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# A frost "buzzsaw" mechanism for erosion of the eastern Southern Alps, New Zealand

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ABSTRACT

In the Southern Alps, New Zealand, large gradients in precipitation (<1 to 12 m year$^{-1}$) and rock uplift (<1 to 10 mm year$^{-1}$) produce distinct post-glacial geomorphic domains in which landslide-driven sediment production dominates in the wet, rapid-uplift western region, and rockfall controls erosion in the drier, low-uplift eastern region. Because the western region accounts for <25% of the active orogen, the dynamics of erosion in the extensive eastern region are of equal importance in estimating the relative balance of uplift and erosion across the Southern Alps. Here, we assess the efficacy of frost cracking as the primary rockfall mechanism in the eastern Southern Alps using air photo and topographic analysis of scree slopes, cosmogenic radionuclide dating of headwalls, paleo-climate data, and a numerical model of headwall temperature. Currently, active scree slopes occur at a relatively uniform mean elevation (~1450 m) and their distribution is independent of hillslope aspect and rock type, consistent with the notion that frost cracking (which is maximized between −3 and −8 °C) may control rockfall erosion. Headwall erosion rates of 0.3 to 0.9 mm year$^{-1}$, measured using in-situ $^{10}$Be and $^{26}$Al in the Cragieburn Range, confirm that rockfall erosion is active in the late Holocene at rates that roughly balance rock uplift. Models of the predicted depth of frost activity are consistent with the scale of fractures and scree blocks in our field sites. Also, vegetated, paleo-scree slopes are ubiquitous at elevations lower than active scree slopes, consistent with the notion that lower temperatures during the last glacial advance induced pervasive rockfall erosion due to frost cracking. Our modeling suggests temporally-averaged peak frost cracking intensity occurs at 2300 m a.s.l., the approximate elevation of the highest peaks in the central Southern Alps, suggesting that the height of these peaks may be limited by a "frost buzzsaw."



## 1. Introduction

Sediment production, transport and storage in mountains are controlled by tectonics and the relative efficacy of erosional processes. At the million-year timescale, variations in sediment flux reflect changes in the tectonic-driving forces or large scale variability of climate (Zhang et al., 2001). At 10,000-year timescales, sediment flux can be significantly affected by the response of fluvial, glacial, periglacial, and hillslope processes to orbitally-forced changes in global climate (Bull and Knuepfer, 1987; Pan et al., 2003). Understanding climate-induced sediment flux variations is particularly important for rapidly uplifting mountain ranges such as the Southern Alps, New Zealand, where large outwash plains evolve in accordance with climate-driven changes in sediment input and long-term variations in foreland basin dynamics (Adams, 1980).

Large west to east gradients in uplift rates (10 to <1 mm year$^{-1}$, Wellman, 1979, modified by Adams, 1980) and precipitation rates (12 to <1 m year$^{-1}$, Griffiths and McSaveney, 1983a) produce strongly divergent erosional responses on either side of the Southern Alps (McSaveney, 1978; Whitehouse, 1988). Modern erosion in the western Southern Alps occurs via fluvial incision (Griffiths, 1979) and shallow and deep-seated landsliding (Hovius et al., 1997; Korup, 2005a), whereas, the eastern Southern Alps erode by a different suite of hillslope processes, including rockfall, debris flows, debris and snow avalanches, and fluvial incision (Pierson, 1980; Whitehouse and McSaveney, 1983; Whitehouse, 1988; Hales and Roering, 2005). The result is that high denudation rates (a maximum of 12 mm year$^{-1}$, Hovius et al., 1997) are typical in the western Southern Alps, consistent with long-term exhumation rates estimated using thermochronology (Tippett and Kamp, 1993, 1995; Batt, 2001; Little et al., 2005). More modest denudation rates (<1 mm year$^{-1}$, Griffiths, 1981; Hales and Roering, 2005) have been estimated in the areally extensive eastern Southern Alps. A back-of-the envelope calculation, which assumes a linear decrease in erosion rate from 10 mm year$^{-1}$ at the Alpine Fault to 4 mm year$^{-1}$ at the Main Divide, yields ~$7\times10^5$ m$^3$ year$^{-1}$ of sediment from westward draining catchments. Assuming a spatially averaged erosion rate of between 1.5 and 0.5 mm year$^{-1}$ across the eastern Southern Alps, yields between $7\times10^5$ and $3\times10^5$ m$^3$ year$^{-1}$ of sediment. This suggests that although erosion rates differ by an order of magnitude, the areally-integrated sediment flux from westward and eastward draining catchments is equal (Fig. 1).

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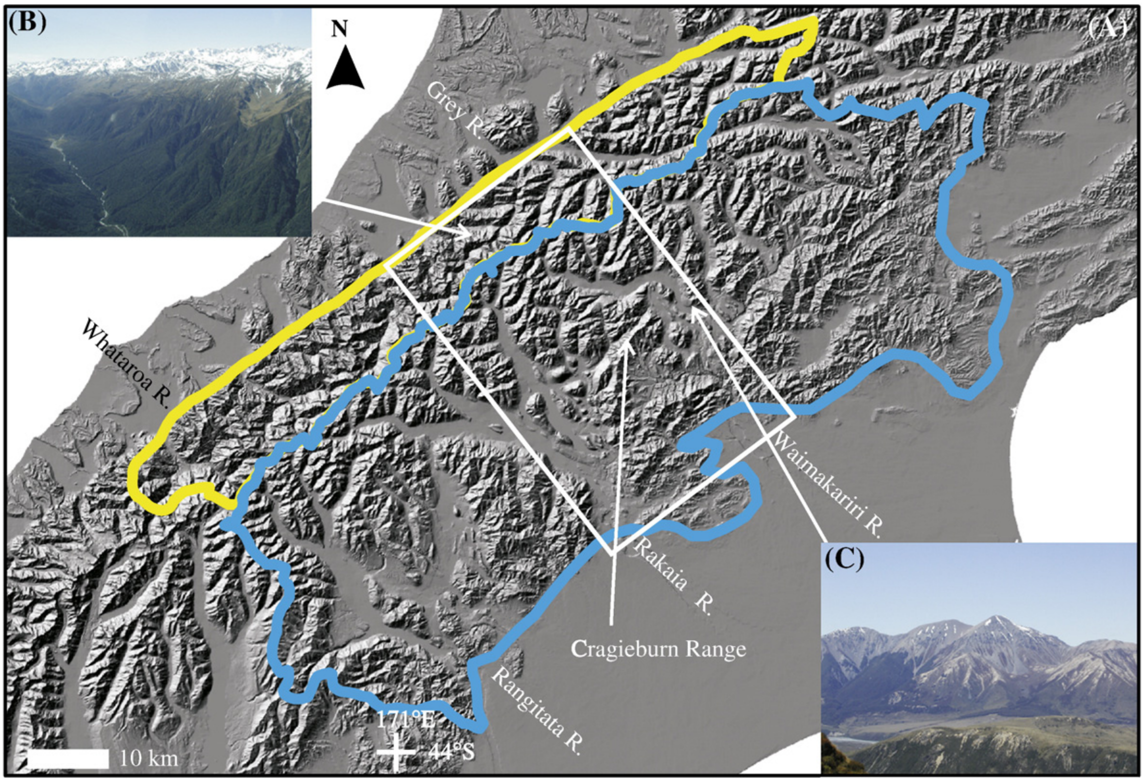


**Fig. 1.** Study area. (A) Shaded relief map of the central South Island, New Zealand. Outlined in blue are the eastward-draining catchments contributing sediment to the Canterbury Plains. The yellow outline represents the westward draining catchments. The white rectangle shows the location of our field area. (B) An oblique aerial photo of the Arahura valley, West Coast. Note the deeply dissected U-shaped valley form. (C) Photograph of Mt. Binser taken from the Cragieburn Range, showing the extensive scree cover typical of this landscape. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Post-Last Glacial Maximum (LGM) erosional processes act on the Southern Alps at rates that depend on the local climatic and tectonic setting and create disparate looking landscapes (Fig. 1). Precipitation and base level lowering rate vary significantly on either side of the main divide (Adams, 1980; Tippett and Kamp, 1995). Western glacial valleys are incised, with fluvial erosion and transport removing much of the landslide-derived hillslope sediment, such that sediment storage occurs predominantly in large landslide masses (Griffiths, 1979; Hovius et al., 1997; Korup, 2005b). Eastward-draining catchments act as sinks for hillslope sediment created through a combination of rockfall, debris flows, and rock avalanches, which transport material derived primarily from mechanical weathering by frost processes and formed large fans and scree deposits (McSaveney, 1978; Pierson, 1980; Whitehouse, 1983; Whitehouse, 1988; Tonkin and Basher, 1990; Brazier et al., 1998; Lynn et al., 2002; McSaveney, 2002; Hales and Roering, 2005).

Many studies have discussed the important role of weathering via frost processes in New Zealand (McSaveney, 1978; Whitehouse, 1988). Here, we investigate the potential impact of this process on the evolution of the eastern Southern Alps based on segregation ice weathering theory (Taber, 1929; Walder and Hallet, 1985; Hallet et al., 1991; Wettlaufer and Worster, 1995; Wilen and Dash, 1995; Wettlaufer et al., 1996; Worster and Wettlaufer, 1999; Zhu et al., 2000; Murton et al., 2001; Rempel et al., 2004; Murton et al., 2006; Dash et al., 2006). This paper is driven by a number of key research questions: What is the potential effect of periglacial erosion on the evolution of a mountain range? How will frost-driven weathering processes affect the likely pattern of erosion and deposition? How do variations in global climate control the efficacy of frost weathering and control the evolution of topography? Our study uses air photo and topographic analysis of scree slopes, cosmogenic radionuclide and weathering rind dating of headwalls, paleo-climate data, and a numerical model of headwall temperature.

## 2. Study site: Southern Alps

The Southern Alps are formed by oblique continental collision between the Pacific and Australian plates (Walcott, 1998). Geologic evidence suggests that uplift is concentrated along the Alpine Fault, a narrow zone of NNE–SSW oriented oblique thrust faults (Norris and Cooper, 2000). Interseismic strain measured using 3.5 years of continuous global positioning system data suggests that the highest vertical deformation rates occur 10 km southeast of the Alpine Fault (Beavan et al., 2004). Thermochronometric data have suggested that the magnitude of slip on the Alpine Fault varies along strike with highest rates of rock uplift corresponding with the greatest topographic relief, around Aoraki (Mount Cook) (Little et al., 2005).

The Southern Alps intersect a major pattern of westerly airflow formed between 40°S and 60°S (Henderson and Thompson, 1999). This results in a strong orographic precipitation gradient across the Southern Alps, with up to 15 m year$^{-1}$ of precipitation falling on the western side and between 4 and 1 m year$^{-1}$ falling on the east (Griffiths and McSaveney, 1983a).

The record of glacial advance and retreat in the Southern Alps has been constrained primarily from the mapping and dating of moraines (much of the early work is summarised in Suggate, 1990). The timing of glacial advance is based on relative chronologies (Gage, 1958; Suggate, 1990), weathering rind ages (Chinn, 1981), detrital $^{14}C$ ages (Suggate, 1990) and cosmogenic surface exposure ages (e.g. Ivy-Ochs et al., 1999; Schaefer et al., 2007) of morainal material. The Otiran glaciation is the youngest, regionally continuous glacial advance and has been correlated to the Last Glacial Maximum (Marine Oxygen Isotope Stage 2), with the greatest glacial extent at ~18 ka and rapid deglaciation beginning at ~14 ka (Suggate, 1990).

The Southern Alps are almost exclusively composed of interbedded sandstones and mudstones of the Torlesse Supergroup. Torlesse turbidites formed in a Jurassic–Cretaceous accretionary prism