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Post-rock-avalanche dam outburst flood sedimentation in Ram Creek, Southern Alps, New Zealand

Lisa M. Harrison [a], Stuart A. Dunning [a,*], John Woodward [a], Timothy R.H. Davies [b]

[a] Department of Geography, Northumbria University, Ellison Place, Newcastle Upon Tyne NE1 8ST, United Kingdom
[b] Department of Geological Sciences, University of Canterbury, Christchurch, New Zealand

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ABSTRACT

Rock avalanches are common in mountainous regions that are tectonically active. They are capable of forming natural dams of uncertain persistence that have significant impacts on the river system over wide spatial scales and possibly over geological time scales. Here we combine field data and digital elevation model (DEM) analysis to show the response of Ram Creek, New Zealand, to 28 years of sediment dispersion following the 1968 emplacement of a co-seismic, rock-avalanche dam that breached catastrophically in 1981. The results show a system that has not attained equilibrium, being unable to move the quantity of dam-derived sediments, and will likely not attain equilibrium before the next major sediment input; it is in a state of persistent disturbance where localised reworking dominates. Erosion in Ram Creek is focussed on lateral bevelling and bedrock gorge widening rather than vertical incision to keep pace with tectonic uplift. Importantly for studies of tectonic geomorphology, this widening — which if sustained will form a strath terrace — does not represent a period of reduced uplift. Stream metrics (concavity and steepness) are unable to differentiate the identified rock-avalanche-induced knickpoint from tectonic and lithological knickpoints.

1. Introduction

In tectonically active mountain environments, catastrophic mass movements — often associated with seismic triggering — can control valley floor geomorphology far beyond the failure site (Pearce and Watson, 1986; Hewitt, 1999, 2006; Korup et al., 2004; Korup, 2005a). It is becoming ever more apparent that large landslide deposits can exert a dominant geomorphic control on the fluvial system (Burbank et al., 1996; Montgomery and Brandon, 2002; Korup, 2005b; Korup et al., 2009, 2010).

Rock avalanches (RAs) are a high-magnitude, low-frequency mechanism of eroding mountain peaks and delivering sediment to valley floors (Hovius et al., 1997; McSaveney, 2002). They commonly involve a minimum volume of ~1×10^6 m^3 of rock and associated cover, which are transported from a discrete source to the valley floor at speeds of 100–250 km/h. In actively incising systems with narrow valleys, they can immediately block a river valley with a highly compact deposit (Hewitt, 1999, 2009; Dunning et al., 2005, 2006; Hewitt et al., 2008). These natural dams can last anywhere from minutes to millennia, posing significant hazard to life and infrastructure (Dunning et al., 2006) and provoking a geomorphic response at varied temporal and spatial scales in fluvial and hillslope systems (Costa and Schuster, 1988; Hewitt, 2006). The RAs supply an abnormal point-load of sediment to the fluvial system as opposed to the distributed, chronic, delivery of smaller landslides. This increases the volume of sediment storage within a catchment as rivers are often forced into a transport-limited state (Adams, 1980; Pearce and Watson, 1986; Korup et al., 2004, 2010; Korup, 2005b; Hewitt, 2006, 2009).

During RA emplacement, intact bedrock is broken apart by brittle fracture, pulverisation, and crushing. This creates distinctive rock-avalanche deposits (RADs) comprised of poorly sorted, angular to very angular clasts of gravel, sand, and (mostly) finer grades with small-scale agglomerates, capped by a boulder carapace (Davies et al., 1999; McSaveney, 2002; Dunning et al., 2006; Mitchell et al., 2007; Hewitt et al., 2008; Hewitt, 2009; Reznichenko et al., 2011). Beneath the coarse surface and near-surface carapace, the bulk of the deposit is therefore composed of bedrock fragmented to sizes finer than the 'normal' bedload of many rivers in mountainous regions.

Rock-avalanche dams can overtop and remain stable (Hewitt, 1998), or breach with stable overflow channel allowing the majority of dam volume to persist. The RADs often persist after overtopping because of self-armouring of the breach channel by the coarse carapace falling into the developing breach channel sides (Dunning et al., 2006). However, if an RA dam breaches and fails catastrophically, the resultant outburst floods are capable of mobilising large volumes of the RA sediment and (if present) impounded lake sediments, rapidly and widely dispersing it downstream. The resulting aggradation in-channel and over any available floodplain buries former geomorphic features creating an RA-forced disturbed landscape. The persistence and distinctiveness of this

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[*] Corresponding author. Tel.: +44 191 227.
E-mail address: stuart.dunning@northumbria.ac.uk (S.A. Dunning).

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disturbance and subsequent fluvial recovery are currently poorly quantified (Hancox et al., 2005; Dunning et al., 2006; Hewitt, 2006; Korup and Clague, 2009; Korup et al., 2010).

Landslide and lake-derived fill and the associated boulder lag deposit (e.g., the carapace), inhibit fluvial incision into bedrock (Hewitt, 2006; Ouimet et al., 2007; Korup et al., 2010) until the river has removed the debris to reach its former bed. Incision therefore lags behind the rates in rivers undisturbed by RADs. Fluvial incision rates through bedrock are important for long-term landscape evolution, as they are assumed to control the rate of catchment denudation (Burbank et al., 1996; Snyder et al., 2000; Kirchner et al., 2001; Korup et al., 2009, 2010). If RAs disturb a large number of catchments, their time scales of disruption to the fluvial system are an unknown factor in understanding landscape evolution of active orogens.

River long profiles have shown promise in identifying catchments with an RAD signal (Korup, 2006). An RAD, if it persists through either retaining a lake or as a post-outburst flood remnant can form a knickpoint, or convex step, in the normally concave river long profile (Korup, 2006) — similar to a fault displacement. This displaces the fluvial profile vertically above the original channel bed, increasing overall profile steepness and decreasing overall profile concavity (Korup, 2006), which is often distinctive in long profile data.

The RA-forced disturbances act over multiple time scales, from short-term (<10^1 years) localised in-channel responses; ~10^4 timescale changes to erosion and deposition patterns in a catchment (Whipple, 2004; Davies and Korup, 2007; Hewitt et al., 2008; Korup et al., 2009) and, potentially geologic timescales as bedrock river profiles adjust to a blockage (Korup, 2006). Some channels may never 'recover' from the interruption, and will adjust to a new RAD or RAD remnant controlled form of equilibrium, whilst other parts of the system, such as alluvial fans, may exhibit cyclic patterns of behaviour controlled by repeated upstream RAD inputs (Davies and Korup, 2007).

Concavity and steepness indices of river profiles have been used as geomorphic indicators (Korup, 2006) to distinguish between the complex interacting tectonic, lithological, and climatic drivers and more localised RA-forced deviations in long profiles using known RA locations. Steepness and concavity indices are based on Flint's Law (Flint, 1974), which describes the change of channel slope as a function of drainage area over the bedrock fluvial section of a channel, omitting alluvial and colluvial reaches in the headwaters (usually between 10^4 and 10^6 m^2) (Snyder et al., 2000; Burbank and Anderson, 2012), where debris flow processes dominate (Montgomery, 2001). Extreme local concavities (>1) are indicative of abrupt knickpoints — idealised in Fig. 1, representing transitions from incisional to depositional states — and/or strong variations in rates of tectonic uplift (Whipple, 2004).

Steep mountainous terrain can prove inaccessible or inconvenient to collect field survey data; especially for regional analyses, it is practical to extract the stream profile data from a digital elevation model (DEM). However, many regional/national DEMs may not be able to resolve comparatively small RA-forced geomorphic impacts because of their coarse resolution relative to the scales of disturbance. The DEMs are also infrequently updated, leading to only snapshots of disturbance; but if sufficient confidence is held in the quality of a DEM, it is possible to carry out field surveys for post-DEM comparison (Snyder et al., 2000), an approach we use here. This study explores the dispersion of sediment from an RAD in Ram Creek, a feeder catchment of the Buller River in northwest Nelson, South Island of New Zealand. Thirty-three years after formation, the RAD failed releasing a damaging flood. We use a combination of field-survey data and DEM analysis to yield profile metrics.

2. Study area

The Brunner Range, located in the Buller River basin of northwest Nelson, New Zealand, reaches a maximum elevation of 1413 m asl with relative relief in the order of a few hundred metres. Ram Creek, a tributary of Dee Creek, feeds into the large Buller River at the base of the fault-bounded Brunner Range, which continues southwest to the Tasman Sea (Fig. 2). Owing to its location west of the Alpine Fault, the Brunner Range is subjected to tectonic uplift rates of ~0.5–1.0 mm y^{-1} (Wellman, 1979), with average rainfall of c. 2300 mm y^{-1} (Nash et al., 2008). The east-dipping Lyell Fault crosses the Ram Creek catchment trending SW–NE near the headwaters. To the east of the fault, muscovite–biotite granites crop out; whereas to the west, rocks are composed of weaker fluvial sandstone and grey-brown mudstones (Soons, 1982; Nash et al., 2008). The river is mainly gorge-confined, typical of the west coast of the South Island, but briefly opens out for several hundred metres at the Ram Creek/Dee Creek confluence before re-entering a narrow (<10-m) gorge.

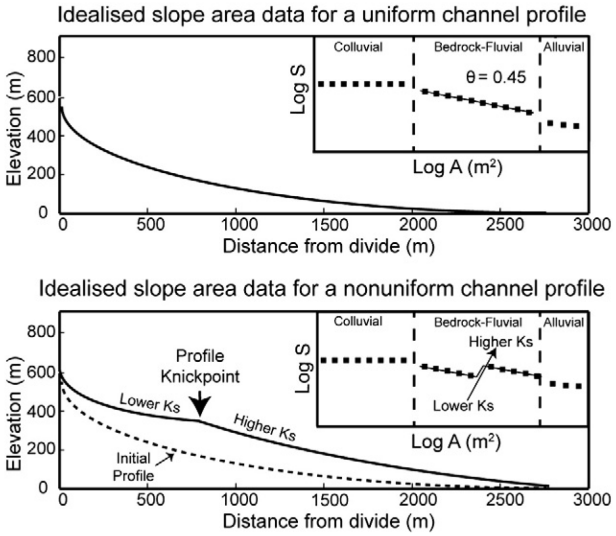

Fig. 1. Conceptual model of an idealised profile (including colluvial, bedrock fluvial, and alluvial reaches) in a log slope–log area space; (A) profile without a knickpoint; (B) profile with a knickpoint. The transition from colluvially dominated to bedrock fluvial-dominated process is the same as (A). However, a knickpoint causes another break within the bedrock fluvial region by an increase in slope with increasing area, which reflects an increase in profile steepness (*ks*) in the reach below the knickpoint.

In 1968 the Lyell Fault ruptured, resulting in the M 7.1 Inangahua earthquake that triggered numerous landslides across the NW Nelson region (Adams, 1981). The largest single valley-blocking event occurred in the headwaters of Ram Creek. A 4.4 × 10^6 m^3 RA with a runout of ~700 m was deposited, c. 2.8 × 10^6 m^3 of which blocked the river forming a 40-m-high dam with a 550-m crest width across the valley (Nash, 2003; Nash et al., 2008). A catchment of 4.5 km^2 fed water and sediment into the lake that formed behind the RAD. This dam remained stable for 13 years until in 1981, after an intense rainfall event, the dam was breached (Nash et al., 2008). Overtopping flow scoured a ~500-m-long, >100-m-wide (at the surface), and up to 40-m-deep triangular breach channel into the dam, eroding ~1 × 10^6 m^3 of dam material (Nash, 2003; Nash et al., 2008).

Nash et al. (2008) described in detail the known sequence of events after failure; a summary is given here. The outburst flood lasted several hours and showed features more in common with a hyperconcentrated flow/debris flow rather than a Newtonian water flood because of sediment entrainment. In keeping with this interpreted rheology, the flood arrived as a series of pulses/waves, with the maximum observed at Dee Creek Bridge being around 2 m high. The bridge was destroyed, and about 22 km downstream of the confluence of Dee Creek with the Buller River a flood with a peak discharge of 4335 m^3 s^{-1} was recorded 4 h after the initial outburst event, of which 1000 m^3 s^{-1} is estimated to represent the peak discharge from the dam site — 01 times the normal annual flood in Ram Creek. Flood sediment was deposited up to c. 5.5 km downstream of the breached dam. Farmland between the Ram Gorge exit and Dee Creek bridge was buried up to 2 m deep in places