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Keck Geology Consortium: Projects 2007-2008
Short Contributions – Alps

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EQUILIBRIUM LINE ALTITUDE VARIANCE WITH PRECIPITATION IN THE SOUTH-CENTRAL ALPS: IMPLICATIONS FOR LONG-TERM EXHUMATION

SCOTT REYNHOUT: Beloit College
Research Advisor: Alison Anders: University of Illinois at Urbana-Champaign

INTRODUCTION

Coupling of climatic and tectonic forcing of exhumation in active mountain belts has been the focus of much recent scientific scrutiny. Variations in temperature and precipitation modify the efficiency of erosion, which can affect patterns of tectonic uplift (Willett et al., 2006). Enhanced climatically-driven erosion increases the local rate of mass removal, which directly increases exhumation rate and potentially incites uplift through isostasy to bring deep crustal rocks to the surface (Champagnac et al., 2007).

Reiners et al. (2003) demonstrated climatic forcing of exhumation across the western Washington Cascades by correlating enhanced precipitation with lowered topography and rapid exhumation rates. Mitchell and Montgomery (2006) used cirque floor elevations in the Cascades as a proxy for Quaternary equilibrium line altitude (ELA), and showed that ELAs decreased with greater precipitation and faster exhumation. Grujic et al. (2006) also observed climatic-tectonic coupling in the Bhutan Himalaya, concluding that variations in precipitation/erosion along orogenic strike led to differential uplift on a local scale, independent of tectonics. In particular, a structural window of focused core exhumation bounded by shallow-angle normal faults was identified as an example of erosion-induced uplift.

This study will evaluate the possibility that the Lepontine Dome of the European Alps underwent climatically-driven focused core exhumation. In particular, this study will determine whether or not paleo-ELAs were lower in the Lepontine region, using cirque floor elevations as a proxy for mean Quaternary ELA. The Dome is an area of focused exhumation (Willett et al., 2006) that overlaps areas of high precipitation and low topography—conditions that mirror those found in Reiners et al. (2003). Lower ELAs within the Dome would suggest that enhanced precipitation accelerated the local rate of glacial erosion. Accelerated local erosion throughout the Quaternary would suggest a strong climatic influence on the long-term exhumation of the Lepontine Dome.

REGIONAL SETTING

The European Alps are a convergent mountain belt created by the collision of African and Eurasian plates, beginning in the Cretaceous (Stampfli et al., 2002). The gneissic Lepontine Dome is the primary exposure of crystalline basement in the southern Central Alps (Fig. 1). The Dome consists of amphibolite-grade rock from the lower Penninic realm, surrounded by Penninic metasediment and structurally-higher Austroalpine units. Spiegel et al. (2000) traced the date of surface exposure of the Lepontine core to ~14 Ma.

The Lepontine Dome is the footwall for the western Simplon normal fault and the eastern Forcla normal faults. Tectonics are responsible for a significant amount of exhumation, but at least half of the nearly 28 km of measured exhumation (Kühni & Pfiffner, 2001) may be the result of enhanced erosion.

The Lepontine area experiences regionally heavy precipitation (Fig. 2) due to the funneling of moist

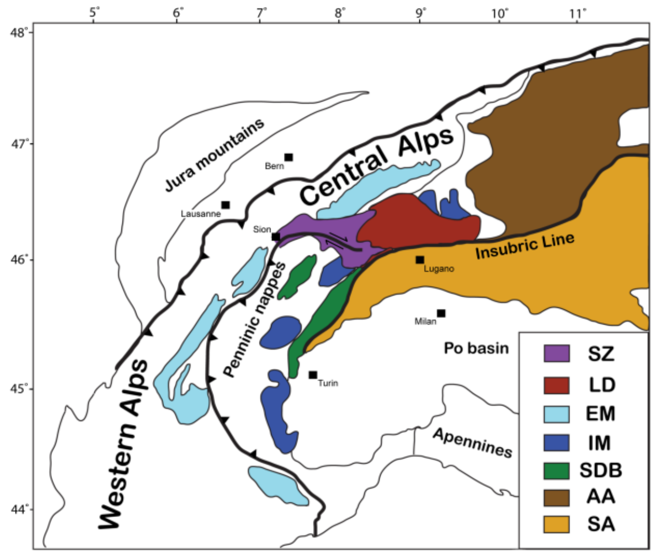

Figure 1. Geologic sketch map of the West-Central Alps, after Schmid & Kissling (2000). SZ = Simplon shear zone; LD = Lepontine Dome; EM = external crystalline massifs; IM = internal crystalline massifs; SDB = Sesia-Dent Blanche unit, AA = Austroalpine units; SA = South Alpine units.

air into the concave Lepontine region from the south. Part of this funneling effect is due to the lowered topography of the Lepontine region, quantified as a concave topographic 'bite' in Rakovec et al. (2001). Modern Alpine precipitation events are influenced by the development of extratropical cyclones associated with Atlantic northwesterly cold fronts in the low-pressure 'lee' south of the Alps (Sturmann & Wanner, 2001).

Glaciation across the Alps at the Last Glacial Maximum (LGM) was extensive, with piedmont glaciers

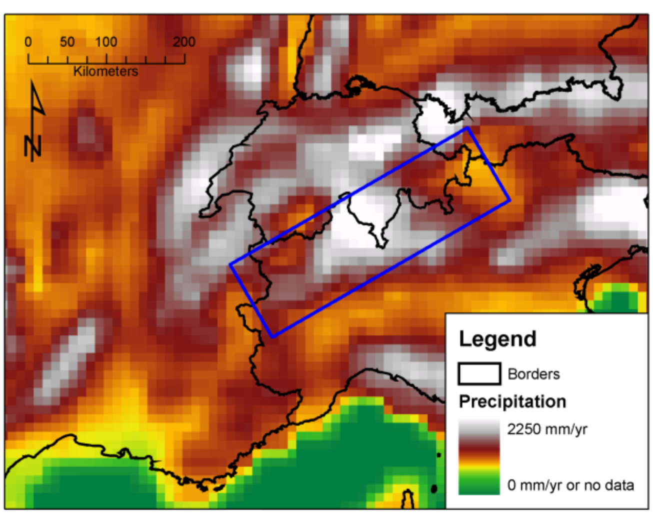

Figure 2. Average yearly Alpine precipitation, 1966-1995. Sourced from Frei & Schar (1998). Blue box outlines the study area.

extending into the Swiss plateau in the north and the Po basin in the South (Kelly et al., 2004). The Alpine ice sheet at the LGM was characterized by radial flow from ice domes. Their occurrence south of the present Alpine weather divide suggests that southerly precipitation was dominant at the LGM. Enhanced precipitation accelerates glacial erosional capacity by depressing equilibrium line altitudes and increasing mass turnover. The large U-shaped Ticino and Toce valleys in the Lepontine Dome served as southern glacier drainages for the Rhône, Rhine, and Engadine Ice Domes (Kelly et al., 2004).

Glaciation has most likely played a large role in erosion since the widespread onset of Pliocene continental glaciations, and Oligocene cool periods could have theoretically brought on very early Alpine glaciations. However, concrete evidence for glacial activity in the southern Central Alps beyond the Pliocene remains elusive.

METHODS

An inventory of cirques was taken for the southern margin of the Western and Central Alps (Fig. 3). Only cirques south of the main Alpine weather divide were used to ensure all measured cirques are influenced primarily by Mediterranean circulation. These cirques provide a range of lithologic units (lower Penninic, upper Penninic, and Austroalpine units) while representing the dominant influence of southerly circulation during the LGM (Kelly et al., 2004).

Cirques were defined as bowl- or armchair-shaped depressions with steep sides and a flattened or overdeepened center; depressions that lacked depth or a flattened bottom were defined as nivation features, and were not counted (Trenhaile, 1976). Cirques currently occupied by glaciers were also not counted. Only depressions closest to the ridgeline were counted, to ensure that overdeepenings in glacial staircases were not included as cirques. Cirque floor elevations were counted from the cirque outlet, defined as the lowest point of the cirque lip. If no outlet was evident, the lowest elevation in the cirque was used.

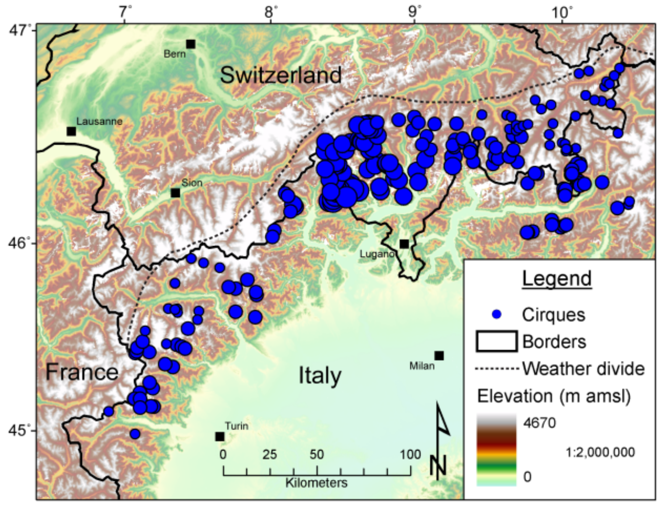

Figure 3. Cirque locations. Icon size is scaled by precipitation; larger icons reflect positive standard deviations from mean precipitation, and smaller icons reflect negative standard deviations from mean precipitation.

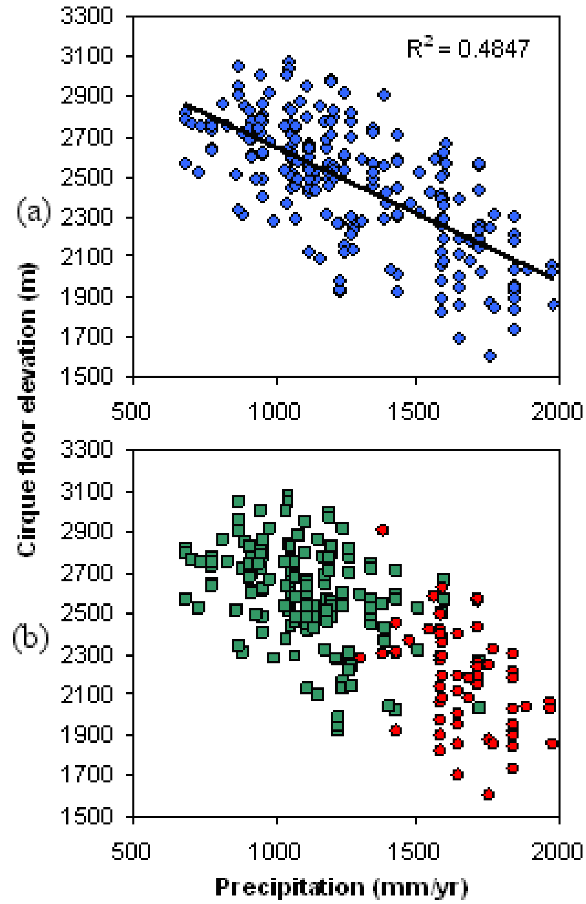

Figure 4. Cirque floor elevations plotted against precipitation, showing (a) the whole data set, and (b) the data set with Lepontine cirques (orange circles) separated from other cirques (green squares).

Cirques were identified using Google Earth Plus v.4.2.0205.5730 at 512 x 512 resolution and medium-low image quality. The source coordinates and aerial photography for the constructed topography were provided by Cnes/Spot image, Tele Atlas, PagineGialle.it, DigitalGlobe, Geocontent, and Terrametrics. The UTM coordinates and elevation for each outlet was determined by pinning placemarks to each cirque outlet. These were manually input into a database and imported into ArcMap as a shapefile.

Averaged annual precipitation data from 1966-1995 was converted into raster format, and then was converted into a polygon file. Cirque locations were joined to the precipitation shapefile, and the joined attribute table was exported to MS Excel. A simple linear least-squares analysis was performed to quantify trends observed in the data. The coefficient of determination (R2) was also calculated as a rough evaluation of the data's correlation.

RESULTS

The graph of precipitation versus cirque floor altitude (Fig. 4a) has a moderate ($R^2 = 0.485$) negative correlation between overall precipitation and cirque floor elevation. The second graph (Fig. 4b) separates cirques from the Lepontine Dome from cirques outside the dome. Lepontine cirques are well-separated from others on the basis of precipitation, reflecting the localized precipitation high in the Lepontine area. In terms of altitude, Lepontine cirques show slightly lower altitudes, although there is significant overlap with outlying regions.

DISCUSSION

The correlation between cirque floor elevation and precipitation suggests ELA depression, and thus an enhancement of glacial erosion, occurred within the

Lepontine Dome. However, several issues must be addressed before a link between precipitation and tectonic development is firmly established.

Trackback

To draw conclusions about long-term erosion rates, the climate regime responsible for enhanced local erosion during the Quaternary must be extended further back in time. The primary influence on Alpine climate is the shape and position of the Alpine chain and its influences on atmospheric movement (Rakovec et al., 2001). As long as the Alpine belt retained its general shape in relation to atmospheric circulation patterns, similar precipitation regimes could be inferred for past environments.

Deep valley incision into the south-central Alps during the Messinian Salinity Crisis circa 5.5 Ma may have been caused by enhanced precipitation in the Lepontine area (Willett et al., 2006). A humid late Miocene Europe would provide an ideal source region for westerlies necessary for heavy precipitation over the Lepontine Dome. Beyond the late Miocene, direct evidence for enhanced precipitation is limited.

Sources of error / alternative explanations

The primary sources of error within the study's methodology lie in the multiple inferences necessary to relate cirques, ELAs, and glaciers. Cirques give only an averaged Quaternary ELA, and significant fluctuations can occur. Regional ELA may not directly correspond to local glaciation because a number of other factors, such as microclimatic differences in precipitation and insolation, may affect individual glaciers. Furthermore, the lack of a quantified time scale for cirque development precludes discussion of concrete glacial erosion rates.

Several alternatives to climatic-tectonic forcing have been proposed. Within the data set, the strong association of heavy precipitation with Lepontine rocks contrasts with the relatively poor association between cirque floor elevation and Lepontine rocks (Fig. 4b). This may suggest that the local precipitation high over the Lepontine Dome was a modern development, and local glaciers had insufficient time to carve cirques before abandoning them upon regional ELA rise.

Other alternative explanations conclude that exhumation across the Alps was primarily tectonic, caused by an Alpine-wide synchronous phase of Miocene lateral extrusion or variations in convergence pattern (Frisch et al., 2000). Precipitation variations would have no impact on long-term exhumation.

It should be noted that unresolved questions remain for the alternate hypothesis, as well. The extensional detachment of the Lepontine Dome occurs at a structurally lower level than the detachment of the Tauern window, another extruded dome in the Eastern Alps (Frisch et al., 2000). This supports assertions that the Lepontine Dome underwent significant rapid exhumation prior to extension (Schlunegger & Willett, 1999), possibly by climatic controls on erosion.

Implications for future work

Several workers have used trimlines and glacial erosional features to construct LGM paleoglacial reconstructions for adjacent areas of the Swiss Alps (Kelly et al., 2004). A similar study could more accurately trace paleo-ELA in the Lepontine area. Alternatively, an estimate of glacially-eroded sediment volume could be made by calculating material lost in cirque formation (Gordon, 1977). Finally, to evaluate the relative efficiency of glacial versus nonglacial erosion, comparative quantitative studies on nonglacial erosion are required.

The results of this paper warn against oversimplification of climate-induced erosion when interpreting Alpine history. Arguing for a tectonic control of orogenic development, Kuhlemann et al. (2002) dismissed long-term climatic forcing on the basis of regional paleofloristic data indicating conditions unfavorable for alpine glaciation. However, regional paleoclimate indicators may not accurately describe local variations of Alpine climate. Local variations in exhumation do exist across the Alps, and local climate variation may help explain apparently contradictory histories of Alpine exhumation.

Construction of a comprehensive Alpine paleoclimatology is necessary to draw firmer conclusions about past Alpine climate. Such a study would integrate fossil records, continent-scale paleotopography, paleowind and paleocurrent data, and in-depth sedimentological studies to better constrain long-term climatic conditions and dominant erosive processes.

CONCLUDING REMARKS

Evidence towards enhanced Quaternary glacial erosion at local precipitation highs has been presented. A strong link between precipitation and cirque floor elevations is demonstrated, indicating an ongoing climatic influence on Quaternary ELA. Erosion-resistant crystalline Lepontine rocks were glaciated more than weaker metasedimentary Austroalpine rocks. This distribution of paleo-ELA independent of variant lithologies suggests climate plays a dominant role in determining the degree of alpine glacial erosion. It also provides preliminary evidence for an alternative, erosional process to extensional unroofing for focused core exhumation, although further research is needed to validate both the amount and timing of localized erosion.

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