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# Oligocene to Pleistocene exhumation patterns across the Apurímac River drainage basin, southern Peru

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**Scope**

The Apurimac River Drainage Basin (ARDB) has been chosen as a natural laboratory in the Andes of South Peru, to study the interaction between tectonic processes, surface processes and climate changes. Erosion and denudation can be regarded as the net effect of this interplay (Willet 1999, Burbank & Anderson 2001, Bishop 2002). The periods of increased deformation and rising of the Andes due to increased rates of collision of Pacific Plates with the South American Plate (Sebrier et al 1988, Carlotto 1998, Pardo-Casas 1987) have resulted in a differential uplift pattern in the study area. This led to differential cooling of the crust that has been recorded by fission track formation in apatite crystals. Fluvial incision and hill slope processes generally are considered the most effective surface operating mechanisms for exhumation of the crust (Burbank 2002, Ducea et al 2003).

**General setting**

The Apurimac River Drainage Basin (Fig.1) extends over 100,000sq km. It developed on the Cordillera Occidental (COC) and Cordillera Oriental (COR) in South Peru. Probably it also located on the northern part of the Altiplano structural domain, if the Altiplano-block reaches that far north. The COR on the one hand consists mainly of meta-morphosed rocks of Precambrian and Paleozoic age and minor of Cenozoic continental and volcanic rocks. The COC on the other hand is mainly composed of Mesozoic marine, continental and volcanic as well as Cenozoic and Quaternary continental and volcanic rocks (Carlotto 1998, Leon Lecaros et al 2000, Jaillard et al 2000, Sempere et al 2002). During the Tertiary abundant magmatism, deposition of clastic sediments in intra-montane basins and volcanism characterized the COC and eventually the Northern Altiplano domain of the ARDB. The COC part of the ARDB is dominated by the "Altiplanicies" ("Puna Surface") with elevations around 4200m (Carlotto 1998, Leon Lecaros et al 2000) and up to 2 km deep valleys of the Apurimac River and its tributaries. Along fault systems in the Cusco region (Fig. 1) shoshonitic volcanoes formed during 6-5 Ma (Carlotto, 1998) till even Pleistocene times. These volcanoes constitute the most distinctive positive relief on the Puna Surface. According to Kono et al (1989) the ignimbritic lava flows ages 19-3 Ma. The COR part of the ARDB is characterized by the ±4 km Apurimac Valley. According to Sebrier et al (1988) the most important tectonic phase responsible for formation of landforms in the Central Andes is Quechua F3 (7-6 Ma).

**Approach**

1) On a GIS (ARC/INFO) platform structural geological and geomorphological analyses have been carried out on long river profiles and on satellite imagery to reveal landforms and faults by means of conversion of DEM

data to slope. The satellite imagery of VNIR (incl. DEM), SWIR and TIR (resp. 15m, 30m & 90m resolution) TERRA-ASTER sensors and 90m resolution SRTM imagery next to IGN's 1:100,000/50,000/25,000 scale topo maps make up the geographical back-bone of the GIS. The geological data-base is comprised of INGEMMET's 1:100,000 scale digital geological maps and Carlotto's 1:400,000 scale geological map of SE Peru.

The processing of 30m resolution TERRA-ASTER DEM data to slope and relief (Florinsky 1996) has aided to the recognition of landforms in relation to and revelation of previously unmapped faults on the ground and on satellite imagery. Long river profiles (Szynkaruk et al, 2004) have been constructed in GIS at 50 m contour interval for all ARDB rivers. Knick-points not always appear at lithogical or tectonic boundaries as in the AYB.

**2**) Apatite Fission Track Thermochronometry (AFTT) results of this study of samples collected in the ARDB and existing radiometric data of Peru (Carlotto and co-workers) are integrated with the geomorphological analyses and investigated in our GIS to reconstruct the exhumation/denudation history of the ARDB. By means of AFTT the cooling history of rock sample can be reconstructed for the period the sample resided in the 120-60°C domain, i.e. in the upper few kilometers of the earth's crust (Andriessen1995, Zentilli & Reynolds 1992, Gallagher et al 1998, de Bruijne & Andriessen 2000). The rivers are incising up to 4 and 2 km deep canyons into the crust of the COR resp. COC, exposing rocks that reveal a substantial part of the late cooling history. Rock samples have been collected along sub-vertical profiles across the river canyons and valleys in the ARDB in order to obtain AFTT age-elevation relationships from "vertical" crustal sections. Horizontal profiles have been sampled in areas lacking such deep "scars". The sub-vertical profiles will allow the estimation of cooling rates that can be converted to exhumation rates when the thermal gradient is known. The horizontal coverage will allow a more regional interpretation when the individual Time-temperature paths are linked in the regional grid.

**Results and discussion**

An ignimbritic lava flow of the Senal Quechua Grande Volcano (**site 1**) has been dated by AFTT, revealing an age of 15.3±0.6 Ma that is in accordance to the age of this volcano suggested on geological maps. The Apurimac River has cut this ignimbrite flow hence this situation puts a constraint to the maximum age of incision by the Apurimac River in this part of the ARDB. All sites are shown in Fig. 1.

Results of AFTT from hard-rock samples of the AYB bodies show a trend of oldest ages in the area east of Cotabambas (**site 2**) in the COC (Early Oligocene exhumation phase at 29.2±1.1 Ma) towards younger ages at the edges of the AYB (**site 3**) (Early, Middle and Late Miocene exhumation phases at respectively 18.9±0.4 Ma, 16.5±1.5 Ma (G. Ruiz, pers. comm.) and 6.7±0.3 Ma). Zircon Fission Track results in this study (G. Ruiz, pers. comm.) revealed cooling ages for the AYB of 34.1±1.8 Ma, at Tamburque SSW of Abancay confirming the 32.5±1.3 Ma (plagioclase K/Ar) age of an AYB granodiorite (Carlotto, 1998).

In one of the sampled AYB-peripheral Cenozoic basins, the Anta Basin (site 4), the AFTT ages (39.3±5.1 to 20.8±4.1 Ma) correspond to the Eocene-Oligocene stratigraphic age of the Fm Anta provided by Carlotto (1998). The ages reflect the source area cooling events since they are not reset. Miocene AFTT ages of 18.2±0.8 to 11.1±1.1 Ma have been obtained for a red conglomerate-sandstone formation underlying the Senal Quechua Grande Volcano flows (**site 1**). However this formation has been mapped as belonging to the Puno Gp. (Eocene-Oligocene). Curiously, AFTT analyses on samples of a red conglomerate-sandstone formation situated on the N-flank of the the Apurimac River at Puente Pasaje (**site 4**) mapped as Permo-Triassic Gp. Mitu deposits, all yielded AFTT cooling ages of Miocene age 9.3-6.7±1.6 Ma with a low Chi-square and P%. We deal either with totally reset Mitu Gp., Jurassic (Carlotto, pers. comm.) or rocks of Miocene (Paruro Fm) age.

The mapped red conglomerate-sandstone Fm Anta (Carlotto, pers. comm.) east of Lake Pomacanchi (**site 5**) has AFTT cooling ages of 9.1±1.6 and 8.1±0.4 Ma in the top part of the section. If this formation is not of Miocene age but has been totally reset to give AFTT cooling ages that are younger than the stratigraphic age, it must have been buried to a depth where t=120°C. The Sicuani Thrust Fault (Carlotto, 1998) flanking the sampled formation could have facilitated burial and later uplift of it. Track length measurements have to sort it out.

In the COR at the south side of the Apurimac River AFTT cooling ages are similar to those of the NW-rim of the AYB (**sites 6,7**) (Late Miocene exhumation phases at 7.3±1.0 Ma and ±6.5 Ma). Notably, on the north side (**sites 8,9**) we have found the youngest ages (Plio-Pleistocene exhumation phase at 1.9±0.2 Ma) like on samples on the west side of the Apurimac River (**site 10**) near the mouth of the ARDB (Plio-Pleistocene exhumation phase at 2.0±0.3 Ma).

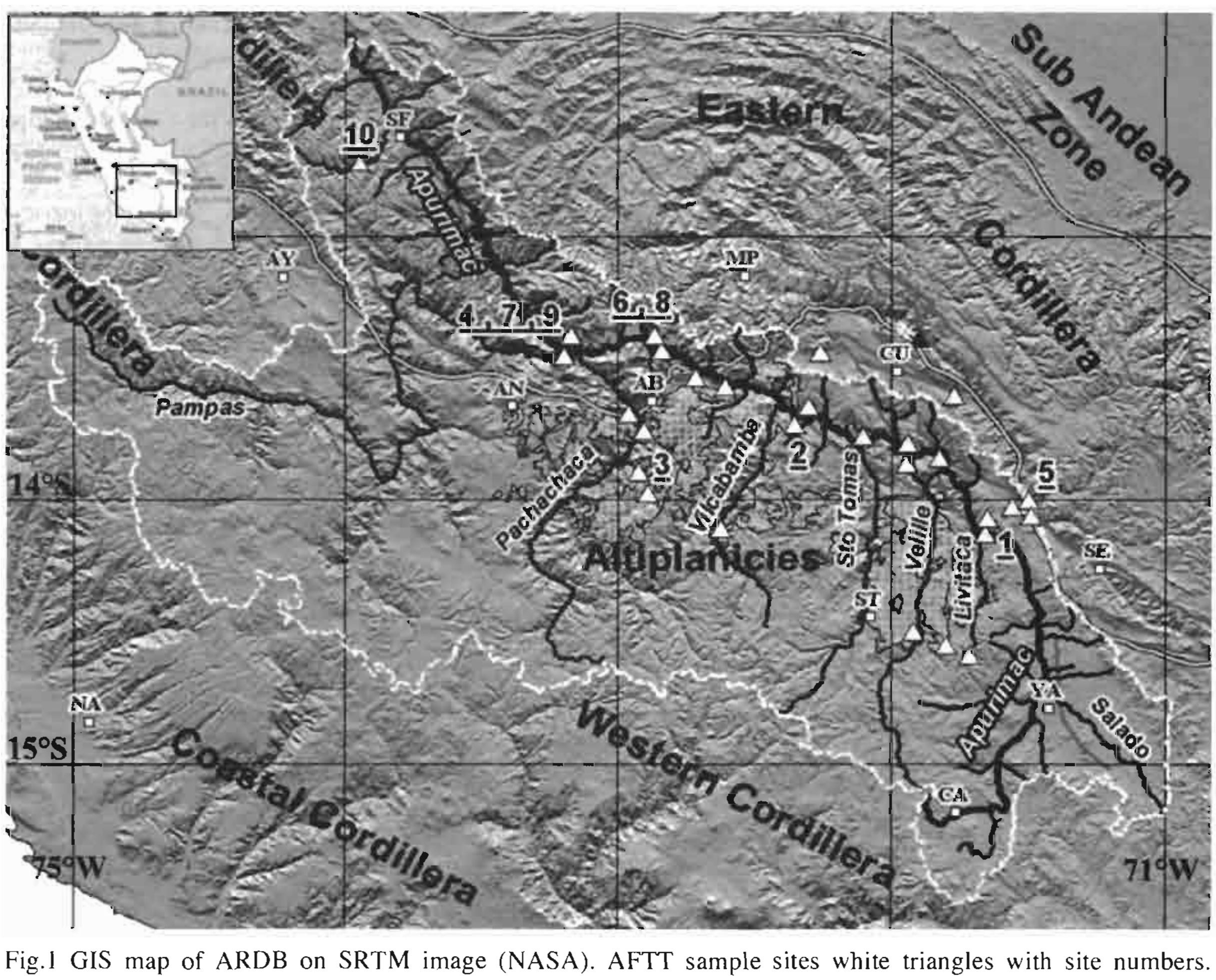


Fig.1 GIS map of ARDB on SRTM image (NASA). AFTT sample sites white triangles with site numbers. Drainage divide ARDB white-dash. Apurimac River and tributaries black. COR limits yellow-black. AYB yellow grid. Faults red (Carlotto-Caillaux). SF = San Fransisco, AY = Ayacucho, AN = Andahuaylas, AB = Abancay, MP = Machu Picchu, CU = Cusco, ST = Santo Tomas, SE = Secuani, YA = Yauri, CA = Caylloma and NA = Nazca

Making estimates of denudation/exhumation in the ARDB required the application of proper geothermal gradients to the sites. From heat-flow studies of Muñoz (2005), Hamza & Muñoz (1996), Springer (1999) and

BRGM Andes GIS, Springer & Forster (1998), Yuan et al (2000) we concluded a geothermal gradient of ±16 °C/km for the COC part and a geothermal gradient of ±12 °C/km for the COR part of the ARDB. These gradients imply that the apatite PAZ (120°C – 60 °C) in the COC is situated at 7.5 – 3.75 km depth and in the COR is at 10.0 – 5.0 km depth. Based up on these assumptions we calculated time-integrated cooling rates for our sites. These in turn have been converted to time-integrated exhumation rates.

In the upstream transect through the Tertiary sedimentary basins east of the AYB (**sites 1,5**), exhumation rates are in the order of 0.5 to 1.0 km/Ma. Along the AYB transect, exhumation rates are between 0.2 to 0.5 km/Ma in the middle of the AYB (**site 2**) and 1.1 to 1.4 km/Ma in the west of the AYB (**site 3**). Cross the Cordillera boundary in the COR exhumation rates are about 5 km/Ma in the N-flank (**sites 8,9**) and about 1.5 km/Ma in the S-flank (**sites 6,7**). The riverbed inclination highly varies in this zone. This probably reflects that local base-level has problems in adjusting in the Pliocene-Recent Period to high rates of differential uplift that has taken place along riverbed intersecting faults. In the NW oriented Apurimac Valley towards the exit of the ARDB, the exhumation rate in the SW-flank is about 2.5 km/Ma (**site 10**).

Sébrier et al (1988) calculated rates of uplift in the order of 1.0 km/Ma for the Central Andes for the period Miocene Quechua F3 event (± 7 Ma) to Recent.

In the process of emplacement the AYB probably applied an ongoing doming effect to the region, forcing streams to their present day position. Besides, the drainage pattern in the ARDB is probably related to regional stress field inherited structures in the COC and COR. The variation in Late Cenozoic to Early Pleistocene cooling histories suggests the existence of various morpho-tectonic domains present as becomes clear from geomorphological analyses and visual inspection of the ARDB relief.

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