Climate-controlled variations in scree production, Southern Alps, New Zealand

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ABSTRACT

The interaction of fluvial, glacial, and hillslope processes controls the development of mountain belts and their response to tectonic and climatic forcing. Studies on the contribution of hillslope processes to mountain erosion have focused on bedrock landslides, as they have a profound and readily observed impact on sediment yield and slope morphology. Despite the ubiquity of scree (or talus) mantled slopes in mountainous terrain, the role of frequent, low-magnitude (<100 m^3) rockfall events is seldom addressed in the context of landscape evolution. Here we quantify the contribution of rockfall erosion across an 80 by 40 km transect in the Southern Alps, New Zealand, by analyzing the spatial extent of scree slopes mapped from aerial photographs and estimating long-term (10–15 k.y.) rockfall erosion rates from the accumulation of slope deposits below bedrock headwalls and in debris and alluvial fans. Along the rapidly uplifting, high-rainfall western margin, where high rates of bedrock landsliding have been previously documented, scree-mantled slopes are sparse. Rainfall decreases exponentially east of the Main Divide, and the proportion of slopes mantled by scree increases monotonically, attaining a maximum value of 70%. The systematic distribution of scree deposits cannot be attributed to lithologic variation, seismicity, or the legacy of glaciation. Instead, climate may serve as a primary control on scree production, as nearly 70% of the mapped scree deposits in our transect are confined to a narrow elevation range of 1200–1600 m above sea level (masl). Our analysis of altitudinal controls on annual temperature variations indicates that scree production via frost-cracking processes may be maximized between elevations of 1600 and 2300 masl, as higher elevations are subject to persistent permafrost which obviates the frost-cracking process. Rates of rockfall erosion near the rapidly uplifting Main Divide are low (<0.1 mm/yr), whereas rates in the scree-dominated eastern areas average 0.6 mm/yr and may approximately balance rock uplift.

Keywords: rockfall, periglacial processes, Southern Alps, scree slopes.

INTRODUCTION

Bedrock erosion by hillslope processes such as bedrock landsliding, rock avalanches, and debris flows significantly affects the size and shape of mountains (Schmidt and Montgomery, 1995; Burbank et al., 1996), and rates of sediment production by bedrock landslides and debris flows are often significant relative to rock uplift and fluvial incision (e.g., Hovius et al., 1997). In mountainous areas, scree-mantled slopes are ubiquitous, and localized studies of headwall retreat show that rockfall occurs at geomorphically significant rates (as much as 4.5 mm/yr) (see reviews in Sass and Wollny, 2001). However, the contribution of small-scale (<100 m^3) rockfalls is seldom addressed in regional assessments of mountain erosion, because such small events are difficult to document across large areas.

The regional pattern of rockfall and scree production reflects the integrated effects of processes typically studied at the scale of individual headwalls. Controls on rockfall activity in alpine environments include availability of erodable bedrock, freeze-thaw cycles, frost cracking, frost wedging (Matsuoka, 2001), vegetation (which both adds cohesive strength to bedrock through root systems and reduces rock strength via chemical and mechanical weathering), glacial loading (which creates oversteepened headwalls and fractures rock) (Miller and Dunne, 1996), and seismic activity (Matsuoka, 2001).

Although it has been proposed that fundamental morphologic characteristics of mountain ranges, such as relief, slope, and drainage density, are controlled by fluvial and glacial incision (Whipple et al., 1999) and large landslides (Schmidt and Montgomery, 1995), the topographic imprint of scree-generating processes is poorly constrained. In contrast to intensive field-based studies of headwall dynamics, we use the spatially and temporally averaged signature of rockfall activity to quantify the contribution of scree production across the Southern Alps of New Zealand. The distribution of scree slopes reflects the accumulation of rockfall events, and debris and alluvial fans emanating from scree-dominated basins provide a postglacial record of scree production. Systematic variations in rock uplift rate, precipitation, and temperature across our study area enable us to relate scree production to climatic- and tectonic-driven factors.

STUDY AREA

The Southern Alps are formed by oblique collision of the Pacific and Australian plates along the Alpine fault (Fig. 1). Uplift rate decays from ~11 mm/yr at the Alpine fault to <1 mm/yr at the eastern range front (Adams, 1980). A prevailing westerly airflow creates a strong orographic effect with maximum precipitation of 15 m/yr mid-slope on the western range front, decreasing to <1 m/yr in the east (Griffiths and McSaveney, 1983) (Fig. 2A). The Southern Alps have been extensively glaciated (Suggate, 1990). In the west, U-shaped valleys have been fluvially dissected during the current interglacial, generating steep vegetated slopes prone to bedrock landsliding. East of the Main Divide, broad glacial valleys have been infilled by active braided streams and debris and alluvial fans (Adams, 1980). Currently, glaciers are found only at relatively high elevations along the Main Divide.

West of the Main Divide, erosion rates via bedrock landsliding and suspended sediment analyses yield estimates of ~2–18 mm/yr and ~6–12 mm/yr, respectively (Griffiths, 1981; Hovius et al., 1997). In contrast, erosion rates in the eastern region of our transect have values <1 mm/yr (Griffiths, 1981) (Fig. 2D).

METHODS

The spatial distribution of scree deposits in the Southern Alps was quantified by aerial photograph mapping within a 40 × 80 km transect (Fig. 1). Our study transect is bounded by the Alpine fault at the western margin and the Canterbury Plains to the east. We generated two estimates for the extent of scree-mantled slopes: the first represents areas covered by active scree, and the second includes scree slopes that are currently mantled by vegetation. These methods provide minimum and maximum estimates of scree distribution in our transect, respectively. Active scree was characterized as areas of light color on the aerial photo that showed a slope-parallel fabric and exhibited consistently moderate (~30°) slope angles (determined from digital elevation model [DEM] analysis). We identified ar-

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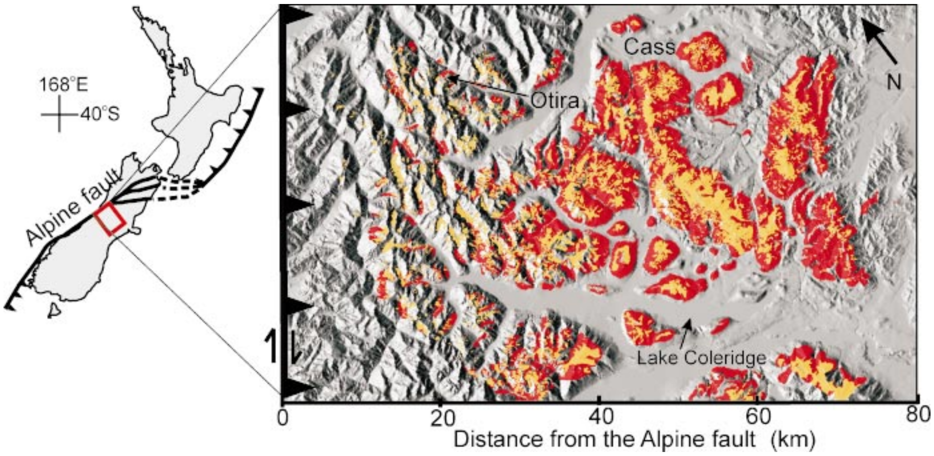

Figure 1. Map of tectonic setting of New Zealand, with subduction in north and south margins, and continental collision occurring along Alpine fault. Inset is shaded relief map of transect across Southern Alps analyzed in this study. Superimposed on map is location of vegetated (red) and unvegetated (orange) scree slopes estimated from aerial photo mapping.

eas of vegetated scree as having similarly moderate slopes combined with evidence for exposed scree where vegetation has been locally removed. Because our analysis focuses on hillslopes, we removed valleys in our calculation of the proportion of slopes mantled by scree. To characterize how the distribution of scree varies with tectonic and climatic variables, we subdivided our transect into 40 swaths, 2 × 40 km, oriented with the long axis parallel to the Alpine fault.

We calculated long-term rockfall erosion rates in the eastern part of our transect by estimating the volume of debris and alluvial fans accumulated on surfaces of known age. We analyzed fans formed at the mouths of small ($<$1 km^2) unglaciated drainage basins, where field observations indicated that rockfall activity dominates sediment production. During the Last Glacial Maximum (LGM) these small steep drainage basins drained directly onto large valley glaciers, such that most sediment produced was likely evacuated. The fans that developed within the Cass Valley and Lake Coleridge sites accumulated after retreat of large valley glaciers ca. 13.5 ka (Suggate, 1990) (Fig. 1). The Cass Valley was isolated from further glacial and fluvial erosion by a bedrock ridge at the head of the valley such that the fans provide a complete record of post-LGM sediment production from the small basins. In the western half of our transect ($\sim$20 km from the Alpine fault), we estimated rockfall erosion rates using scree deposits situated along the margin of valley walls that were occupied by glaciers at 10–12 ka (Ivy-Ochs et al., 1999).

For the eastern sites, we estimated the volume of each debris or alluvial fan using a 25 m DEM, interpolating proximal valley wall and floor elevations as basal datums. In the western sites, we used ground-based surveys to estimate the area of scree deposits and applied a catenary curve to valley profiles to estimate the geometry of underlying bedrock slopes (Hirano and Aniya, 1988). Scree production rate was calculated by dividing the volume of each deposit by the time since deglaciation and basin source area. We generated bedrock erosion rate estimates by adjusting for the density of fan or scree material (1600 ± 100 kg m^{-3}) and bedrock (2700 ± 100 kg m^{-3}) (Sass and Wollny, 2001). Because the debris and alluvial fan calculations do not account for scree stored with basins above each fan, erosion rate estimates for the eastern sites reflect minimum values.

RESULTS

The distribution of scree, which reflects rates of production and removal by fluvial processes, varies systematically across our transect (Fig. 2B). In the western Southern Alps, scree deposits are small, sparse, and account for $<$10% of hillslope area (Fig. 1). These deposits are typically found beneath isolated unvegetated headwalls at high elevations. Sparse evidence for relict (vegetated) scree slopes exists west of the Main Divide. The fraction of scree increases to 10%–20% at higher elevations along the range axis, where scree deposits form along the margins of U-shaped valleys and are disconnected from the channel network, suggesting that the preservation potential is relatively high. Bedrock exposure is common in this area because much of the landscape is above the tree limit. East of the Main Divide the fraction of total (vegetated and active) scree-mantled slopes increases monotonically (Fig. 2B), reaching a maximum value (70%) between 40 and 65 km from the Alpine fault. The proportion of active

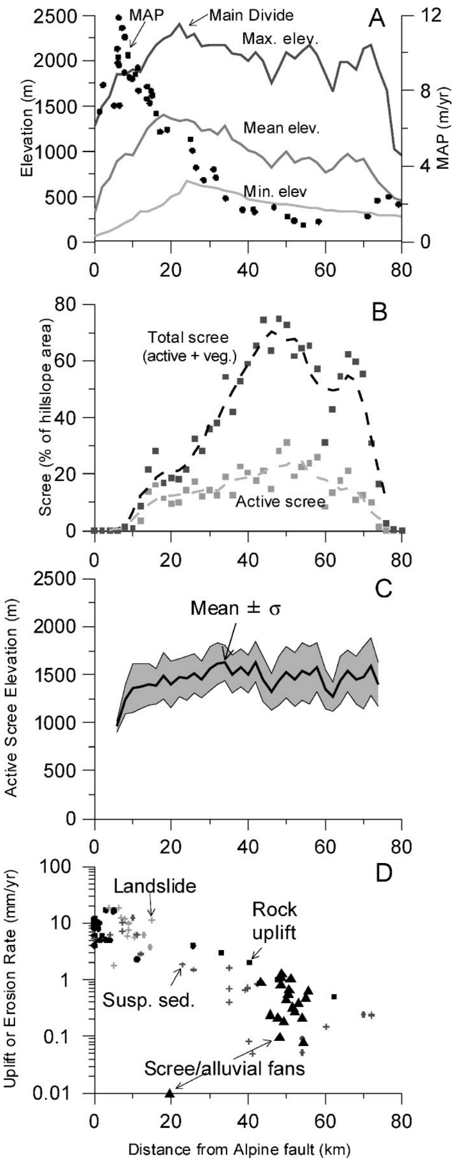

Figure 2. A: Graph showing minimum (light gray), mean (dark gray), and maximum (black) elevations calculated for 2 km swaths across transect. Black squares represent mean annual precipitation (Griffiths and McSaveney, 1983). B: Minimum (light gray squares) and maximum (dark gray squares) estimates of fraction of hillslopes mantled by scree across our transect. Note rapid increase in scree mantling in eastern part of range. C: Variation in elevation of active scree deposits (orange zones in Fig. 1). Solid black line and shaded region represent mean and standard deviation of elevation values. Note relatively consistent elevation of scree slopes. D: Distribution of rock uplift and erosion rate estimates. Uplift estimates, using geologic indicators and tilt of paleolake terraces (black squares; Adams, 1980), are approximately equal to estimates of scree production in eastern region (this study; black triangles) and bedrock landsliding in west (light gray circles) (Hovius et al., 1997). Other estimates of bedrock erosion from suspended sediment are shown (dark gray circles) (Griffiths, 1981). MAP—mean annual precipitation.

scree remains relatively constant between 20% and 30% (Fig. 2B). In this region, scree often mantles entire hillslopes, and some exceed 1 km in length. Convex scree-mantled ridges and small isolated bedrock headwalls dominate the headwaters of small basins. Field observations suggest that scree production in this area is transport limited, such that active transport is required to expose bedrock faces.

To analyze how climatic variables may affect rockfall initiation, we calculated the elevation distribution of scree slopes across our transect. For this analysis we used the distribution of active scree because it allows for comparison with the modern climatic regime. Despite systematic variations in precipitation, rock uplift, and relief, the mean elevation of active scree slopes (Fig. 2C) is surprisingly consistent at ∼1400 m, and nearly 70% of the deposits occur between 1200 and 1600 masl.

Minimum erosion rates calculated from measurements of 15 debris and alluvial fans in the eastern region (Cass Valley and Lake Coleridge) have a mean value of 0.6 ± 0.4 mm/yr (Table DR1).[1] Near the Main Divide, our field-based estimates of scree production rates are uniformly low (0.01 mm/yr).

DISCUSSION AND CONCLUSIONS

Previous studies of individual headwalls have recognized many factors that control scree production, including rock type, vegetation, temperature, earthquakes, and time since deglaciation (e.g., Sass and Wollny, 2001), although the relative importance of these factors remains elusive. Our method uses regional patterns in scree distribution, which increases systematically from west to east, to infer how climatic and tectonic factors influence rockfall activity across the Southern Alps. Variations in lithology and metamorphic grade do not account for the observed scree distribution. Jointed sandstones and argillites of the Torlesse Supergroup are dominant from 20 to 80 km along our study transect. These rocks have been deformed such that no preferential trends in sandstone/shale ratio or joint orientation exist (MacKinnon, 1983). As a result, systematic changes in mechanical rockfall susceptibility appear unlikely, as estimates of both rock mass strength (Augustinus, 1995) and rock quality designation (Deere and Deere, 1988) (Table DR2; see footnote 1) generate consistent values near the Main Divide and in the east region of our transect, despite strong variations in scree mantling (Fig. 2B). At 20 km along our transect, a discrete change occurs from sandstone-argillite to schist (MacKinnon, 1983). Although it has been suggested that schists and other higher-grade metamorphic rocks west of the Main Divide may obviate scree production (Whitehouse, 1988), we observe continuity in the distribution of scree-mantled slopes across this distinct lithologic boundary.

Over geologic time scales, large-magnitude earthquake events have frequently occurred along the Alpine fault, whereas seismic activity has been less persistent in the eastern part of our transect (Pettinga et al., 2001). During large-magnitude earthquakes, rockfall activity is concentrated near the epicenter and decays with distance (Adams, 1980). Given that the Alpine fault is the dominant seismic source in our study area, our observed scree distribution is inconsistent with earthquakes as the primary scree-generating mechanism.

Glaciation has been proposed as a control on rockfall activity by steepening headwalls and increasing fracture density by glacial loading and valley modification (Miller and Dunne, 1996). We recognize the importance of these mechanisms in generating rockfall in the Southern Alps; however, if glacial activity is dominant in setting the stage for scree production, scree deposits should be most prevalent along the Main Divide, coincident with the maximum extent of glaciation. Instead, our analyses suggest that the zone of maximum scree extent is offset from the axis of maximum glaciation by ∼40 km.

The concentration of active scree within a narrow and distinct altitudinal zone (Fig. 2C) suggests that rockfall activity is controlled by the integrated effects of precipitation and temperature (which vary with elevation and govern vegetation patterns). West of the Main Divide, high pore pressures associated with high rainfall rates have been proposed to enhance bedrock landsliding on steep, heavily vegetated slopes, where Hovius et al. (1997) documented rapid rates of landslide-driven sediment flux (1.2×10^5 to 1.1×10^6 m^3/yr^{-1}). Between 0 and 10 km along our transect a small fraction of the landscape has elevation values above the tree limit (∼1400 m) (Fig. 2A), and dense root systems may suppress significant rockfall erosion in favor of deeper bedrock failures. Approaching the Main Divide, mean and maximum elevations increase markedly, such that a large proportion of the landscape is above the tree limit and scree-mantled slopes become more prevalent (Fig. 2B). East of the Main Divide, the proportion of the landscape covered with active scree remains approximately constant (20%–30%), consistent with relatively high maximum elevations and a large proportion of the landscape above the tree limit.

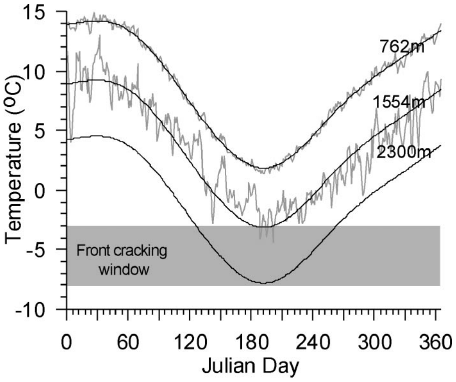

Figure 3. Annual air-temperature variations for different elevations in central Southern Alps. Temperature data averaged over period >50 yr at The Hermitage, Mount Cook (762 m, light gray line) were fit with representative spline (dark line). Using calculated lapse rate of 0.6 °C/100 m (see text), we reproduced this spline at 1554 m and 2300 m. Recreated spline at 1554 m was compared with 5 yr worth of data collected at that elevation (light gray line) and shows faithful reproduction of annual variation at that elevation. At 1554 m elevation, <10 d fit within frost-cracking window (−3 to −8 °C), compared with >60 d at 2300 m.

The efficacy of periglacial processes at producing scree depends on altitudinal temperature variations. Recent studies of rock deformation in periglacial environments suggest that the accretion and subsequent freezing of water in large pores may be a dominant factor in rock fracture or displacement (this process is commonly referred to as frost cracking) (Walder and Hallet, 1985). Theoretical (Walder and Hallet, 1985), experimental (Hallet et al., 1991), and field-based studies (Anderson, 1998) suggest that frost cracking is efficient within a limited temperature range (−3 to −8 °C) and requires available water. This suggests that where water is readily available, the rate of frost cracking depends on the proportion of time that rock is at temperatures between −3 and −8 °C (Fig. 3). As mean annual temperature (MAT) falls below −1 °C, however, a permafrost condition ensues (Anderson, 1998), limiting the amount of available water and reducing the effectiveness of the frost-cracking process. This ‘‘high and frozen’’ condition may exist at elevations above 2300 m in the Southern Alps, consistent with observations of sparse scree and frequent deep-seated bedrock landslides at high elevations (>2500 m) (McSaveney, 2002). At MAT above −1 °C (or elevations below 2300 m), frost cracking may be a viable scree-production mechanism.

Analysis of annual air-temperature fluctuations enables us to quantify the frequency with which rocks of a particular elevation may oc-

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[1] GSA Data Repository item 2005129, Table DR1, calculated erosion rates from fan volumes, and Table DR2, values for different sites within the Southern Alps, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

cupy the frost-cracking temperature window. We averaged and smoothed (using splines) 20+ yr of daily temperature data for 5 sites in the central Southern Alps, spanning 800 m of elevation (738–1554 m) (National Institute for Water and Atmosphere, 2004) (Fig. 3). We compared the difference between smoothed splines at each of these five sites and calculated an average lapse rate of 0.6 ± 0.1 °C/100 m. Using the estimated lapse rate, we calculated the temperature distribution for 2300 m elevation (Fig. 3). At 1554 m (the highest elevation of available temperature data) <10 d fall within the frost-cracking window during a typical year. In contrast, at 2300 m, much of the winter (>60 d) is spent within the frost-cracking zone, suggesting that a small range of elevations (1600–2300 m) has the potential for sustained frost cracking. Scree deposits form via rockfall erosion of bedrock headwalls, thus the concentration of scree within a limited elevation zone (1200–1600 masl) slightly below the frost-cracking window is consistent with frost cracking as the primary control on rockfall erosion.

The pattern of all mapped scree represents a temporally integrated signature of rockfall activity (Fig. 2B). During the last glacial maximum, the altitudinal zone of efficient frost cracking was considerably lower (Suggate, 1990), such that a significant fraction of terrain in the eastern part of our transect may have undergone frequent rockfall activity. This notion is consistent with our observation that as much as 70% of hillslopes in the area reveal scree mantling. By contrast, higher elevation zones near the Main Divide have had less time within the altitudinally defined frost-cracking zone (Fig. 2B).

In the absence of profound lithologic or seismic controls on rockfall activity, these results highlight the potential for feedbacks between mountain elevation and erosional processes. Whereas previous studies have focused on local relief and glacial equilibrium altitude in assessing topographic controls on denudation (e.g., Schmidt and Montgomery, 1995; Brozovic et al., 1997), here we illustrate the importance of absolute elevation in dictating climatic controls on erosion mechanics.

Quantification of erosion rates in the western portion of the Southern Alps suggests that sediment flux may accommodate tectonic mass influx into the orogen (Hovius et al., 1997). Uplift rates of 0.5–1.0 mm/yr for the eastern Southern Alps have been estimated via fission-track analyses (Tippett and Kamp, 1993), although these rates remain ambiguous because the effects of lateral advection on fission-track ages are difficult to constrain (Batt and Brandon, 2002). South of our transect, uplift estimates based on the tilting of paleolakeshores reveal similar rates (<1 mm/yr), but their applicability to our study area has not been demonstrated (Adams, 1980). Despite these uncertainties, available rock uplift estimates in the eastern region of the Southern Alps approximate estimates of long-term rockfall erosion, suggesting that rockfall erosion may balance tectonic mass flux.

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