Cirques, peaks, and precipitation patterns in the Swiss Alps: Connections among climate, glacial erosion, and topography

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ABSTRACT

Glacial erosion, a process influenced by climate, has been implicated in limiting the relief of mountain ranges. However, climate itself is sensitive to large-scale topography, suggesting that climate, topography, and glacial processes form a coupled system. Large spatial gradients in precipitation exist in the southern Swiss Alps, allowing us to study this coupling in a region of climate variability. More than 500 cirques were identified, and neighboring peaks were found to co-vary in elevation with cirque floors (R^2 0.64). Cirque headwall relief does not vary with precipitation or cirque floor altitude. These relationships confirm the hypothesis that cirque formation restricts peak altitudes via slope processes that limit the relief of cirque headwalls. We compared the position of the regional equilibrium line altitude (ELA) estimated from modern climate to a surface defined by the cirque floors. The modern ELA and cirque floor surfaces are similar in shape, illustrating the impact of spatial variability in precipitation on glacial processes and topography. Precipitation variability in this region is partially dictated by large-scale topography. Therefore, precipitation patterns, glacial process domains, and topography must evolve together.

INTRODUCTION

The significance of glacial erosion in alpine landscapes and the sensitivity of glaciers to climate suggest that climate influences the evolution of mountain topography. Peak elevations correlate with snowlines in the Himalaya (Brozovic et al., 1997), Basin and Range (Foster et al., 2008), and Cascade Range (Mitchell and Montgomery, 2006). Exhumation rates increase with glacial extent in the Chugach Range (Spotila et al., 2004), and erosion by cirque glaciers dominates landscape evolution in the Kyrgyz Range (Oskin and Burbank, 2005). These observations have motivated the hypothesis that glaciers act as a "buzz saw" by shaving off topography that rises above the equilibrium line altitude (ELA) (e.g., Brozovic et al., 1997). Conceptual and numerical models lend support to this hypothesis (Brocklehurst and Whipple, 2002; Tomkin, 2007).

The glacial buzz saw hypothesis states that climate exerts a strong control on topography, limiting it to altitudes near the ELA. One possible mechanism for the buzz saw is that cirque formation sets the base level for slopes rising above cirque basins (Mitchell and Montgomery, 2006). The steep headwall above a cirque basin cannot be indefinitely tall but must be limited by rock strength (Schmidt and Montgomery, 1995). Therefore, cirques limit maximum topography. New data from southern Switzerland support the glacial buzz saw hypothesis and confirm that cirque formation is a dominant mechanism by which the buzz saw operates. Topography influences temperature and precipitation and, therefore, the ELA. Topography and climate evolve together, creating a dynamic interaction between glacial processes and peak altitudes.

Cirque formation has been explained by rotational flow of cirque glaciers (Sugden and John, 1976), variations in subglacial water pressure (Hooke, 1991), and periglacial freeze-thaw processes (McCall, 1960). Some have suggested that cirques form at an average Quaternary ELA (e.g., Flint, 1957; Porter, 1964) based on the observation that the surface defined by cirque floors is parallel to the modern snowline and reconstructed past ELAs in some areas (Porter, 1964; Leonard, 1984; Porter, 1989; Evans, 1999). Cirques may also form at the head of larger glaciers, well above the ELA (e.g., Holmlund, 1991), and numerical modeling produces cirques several hundred meters below the time-averaged ELA (MacGregor et al., 2009).

We investigate the relationship among cirques, local peaks, and climate in the southern Swiss Alps, where modern precipitation patterns are well documented and highly variable in space. Precipitation gradients are pronounced in the Ticino canton of Switzerland, where precipitation rates are twice those of regions only 50 km to the east and west (Fig. 1) (Frei and Schär, 1998). Precipitation gradients are relevant because previous work in the British Columbia Coast Range (Ostrem, 1972), Cascade Mountains (Porter, 1977), and San Juan Mountains (Leonard, 1984) has shown that glaciation thresholds and ELAs correlate with precipitation. Ticino's enhanced precipitation occurs in an area of diminished maximum and mean elevation (Fig. 1). This topographic low is not the result of differences in rock erodibility, or differences in average slopes relative to surrounding areas (Kühni and Pfiffner, 2001).

A comparison of cirque and peak elevations with an ELA calculated from climate data bolsters the glacial buzz saw hypothesis. Cirque basin relief measurements confirm a mechanistic explanation for the glacial buzz saw: glacial erosion controls peak elevation indirectly through the formation of cirques, which set a base level for slope processes. The observed connection between the regional ELA and range-scale maximum topography requires precipitation and topography to have co-evolved in Ticino.

METHODS AND RESULTS

We define cirques as overdeepenings or flat areas located within theater-shaped valley heads. Five hundred cirques were located using the 1:25,000 scale topographic contour maps produced by Swisstopo Swiss National Maps (Fig. 1). A characteristic of many cirques is the presence of a tarn or swamp, indicating an overdeepening. For each cirque, the latitude, longitude, aspect, and altitude of the cirque outlet (in the case of a lake) or floor were measured. Only the uppermost cirque was marked in valleys with several overdeepenings, and overdeepenings located beneath permanent glacial ice were not noted. To measure headwall relief, we recorded the altitude for each cirque's highest adjacent peak or ridge.

Twenty years (1971–1990) of gauge data from 6700 sites across the Alps were used by Frei and Schär (1998) to produce a regular grid of annual precipitation with ~25 km resolution. We interpolated between these points (inverse distance weighting, second power) to create a continuous 2-km-resolution map of precipitation. A digital elevation model (DEM) was constructed from 3 arc-second Shuttle Radar Topography Mission (SRTM) elevation data projected into Swiss Grid coordinates with 90 m resolution. Gaps in the data were filled by merging the 90 m DEM with a 250 m DEM produced by Swisstopo.

Cirque floor elevations and peak elevations are well correlated across the region ($R^2 = 0.64$) (Fig. 2A). This correlation is not strongly influenced by the fact that peaks are necessarily higher than cirques. We tested this possibility by randomly assigning peaks to cirques within our data set and discarding cases in which the peak elevation was lower, and we found no

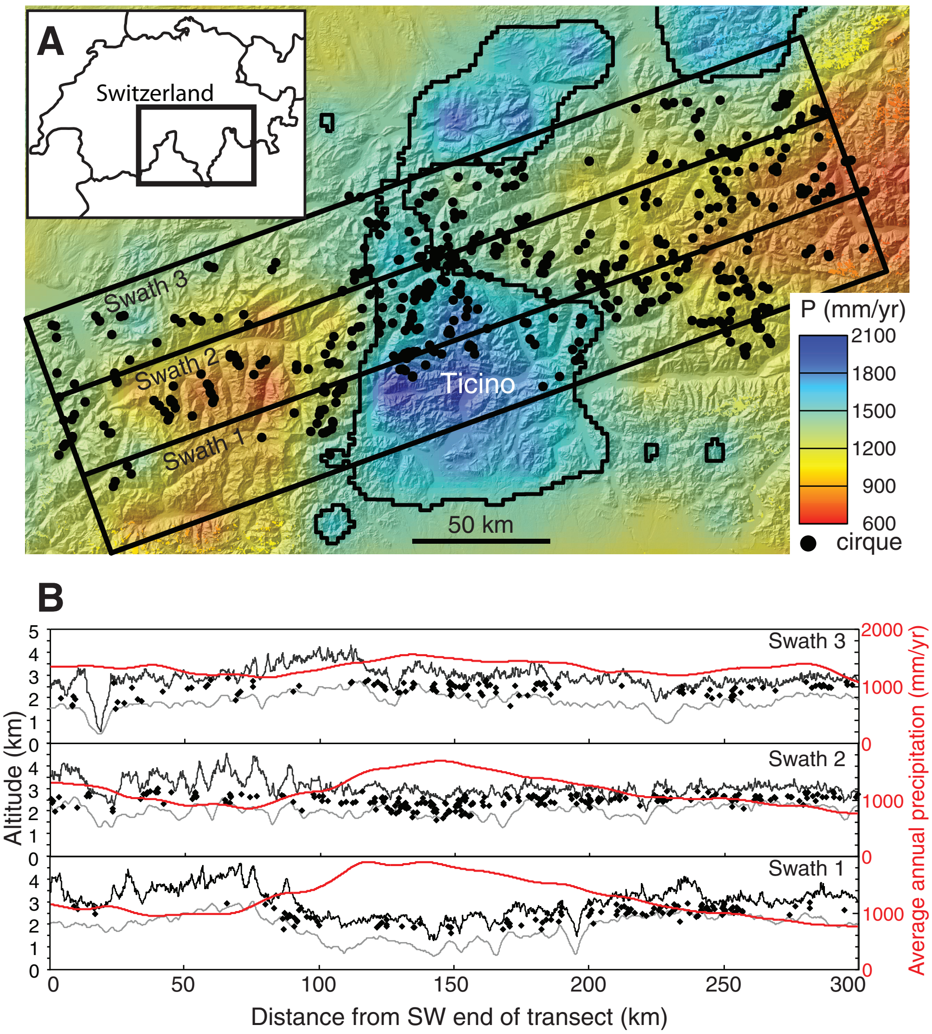

Figure 1. A: Precipitation pattern in color scale over study region (see inset map); topography is indicated by shaded relief. Black contour line shows 1500 mm/yr precipitation rate. Ticino, located in south-central section of study area, is wetter and has lower peak elevations than regions to east and west. B: Swaths indicated above. For each, maximum and mean elevations are shown as black and gray lines, respectively, while average annual precipitation is given by red line. Cirques are shown as black circles or diamonds in panels.

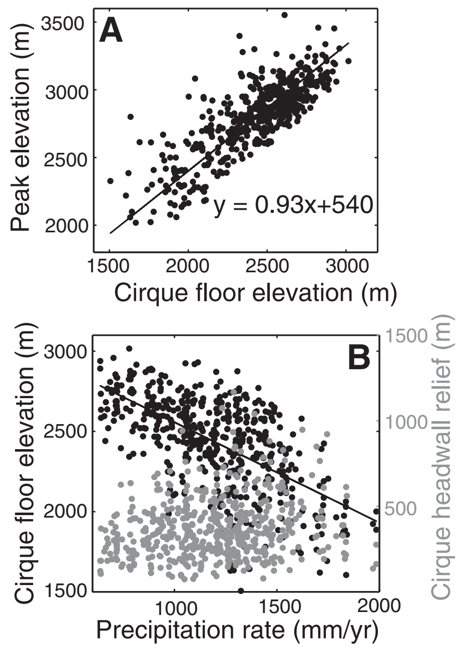

Figure 2. A: Comparison of cirque floor elevations with elevations of neighboring peaks. Peaks and cirque floors are well correlated (R^2 = 0.64), and structural analysis gives a best-fitting line with a slope of 0.93, indicating that as cirque floor elevations vary, peak elevations vary by nearly same amount. B: Relationship between precipitation rates and cirque floor elevations (in black on left axis), and cirque headwall relief (in gray on right axis). Annual precipitation is inversely correlated with cirque floor elevation (R^2 = 0.38), while headwall relief is insensitive to precipitation.

correlation between peak and cirque elevations (R^2 = 0.06). A more important factor than the correlation is the slope of the relationship. Structural analysis, which allows for errors in both variables (Mark and Church, 1977), yields a best-fitting line with a slope of 0.93, indicating that as cirque elevations vary, peak elevations vary by nearly the same amount. We assume that random and measurement errors are comparable for cirques and peaks, an assumption supported by similar standard deviations in both. The slope near 1 indicates that the relief of cirque basins, which averages 370 ± 175 m (n = 500), does not depend on cirque floor elevation. While cirque elevations and peak elevations are also somewhat correlated with local precipitation (R^2 = 0.38 and 0.30, respectively), the relationship between cirque relief and precipitation is very weak (R^2 = 0.03) (Fig. 2B).

Spatial variability in the modern ELA results from the spatial variability in precipitation across the region. Ohmura et al. (1992) documented the relationship between precipitation and temperature at the ELA of 70 modern glaciers across the globe:

$$P = 9T^2 + 296T + 645, \qquad (1)$$

where P is annual precipitation in mm/yr, and T is average summer temperature at the ELA in °C. This relationship is similar to that found by Zemp et al. (2007) for just the Alps. To estimate the regional modern ELA, we first solved Equation 1 for T and determined the average summer temperature of the ELA given modern precipitation rates. We then estimated the elevation at which this summer temperature occurred using:

$$z = \frac{T - T_0}{\Gamma}, \qquad (2)$$

where z is elevation in m, T_0 is the temperature at sea level in °C, and Γ is the atmospheric lapse rate in °C/m. Summer average temperatures for A.D. 1961–1990 from 14 southern Swiss weather stations between 200 and 2700 m in altitude were obtained from the Federal Office of Meteorology and Climatology MeteoSwiss (http://www.meteoschweiz.admin.ch/web/en/climate/swiss_climate/tabellen.html). There is a strong correlation between altitude and summer average temperature (R^2 = 0.98), which gives a best-fitting sea-level temperature of 21 °C and lapse rate of –6.5 °C/km. Using Equations 1 and 2, we constructed a map of the modern ELA based on the precipitation map (Fig. 3). The standard error for estimated temperature of the ELA based on precipitation data is 0.5–1.4 °C, which translates to ~100–250 m of uncertainty in the ELA using Equation 2 (Ohmura et al., 1992; Zemp et al., 2007). Added to this uncertainty, there is the uncertainty in measurement of mountain precipitation, especially snow, which is likely to be on the order of tens of

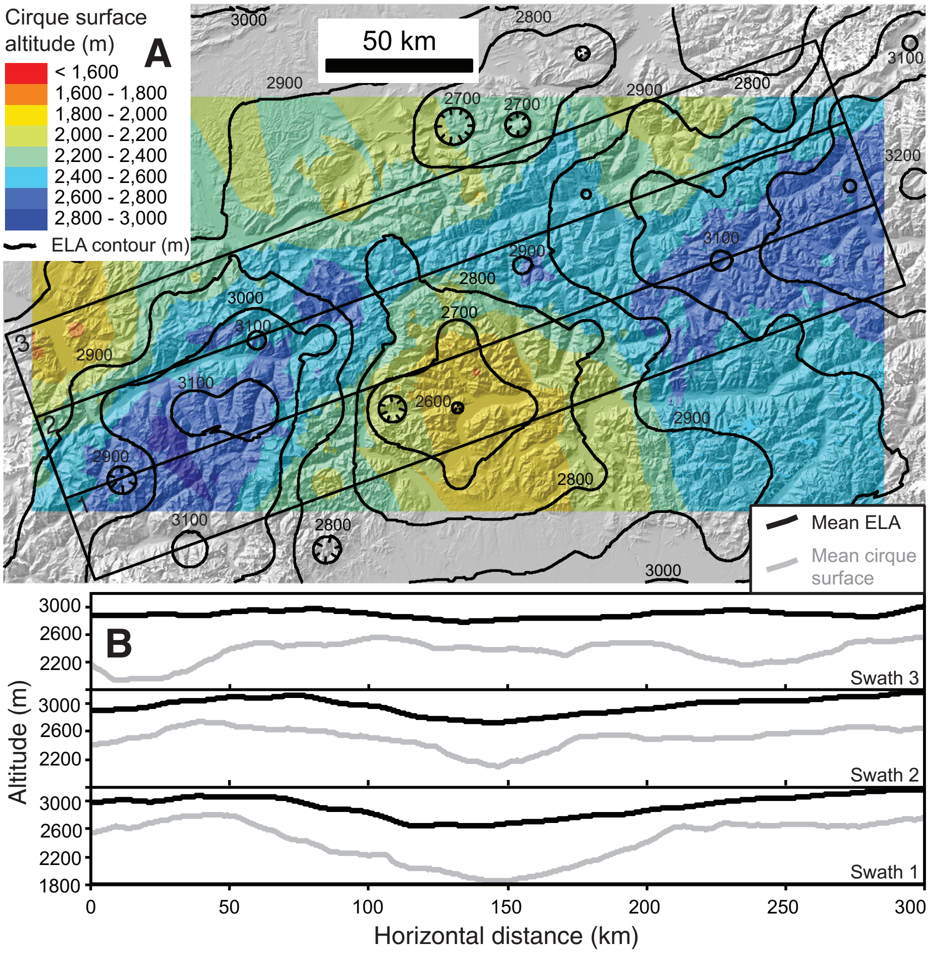

Figure 3. A: Surface defined by cirque floors is shown in color scale draped over shaded relief depiction of topography. Smoothed contours of estimated modern equilibrium line altitude (ELA) are shown in black. ELA contours are similar in shape to cirque floor surface. B: Cross sections from swaths indicated above. Modern ELA (in black) has ~700 m of relief, while cirque floor surface (in gray) has ~1100 m of relief.

percent, and the spatial interpolation of precipitation data. Nevertheless, the variability in the calculated ELA is consistent with the variability of snowlines in the Swiss Alps measured using photogrammetric techniques (National Snow and Ice Data Center, 1999).

Using the coordinates and elevations of the cirque outlets derived from the topographic maps, we interpolated a best-fit "cirque floor surface" by inverse-distance weighting (first power, 12 point minimum) to compare to the modern ELA. The modern ELA surface and the surface defined by cirque floors across the southern Swiss Alps are similar in shape (Fig. 3). Both mimic the precipitation pattern across the region by dipping to lower elevations in Ticino. The robustness of the pattern indicates that glacial erosion has occurred at lower altitudes in Ticino relative to surrounding areas throughout the Quaternary. Interestingly, the relief of the cirque floor surface is larger than that of the modern ELA surface (~1100 m versus ~700 m).

DISCUSSION

The data are consistent with the glacial buzz saw hypothesis, and they provide an independent confirmation of the mechanistic explanation for the buzz saw suggested by Mitchell and Montgomery (2006). Cirque elevations track the ELA across the study region, as do peak elevations (Figs. 2 and 3). Cirques have a nearly fixed relief across the study area, despite large variations in the precipitation rate and cirque elevations. This suggests that slope processes limit the relief of cirque headwalls and, therefore, maximum topography. Headwall-lowering processes primarily depend on the slope and rock strength, and this is consistent with our observations that relief is fixed and not strongly tied to the rate of precipitation. If we accept the dominant view that cirques form near a long-term average ELA, then the glacial buzz saw theory limits maximum topography indirectly by setting a base level for headwall scarps.

An alternate hypothesis is that peak elevations determine cirque elevations. This relationship is possible if cirque overdeepenings only appear once a threshold glacial size is attained. In this scenario, the connection between precipitation and glacier size implies that precipitation rate and headwall relief should be negatively correlated, because glaciers in wetter areas would need smaller accumulation areas to form cirques. Since headwall relief and precipitation rates are uncorrelated, this explanation is not preferred.

Spatial variability in the modern ELA is driven by enhanced precipitation in the Ticino region. The enhanced precipitation depends on two factors: the occurrence of storm events during southerly flow (Schär et al., 1998), and the topographic depression of Ticino (Schneidereit and Schär, 2000). These factors were likely acting throughout the Quaternary: the large-scale circulation pattern associated with flow from the south is present and even potentially enhanced in global circulation models of the Last Glacial Maximum (LGM; e.g., Harrison et al., 1992), while paleoclimate evidence supports the occurrence of southerly flow events during glacial periods (Florineth and Schlüchter, 2000) and wet conditions (Prentice et al., 1992; Collier et al., 2000).

The modern ELA calculation shows a strong correlation with cirque floor surfaces (Fig. 3), but it underpredicts topography relief in the wettest areas (by up to 400 m). This difference could be a result of the assumptions in our ELA model. Alternately, it could reflect that either the Quaternary average ELA was more variable than the modern ELA, or that cirques do not form strictly parallel to the ELA and are influenced by precipitation-dependent erosion rates.

It is possible that paleoprecipitation rates were more variable than those today, and any increased southerly flow during the Quaternary (e.g., Harrison et al., 1992) could have enhanced orographic precipitation in Ticino. An increase in the relief of the ELA surface by 400 m to fit the cirque floor surface would require an additional variation in precipitation of ~750 mm/yr. While not within the scope of this paper, the possibility of such a significant change in precipitation could be addressed using a combination of climate modeling and glacial reconstruction (e.g., Kuhlemann et al., 2008).

It is also possible that higher relief of the cirque floor surface represents the relative efficiency of glacial erosion across the region rather than proportional variability in the ELA. Tomkin and Roe (2007) estimated that doubling the precipitation rate would roughly double the erosion rate of otherwise identical glaciers. With an assumed characteristic erosion rate of ~0.5mm/yr and a doubling of precipitation, the 400 m of additional glacial erosion in Ticino could be accomplished in ~800,000 yr, a plausible time frame. Comparative measurements of glacial erosion rates or glacial sediment volumes could either support or undermine this hypothesis.

Finally, the large-scale topography of Ticino is partially responsible for the precipitation pattern and depression of the ELA: topography influences climate. Spatial variability in peak and cirque elevations is matched by corresponding variability in the ELA and precipitation rates in the southern Swiss Alps, indicating a climatic control on topography. Alpine glaciers are sensitive to both topography, through the decrease in temperature with elevation, and precipitation rates. The evolution of the southern Swiss Alps reflects an interplay between climate and topography realized through glaciation.

CONCLUSIONS

(1) Peak and cirque elevations vary together, following changes in the ELA across climate gradients in the southern Swiss Alps. The close association of peaks, cirques, and the precipitation-controlled variability in the ELA supports the glacial buzz saw hypothesis because maximum topography is depressed where the ELA is depressed.

(2) The constant relief of cirque basins across the region, despite large variations in elevation and precipitation rate, validates a process-based mechanism for the glacial buzz saw. The elevation of cirque formation is tied to the ELA, and slope processes limit the relief of headwalls standing above cirque basins.

(3) Climate and topography are coupled through processes of glacial erosion and orographic precipitation: topography influences the spatial variability in precipitation rates, the extent of glaciation depends on both topography and precipitation rates, and maximum topography is in turn limited by glacial erosion. This feedback may help maintain and even enhance large-scale topographic undulations in alpine terrain.

ACKNOWLEDGMENTS

This work was inspired by a 2007 Keck project in the Swiss Alps, and we thank Scott Reynhout for his preliminary work comparing cirque elevations and precipitation patterns. Neil Shea contributed to data collection efforts. We thank Michael Church and David Montgomery for their input. This paper greatly benefited from constructive reviews from Simon Brocklehurst, Eric Leonard, James Spotila, and two anonymous reviewers.

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Manuscript received 12 September 2009
Revised manuscript received 2 October 2009
Manuscript accepted 8 October 2009

Printed in USA