Precipitation, focussed erosion and crustal flexural accommodation in the Eastern Altiplano (Bolivia)

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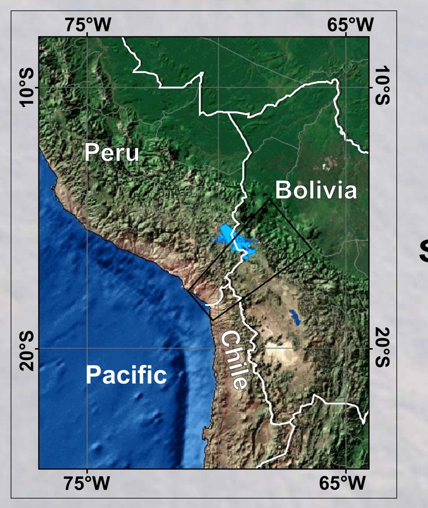
Introduction

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 topographic 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. Only the Rio Consata and the Rio La Paz (Fig. 2) drain the Bolivian Altiplano and cut across the Cordillera Real, immediately adjacent to its highest peaks (e.g., the 6.368 m-high Illampú). Both rivers are important in routing sediments from the orogen interior to the Andean foreland.



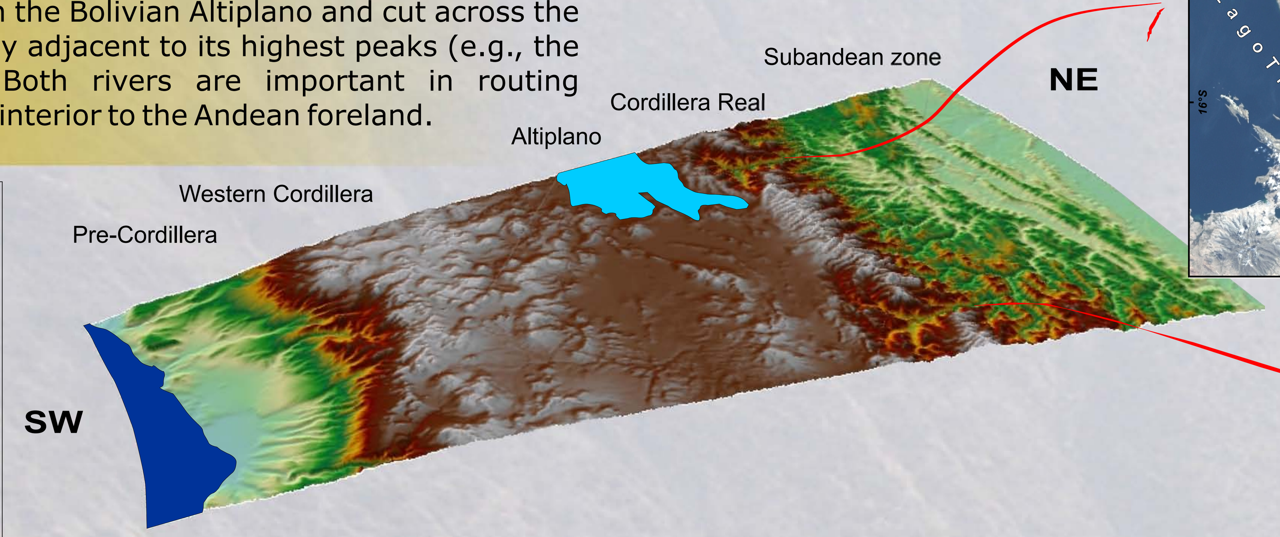
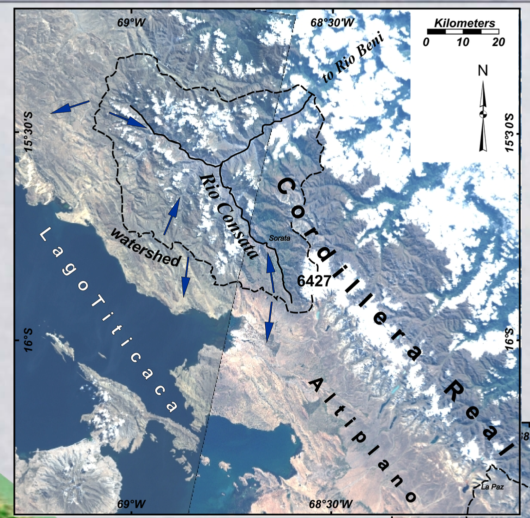


Fig. 1: SW - NE sections across the Andes from the Pre-Cordillera to the Subandean zone at circa 18°S. The area of the 3 D view is marked in red on the overview map. Please note the incision of the Altiplano and the deep gorges through the Eastern Cordillera caused by the Rio Consata and the Rio La Paz.



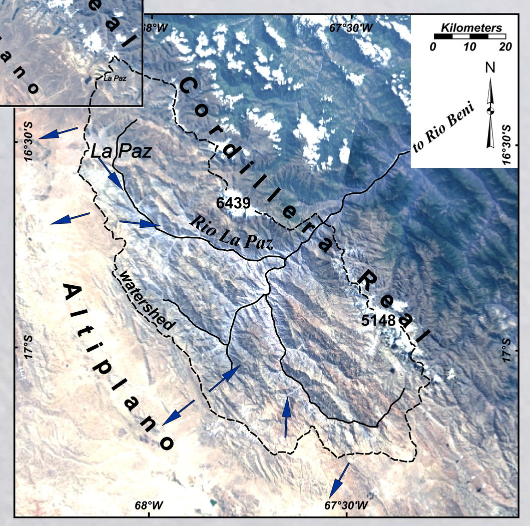
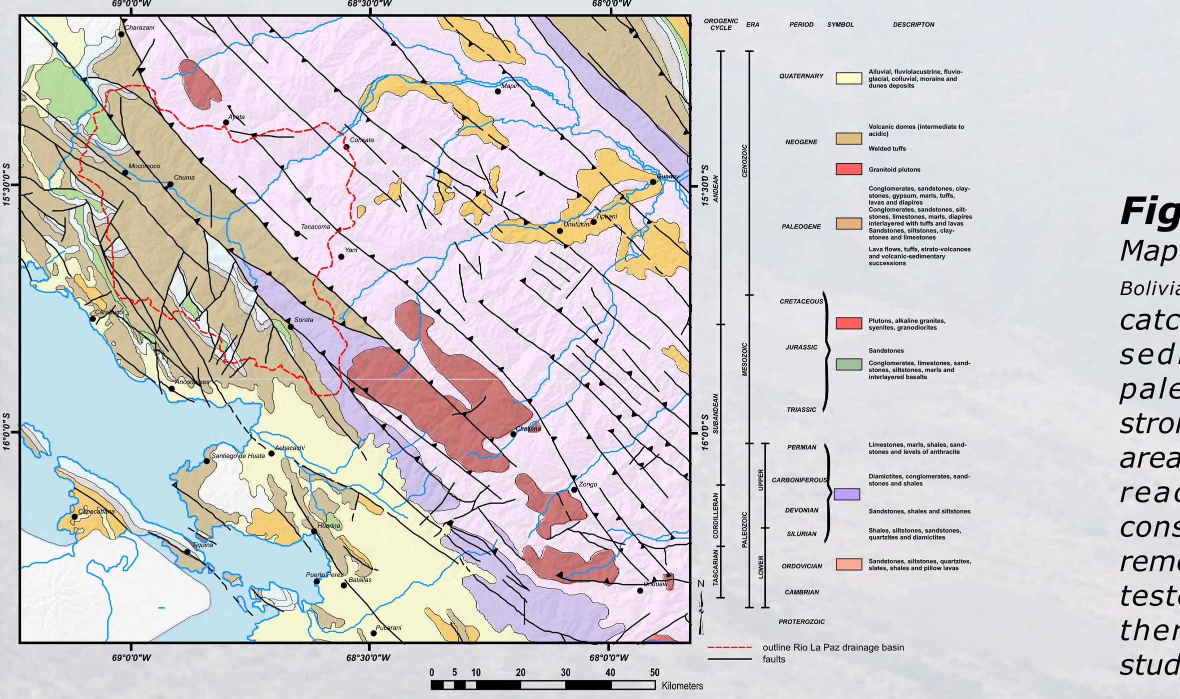


Fig. 2: Rio Consata (left) and Rio La Paz (below) catchment areas on the Altiplano (black outline). Blue arrows indicate the flow direction of channels close to the watershed. Image: Landsat 7, Band 3,2,1.

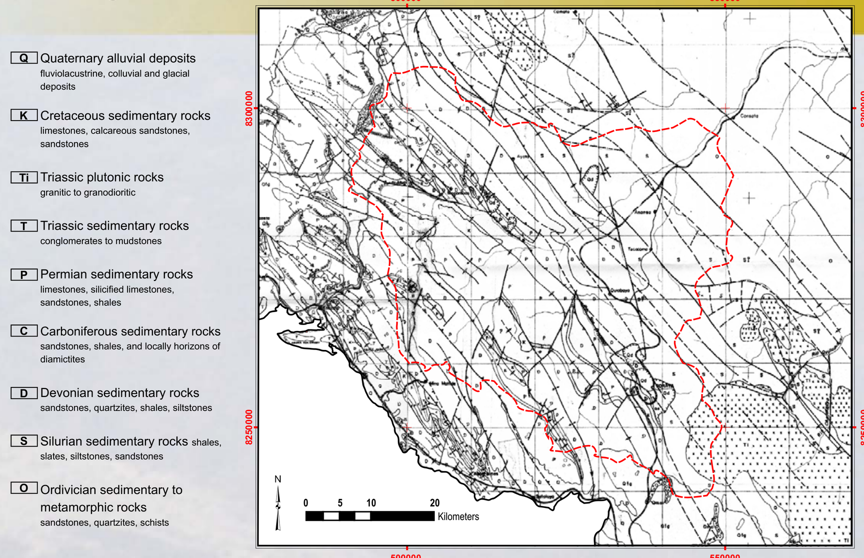
Geological setting

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.



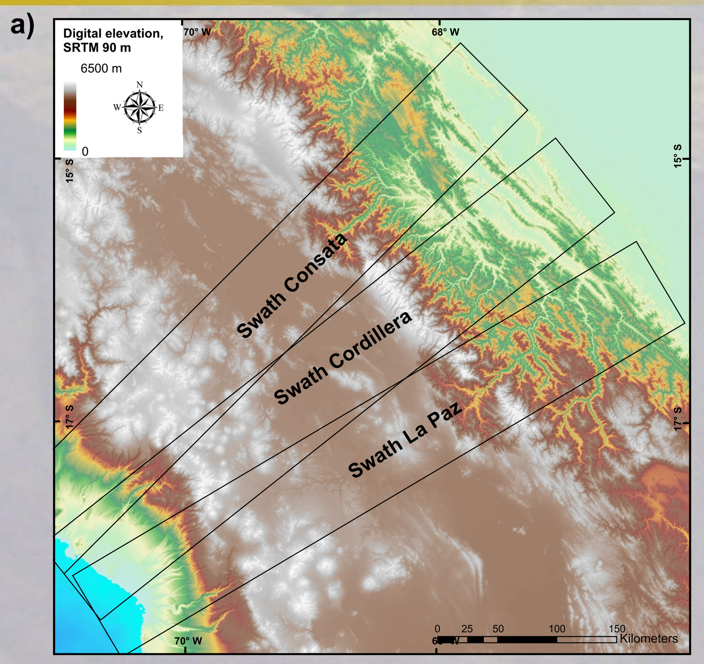
In the area of the Consata drainage system, the Eastern Cordillera comprises essentially metasedimentary siliciclastic rocks of Paleozoic age. These rocks are overlain by Cretaceous to Paleocene and/or Neogene deposits with an angular unconformity (Fig. 3). The deformation is recorded in NW-SE striking faults and folds (Fig. 4). 150 km SE of the Rio Consata cross-cutting relationships between dated strata and the incised Rio La Paz valley indicate that incision in the in the Cordillera Real postdates 5 Ma. There, Apatite fission track ages indicate that the maximum exhumation later than 10 Ma was not significant enough to be recorded by apatite fission track presumably as shortening in the Cordillera ceased at that time (Müller et al., 2002; Elger et al., 2005).

Fig. 4: Preliminary Geological Map of the area (Servicio Geologico de Bolivia, 1995). The Rio Consata catchment covers a (meta-) sedimentary succession of paleozoic strata which are strongly folded and faulted. This area has the potential to show reactivated deformation in consequence to incision and removal of sediments. This will be testet with low temperature thermochronology and field studies.



Geomorphology and rainfall

The rainfall pattern along the Eastern Cordillera mimics the patterns of topographic relief (Fig. 5a, b). Based on high-resolution Tropical Rainfall Measurement Mission (TRMM) rainfall data (Fig. 5c), we observe an influx of higher rainfall along the trend of the valley towards the Altiplano. The Rio La Paz area shows a different pattern, because dry winds blow from the altiplano along the valley towards the East.



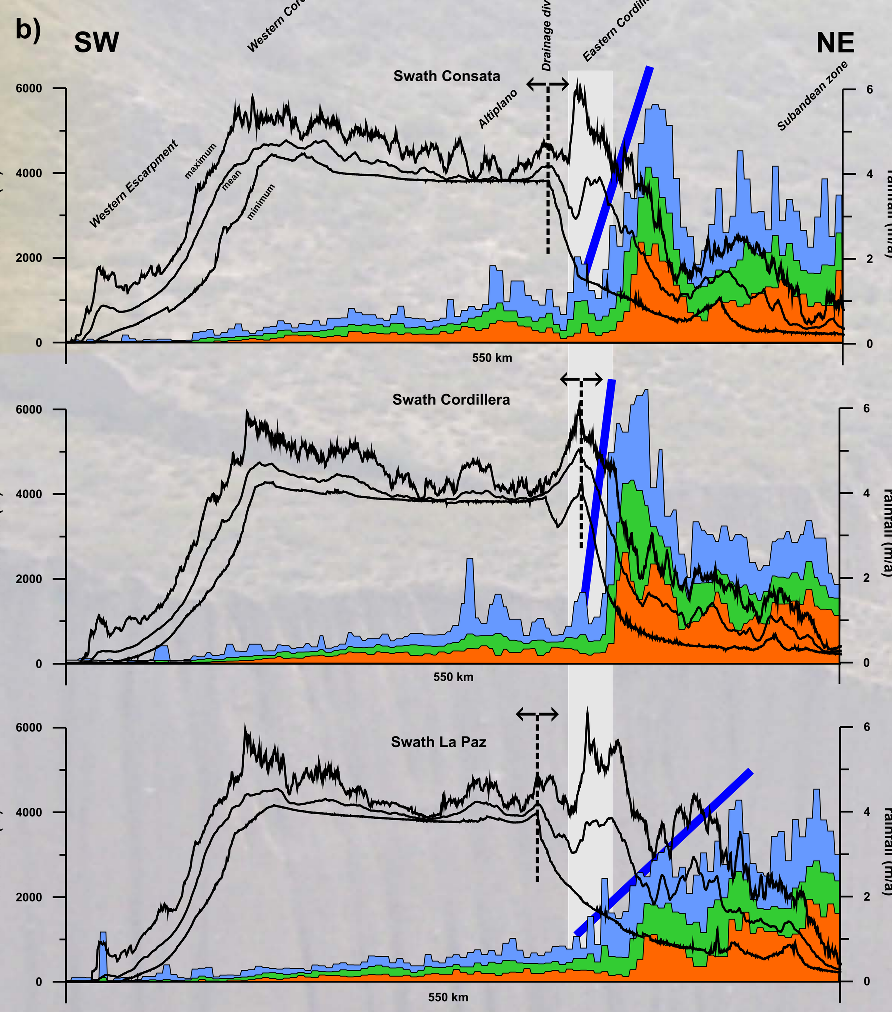
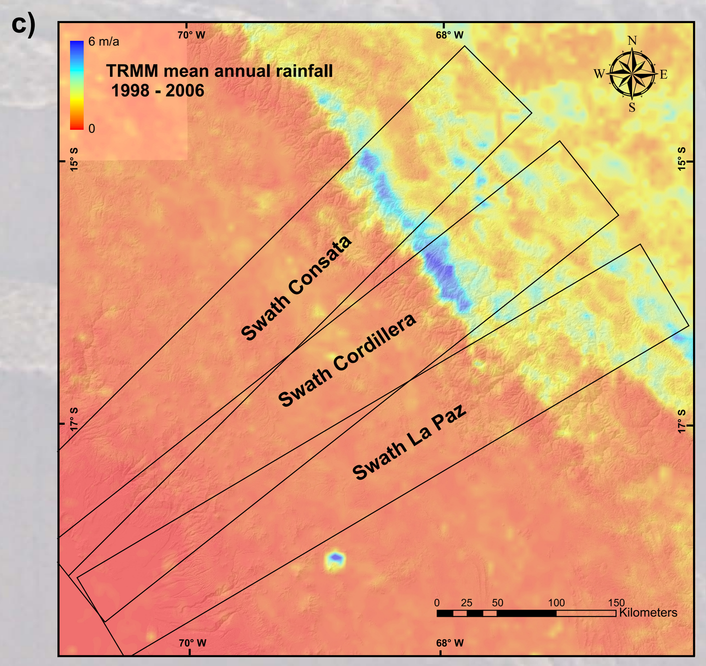
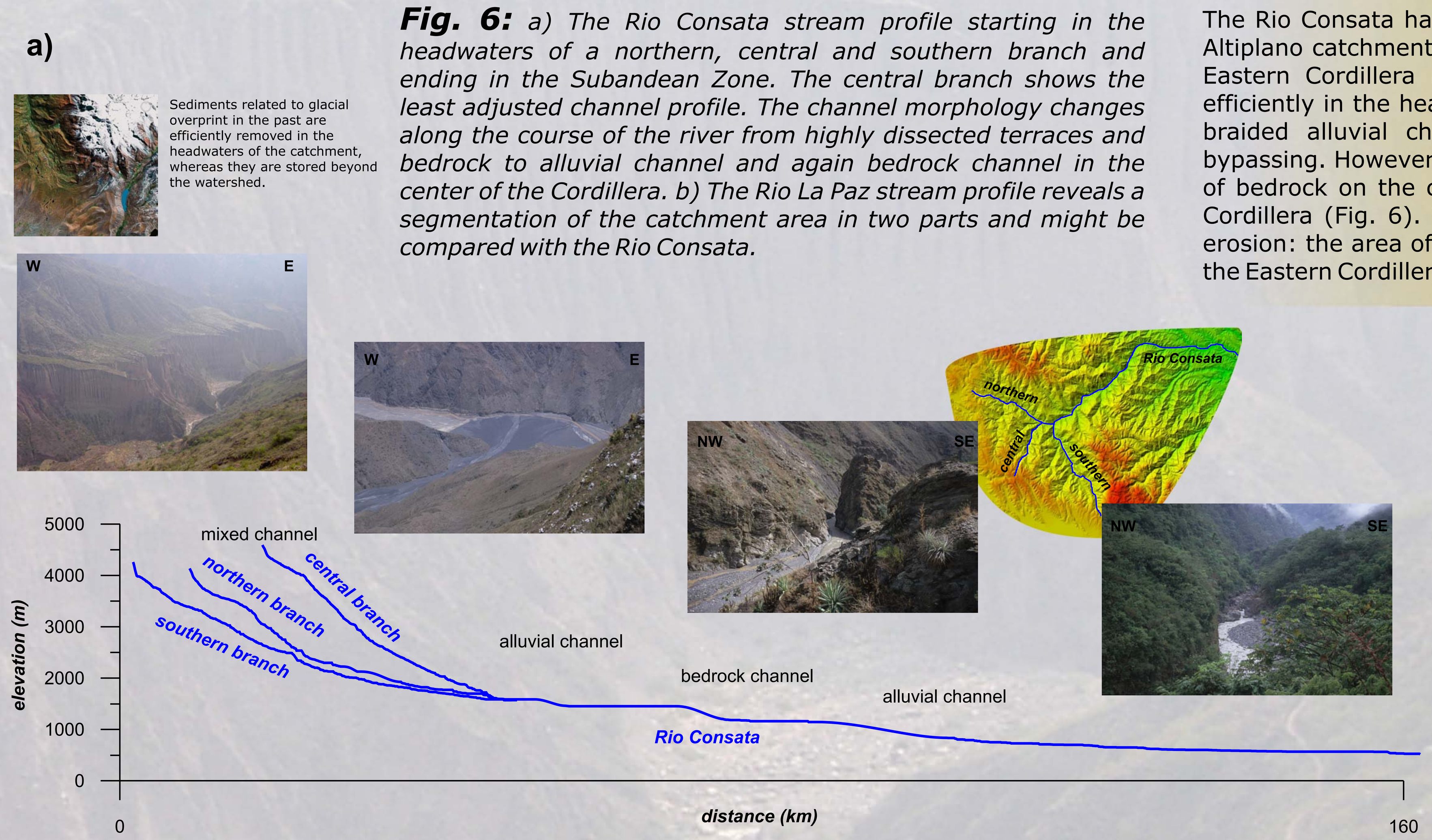


Fig. 5: a) Extend of the 3 swath profiles on top of the SRTM 90 m digital elevation model; b) Cross-sections showing the minimum, mean and maximum values for elevation (black lines) and mean annual rainfall (coloured). The relation between relief and rainfall is significant and highlighted by the inclined blue line; c) TRMM rainfall map. Note the higher rainfall values in the Rio Consata valley.

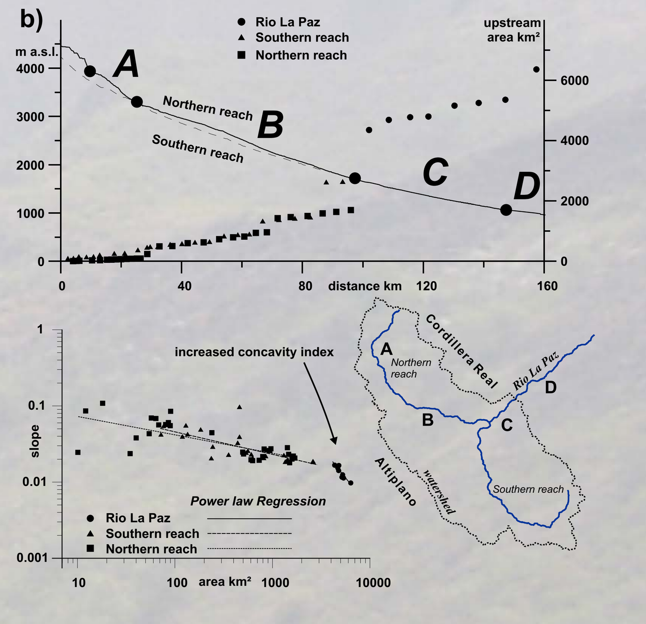


River profile

Fig. 6: a) The Rio Consata stream profile starting in the headwaters of a northern, central and southern branch and ending in the Subandean Zone. The central branch shows the least adjusted channel profile. The channel morphology changes along the course of the river from highly dissected terraces and bedrock to alluvial channel and again bedrock channel in the center of the Cordillera. b) The Rio La Paz stream profile reveals a segmentation of the catchment area in two parts and might be compared with the Rio Consata.

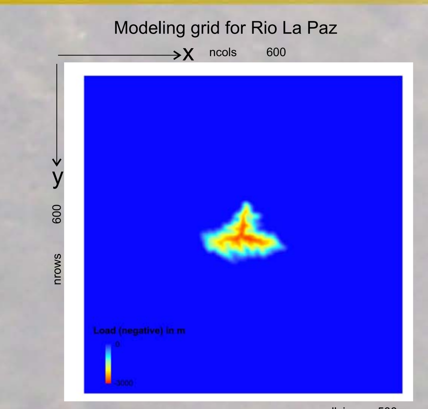


The Rio Consata has removed approx. 1320 km³ of rock from the Altiplano catchment area (~ 2600 km²) and has cut down into the Eastern Cordillera more than 2500 m. Sediments are removed efficiently in the headwaters. Farther downstream, the presence of braided alluvial channels and gravel sheets indicate sediment bypassing. However, fluvial incision has resulted in partial exposure of bedrock on the channel floor where the river cuts through the Cordillera (Fig. 6). Two locations correspond to enhanced surface erosion: the area of the drainage on the Altiplano and the sector in the Eastern Cordillera affected by bedrock incision.



Interpretation

Flexural modelling indicates that crustal flexural uplift is fundamentally influenced by erosional removal of material. Flexural uplift in turn helps intercept westward moisture transport, thus suggesting a positive feedback mechanism between tectonics and climate, which ultimately influences the overall morphology of the Eastern Cordillera. The used numerical models consider flexural accommodation to focused erosion (e.g., Tucker & Slingerland, 1994)(Fig. 7). It provides an explanation for the presence of the highest peaks just next to the location where the Rivers (Rio Consata and Rio La Paz) cut 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

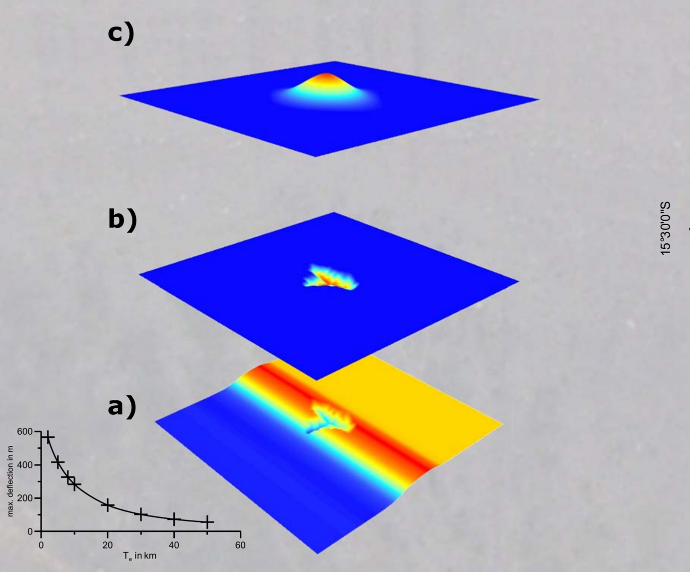
3) smoothing the result by a 5cell radius mean

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. 7: 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 Consata 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. 250 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).

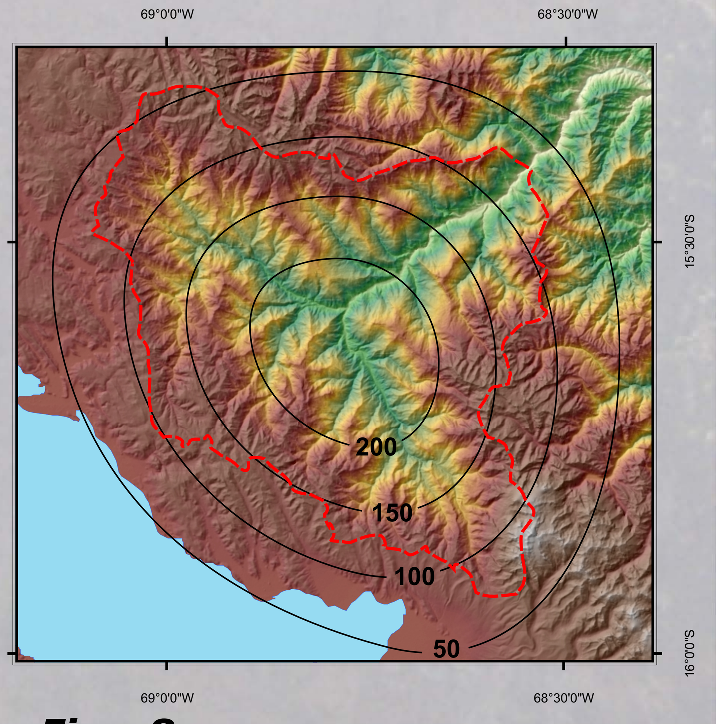


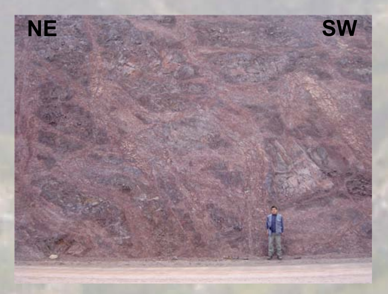
Fig. 8: Flexural rebound calculations plotted on the location of the Rio Consata drainage basin (red line). Maximum rebound occurs in the area of bedrock incision of the Rio Consata. Note that at the western boundary of the drainage basin, a theoretical rebound of 100 m is possible.

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).
- This flexural uplift in turn helps to intercept westward moisture transport, suggesting a positive feedback mechanism between tectonics and climate.
- Fast change of morphology at the Altiplano causing critical slopes.

View from the Altiplano towards the Rio Consata catchment.

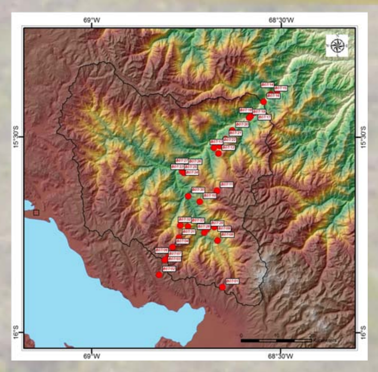


Fault zone in cretaceous red sandstone (left) and paleozoic sediments (right).

Coarse glacio-fluvial sediments in the Rio Consata

Conclusion

Morphometric data and precipitation pattern suggest a significant link between precipitation, topographic evolution and erosion processes. Similar conclusions had been suggested for the morphometry of the La Paz drainage basin (Zeilinger and Schlunegger, 2007). It provides an explanation for the presence of the highest peaks just next to the location where the La Paz and the Consata Rivers cut into the bedrock across the Cordillera Real. However, it is unclear at the moment through which process, and at what time, opening of these drainages and hence initiation of these feedback mechanisms occurred.



Work in progress:
Sampling for Apatite FT and (U-Th/He) was carried out along the Rio Consata at the Cordillera Real.

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