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Growth pattern of the Andean Puna plateau constrained by apatite fission track, apatite (U-Th)/He, K-feldspar $^{40}Ar/^{39}Ar$, and zircon U-Pb geochronology

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Understanding the principal controls on Late Cenozoic climate changes requires to distinguish between effects of global climate change from those associated with mountain range uplift. Uplift of the Andean plateau is particularly important since the Andes form the only orographic barrier to atmospheric circulation in the southern hemisphere.

We present new thermochronologic data from 9 different igneous intrusions from the Puna plateau and the Eastern Cordillera in northwestern Argentina (~23-26°S). The data consists of apatite fission track elevation transects (32 samples), apatite (U-Th)/He, K-feldspar $^{40}Ar/^{39}Ar$ step-heating, and zircon U-Pb data from exhumed Paleozoic to Miocene granitoids rocks (Sierra de Macon, Complejo Oire, Valle Luracatao, Colome granite, Cerro Durazno, Aguilar granite, Fundicion granite, Cobres granite, Nevado de Acay, Fig. 1). The new results suggest that uplift and exhumation started earlier than previously assumed.

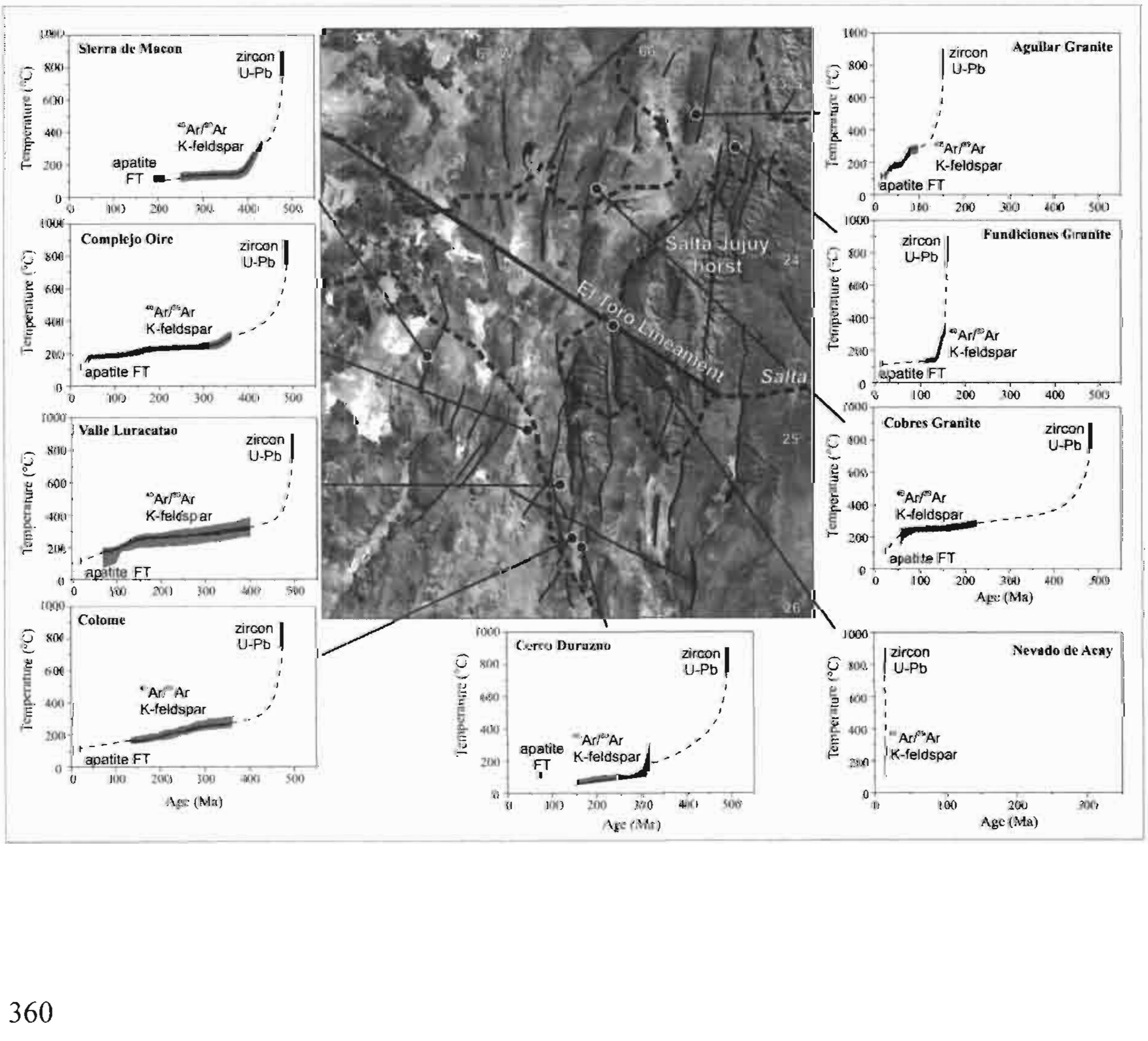

Fig. 1: Topographic shaded map of the eastern Puna (23-26°S) showing sample locations (black dots) and results from K-feldspar thermal modeling as temperature versus age diagrams.

Changes in exhumation rates can be derived from the cooling history of the shallow crust by using low-temperature thermochronometers such as the apatite fission-track (AFT) and (U-Th)/He systems. Cooling ages collected on vertical elevation transects track the thermal history of a crustal section relative to the Earth's surface. When samples cool through their closure temperatures (<110°C for apatite fission-tracks, ~40-80°C for (U-Th)/He) in response to crustal shortening, reverse faulting and exhumation, their age vs. elevation relationship and their fission track length distribution can be used as a proxy to the timing of fault activity, and to determine exhumation rates using reasonable assumptions about the geothermal gradient (Stockli et al. 2000). Higher temperature thermochronometers such as K-feldspar ^{40}Ar/^{39}Ar step-heating (~150-350°C) and zircon U-Pb analysis provide constraints on paleo-geothermal gradients (Lovera et al. 2002), which can be used to assess older tectonically induced cooling episodes. Consequently, the combined high and low-temperature thermochronologic data allows to reconstruct the thermal history of the Puna plateau from intrusion to exhumation.

Zircon U-Pb ages indicate an **Early Ordovician intrusion** phase. Temperature-time paths inferred from ^{40}Ar/^{39}Ar thermochronology using multi diffusion domain modelling of alkali feldspar ^{40}Ar release spectra (Lovera et al. 2002) imply that the Ordovician intrusions (Sierra Macon, Complejo Oire, Valle Luracatao, Cobres granite, Colome granite, Cerro Durazno) at the present day Puna margin underwent slow cooling (~0.2-0.5°C/m.y) during Devonian and Middle/Late Jurassic times. The regional extent of consistent thermal histories during this time interval implies the presence of a stable thermal structure with low regional exhumation rates (<0.02 mm/yr). From Jurassic to present, samples were affected by 3 distinct episodes of more rapid cooling. **Between ~160 and 90 Ma**, samples from the southeastern Puna margin experienced an increase in cooling rates by a factor of 2 to 4. The onset of rapid cooling reflects the erosional response to the development of regionally significant topographic gradients in the rift area of the Cretaceous Salta Rift. Zircon U-Pb ages from 2 plutonic bodies related to the pre-rift stage of the Salta Rift indicate an intrusion phase in Late Jurassic times (160-150 Ma). An eightfold increase in cooling rates during the Late Cretaceous to Mid-Paleocene is related to thermal subsidence in the initial post-rift stage of the Salta Rift in the northern Puna.

For the following Cenozoic episode, apatite fission-track and (U-Th)/He data indicate a multi-stage cooling and plateau growth history. Higher cooling rates from **~100 to 50 Ma** can be associated with exhumation of normal-faulted, elevated and exhumed rift shoulders during horst-and-graben rift tectonics of the intracontinental Salta Rift (~80-75 Ma and 65-60 Ma, Galliski & Viramonte 1988). Cooling and exhumation from **~45 to 30 Ma** is seen in the apatite fission track data from the crystalline basement in the southern Puna (~30.3 Ma, Andriessen & Reutter 1994; ~38-29 Ma, Jordan & Alonso 1987, Coutand et al. 2001; ~29-25 Ma, Carrapa et al. 2005), and attributed to Eocene (Incaic) crustal shortening and thickening, and the generation of a topographic high of a Proto-Eastern Cordillera (Andriessen & Reutter 1994). **~25-21 Ma**: More rapid cooling and exhumation over at least 620 m vertical elevation (Cobres granite) with exhumation rates of ~0.17 mm/yr (Fig. 2) from Oligocene to early Miocene are consistent with the oldest ages of known Neogene shortening structures from the central Andes. **~20-16 Ma**: The combined Valle Luracatao and Complejo Oire elevation vs. age transects indicate rapid Miocene cooling with high exhumation rates (~0.44 mm/yr) over an elevation interval of at least 2360 m (Fig. 2).

Similar cooling and exhumation ages are also recorded in the Colome (~17 Ma) and Cachi transects (~15 Ma). **~15-12 Ma**: The youngest rapid cooling interval with exhumation rates of ~0.25 mm/yr is recorded in the Fundicion elevation transect (Fig. 2). This age interval is consistent with the previously suggested onset of principal uplift and deformation structures in the Puna and Eastern Cordillera (~13 to 17 Ma: e.g. Marrett & Strecker 2000), and correlates with the eastward shift of folding and thrusting from the plateau into the eastern foreland (Allmendinger & Gubbels 1996). Apatite (U-Th)/He ages of 9-12 Ma (Fundicion and Colome granite) indicate that mid-Miocene shortening led to surface exhumation. This age interval is also consistent with paleoaltitude data, which suggests that a substantial, ~400 km wide proto-Central Andean mountain range was in place between 15 and 9 Ma (Hartley 2003). An intrusion age of ~13 Ma for the Acay monzonite stock is consistent with the emplacement of fault-controlled intrusive domes in the Puna that were emplaced during Mid-Miocene time.

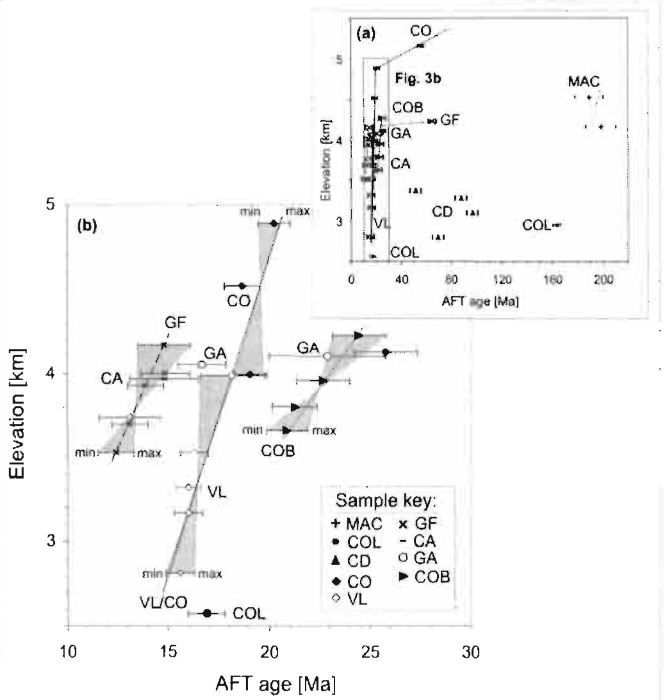

Fig. 2: Summary of apatite fission-track (AFT) ages (a) for all samples (Present-220 Ma) versus sample elevation. Error bars indicate 1s-error. COB = Cobres granite, GA = Aguilar granite, GF = Fundicion granite, COL = Colome granite, CD = Cerro Durazno, CO = Complejo Oire, VL = Valle Luracatao, MAC = Sierra de Macon. (b) Neogene AFT ages (~10-30 Ma) with elevation vs. age linear trends (min./max. values).

The new thermochronologic and structural data constrain a higher-resolution thermal history and suggest that Neogene (Puna) plateau construction occurred in a thermally and structurally preconditioned crust. We argue, that Late Eocene to Early Oligocene (Incaic) deformation may have had a previously underestimated influence of structural pre-conditioning on the plateau growth. Previous workers provided independent evidence of uplift and exhumation of a Proto-Eastern Cordillera at ~30 Ma (Andriessen & Reutter 1994) and in the Chilean Precordillera at ~50-30 Ma (Maksaev & Zentilli 1999). Interestingly, these sites of known Eocene-Oligocene shortening structures and exhumation correlate with the present-day eastern and western structural margins of the Puna plateau. This suggests that the lateral structural boundaries and dimensions of the (Puna) plateau were preset and layed out mainly by Late Eocene to Early Oligocene (Incaic) deformation, which generated a (low-elevation) **Proto-Puna plateau** with ~30% of its present elevation (Wodzicki 2000). Similar to the present-day Puna plateau, the proto (Puna) plateau was confined to the west by an active volcanic arc (Cretaceous-Eocene arc, Haschke & Günther 2003) and to the east by the topographic high of a Proto-Eastern Cordillera. Subsequent Miocene crustal shortening and thickening within these preset lateral dimensions caused uplift of an already existing (low-elevation) plateau structure, which led to its present high-altitude elevation. The presence of an early (Eocene-Oligocene) precursor plateau should be accounted for in future models on Cenozoic climate change.

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