How is the Altiplano affected by the Rio La Paz drainage system?

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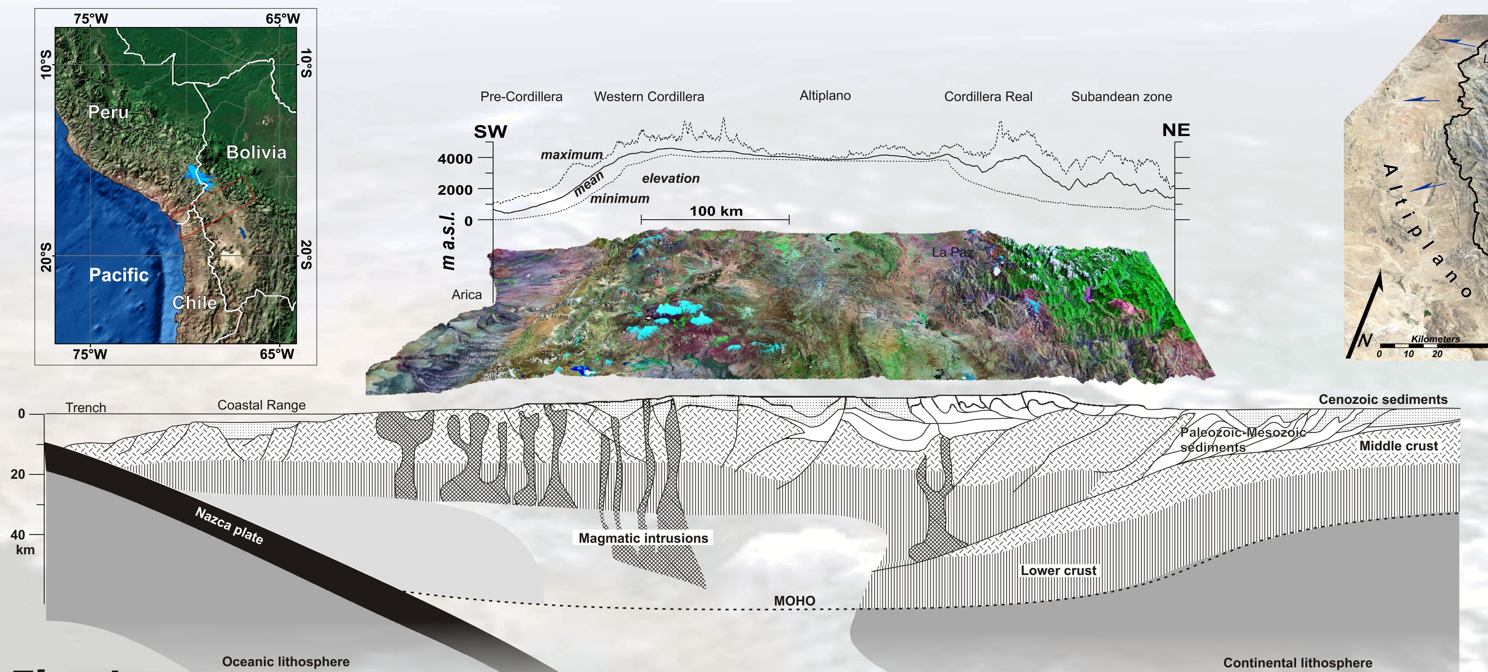


Fig. 1: SW - NE sections across the Andes from the Pre-Cordillera to the Subandean zone at circa 18°S. The area of the 3 D view is marked in red on the overview map. The profiles at the top are mean-, maximum- and minimum elevation calculated for a section of 10 km width. The tectonic setting is illustrated by a simplified section, modified after Jaillard et al. (2002), based on compilation after Allmendinger et al., (1997), Scheuber and Giese (1999), Giese et al. (1999) and Rochat, (2000). Elevation: 90 m SRTM dataset; Image: Landsat7, Band 7,4,2.

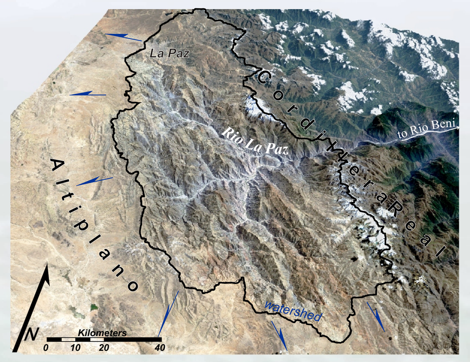


Fig. 2: Rio La Paz catchment area on the Altiplano (black outline). Blue arrows indicate the flow direction of channels close to the watershed. Elevation: 90 m SRTM data, 2x exaggerated; Image: Landsat7, Band 3,2,1.

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).

Geological setting

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 Paleocene 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 of the Cordillera Real close to the Nevada Illimani of around 8 - 10 Ma (Fig. 4) indicate that the major exhumation occurred during the Quechuan phase of deformation (11 - 5 Ma).

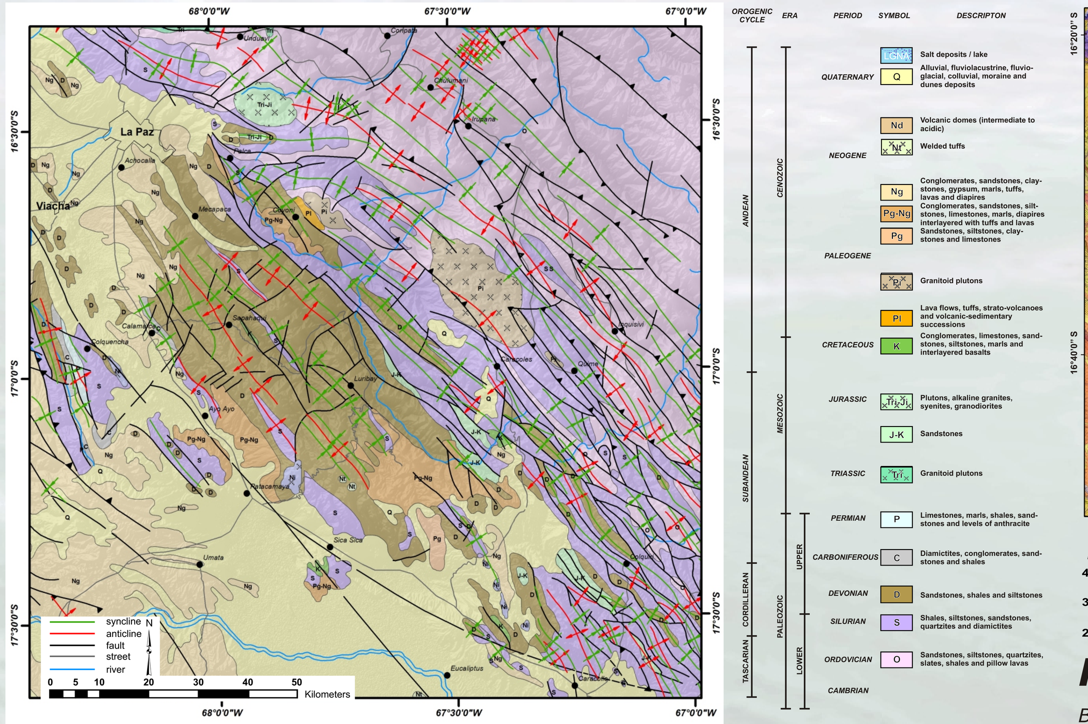


Fig. 3: Geological overview of the area (MAPAS DE BOLIVIA A ESCALA 1:1.000.000, SERVICIO NACIONAL DE GEOLOGÍA Y MINERÍA SERGEOMIN, 2001). The Eastern Cordillera (also Cordillera Oriental) is a N-S striking bivergent thrust system that is limited by faults and Thrusts. It holds an almost complete stratigraphic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

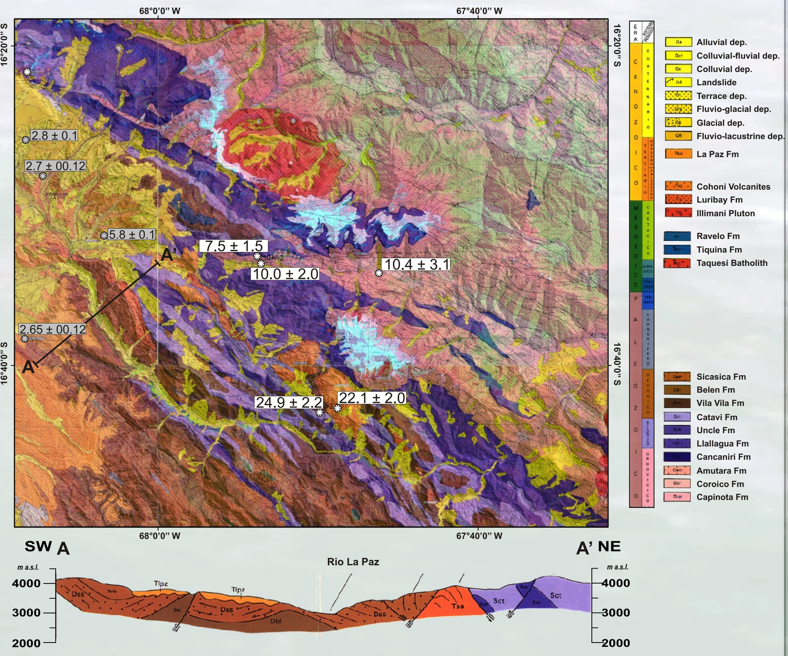
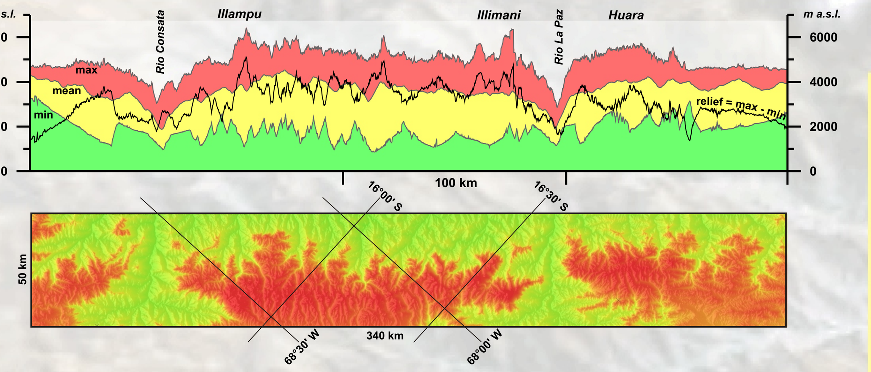


Fig. 4: Geological Map of the area (from Carta geologica de Bolivia, 5944, Servicio Geologico de Bolivia, 1995). The section clearly illustrates the unconformity between the La Paz Fm and the Paleozoic/Mesozoic strata. The La Paz Fm was deposited between 5.8 and 2.65 Ma (K/Ar on Biotite, Lavenu et al., 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.

Fig. 5: Topographic cross-sections display the minimum, mean and maximum elevations extracted from a SRTM 90 m digital elevation model within a 50 km-wide swath that runs along the Cordillera Real. Lowest magnitudes of ca. 2000 m of mean elevations are found where both rivers cross the Cordillera Real and highest maximum elevations next to the valleys.



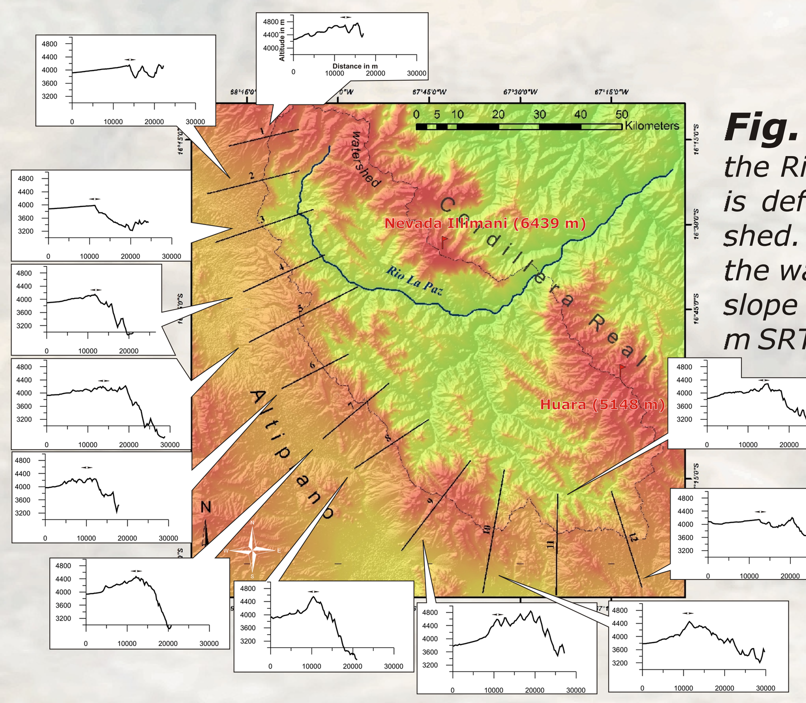


Fig. 6: The catchment area of the Rio La Paz drainage system is defined by a distinct watershed. Profiles running across the watershed reveal a downhill slope towards the Altiplano. 90 m SRTM data.

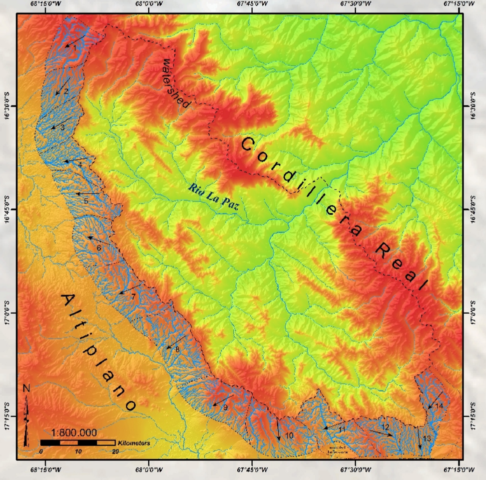


Fig. 7: Analysis of drainage pattern in a 10 km wide bufferzone of the watershed on the Altiplano. The linear directional mean was calculated for the oulined zones.

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 characterization of how relief has adjusted in response to erosion by the Rio La Paz is based on topographic cross-sections** (Fig. 5 and 6) and the analysis of drainage on the Altiplano (Fig. 7).

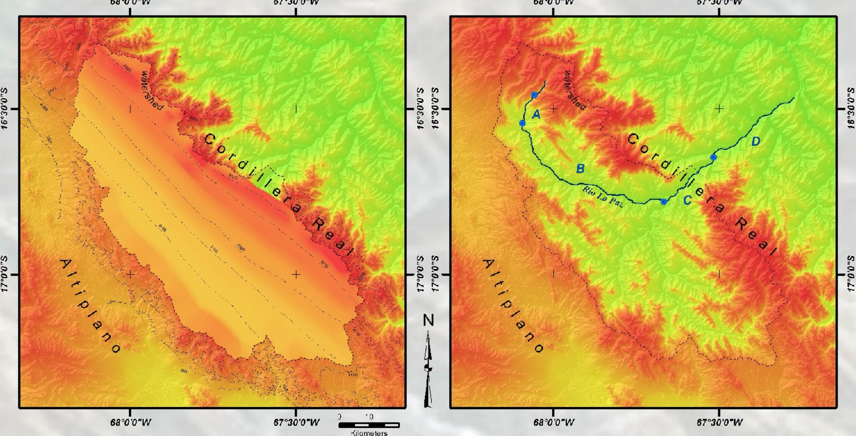


Fig. 8: a) A volume of about 3950 km³ was transported by the Rio La Paz drainage system away from the Altiplano to the Rio Beni (based on a reconstructed former surface). b) Course of Rio La Paz with segments outlined in the stream profile (Fig. 9). West of the Cordillera Real the drainage networkd is dendritic. It changes to a linear drainage where the Rio La Paz cuts across the Cordillera Real.

River profile

The Rio La Paz drainage basin (Fig. 8) 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 (Fig. 9).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 incises to depth of > 2000 m in just a 15 km-long portion. There, exposure of bedrock on the channel floor is frequently observed.

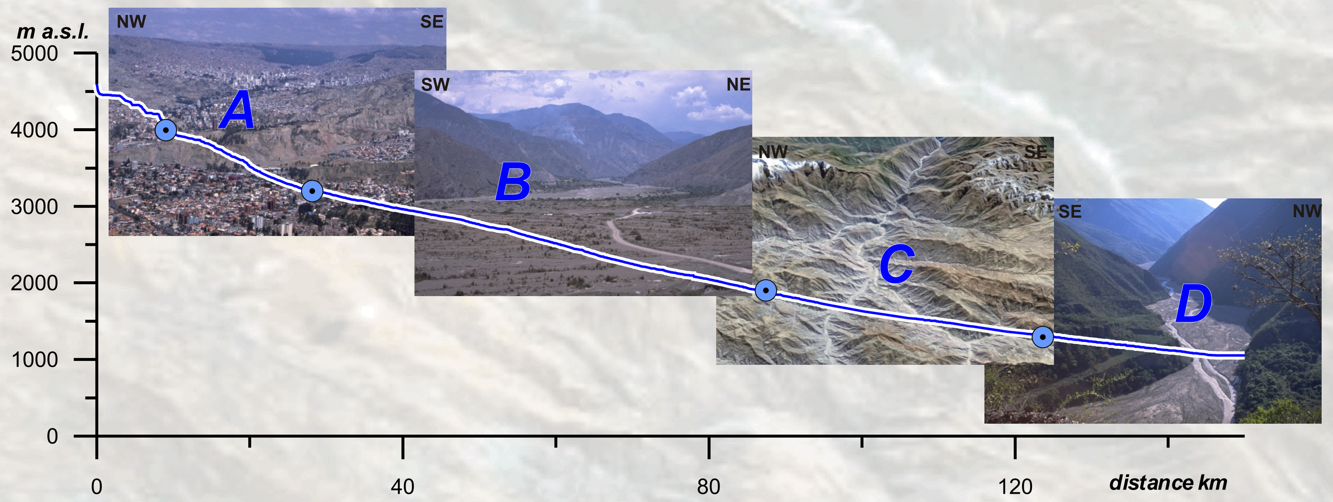
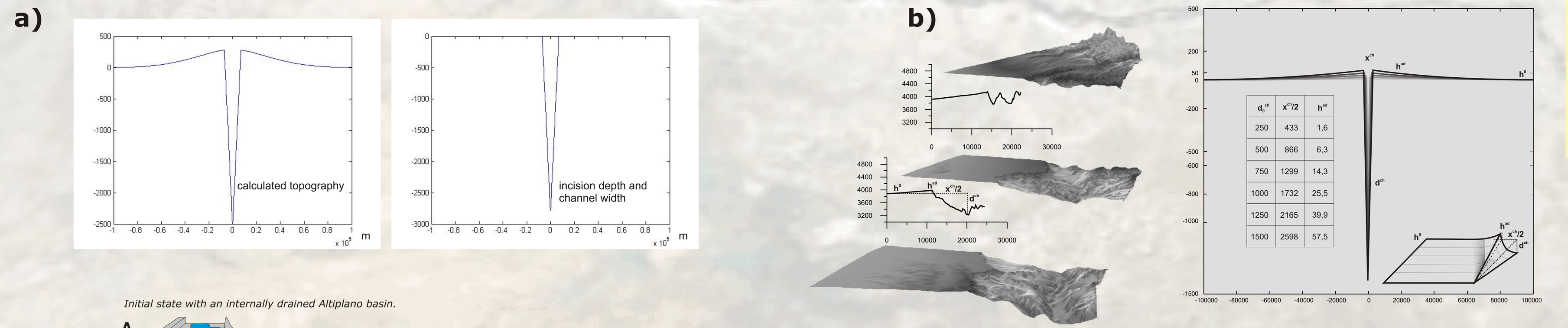


Fig. 9: The Rio La Paz drainage basin is made up of two segments. They are separated by a zone where the longitudinal stream profile of the La Paz river displays a convex-up directed curvature (B). Above and beneath this segment, the stream profile is graded with continuously decreasing channel gradients in the downstream direction.

Fig. 10: Simple numerical approach for the two observed scenarios:
a) Valley of Rio la Paz across the Cordillera Real: the theoretical flexural rebound measures between 200 and 400 m, and it is identifiable over a lateral distance of several tens of kilometres. This magnitude of response to ca. 2000-3000 m of requires a crust with a low flexural rigidity (Turcotte & Schubert, 1982). It is likely that weakening of the crust was accomplished by an enhanced heat flow as suggested by the presence of active volcanoes. (Turcotte & Schubert, 1982, page 123 eqn 3-111), Young modulus = 1e11, elastic thickness = 10000 m ; poison ratio 0.25).
b) Theoretical flexural rebound at the drainage divide. FE solution of 1-d flexure equation testing against periodic load solution (Turcotte & Schubert, 1982, page 123 eqn 3-111), Young modulus = 1e11, elastic thickness = 10000 m ; Poison ratio 0.25).



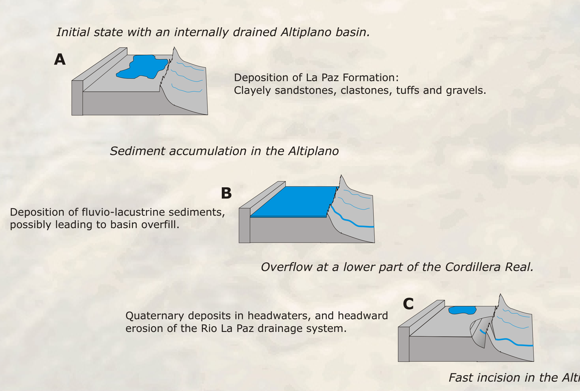


Fig. 11: Development of the Rio La Paz drainage system W of the Cordillera Real by the formation of an outlet through the Cordillera Real. This outlet was most likely the result of an overflow in the Altiplano after a period of sediment accumulation (La Paz Fm) in the basin. Although the interpretation of overflow and subsequent regressive erosion are likely scenarios for the establishment of the La Paz drainage basin, it is unclear.

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. 10). We propose that the development of the Rio La Paz drainage system W of the Cordillera Real was triggered by the formation of an outlet through the Cordillera Real (Fig. 11).

Conclusion

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.

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).

City of La Paz, view to NE

Illimani, view to E

Sediment stored as terrace in the Rio La Paz drainage system

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