portions of these slides have been stable since the time between the deposition of the oldest tephra on the landslide and the preceding tephra.

Tephras older than the Rotoma (ca. 9420 cal. yr B.P.) were not found on the body of any landslide. While unambiguous evidence of the absence of a tephra is difficult to prove, we propose that the discovery of every major tephra younger than the Waiohau Tephra (ca. 14,010 cal. yr B.P.) present as undisturbed layers on landslides makes the absence of the Waiohau and Rerewhakaaitu (ca. 17,500 cal. yr B.P.) Tephras notable. This absence means that either: (1) landslides initiated before the deposition of these tephras and did not stabilize for long enough to preserve any undisturbed tephra, or (2) widespread slope instability did not initiate

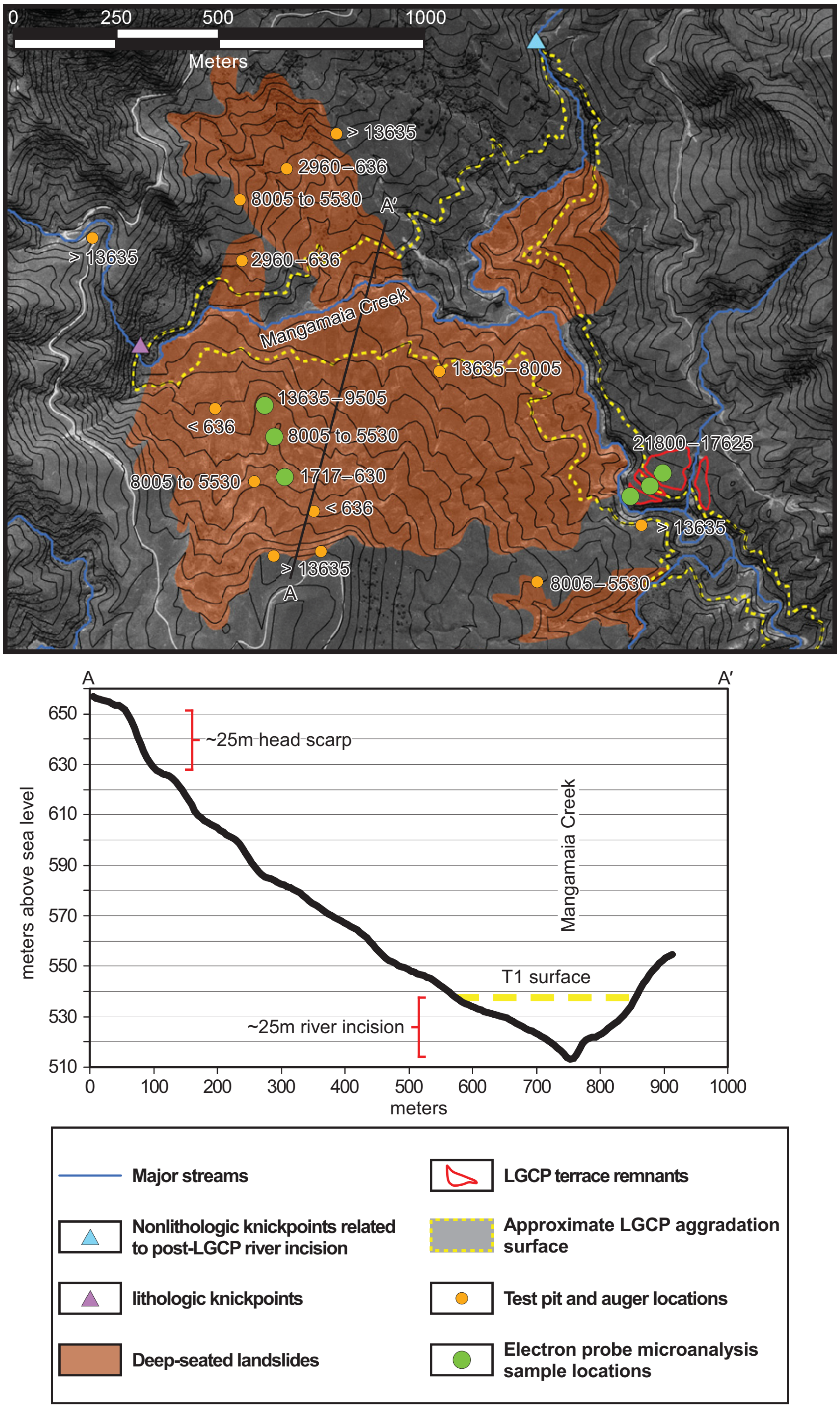

Figure 8. Landslides and last glacial coldest period (LGCP) terrace remnants in the Mangamaia tributary in the headwaters of the Mangatu River. Stabilization age ranges (cal. yr B.P.) are noted next to the test pit locations. Contour interval is 10 m. In the lower-right corner, note the two clear pre-Rerewhakaaitu (ca. 17,500 cal. yr B.P.) degradation terrace treads (red outlines) separated by ~13 m of elevation difference from the upper LGCP terrace remnant, which is an alluvial-fan surface. These are mapped by global positioning system and dated by tephrochronology. The bedrock strath outcrops 4 m below the surface of the lowest tread at this location. Cross section A-A′ shows that the ~25 m height of the headscarp on the large central landslide closely matches the ~25 m of post-LGCP river incision. It also shows that without incision, there would have been no accommodation space for the body or toe of the landslide. EMPA—electron probe microanalysis.

until after the deposition of the Waiohau Tephra. The link between slope instability and river incision described herein means that the timing of river incision can help to inform which of these hypotheses is more likely.

River incision initiated between ca. 21,860 cal. yr B.P. and 17,500 cal. yr B.P. and cut one to two degradation terrace treads, separated by up to 15 m, before deposition of the Rerewhakaaitu Tephra (ca. 17,500 cal. yr B.P.; Fig. 8; Marden et al., 2008, 2014). This initial incision, however, did not completely cut through and remove the T1 aggradation gravels at most locations, which kept the river's erosive capacity decoupled from bedrock (Fig. 8; Marden et al., 2008). The initial incision was followed by relatively slow river incision, with terraces overlain by the Waiohau Tephra (ca. 14,010 cal. yr B.P.) typically less than 4–8 m below the lowest degradation terrace overlain by the Rerewhakaaitu Tephra (Marden et al., 2014). The most rapid incision through significant amounts of bedrock below the T1 aggradation gravels occurred after the deposition of the Waiohau Tephra (ca. 14,010 cal. yr B.P.), particularly in the upper catchments (Marden et al., 2014). This period of rapid incision occurred prior to the deposition of the oldest basal tephra on landslides (Rotoma, ca. 9420 cal. yr B.P.), suggesting that the lack of the Waiohau Tephra on post-LGCP landslides likely relates to the post-Waiohau debuttressing of hillslopes due to rapid river incision into bedrock. We infer that widespread post-LGCP slope instability initiated in the period after the deposition of the Waiohau Tephra (ca. 14,010 cal. yr B.P.) and before the deposition of the Rotoma Tephra (ca. 9420 cal. yr B.P.).

The signal of rapid incision and debuttressing appears to be nearly synchronous in the upper Waipaoa sedimentary system from the headwaters to the main stem (Fig. 7). This is at odds with a hypothesis of migrating knickpoints that initiate on main-stem rivers and translate the incision response through the landscape (Crosby and Whipple, 2006; Berryman et al., 2010). Simultaneous river incision along the entire length of main-stem rivers was proposed by Gomez and Livingston (2012) based on terrace-abandonment ages presented by Marden et al. (2008) and supported further by Marden et al. (2014). The detailed tephrochronology presented here confirms that the initial rapid incision occurred at almost the same time on the main-stem rivers as at the headwaters of the Mangatu River (Figs. 7 and 8). Further, degradation terraces cut into the T1 aggradation surface in the headwaters are the same age as main-stem degradation terraces that lie upstream of a major lithologic knickpoint (Fig. 5). Such a lithologic barrier would limit the upstream advance of a migrating knickpoint induced by base-level fall or an increase in stream power. The lack of any progressively younger landslide tephra cover beds upstream (Fig. 7) also indicates that deep-seated landsliding, which we have shown is strongly coupled to river incision, was nearly synchronous throughout the upper Waipaoa sedimentary system and did not translate upstream as a result of migrating knickpoints. The nonlithologic knickpoints correlated to post-LGCP incision in the Waipaoa sedimentary system probably initiated at a threshold stream power high up in the fluvial network, migrating slowly from these threshold locations as alternatively proposed by Crosby and Whipple (2006).

The timing of the initiation of river incision, the onset of rapid bedrock incision, and large-scale hillslope response closely matches the timing of the transition from the LGCP and the climatic amelioration following the late glacial climate reversal observed in many climate proxies (e.g., Alloway et al., 2007; Barrell et al., 2013). Dramatic changes in upland erodibility between ca. 21,860 cal. yr B.P. and 17,500 cal. yr B.P. (Fig. 3) provide a mechanism for linking climate with aggradation and incision by replacing bed-load overcapacity with undercapacity (Berryman et al., 2000; Eden et al., 2001; Litchfield and Berryman, 2005; Marden et al., 2008; Gomez and Livingston, 2012; Upton et al., 2013). Widespread destabilization of hillslopes, however, did not commence until after the transition to full podocarp-angiosperm forest cover after the late glacial climate reversal at ca. 11,800 cal. yr B.P. At this time, hillslope sediment undersupply was likely at a maximum, and the rivers and tributaries of the Waipaoa sedimentary system had re-engaged with bedrock after scouring the remaining T1 aggradation gravels from their beds.

Conceptually, the upper Waipaoa sedimentary system was primed for significant post-LGCP incision. From the beginning of LGCP aggradation at ca. 28,000 cal. yr B.P. to resumption of incision into bedrock after ca. 11,800 cal. yr B.P., uplift of ~1–4 mm yr^{-1} proceeded while rivers and streams were aggrading and decoupled from bedrock (e.g., Fuller et al., 2009). During this time, when river incision was out of equilibrium with ongoing tectonic uplift, a "backlog" of river incision developed as aggrading valley bottoms were uplifted relative to average interglacial sea level. Hillslopes buttressed behind aggradation fill most likely attained an equilibrium slope profile through ongoing periglacial or shallow mass movement processes. In this model for landscape evolution during the LGCP, valley floors became aggradation plains and experienced net surface uplift, whereas hillslopes continued to erode and likely attained some degree of slope stability equilibrium.

Conceptual Time Series for Hillslope Response

The likely causative effect of climate change–driven vegetation change and precipitation changes (Gomez et al., 2013) on river incision allows us to further refine our tephra-based chronology of hillslope response to infer that significant incision-induced destabilization of hillslopes progressed after the transition to full podocarp-beach-angiosperm forest cover at ca. 11,800 cal. yr B.P. This enables us to develop a conceptual model of the timing and magnitude of hillslope response to climate change–induced river incision (Fig. 9). In this model, tectonic uplift on an active margin drives bedrock river incision over glacial-interglacial cycles, but climate change, the swing between glacial and interglacial cycles, causes the conditions responsible for river aggradations or incision. During glacial cycles, rivers and streams aggrade, and valley bottoms in the upper Waipaoa sedimentary system are uplifted relative to average interglacial sea level by ongoing tectonic processes. During interglacial cycles, rivers and streams incise, first through aggradation gravels and then through uplifted bedrock valley bottoms, debuttressing hillslopes and propagating the interglacial erosion upslope through deep-seated landslides.

During the LGCP (ca. 28,000–18,000 cal. yr B.P.), minimal forest cover, possible periglacial weathering, including climatically sensitive frost cracking (e.g., Schaller et al., 2002; Hales and Roering, 2005) in the uplands, and increased seasonality led to sediment overcapacity and aggradation. At this time, uplift continued without significant river incision because rivers and streams were decoupled from bedrock by thick deposits of aggradation gravel. This created a situation in which erosion progressed on hillslopes and interfluves, but the floors of valleys experienced net surface uplift, creating a "backlog" of river incision (Fig. 9A).

The transition to interglacial conditions from ca. 18,000 to 11,800 cal. yr B.P. included the late glacial climate reversal between ca. 13,700 and 11,800 cal. yr B.P. (Alloway et al., 2007; Barrell et al., 2013). During this time, changes in vegetation and possibly precipitation triggered a switch from mainly aggradation to river incision as hillslopes were vegetated, and rivers experienced sediment undersupply, and possibly increased discharge. T1 aggradation gravels were scoured away, but incision into bedrock was minimal (Figs. 9B and 9C). As river incision oversteepened hillslopes, threshold angles for mass wasting were approached. Hillslope debuttressing began, but the hillslope response was limited to slopes below the level of the projected T1 aggradation terrace (Figs. 9C and 9D).

After ca. 11,800 cal. yr B.P., podocarp-angiosperm-beech forests expanded to the maximum upland extent. Sediment-starved rivers caused rapid and large-scale river incision into bedrock (Fig. 9E). This also potentially increased the depth of the damage zone for groundwater wetting and drying by dropping the effective hillslope groundwater table (Fig. 9E). Debuttressed, threshold hillslopes experienced widespread landsliding triggered by heavy and/or long-duration precipitation events and possibly earthquakes (Figs. 9E and 9F).

In the mid-late Holocene (post-7000 cal. yr B.P.), hillslopes continued to respond as rivers incised to balance tectonic uplift (Gomez and Livingston, 2012), causing local base-level drop and oversteepened slopes to propagate upslope. In places, interfluves lowered and retreated away from areas of greatest local base-level fall due to the upslope propagation of landslides (Fig. 9G). Through the response to climate-modulated, tectonic uplift–driven river incision, the morphology of the upper Waipaoa sedimentary system was modified, releasing large amounts of sediment from hillslope storage and transferring it to storage in terrestrial and marine depocenters (Bilderback, 2012). While previous work has surmised changing hillslope erosion rates through glacial-interglacial cycles (Fuller et al., 2009), here, we pinpoint the mechanism, location, and timing of post-LGCP hillslope sediment production.

CONCLUSIONS

We have identified 236 deep-seated landslides that have been active since the end of the LGCP (ca. 18,000 cal. yr B.P.) in 141 km^2 of detailed upper Waipaoa catchment study areas (Fig. 5). Depending on the underlying geology, landslides make up between 13% and 35% of the surface area of these study areas. Landslide aspect is not closely linked with bedding

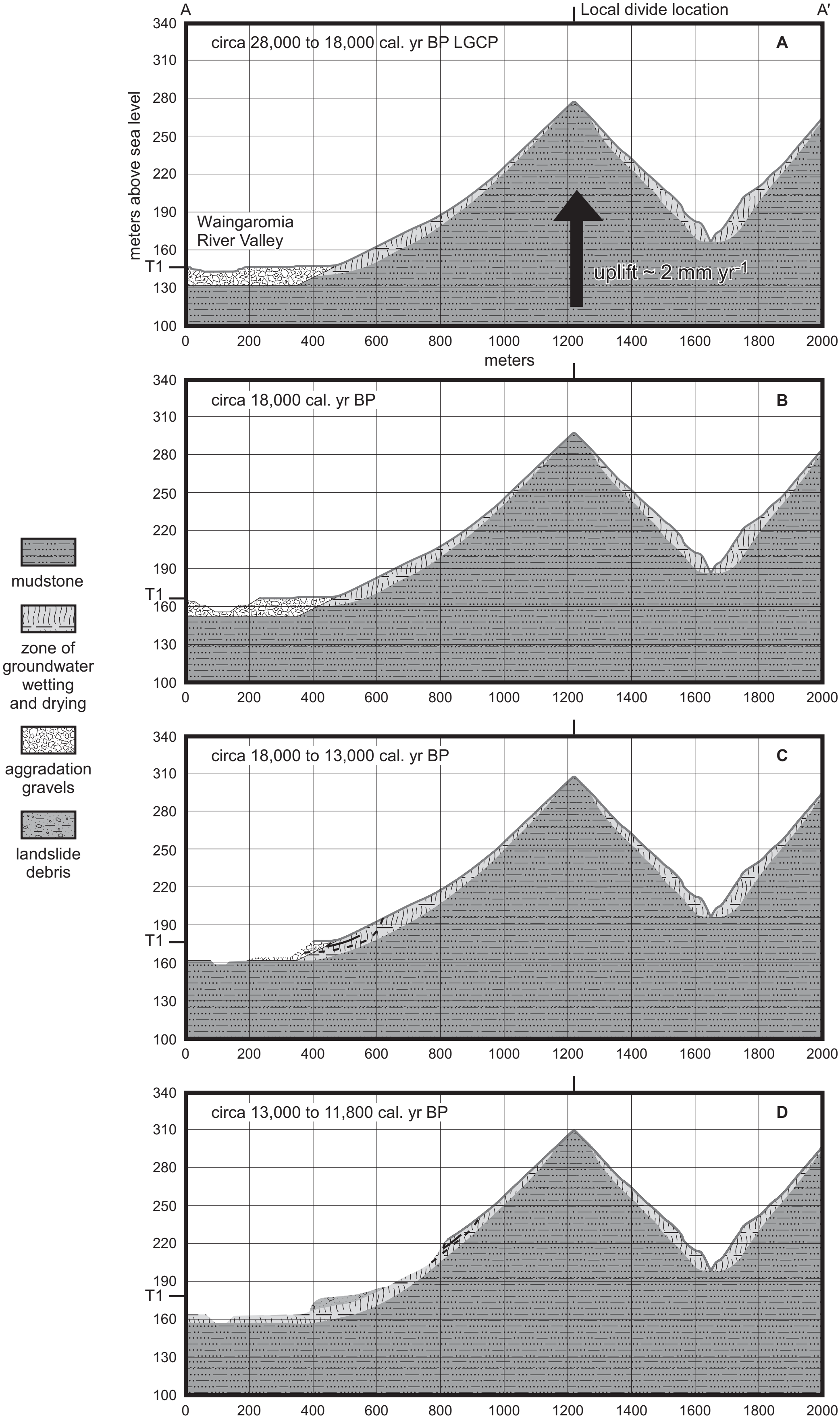

Figure 9 (*on this and following page*). (A–G) Conceptual time series of the magnitude of hillslope response to climate change–induced river incision described in the Discussion section. Profile A-A′ is modeled off the present-day profile across a hillslope and interfluve adjacent to the Waingaromia River shown in Figure 5. The cross section crosses the smaller tributary on the right above the post–last glacial coldest period (LGCP) incision-related knickpoint; therefore, no change in basic hillslope geometry is expected in this area. Dashed lines are landslide slip planes; arrows indicate sense of movement.

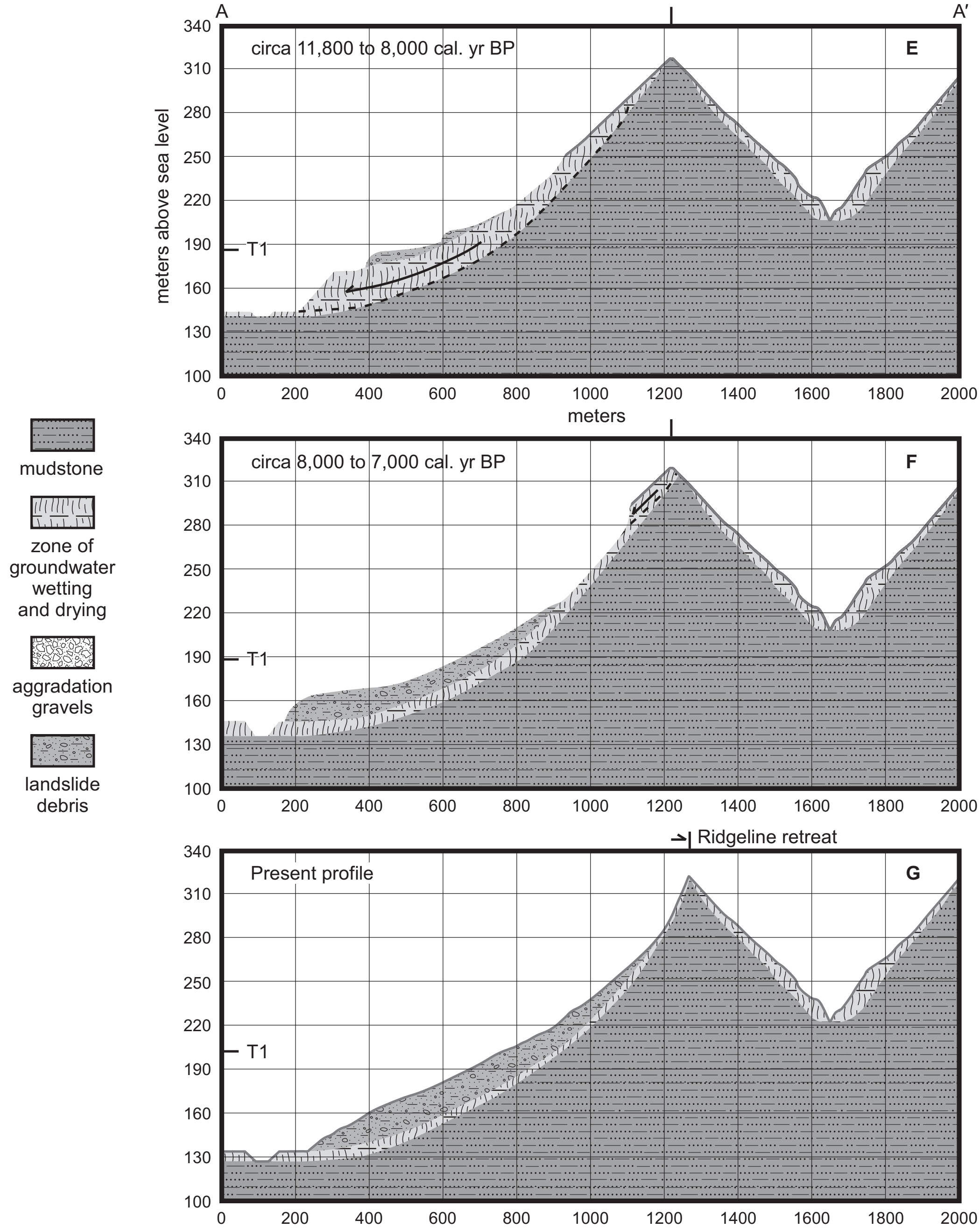

Figure 9 (*continued*).

structure. Dip-slope landslides are approximately randomly correlated to underlying geologic structure, with only ~25% of landslides with nearby bedrock attitude measurements constituting dip-slope landslides. Further, deep-seated bedrock landslides are spatially and temporally correlated with post-LGCP river incision. We conclude that slopes underlain by low-strength and highly sheared bedrock were debuttressed by river incision, and as hillslopes reached threshold gradients, they responded by gravitational collapse. These deep-seated bedrock landslides may have been triggered by intense or long-duration precipitation events or by seismic events, but the underlying causes for the widespread landsliding observed are river incision and low bedrock mass strength.

Landform tephrochronology indicates that widespread slope instability did not begin until after the deposition of the ca. 14,010 cal. yr B.P. Waiohau Tephra, confirming the conclusions of previous studies. Our results further confirm that the signal of rapid incision and debuttressing appears to be near-synchronous in the upper Waipaoa sedimentary system from the headwaters to the main stem. Within the limits of the tephrochronology, there is good agreement between the timing of hillslope debuttressing and other independent terrace-based degradation estimates of the timing of most rapid river incision after the LGCP. Through investigation of the timing of coupled river incision and landslide activity, confirmation of similar incision histories at the main stem and headwaters, and assessment of the minimum age of ancient scree exposures, we bolster the argument that climate change leading to alterations in upland vegetation influenced the morphology of the terrestrial Waipaoa sedimentary system through changes in sediment supply to and, possibly, discharge of rivers. These investigations also indicate that the nonlithologic knickpoints observed in the modern Waipaoa sedimentary system did not initiate in main stems and propagate throughout the fluvial network, but rather initiated at a threshold stream power high up in the fluvial network and retreated at slow rates to their current locations.

We have produced a conceptual model that shows how hillslopes in the Waipaoa sedimentary system responded to climate and vegetation change during the last glacial-interglacial transition. Generally, this conceptual model could be applied to any active margin catchment where climate change or land-use change can influence rivers to switch between modes of aggradation or bedrock incision. While generally applicable, the magnitude and rates of hillslope response will vary with local climate and geologic conditions. Widespread deep-seated landsliding caused by slope oversteepening and debuttressing resulted from climate-modulated, uplift-driven river incision. These post-LGCP deep-seated landslides shaped the modern morphology of the Waipaoa sedimentary system to the extent that even interfluves were, in places, shifted and lowered. Through this work, we have shown how climate and tectonic uplift have shaped hillslope morphology and substantially influenced the evolution of a landscape.

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