Focussed erosion and possible flexural accommodation: A case study from the eastern edge of the Altiplano

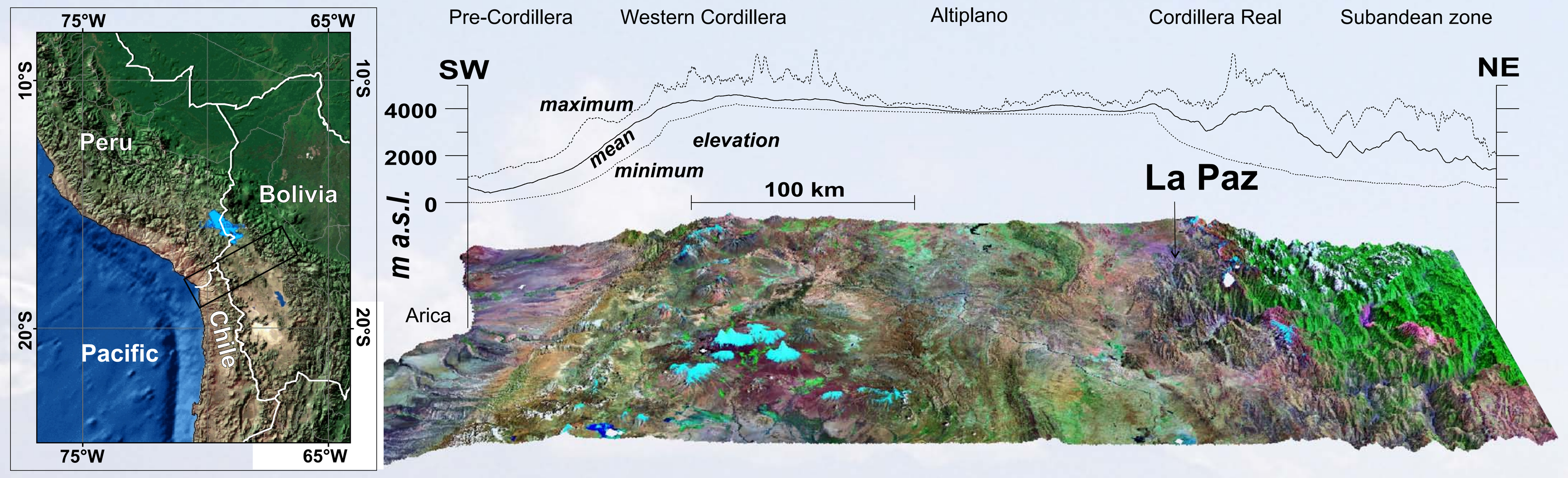
Gerold Zeilinger (1), Fritz Schlunegger (2) & Guy Simpson (3)

(1) Institute of Geosciences, University of Potsdam, Karl-Liebknecht-Str. 24/25, D-14476 Golm/Potsdam (2) Institute of Geological Science, University of Bern, Baltzerstrasse 1 - 3, CH - 3012 Bern (3) Geological Institute, ETH Zürich, Haldenbachstr. 44, HAD F 1, CH - 8092 Zürich

Introduction

The Altiplano constitutes coalesced intramontane basins that were established during the orogeny of the Andes and it is today the second highest plateau on Earth (see Fig. 1 for location and geological section across the Andes). It represents an almost perfectly closed basin with distinct barriers defined by the Western Cordillera and Cordillera Real in the east. The only prominent location where the Altiplano is not limited by a topographic barrier, and where a drainage system has cut into the plateau comprises the Rio La Paz drainage system (Fig. 2).

Fig. 1: SW - NE sections across the Andes from the Pre-Cordillera to the Subandean zone at circa 18°S. The area of the 3 D view is marked in red on the overview map. The profiles at the top are mean-, maximum- and minimum elevation calculated for a section of 10 km width. Please note the incision of the Rio La Paz into the Altiplano indicated by the minimum elevation at the Eastern Cordillera. Elevation: 90 m SRTM dataset; Image: Landsat7, Band 7,4,2.



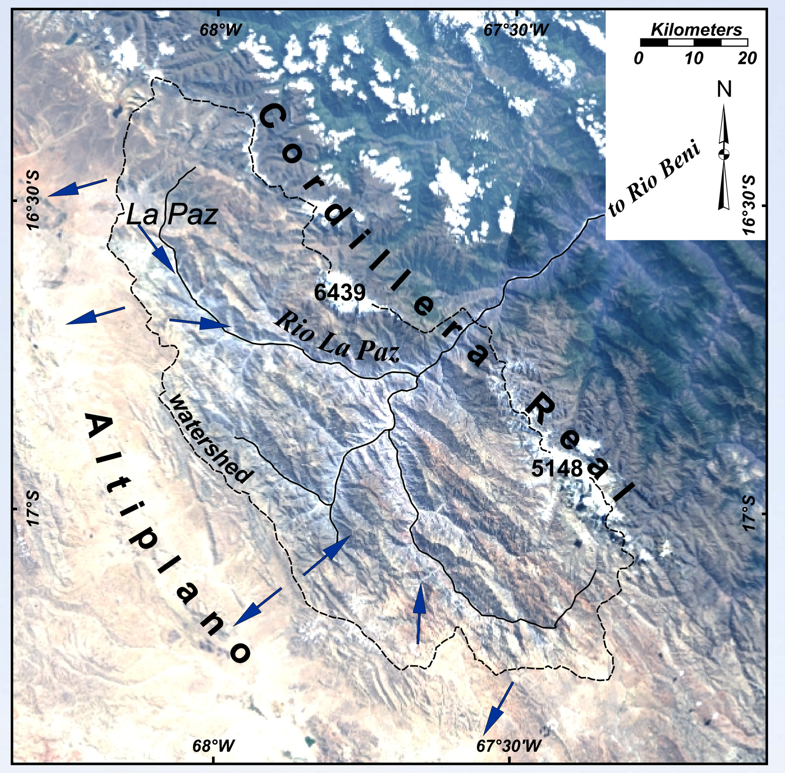
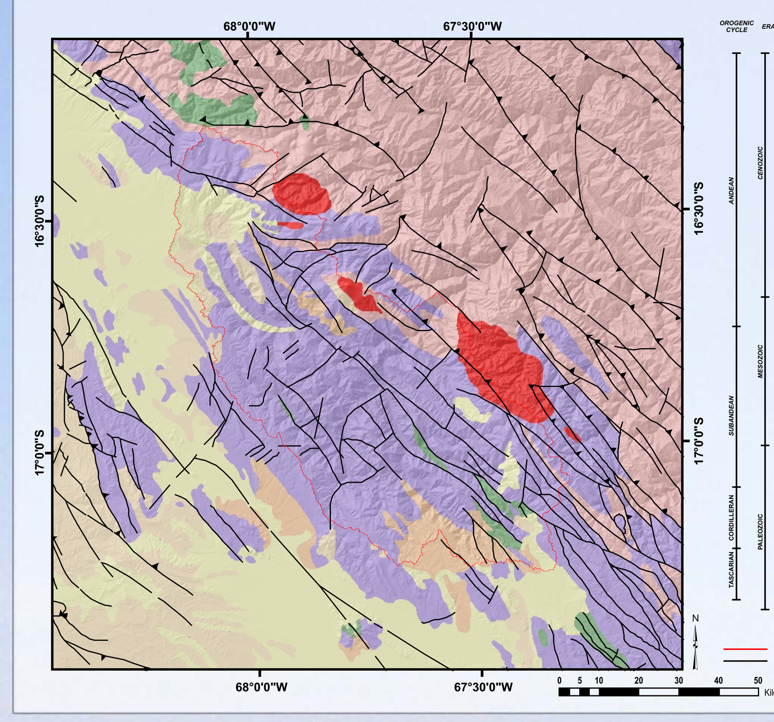


Fig. 2: Rio La Paz catchment area on the Altiplano (black outline). Blue arrows indicate the flow direction of channels close to the water-shed. Image: Landsat7, Band 3,2,1.

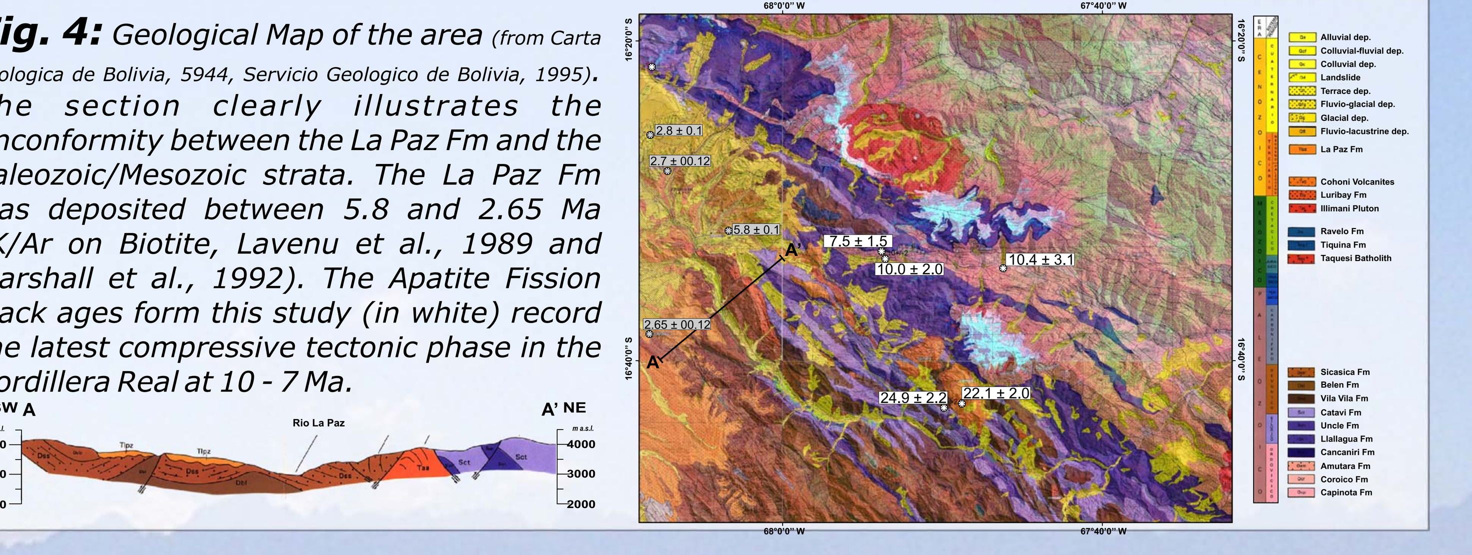
Geological setting

Fig. 3: Geological overview of the area (MAPAS DE BOLIVIA A ESCALA 1:1.000.000, SERVICIO NACIONAL DE GEOLOGÍA Y MINERÍA SERGEOMIN, 2001). The Eastern Cordillera (also Cordillera Oriental) is a N-S striking bivergent thrust system that is limited by faults and Thrusts. It holds an almost complete stratigraphic sequence from Proterozoic to recent rocks of marine and continental facies.



In the area of the La Paz drainage system, the Eastern Cordillera comprises essentially metasedimentary siliciclastic rocks of Ordovician age. These rocks are overlain by Cretaceous to Paleo-cene and/or Neogene deposits with an angular unconformity (Fig. 3). Cross-cutting relationships between dated strata and incised valley indicate that incision in the headwaters of the Rio La Paz in the Cordillera Real postdates 5 Ma. Apatite fission track ages close to the Nevada Illimani (Fig. 4) indicate that the maximum exhumation later than 10 Ma was not significant enough to be recorded by apatite fission track presumably as shortening ceased at that time (Müller et al., 2002; Elger et al., 2005).

Fig. 4: Geological Map of the area (from Carta geologica de Bolivia, 5944, Servicio Geologico de Bolivia, 1995). The section clearly illustrates the unconformity between the La Paz Fm and the Paleozoic/Mesozoic strata. The La Paz Fm was deposited between 5.8 and 2.65 Ma (K/Ar on Biotite, Lavenu et al., 1989 and Marshall et al., 1992). The Apatite Fission track ages form this study (in white) record the latest compressive tectonic phase in the Cordillera Real at 10 - 7 Ma.



Geomorphological setting

The morphometric analyses raises two major questions concerning the development of this drainage system: 1) why is the Rio La Paz cutting the Cordillera Real between the high peaks of Nevada Illimani (6439 m) and Huara (5148 m) and 2) why is the dispersal direction of the drainages beyond the watershed of the Rio La Paz in the opposite direction, i.e. perpendicular to the drainage divide? The character-ization of how relief has adjusted in response to erosion by the Rio La Paz is based on topographic cross-sections (Fig. 5 and 6).

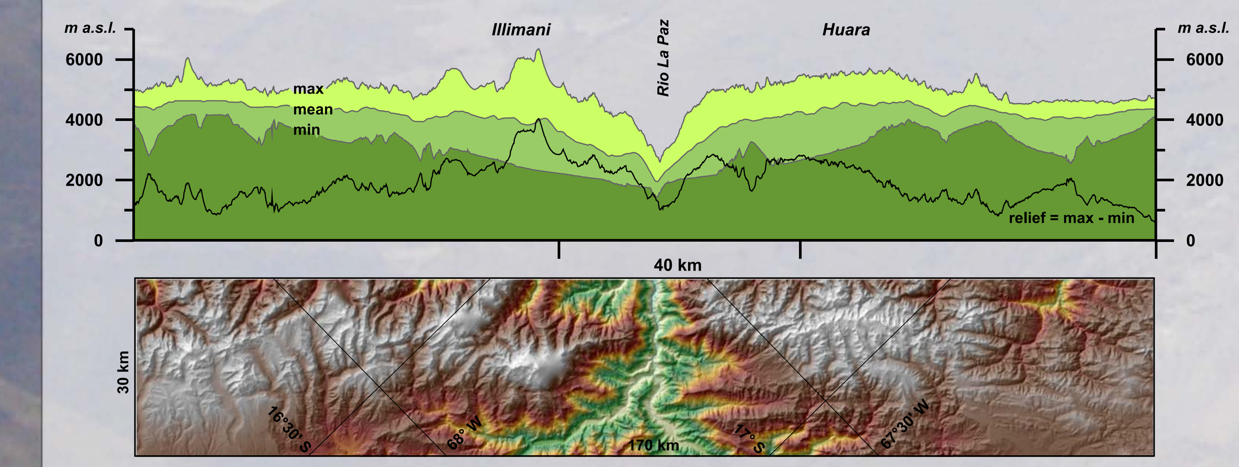
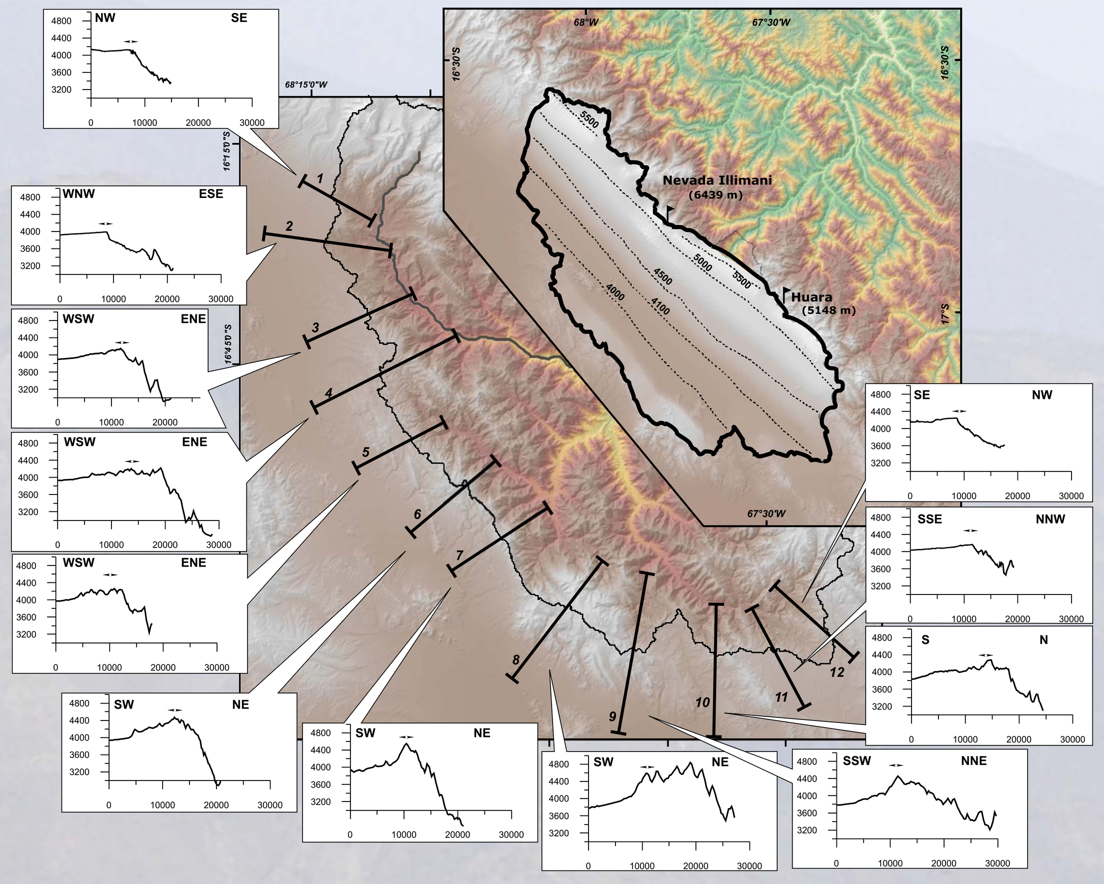


Fig. 5: Topographic cross-sections display the minimum, mean and maximum elevations extracted from a SRTM 90 m digital elevation model within a 30 km-wide swath that runs along the Cordillera Real. Lowest magnitudes of ca. 2000 m of mean elevations are found where the river cross the Cordillera Real and highest maximum elevations next to the valley.

a) The catchment area of the Rio La Paz drainage system is defined by a distinct water-shed. Profiles running across the watershed reveal a downhill slope towards the Altiplano. 90 m SRTM data.

b) A volume of about 3950 km³ was transported by the Rio La Paz drainage system away from the Altiplano to the Rio Beni (based on a reconstructed former surface).

Fig. 6:



River profile

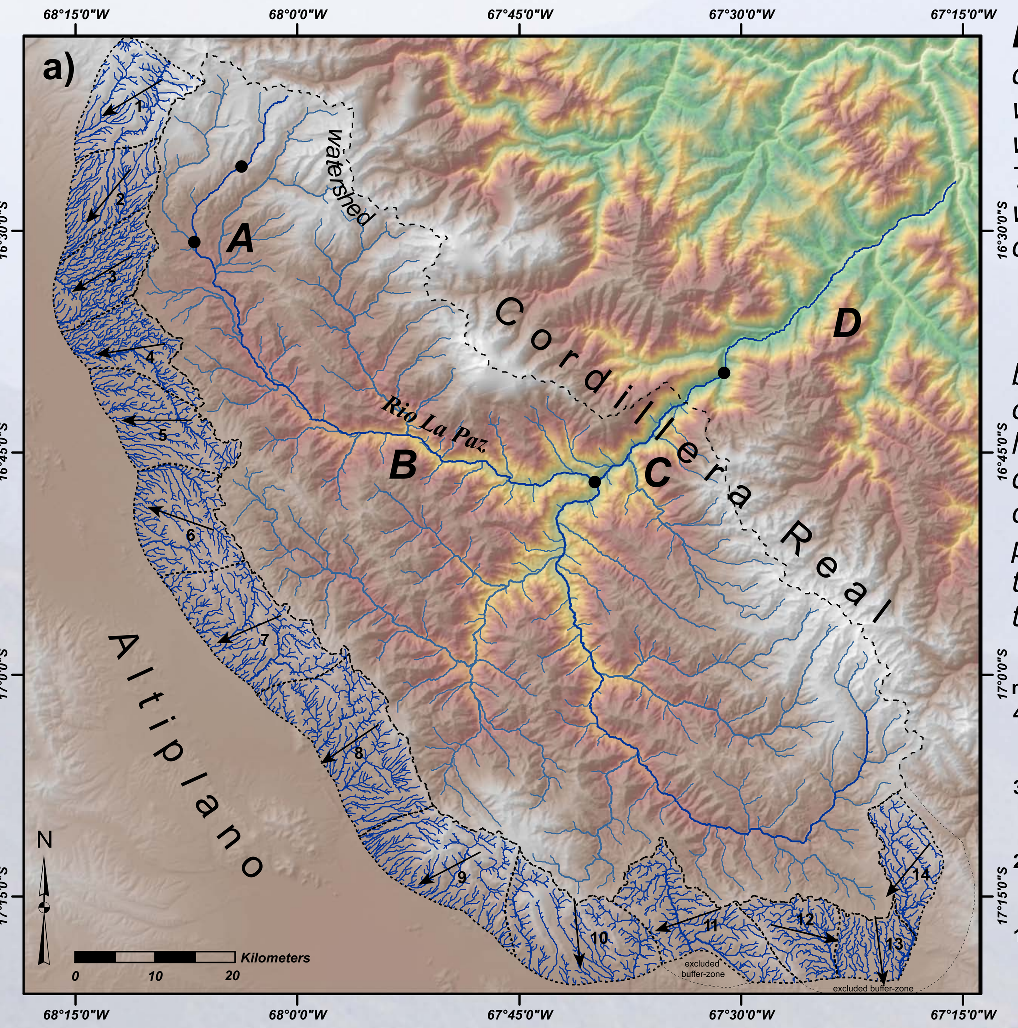
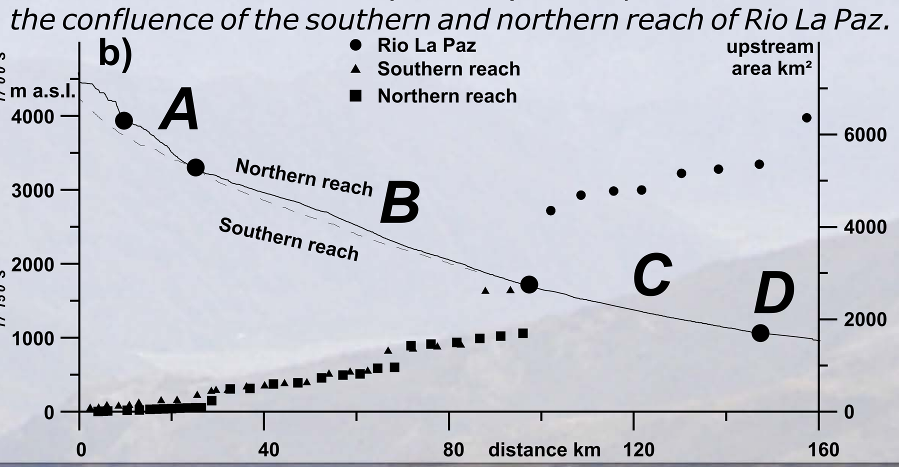
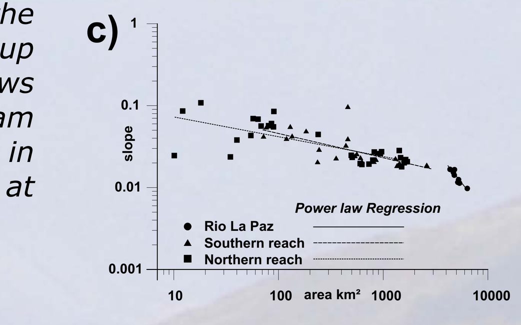


Fig. 7: a) Analysis of drainage pattern in a 10 km wide buffer zone of the watershed on the Altiplano. The linear directional mean was calculated for the outlined zones.

The Rio La Paz drainage basin (Fig. 7) is made up of two segments: the lower segment shows evidence of fluvial incision and valley lowering and is separated from the upper segment by a zone with a convex-up directed curvature in the stream profile).The upper portion that comprises the headwaters is located on the Altiplano west of the Cordillera Real. Where the river cuts perpendicular across the Cordillera Real the valley increases to depth of > 2000 m in just a 15 km-long portion. There, exposure of bedrock on the channel floor is frequently observed.

b) The Rio La Paz stream profile reveals a segmentation of the catchment area in two parts. They are separated by a zone where the longitudinal stream profile of the Rio La Paz displays a convex-up directed curvature (B). The channel profile southern reach shows only a straight gradient. Above and beneath this segment, the stream profile is graded with continuously decreasing channel gradients in the downstream direction (A and C). The upstream area doubles at the confluence of the southern and northern reach of Rio La Paz.

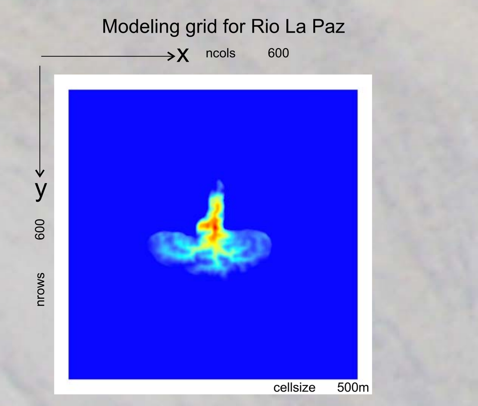




c) Slope area plot for Rio La Paz. In the low upstream areas ranging from 1 to 10 km² the increase in slope declines. SRTM 90 m digital elevation model (CGIAR-CSI SRTM 90m).

Interpretation

The morphometric analyses illustrates the flexural response to surface erosion. The response is interpreted here to be seen by the re-routing of all drainages towards the Altiplano beyond the drainage divide. Support for this interpretation is provided by numerical models that consider flexural accommodation to focused erosion (e.g., Tucker & Slingerland, 1994)(Fig. 8). This model explains why all drainages beyond the watershed disperse their waters to the Altiplano. It also provides an explanation for the presence of the highest peaks just next to the location where the La Paz River cuts into the bedrock across the Cordillera Real.



Processing steps

1) creating an artificial mountain ridge based on values of swath profile

2) calculating the difference between actual topography and artificial topography in an area similar to the drainage area

3) smoothing the result by a 5cell radius mean

4) forming a buffer of 5 cell and outline values are used for interpolation between the artificial surface and the grid representing the incision

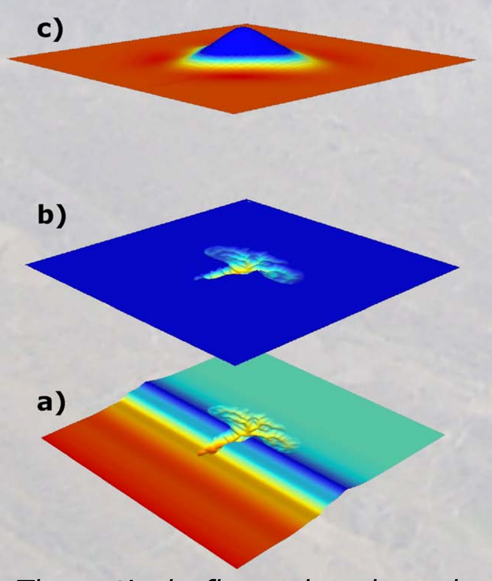
5) combining the artificial grid with the incision grid

6) subtracting the artificial grid from the combined one --> incision is now relative to a surface of 0 and can be used as load for the modelling

Fig. 8: Simple numerical approach with the Finite element method for a 2-D plate flexure using a regular 4 node rectangular grid with non-conforming shape functions after Zienkiewicz and Taylor (vol 2 page 124-126) formulated in terms if w and dwdx dwdy by G. Simpson.

a) Grid with 600 x 600 cells representing the generalized topography of the Eastern Cordillera and the Rio La Paz drainage basin (3 x exaggerated).

b) Load normalized to 0 used as input for modelling. The highest load is at the location of deepest valley incision (3 x exaggerated).



c) Theoretical flexural rebound (100 x exaggerated) measures at the maximum approx. 300 m, and it is identifiable over a lateral distance of several tens of kilometres. This magnitude of response to ca. 2000-3000 m of incision requires a crust with a low flexural rigidity (Turcotte & Schubert, 1982). It is likely that weakening of the crust magnitudes of 10 km for the elastic thickness was accomplished by an enhanced heat flow as suggested by the presence of active volcanoes (Tassara, 2005).

(Modelling parameters: Young modulus = 1e11, elastic thickness = 10000 m ; Poison ratio 0.25).

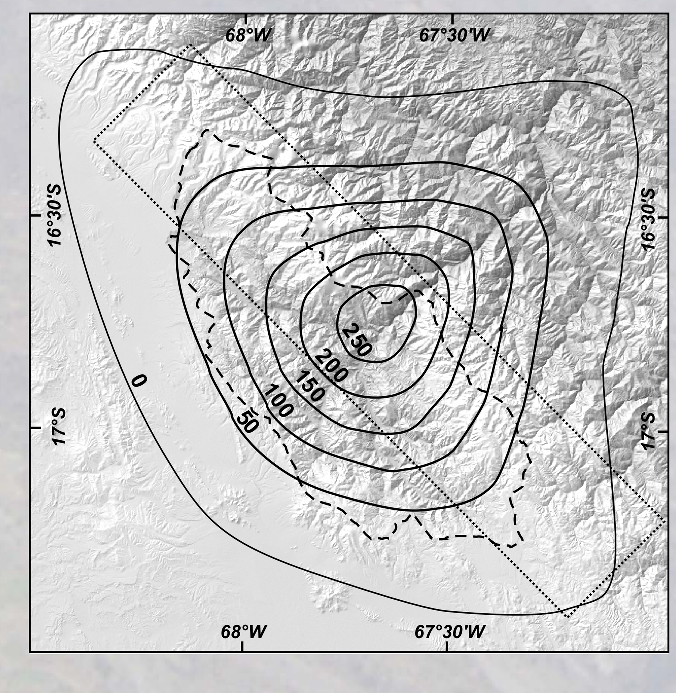


Fig. 9: Flexural rebound calculations plotted on the location of the Rio La Paz drainage basin (stippled line). The box indicates the location from the swath profile shown in figure 5. Maximum rebound occurs in the area of bedrock incision of the Rio La Paz. Note that at the western boundary of the drainage basin, a theoretical rebound of 50 m is possible.

Conclusion

The effects:

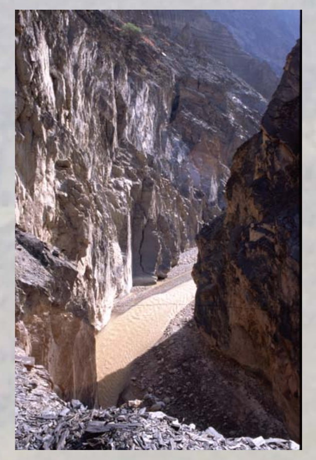
Triggering of processes acting in case of unexpected erosion events and the tectonic feedback in the interior of an orogen. Particularly, when the active zone of deformation propagated already to the foreland, the interior of an orogen might be subject to a new pulse of deformation triggered by mass redistribution caused by a climatic change. This will cause then the feedback mechanisms between crustal unloading and rebound.

- Additional sediment supply for the sediment accumulation area (Amazon basin) from a sediment trap (Altiplano).
- Local uplift of areas bounding the catchment areas and uplift of the peaks next to the river gorge. This features might have been caused by crustal bending (flexural feedback to erosion).
- Fast change of morphology at the Altiplano causing critical slopes (see La Paz).

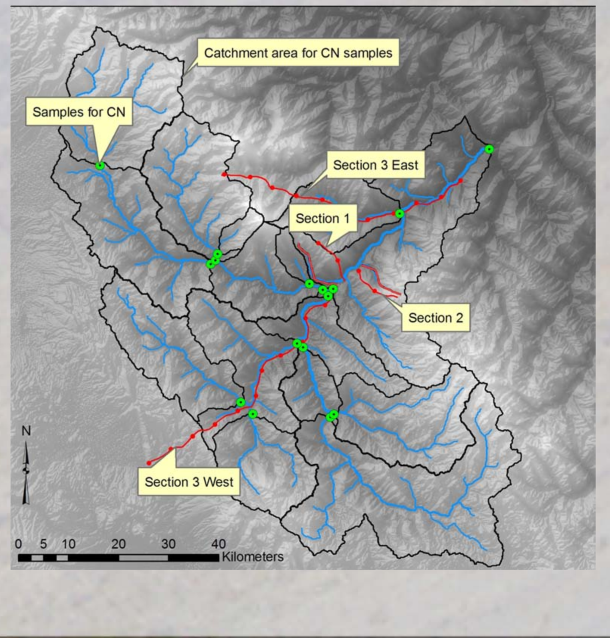
The morphometry of the La Paz drainage basin can be considered to partly result from the feedback mechanism between erosion and crustal bending. This feedback explains why all drainages beyond the watershed disperse their waters to the Altiplano. It also provides an explanation for the presence of the highest peaks just next to the location where the La Paz River cuts into the bedrock across the Cordillera Real. However, it is unclear at the moment through which process, and at what time, opening of the La Paz drainage and hence initiation of theses feedback mechanisms occurred.

Illimani, view to E

Sediment stored as terrace in the Rio La Paz drainage system, view to NW



Bedrock incision in the Rio La Paz channel, view to S



Work in progress:

Sampling for Apatite FT and (U-Th/He) was carried out along 3 main profiles at the Cordillera Real

1) Huara - Rio La Paz
2) Illimani Rio La Paz
3) Profile along main axis of Rio La Paz system

Additionally to the profilse distinct samples from the Rio La Paz drainage were taken for surface dating (catchment-wide erosion rates from alluvial sediments).

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