Geomorphology 214 (2014) 283–306

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Post-Last Glacial Maximum fluvial incision and sediment generation in the unglaciated Waipaoa catchment, North Island, New Zealand

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ARTICLE INFO

Article history:
Received 20 January 2013
Received in revised form 20 February 2014
Accepted 20 February 2014
Available online 1 March 2014

Keywords:
Post-LGM
Onshore fluvial incision
Sediment generation
Landscape response
Hikurangi Margin

ABSTRACT

Small river systems contribute a significant component of sediment delivered to oceans, but the temporal evolution of fluvially eroded landscapes is needed. A sequence of postglacial terraces in the unglaciated Waipaoa River catchment provides the opportunity to document fluvial incision and sediment flux on an ~2000-year timescale since the Last Glacial Maximum (LGM), which has previously only been undertaken for the entire post-LGM period. This study also calculates sediment mass, where previously sediment volume was calculated. Using a 15-m DEM, field mapping and surveying, and tephrochronology, we calculate rates of fluvial incision and sediment volumes excavated during successive age-constrained, postglacial, incision events and correlate these with a framework of inferred climatic events established for New Zealand. We identify seven periods of terrace formation each succeeded by a period of fluvial incision, six in total. Although the magnitude of the response during each incision event and thus the sediment volumes generated varied through time and across subcatchments draining two contrasting lithological terrains, we conclude that incision events were essentially synchronous, at least within the timeframe constrained by the ca. 2000 year interval between successive eruptive airfall events. Slope relaxation processes were simultaneous with incision thereby indicating that both processes were likely climate driven. We identify a period of accelerated fluvial incision ~7 mm y^{-1} commencing before ca. 14.0 cal. ka BP (during the early postglacial period) and ceasing ca. 7.9 cal. ka BP toward the end of the Early Holocene Warming period. The magnitude of this incision response was significantly higher in subcatchments draining highly erodible lithologies in the higher uplifting parts of the catchment when river bedload was at over capacity. In contrast, within the remainder of subcatchments draining the more resistant lithologies and in areas of lower uplift (and in parts subsiding), incision and sediment generation was moderated by the presence of knickpoints. Overall, since abandonment of the LGM to present day, fluvial incision in the Waipaoa and the adjacent Waimata catchments generated ~16.7 km^3 of sediment of which ~10 km^3 (~90% of the estimated 35 Mt of glacial–postglacial slope and shelf sediment mass) was potentially available for transport offshore. Of this, 14.08 km^3 (7.4 km^3 derived from 'upper' and 6.7 km^3 from 'remainder' of subcatchments) was excavated from Waipaoa catchment at an average of ~0.6 km^3 ka^{-1} of which ~80% was generated by ca. 7.9 cal. ka BP. This potentially validates previous accounts of high rates of offshore sediment flux before 8000 ^{14}C YBP (ca. 8877 cal. YBP). Thereafter, for the period mid-Holocene cooling and variability (MHCV) (ca. 6.5 cal. ka BP) until the present day, the rate of incision across all subcatchments slowed to ~2 mm y^{-1} and generated just ~20% of the total sediment volume. In part, this reflected a depletion of available sediment as rivers in the upper subcatchments returned to a steady state and, coincidental with an increase in accommodation space in the rapidly growing coastal floodplain, sediment flux to the marine depocentres was thereby limited.

1. Introduction

The incision of alluvial channels has played a key role in translating tectonic and climatic signals throughout drainage systems with estimates of the flux and fate (temporary storage versus delivery to the ocean) of the sediment generated by fluvial incision proving to be nonlinear (Meade, 1982; Walling, 1983; Phillips, 1987) and complex

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http://dx.doi.org/10.1016/j.geomorph.2014.02.012
0169-555X/

(Milliman and Syvitsky, 1992). A better understanding of the dynamics of fluvial systems and of the temporal evolution of fluvially eroded landscapes is needed (Phillips et al., 2007) especially for small river systems (<10,000 km^{-2}) that contribute much more sediment to the world's oceans than previously thought (Milliman and Syvitsky, 1992). This deficiency may in part be explained by a paucity of locations where field data is sufficient to construct more than just an initial and final longitudinal river and terrace profile (Moshe et al., 2008) from which to evaluate the temporal history of sediment generation by fluvial incision, its flux to the world's oceans and relationships with inferred climatic events, vegetation change, and tectonic influences.

Unglaciated river catchments draining the tectonically active subduction margin on the east coast of New Zealand's North Island contain a sequence of well-preserved, age-constrained fluvial terraces and meanders of late Pleistocene and Holocene age (Berryman et al., 2000; Eden et al., 2001; Litchfield and Berryman, 2005; Marden et al., 2008a; Berryman et al., 2010). An understanding of this fluvial sequence is fundamental to interpreting the onshore landscape response to individual incision events and to validate the record of land-to-ocean transfer of terrigenous sediment preserved on the adjacent continental slope and shelf (Carter et al., 2010; Gerber et al., 2010) — a major goal of source-to-sink landscape evolution studies in the Hikurangi subduction margin of New Zealand.

Within the Waipaoa River catchment, the onshore portion of the Waipaoa sedimentary system (WSS) (Carter et al., 2010; Gerber et al., 2010; Wolinsky et al., 2010), the extent and age of a suite of four major, widespread, intercorrelated, fluvial terraces have previously been documented (Berryman et al., 2000; Eden et al., 2001; Litchfield and Berryman, 2005; Phillips et al., 2007; Berryman et al., 2010). The youngest and most widely preserved of these, dated at ~30 to 18–15 cal. ka, spans the Last Glacial Maximum (LGM) and has an associated gravel unit beneath the Poverty Bay floodplain. These LGM aggradation deposits have been buried by reworked gravel units, marine and marginal marine deposits that accumulated during the postglacial marine transgression, culminating at ca. 7.0 cal. ka BP (Brown, 1995; Berryman et al., 2000; Marden et al., 2008a; Berryman et al., 2010; Wolinsky et al., 2010).

The period of transition from the LGM terrace to the postglacial period represents a time of marked and rapid fluctuations in climate (Lowe et al., 2008) and vegetation cover (McGlone et al., 1993) coincident with the initiation of an extended period of fluvial incision (Gomez and Livingston, 2012). However, considerable debate remains as to when within the climate cycle the all-important incision events, leading to the formation of terraces, occurred. Within Waipaoa catchment, dateable organics and the presence of silicic tephra — deposited on average every 2000 years since the LGM — provide a minimum age for terrace coverbed materials. Their preservation forms the basis for a high resolution interpretation of (i) the approximate timing of floodplain construction and abandonment, (ii) the initiation of onshore fluvial incision, (iii) the triggering of extensive hillslope adjustment, and (iv) the timing of periods of sediment flux to Poverty Bay and the Hikurangi Margin (Orpin et al., 2002).

Previously, Marden et al. (2008a) compared the total postglacial sediment volume excavated by fluvial incision from the Waipaoa catchment with estimates of the postglacial onshore storage component comprising the Poverty Bay flats and the offshore slope and shelf deposits (Foster and Carter, 1997; Orpin et al., 2002; Orpin, 2004). Estimates of shelf and slope sediment accumulation are based on sediment above two major seismic reflectors: one (assumed to be of the last glacial age) defines the unconformity between unconsolidated postglacial mud and the underlying deformed and indurated Neogene strata; the other, a conformable reflector in the top 15-m of the prism, has been assumed to be early Holocene in age (8–10,000 ^{14}C YBP) after Pantin (1966). The presence of the Tuhua tephra (ca. 6.9 cal. ka BP) at 14.13 m depth in the *Calypso* core MD97-2122 (Gomez et al., 2004) from the Poverty Bay mid-shelf basin (Fig. 1A) is considered to confirm that the underlying reflector is early Holocene in age (Orpin, 2004). In addition, the offshore sediment storage pattern appeared to support the contention of an early (before 8000 ^{14}C YBP, ca. 8877 cal. YBP) and rapid phase of onshore fluvial incision that potentially produced ~12 km^3 of offshore sedimentation, followed by a period of slower incision during which ~8–11 km^3 of offshore sediment accumulation occurred in the last 8000 years of the Holocene period (Pantin, 1966; Foster and Carter, 1997). By comparison, Foster and Carter (1997) estimated that 20 km^3 of mud has been deposited on the Poverty Bay shelf since ca. 18,000 cal. YBP, of which 8 km^3 accumulated since ca. 8000 cal. YBP; and Orpin (2004) concluded that during the mid to late Holocene a further 3-km^3 lobe of postglacial hemipelagic sediment accumulated in mid-slope basins. More recently, offshore seismic and multibeam data support the possibility that a potential extrabasinal source of shelf sediment, as indicated by the presence of greywacke (Torlesse) lithologies, flowed into Poverty Canyon during the most recent sea-level low stand. The presence of the Torlesse gravel is significant in that it highlights how the WSS was not a closed sedimentary system in the past, just as recent sedimentary research has shown is the case today (Parra et al., 2012).

Using a 25-m DEM, Marden et al. (2008a) estimated the total postglacial sediment volume eroded by channel incision from Waipaoa catchment to be ~9.4 and ~2.6 km^3 from Waimata catchment and concluded that though accounting for ~25% of the postglacial shelf and slope sediment accumulation these volumes were likely underestimated. More recently, the post-LGM history of terrace formation and sediment volume generated by fluvial incision has been documented for a 2.2-km^2 reach of Waihuka River — a sub-catchment of the Waipaoa River (Berryman et al., 2010) — however, this has not been previously attempted for the Waipaoa catchment as a whole.

We present a reconstruction of longitudinal terrace and river profiles, at subcatchment scale, with the aim to: (i) establish the post-LGM history of terrace formation and timing and number of incision events to determine if terrace abandonment was synchronous across subcatchments, (ii) relate this terrace history to a framework of inferred climatic events established for New Zealand, (iii) derive rates of incision and estimates of fluvially derived sediment volumes, iv) validate an early (before 8000 ^{14}C YBP, ca. 8877 cal. YBP) and rapid period of offshore sedimentation; a goal of the MARGINS Source-to-Sink landscape evolution studies in the Hikurangi subduction margin of New Zealand.

2. Tectonics and geology

The Waipaoa River catchment (2150 km^2) is situated within the active forearc of the Hikurangi subduction margin, in an area of widespread uplift and consequent normal faulting (Berryman, 1988; Lewis and Pettinga, 1993; Litchfield et al., 2007; Wilson et al., 2007; Berryman et al., 2009) (Fig. 1A). Longitudinal profiles of Pleistocene and Holocene-aged alluvial terraces that extend almost the full length of Waipaoa River suggest tectonic deformation takes the form of broad regional uplift with maximum uplift of ~4 mm y^{-1} near the crest of the Raukumara Range decreasing to 1–2 mm y^{-1} in the middle of the catchment and averaging a range of 0.5–0.9 mm y^{-1} (Yoshikawa, 1988; Litchfield and Berryman, 2006; Wilson et al., 2007). In contrast, coastal areas near Gisborne City display signs of late Quaternary vertical deformation involving uplift and subsidence (Ota et al., 1991, 1992; Brown, 1995; Berryman et al., 2000; Wilson et al., 2006). This likely reflects seamount subduction processes on the structure and morphology of the frontal wedge (Pedley et al., 2010) below the middle part of the catchment and by a combination of deep-seated subduction and local deformation associated with active faults and folds below the lower valley area (Berryman et al., 2000; Litchfield and Berryman, 2006; Berryman et al., 2010).

The catchment lies 100–200 km downwind of the central North Island volcanoes and, on average every 2000 years since the LGM, has received silicic airfall tephra derived from either the Okataina or the