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Climate influence on volcano edifice stability and fluvial landscape evolution surrounding Mount Ruapehu, New Zealand

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ABSTRACT

Large volcanic debris avalanches are triggered by failure of the steep flanks of long-lived composite cones. Their huge deposits change the landscape and drainage pattern surrounding stratovolcanoes for thousands of years. At Mt. Ruapehu, New Zealand, we identified seven major flank-collapse events that produced debris avalanches travelling down pre-existing river catchments for up to 90 km from source. In two cases the extreme mass flux into the river valleys led to their complete truncation from the volcano, while four drainage systems were subsequently re-established along similar pathways influenced by regional strike-slip faulting, which caused localized graben formation. In all cases the volcanic debris-avalanche deposits currently form distinctive plateaus at or near the highest topographic elevations of each river valley margin. The timing of the flank failures indicate that inter-eruptive cone destabilization of Mt. Ruapehu is affected by climate change and occurs most commonly during interstadials when glaciers on the cone are in retreat, whereas syn-eruptive collapses are most prominent during cold stages. Dated debris-avalanche deposit levels, along with those of up to four stadial-related aggradational gravel terraces between c. 125 and 18 ka, were used to calculate regional uplift rates in this area. Rates of between 0.2 ± 0.1 mm yr^{-1} to 3.8 ± 0.8 mm yr^{-1} are found for four river systems dissecting the central North Island of New Zealand. In three cases incision below the diamicton sequences and into the basement, allowed quantification of sediment-flux rates into the Tasman Sea of 107,000 ± 1,200 m^3 yr^{-1} to 177,000 ± 3,500 m^3 yr^{-1} since debris-avalanche emplacement.

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1. Introduction

Aggradational fluvial terraces along river valleys are frequently used to determine approximate regional tectonic uplift rates (e.g., Leopold and Bull, 1979; Merritts et al., 1994; Personius, 1995; Burbank et al., 1996; Li et al., 1997; Tebbens et al., 2000; Maddy et al., 2001; Pazzaglia and Brandon, 2001; Bridgland and Westaway, 2008; Viveen et al., 2013). This method was previously applied to well-preserved Quaternary aggradational fluvial terraces formed throughout many parts of the eastern and central North Island of New Zealand (Vella et al., 1988; Personius, 1995; Burbank et al., 1996; Li et al., 1997; Berryman et al., 2000; Pazzaglia and Brandon, 2001; Litchfield, 2003; Litchfield and Berryman, 2005, 2006). These authors assume that formation of these gravel terraces was dominantly controlled by climate-erosion-landscape interactions. They are thought to form during glacial periods when rates of upper-catchment erosion and sediment supply into the river are high (Milne, 1973a; Yoshikawa et al., 1981; Porter et al., 1992; Sugai, 1993; Fuller et al., 1998; Bridgeland, 2000; Litchfield and Berryman, 2005, 2006; Bridgland and Westaway, 2008; Gibbard and Lewin, 2009; Lewin and Gibbard, 2010). The age of cessation of gravel deposition on these aggradational terraces were obtained by the stratigraphy and independent age estimates from overlying loess and tephra layers (Milne, 1973a; Pillans, 1994; Litchfield and Berryman, 2005).

In the central North Island of New Zealand, additional distinct terraces and surfaces occur in most river catchments, radiating from the major stratovolcanoes of Mts. Ruapehu and Tongariro. Cronin et al. (1996) noted a climate-relationship with distinct periods of volcanic mass-flow aggradation on the outer flanks of the volcanoes. However, it was unclear how these related to the distal river valleys, which may have also non-volcanic portions to their catchments. Ancient mass-flow deposits from Mt. Ruapehu form distinctive terraces on the highest topographic elevations along several river valleys. These together with climate-related gravel aggradation terraces offer the potential for determination of regional uplift rates, as long as the ages of the units are well known. The mass-flow deposits, related to large-scale flank failures of the stratovolcano, were recently mapped and dated along six river valleys radiating from it (Tost et al., 2014; Tost and Cronin, 2015). Mass-wasting events of ice-capped composite cones can be related to rapid deglaciation in temperate parts of the world (Alloway et al.,

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1986; Capra, 2006; Roverato et al., 2011; Deemingl et al., 2012; Capra et al., 2013). The loss of glaciers from heavily glaciated volcanoes may lead to eustatic uplift, as well as the loss of slope-buttressing (Capra, 2006). Previous studies noted that rapid glacier retreat is followed by enhanced erosion and stream discharge, as well as greater water flow into groundwater and internal fluid circulation (e.g., Haeberli et al., 1997; Davies et al., 2001; Arenson and Springman, 2005; Capra, 2006; Gruber and Haeberli, 2007; Günzel, 2008; Clague, 2009; Harris et al., 2009; Huggel, 2009; Huggel et al., 2012). These may also collectively lead to destabilization of steep volcano flanks and possibly prime them for collapse.

Volcanic debris avalanches often exceed several km^3 in volume and their emplacement rapidly alters the pre-existing landscape through valley filling, river damming and drainage re-direction (Crandell et al., 1984; Siebert, 1984; Procter et al., 2009; Zernack et al., 2012; Tost et al., 2015). The deposits may also be rapidly modified and reshaped, producing subsequent very high annual sediment remobilisation fluxes, e.g., 10^3 to 10^6 Mg/km^2 following the Mt. St. Helens (USA) collapse (e.g., Milliman and Syvitski, 1992; Mercado et al., 1996; Major et al., 2000).

The aims of this research were thus to: i) identify and correlate the volcanic terraces in relation to aggradational fluvial terraces exposed along major river catchments surrounding Mt. Ruapehu; ii) calculate approximate uplift and sediment flux rates in reaches of each river catchment where the terraces are best expressed (typically 20–50 km from Mt. Ruapehu); and iii) to examine if there is any relationship between debris-avalanche timing and climate change.

1.1. Geological setting

Mt. Ruapehu is a stratovolcano with an eruption history that spans at least the last 340 ka (Tost and Cronin, 2015). It is located at the southwestern boundary of the Taupo Volcanic Zone (TVZ), and is related to oblique subduction (1.27°/Ma) of the oceanic Pacific Plate beneath the continental Australian Plate (Graham et al., 1995; Wilson et al., 1995). The TVZ is the dominant focus of late-Pliocene to Quaternary volcanic activity in New Zealand (Graham and Hackett, 1987; Wilson et al., 1995), and one of the most productive magmatic systems on Earth (e.g., Wilson et al., 1995; Price et al., 2005).

Mt. Ruapehu is sited within an active graben and the landscape surrounding the composite massif forms a vast ring plain, comprising overlapping fans of sediment made up of laharic and fluvial deposits as well as pyroclastic flow and tephra fall units (Cole et al., 1986; Hackett and Houghton, 1989; Donoghue et al., 1995; Graham et al., 1995; Cronin and Neall, 1997). Beyond this, major debris-avalanche deposits and other long-runout lahar units extend up to 90 km from the volcano (Keigler et al., 2011; Tost et al., 2014, 2015). The distal southern Ruapehu ring-plain area is generally down-thrown due to ongoing normal and strike-slip faulting, which produces cross-cutting geometries with marginal rift-boundary faults (Villamor and Berryman, 2006a,b). Field work for this study was carried out along six major river catchments that radiate from and dissect the Mt. Ruapehu and Mt. Tongariro ring plains (Fig. 1). These are, from southeast to northwest: the Hautapu, Turakina, Mangawhero, Manganuioteao, Whakapapa and Whanganui rivers. The latter four currently rise from Mt. Ruapehu and/or Mt. Tongariro, whereas the Hautapu and Turakina Rivers are cut off from the volcano and originate from wetlands on the proximal to medial southern and southeastern Ruapehu ring plain (Fig. 1) (Rogers, 1993). The river catchments generally have a northeast to north-northeast trend, similar to the main structural orientation of the TVZ, although regional faulting (Villamor and Berryman, 2006a,b) occasionally deflects their routes towards the west or northwest. Mapping and identification of non-volcanic fluvial gravel-aggradational terraces showed that they are best preserved in the medial to distal reaches (20–50 km) of four river valleys (Hautapu, Mangawhero, Manganuioteao and Whanganui rivers). The most widespread terraces in the study area and their approximate age are summarized in Table 1.

2. Methods

The extents of volcanic and non-volcanic terraces were mapped at 1:50,000 scale, supplemented by a regional 8 m digital elevation model, and elevations were measured using hand-held GPS. Coverbed sequences were examined for dated loess and rhyolitic tephra layers to estimate terrace-emplacement ages (cf., Cronin et al., 1996; Keigler et al., 2011). Coverbed stratigraphy was correlated to a well-known loess sequence c. 50 km downstream of the Hautapu River where it enters the Rangitikei River valley (Milne, 1973a,b; Pillans, 1994). Andesitic lava clasts within the volcaniclastic terraces were dated using the $^{40}Ar/^{39}Ar$ radiometric method (Tost and Cronin, 2015), and these volcanic origin ages provided upper limits to deposition ages (Table 1).

Approximate regional uplift rates were obtained following the method of, among others, Berryman et al. (2000) and Litchfield and Berryman (2006), assuming that each non-volcanic aggradational terrace was related to stadial climates, and down-cutting of the river is a warm-climate phenomenon. This assumption is based on the climate-sedimentation model proposed by Suggate (1965), revised by Eden (1989) and later by Viveen et al. (2013), where a reduction in vegetation cover during cold climates increases the erosion in the headwaters of the river systems, filling the valleys downstream with gravels and sands. During interglacial periods, rainfall increases and forest cover re-establishes (McGlone et al., 1984), reducing erosion (Litchfield and Berryman, 2006). During stadial climates, sea level is significantly lowered (glacio-eustatic base-level fall), resulting in a steeper longitudinal profile of the river, and, hence, an increase in its stream power (e.g., Leopold and Bull, 1979; Merritts et al., 1994). As a consequence, coarser sediments are deposited farther downstream than under interstadial climatic conditions and can form vast aggradational plains in the medial to distal reaches of a river system (e.g., Begin et al., 1980; Merritts et al., 1994; Tebbens et al., 2000; Maddy et al., 2001; Bridgland and Westaway, 2008; Viveen et al., 2013). Within the study area, the theory of enhanced river aggradation during cold stages is supported by stratigraphic field evidence of coverbed sequences, outlining fluvial gravels overlain and/or intercalated with fine-grained loess deposits, and separated from each other by thick paleosol horizons (Fig. 2). The uplift-calculation model assumes constant river levels during glacial and interglacial periods and similar aggradation altitudes (relative to river level) during cold periods within a specific area. Rock-uplift rates are calculated by measuring the altitude difference between the individual aggradational terraces of known age (Berryman et al., 2000; Litchfield and Berryman, 2006). In this study, multiple terrace altitudes were measured by hand-held GPS along the individual river catchments (Table 2). The calculations of approximate uplift rates are limited to areas were mass-flow deposits of known age are exposed to ensure accurate identification of younger non-volcanic aggradational terraces.

In order to quantify sediment volumes eroded from individual river catchments following volcanic mass-flow emplacement, terrace-elevation differences were measured between the volcaniclastic units and the lowermost of the fluvio-glacial gravels, the T1 Terrace (formed between 18 and ~10 ka BP; Pillans, 1994). Measurements were made at localities where the re-established river systems incised into the uppermost volcaniclastic terraces of known age (Tost and Cronin, 2015), as well as the underlying late-Pliocene basement (Fig. 3). Therefore, approximate sediment fluxes could only be calculated for the Hautapu, Mangawhero and Manganuioteao river systems. At the target localities, the maximum valley width was measured from the 8 m digital elevation model and multiplied by the obtained elevation difference measured by GPS. A long-term average rate was calculated over the period between final mass-flow emplacement within the river catchment and the T1 Terrace. Although it is expected that rates of erosion are highest soon after emplacement of the debris avalanche units (e.g., Procter et al., 2009), the time window chosen was based on the most reliably identified altitude reference of the T1 Terrace at all sites.

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