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Geochronologic and stratigraphic constraints on canyon incision and Miocene uplift of the Central Andes in Peru

J.-C. Thouret [a,*], G. Wörner [b], Y. Gunnell [c], B. Singer [d], X. Zhang [d], T. Souriot [a]

[a] *Laboratoire Magmas et Volcans, UMR 6524 CNRS, OPGC et IRD, Université Blaise Pascal, 63038 Clermont-Ferrand cedex, France*
[b] *GZG Abt. Geochemie, Universität Göttingen, Goldschmidtsrasse 1, 37077 Göttingen, Germany*
[c] *Department of Geography, Université Denis Diderot Paris 7 and UMR 8591 CNRS, 2 Place Jussieu, 75251 Paris cedex 05, France*
[d] *Department of Geology and Geophysics, University of Wisconsin, Madison, WI 53706-1692, USA*

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Abstract

The deepest valleys of the Andes have been cut in southern Peru by the Ríos Cotahuasi Ocoña and Colca–Majes. These canyons are Late Miocene landforms based on a new ignimbrite stratigraphy supported by 42 new $^{40}Ar/^{39}Ar$ age determinations obtained on plateau-forming and valley-filling ignimbrites. Between 19 and 13 Ma, a gently sloping surface bevelling the clastic wedge southeast of the developing mountain front was mantled by widespread ignimbrites. After 13 Ma, this paleosurface was tilted up from 2.2 km a.s.l. at the mountain front to 4.3 km a.s.l. at the base of the Pliocene and Pleistocene volcanoes that crown the southwestern edge of the Altiplano. The canyons incised this topography after 9 Ma, while the dated base of younger ignimbrite valley fills suggests that these canyons had been cut down to near their present depths as early as 3.8 Ma. By 1.4 Ma, however, the canyons had been almost completely refilled by 1.3 km-thick unwelded pyroclastic deposits, which were subsequently eroded. Valley incision since 9 Ma at an average rate of 0.2 mm yr^{-1} is the response to topographic uplift after 13 Ma combined with increasing runoff due to a wetter climate recorded after 7 Ma. Although long-term aridity generated an imbalance between high long-term uplift rates and low plateau denudation rates, the combination of aridity and volcanism still promoted canyon incision because episodic volcanic fills maintained a cycle of catastrophic debris avalanches and subsequent dam breakouts.

Keywords: Andes; Peru; valley incision; tectonic uplift; ignimbrites; argon dating

1. Introduction

Tectonic uplift simultaneously generates topographic gradients that result in increased erosion (Montgomery and Brandon, 2003) and orographic barriers that collect precipitation. Removal of mass by erosion is thus focussed along narrow belts of relief and can itself induce further rock uplift, thus creating a positive feedback to evolving orogenic fronts (e.g. Willett, 1999; Thiede et al., 2004; Whipple and Meade, 2006). The western margin of the Central Andes represents an extreme case in this scenario since several kilometers of uplift has occurred in a hyperarid region, where long-term denudation rates remain particularly low but the history of valley incision documents a long record of topographic uplift and climatic changes.

* Corresponding author.
E-mail addresses: thouret@opgc.univ-bpclermont.fr (J.-C. Thouret), gwoerne@dwdg.de (G. Wörner), gunnell@idf.ext.jussieu.fr (Y. Gunnell), bsinger@geology.wisc.edu (B. Singer), zhangx@geology.wisc.edu (X. Zhang), souriot@opgc.univ-bpclermont.fr (T. Souriot).

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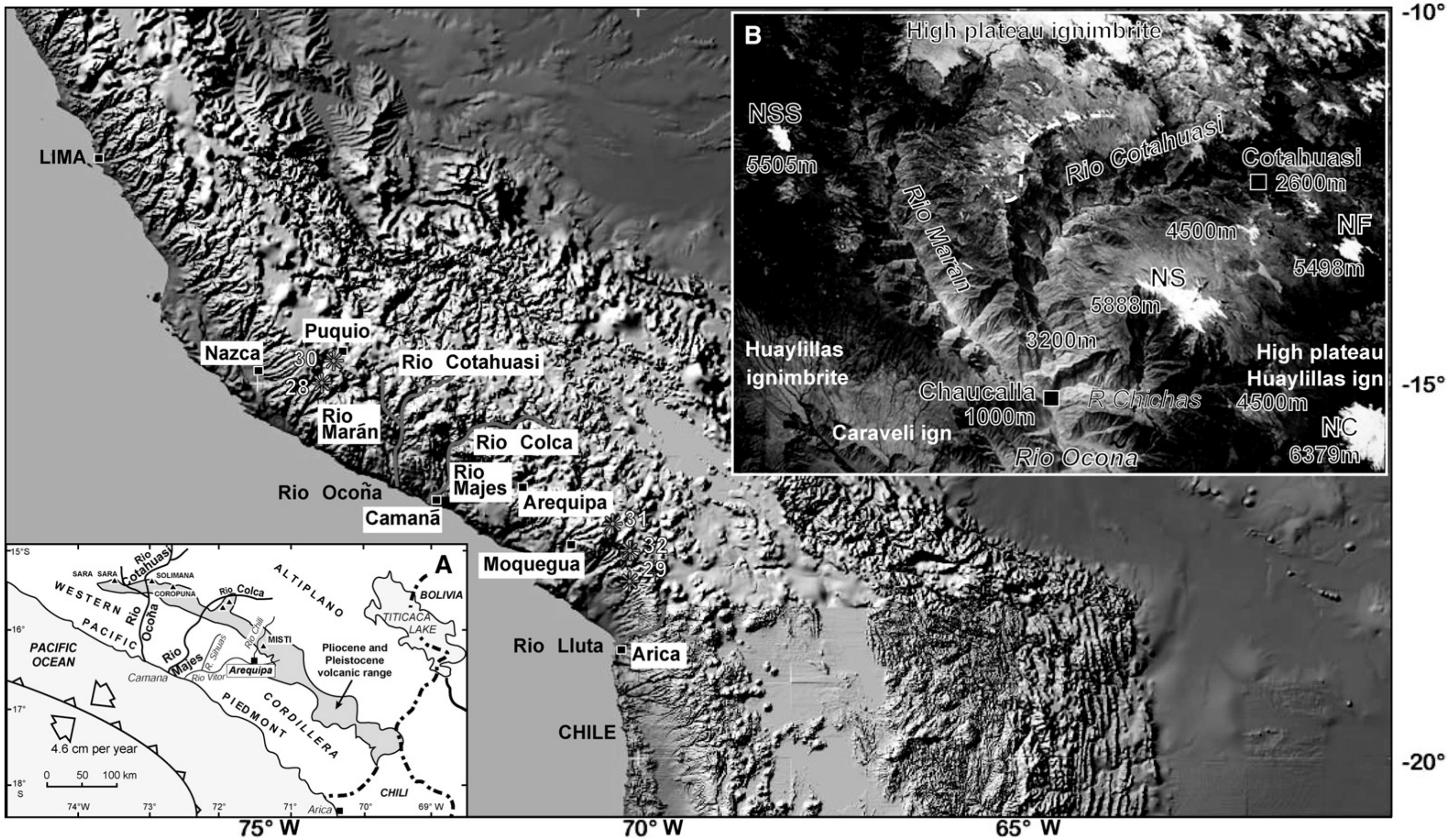

Fig. 1. Topographic Digital Elevation Model (USGS GTOPO 30 DEM) of the Central Andes (http://www.geo.cornell.edu/geology/cap/CAP_WWW.html) showing the location of the main valleys and canyons in southern Peru and northern Chile (in addition to 37 sites in Fig. 2, five sites with $^{40}Ar/^{39}Ar$ age determinations show numbers keyed to Table 1). A: map of southern Peru showing the principal structural units and the Pliocene and Pleistocene volcanic arc; B: Shuttle image of the Cotahuasi, Ocoña, and Marán confluence (www.lpi.usra.edu/publications/slidesets/geology/sgeo/slide_22html; STS-41D. August-September 1984, Picture No.14-34-005). Plateau-forming Huaylillas and Alpabamba ignimbrites at 4000–4500 m a.s.l. mantle the Miocene paleosurface and support the Pliocene and Pleistocene volcanoes (NS: Nevado Solimana 5888 m a.s.l.; NC: Nevado Coropuna 6379 m a.s.l.; SS: Nevado Sara Sara 5505 m a.s.l.; NF: Nevado Firura 5498 m a.s.l.). Note the Chaucalla–Las Lomas ridge formed by 1.6 km–thick ignimbrite cooling units; the whitish ignimbrite blanketing the high plateau 20 km north of the town of Cotahuasi; and a prominent arcuate scar above the northwest Cotahuasi canyon edge pointing to potential sources for the most recent pyroclastic valley fill found in the deepest canyon section.

The uplift chronology of the Central Andes is controversial (Gregory-Wodzicki, 2000; Lamb and Davis, 2003; Ghosh et al., 2006). It is currently considered that Andean deformation and uplift began in the Western and Coastal Cordilleras ~50 Ma ago, developed later and more slowly in the Eastern Cordillera (40 to 10 Ma), and accelerated in both Cordilleras and the Altiplano around 25 to 20 My ago (Elger et al., 2005). In the Western Cordillera, this early uplift led to the deposition of a thick continental clastic wedge (defined stratigraphically in southern Peru as the Moquegua Group; Kennan, 2000) and was accentuated by the eruption of large-volumes of plateau-forming ignimbrites.

We focus on Neogene ignimbrites and lavas, which provide excellent regional markers for tracing landscape evolution and the history of valley formation on the western slope of the Central Andes (Myers, 1979; Noble et al., 1984; Sébrier et al., 1988; Wörner et al., 2000; Thouret et al., 2001; Wörner et al., 2002; Thouret et al., 2003, 2005; Quang et al., 2005; Paquereau-Lebti et al., 2006; Schildgen et al., 2007). Here, abundant datable volcanic rocks preserved as valley fills at various levels in the Cotahuasi and Ocoña canyons of southern Peru (Figs. 1 and 2) are used for dating phases of valley incision and orogenic uplift as well as assessing the geomorphic effects of climate change. Critical to this

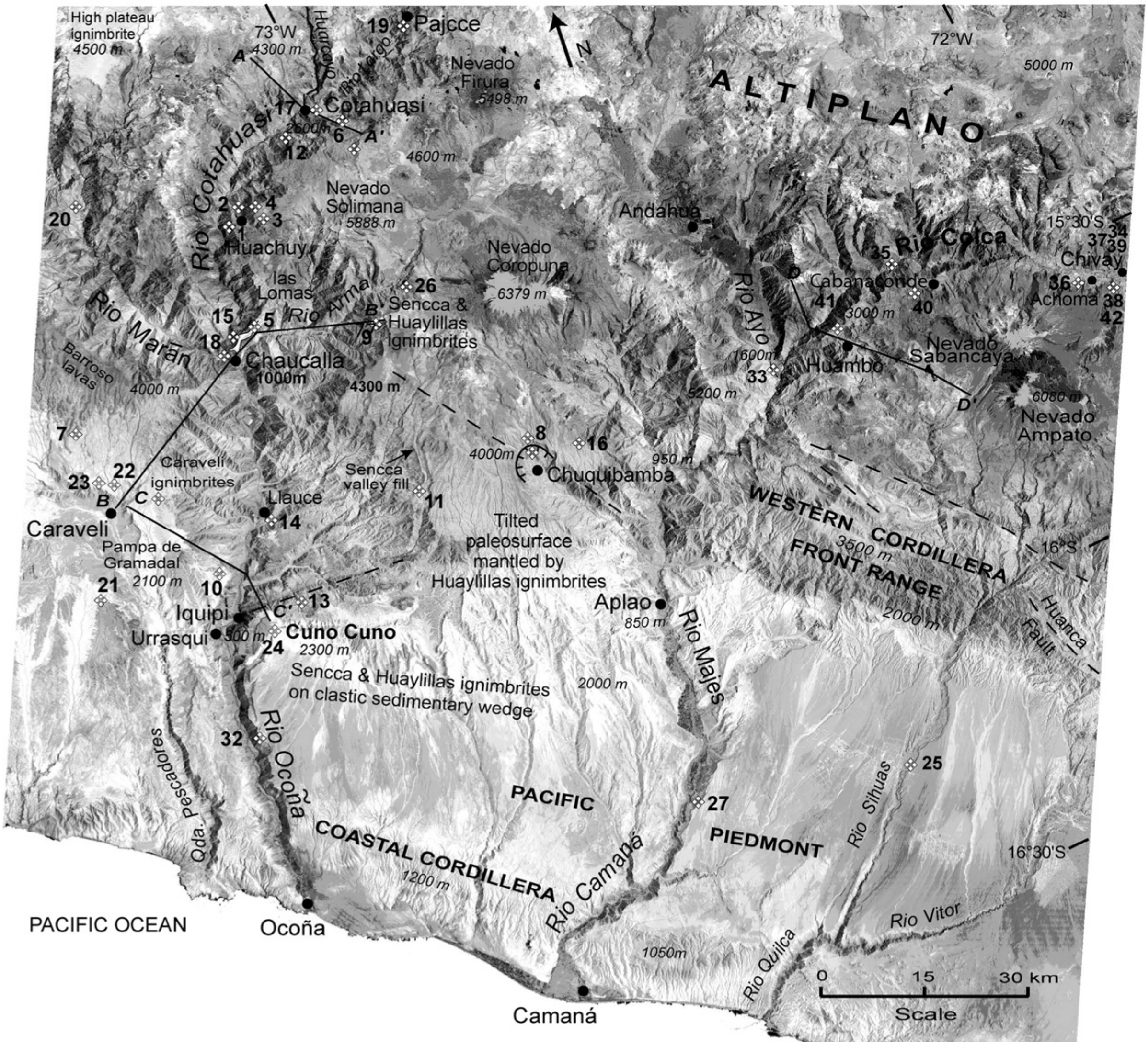

Fig. 2. Landsat image showing the two canyon networks of Cotahuasi–Ocoña and Colca–Majes and structural units on the western slope of the Central Andes. Location of four cross sections (A–A′, B–B′, C–C′, and D–D′) depicted in Electronic Supplement Fig. 1 in the Appendix is indicated. Faults, localities, and volcanoes mentioned in the text are shown. The sites of the $^{40}Ar/^{39}Ar$ age determinations are keyed to Table 1 and further described in the Electronic Supplement table in the Appendix (dated sites outside of the canyon area are indicated in Fig. 1).

Table 1
Summary of $^{40}Ar/^{39}Ar$ ages for the Ocoña–Cotahuasi and Colca canyons, Peru

Sample code no.	UTM Easting (UTM)	UTM Northing (UTM)	Elevation (m a.s.l.)	Lithology	Dated material	Age (Ma)[a] ±2σ
Ocoña and Cotahuasi canyons: post-incision volcanic rocks						
Late Pleistocene lava flows						
1-COTA-05-10	0706959	8299105	2235	Andesitic lava flow	Groundmass	0.34±0.06
2-COTA-05-11	0708072	8301599	2345	Andesitic lava flow	Groundmass	0.45±0.01
3-COTA-05-15	0715085	8302926	4180	Andesitic lava flow	Groundmass	0.66±0.01
4-COTA-05-06	0712734	8300308	3940	Andesitic lava flow	Groundmass	0.68±0.03
Top of pyroclastic valley fill						
5-PIG-03-123	0705449	8277851	2300	Andesitic lava flow	Feldspar	1.36±0.27
6-PIG-05-01	0725754	8312325	4060	Andesitic lava flow	Feldspar	1.5±0.32
Upper Sencca-type ignimbrites						
7-OCO-05-06	0719720	8273650	3550	Rhyolitic pumice	Feldspar	1.95±0.16
					Biotite	1.76±0.17
8-PIG-00-06	0669009	8257827	2550	Rhyolitic pumice	Feldspar	1.81±0.11
9-PIG-00-25	0750350	8252890	3600	Rhyolitic pumice	Feldspar	1.93±0.04
10-OCO-04-08	0698800	8243130	1675	Rhyolitic pumice	Feldspar	1.96±0.06
11-OCO-05-04	0716172	8251325	1840	Rhyolitic pumice	Feldspar	2.09±0.06
					Biotite	2.02±0.04
12-PIG-04-02	0725754	8312325	3570	Rhyolitic pumice	Feldspar	2.04±0.14
13-OCO-04-05	0704400	8237700	750	Rhyolitic pumice	Feldspar	2.05±0.29
Lava flow in Ocoña valley						
14-OCO-05-11	0706950	8253980	830	Andesitic lava flow	Groundmass	2.27±0.05
Lower Sencca ignimbrites and base of valley fill						
15-PIG-03-122	0705447	8277592	2105	Rhyolitic pumice	Feldspar	2.35±0.95
16-PIG-00-24	0752577	8262398	3890	Rhyolitic pumice	Feldspar	3.16±0.04
17-PIG-00-28	0727316	8316532	2800	Vitrophyre	Feldspar	3.7±0.1
18-OCO-05-12	0704831	8277228	1665	Rhyolitic pumice	Groundmass	4.84±0.07
Lower Barroso lava flows						
19-BAR-03-01	0745259	8331693	3510	Andesitic lava flow	Groundmass	5.80±0.10
Caraveli ignimbrites						
20-PIG-00-07	0676539	8312021	2420	Rhyolitic pumice	Feldspar	8.97±0.06
21-CARA-05-07	0683470	8233701	1750	Rhyolitic pumice	Feldspar	9.40±0.83
					Biotite	8.98±0.15
22-PIG-00-04	0669009	8257827	2550	Rhyolitic pumice	Feldspar	9.02±0.11
23-PIG-00-03	0670228	8257664	2350	Rhyolitic pumice	Feldspar	9.15±0.31
Ocoña and Cotahuasi region: pre-incision volcanic rocks						
Huaylillas ignimbrites						
24-PIG-03-126	0704629	8229204	2275	Rhyolitic pumice	Feldspar	13.21±0.53
					Biotite	13.19±0.07
25-PIG-00-31	0730308	8308079	4300	Rhyolitic pumice	Feldspar	14.23±0.07
26-PIG-00-33	0806185	8189594	1000	Rhyolitic pumice	Feldspar	14.25±0.08
Tuff intercalated in upper Moquegua Formation						
27-PIG-00-32	0772378	8193673	850	Rhyolitic pumice	Feldspar	16.25±0.10
Alpabamba ignimbrites						
28-PIG-00-11	0552154	8374953	3200	Rhyolitic pumice	Feldspar	18.23±0.17
29-PIG-00-41	0939492	8115952	2900	Rhyolitic pumice	Feldspar	18.90±0.50

Table 1 (*continued*)

Sample code no.	UTM Easting (UTM)	UTM Northing (UTM)	Elevation (m a.s.l.)	Lithology	Dated material	Age (Ma)[a]±2σ
Ocoña and Cotahuasi canyons: post-incision volcanic rocks						
Nazca ignimbrites						
30-PIG-00-10	0552154	8374953	3500	Rhyolitic pumice	Feldspar	22.16±0.34
31-PIG-02-02	0295064	8091468	1718	Rhyolitic pumice	Feldspar	23.92±0.49
32-PIG-00-38	0324519	8134616	4150	Rhyolitic pumice	Feldspar	24.43±0.17
Colca canyon: post-incision volcanic rocks						
Pleistocene lava flows						
33-COL-04-17	0794950	8261980	1885	Andesitic lava flow	Groundmass	0.13±0.02
34-BAR-01-62	0221365	8272955	3443	Andesitic lava flow	Groundmass	0.15±0.01
35-COL-04-16	0216104	8273569	2240	Andesitic lava flow	Groundmass	0.54±0.06
36-COL-04-01[b]	0209790	8267148	3460	Andesitic lava flow	Groundmass	0.61±0.01
37-BAR-01-61	0219485	8274091	3445	Andesitic lava flow	Groundmass	0.65±0.01
38-COL-04-14	0215841	8267571	3600	Andesitic lava flow	Groundmass	0.65±0.02
39-COL-04-03	0219425	8274042	3770	Andesitic lava flow	Groundmass	0.68±0.01
40-COL-04-07	0803300	8264075	2980	Andesitic lava flow	Groundmass	1.06±0.05
41-COL-04-10	0815528	8270769	3350	Andesitic lava flow	Groundmass	1.07±0.03
Upper Sencca ignimbrites						
42-PATA-04-02	0220955	8260826	4675	Rhyolitic pumice	Feldspar	2.20±0.15

Notes: Numbers (first column) are keyed to the text and to the Electronic Supplement tables in the Appendix and Figs. 1 and 2.

[a] Ages are calculated relative to 1.194±0.012 Ma Alder Creek rhyolite sanidine (Renne et al., 1998). Ages of feldspar and biotite separates are isochron ages from laser fusion experiments while ages of groundmass separates are plateau ages from incremental heating experiments. More details in Electronic Supplement Tables 1 and 2 in the Appendix and text.

[b] Isochron age is 0.61±0.01 Ma; plateau age is 0.61±0.01 Ma (M. Fornari, pers. comm.). For age standard age used, see Delacour et al. (2007).

study is (1) the presence of an elevated paleosurface, which bevels the Moquegua formation, and (2) a 25 My-old Miocene marine layer that is covered by a ~24 Ma ignimbrites (Fig. 2 and Electronic Supplement Fig. 2 in the Appendix). Tracking the uplift and incision of this extant paleosurface constitutes the key for understanding the Neogene and Quaternary denudation sequence. The refined volcaniclastic stratigraphy we document for southern Peru is based here on 42 new $^{40}Ar/^{39}Ar$ age determinations on volcanic rocks from the area between Nazca and Arequipa (Figs. 1 and 2, Table 1, and the Appendix). We reconstruct a 25 Ma chronology of volcanism and repeated valley incision into the initial seaward-sloping paleosurface (Fig. 1), interrupted by episodes of temporary valley refilling (Fig. 2), in relation to tectonic uplift, changes in runoff regimes, and the type and timing of volcanic activity. The data indicate a major phase of uplift on the western slope of the central Peruvian Andes during the Late Miocene.

2. Geological setting and stratigraphy of the Central Andes in southern Peru

The deepest canyons of South America were cut by the Ríos Cotahuasi, Ocoña, and Colca at 15–16°S (Figs. 1 and 2). Although their valley heads currently impinge beyond the Quaternary volcanic arc into the semi-arid Altiplano (rainfall 250–350 mm yr^{-1}), these canyons occur in a region where rainfall is <100–200 mm yr^{-1}. Another paradox is that the deepest Andean valleys should exist here while similar strike-perpendicular valleys in central Peru (north of 15°S) and northern Chile (south of 30°S) are shallower despite present-day precipitation being higher in those areas (Hoke et al., 2005) and plateau elevations between canyons being similar.

The Cotahuasi–Ocoña catchment is 4200 km^2 and extends from the western edge of the Altiplano to the Pacific across the Western and Coastal Cordilleras (Fig. 1). Whereas the lowermost reach of the Río Ocoña cuts a narrow canyon into the Precambrian rocks and sedimentary cover of the Coastal Cordillera, the upper and middle courses of the Ríos Ocoña and Cotahuasi form the deepest canyon section, with maximum relief between the plateau edge and the valley bottom ranging between 2.5 and 3.5 km (Figs. 2–4). Incision has affected late Oligocene to middle Pleistocene volcanic rocks overlying Paleogene and Mesozoic sediments. Deeper sections of the canyon and valley flanks in the Coastal Cordillera expose Cretaceous plutons and Paleozoic to Precambrian metamorphic rocks. The canyon's catchment reaches a maximum width of 45 km in the granitoid plutons.

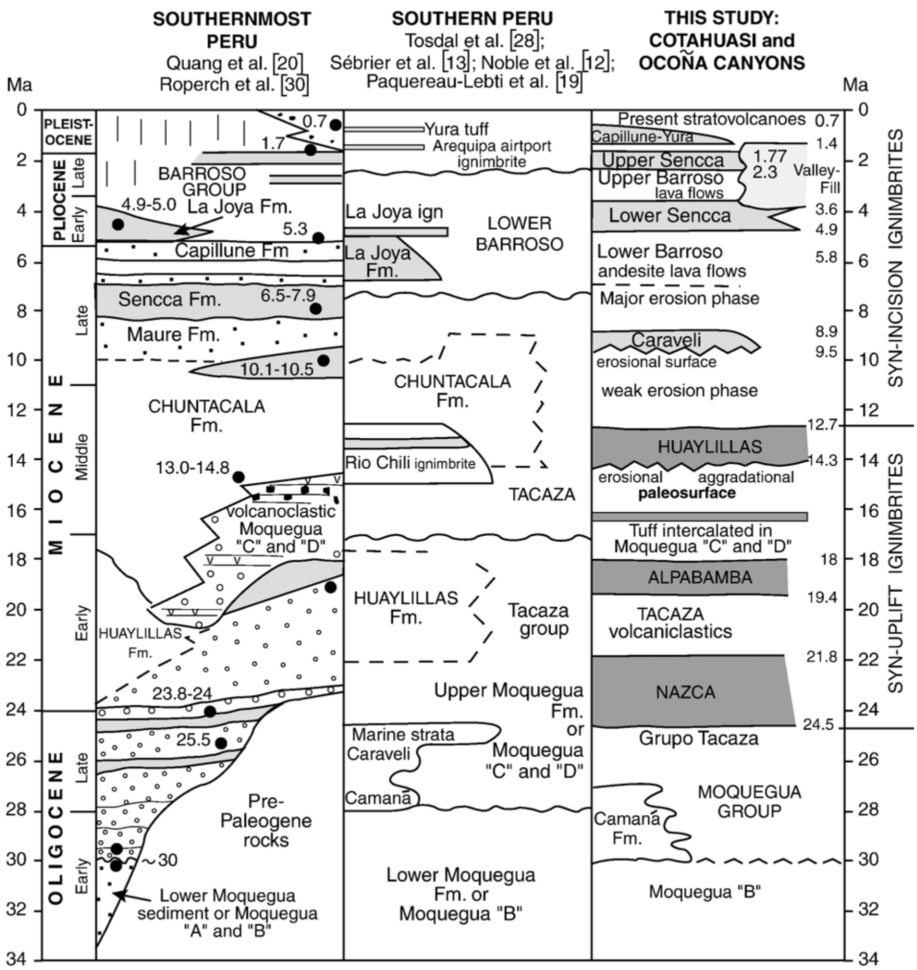

Fig. 3. Composite stratigraphic scheme collated for southernmost Peru after Quang et al. (2005), Roperch et al. (2006), southern Peru (Tosdal et al., 1981; Noble et al., 1984; Sébrier et al., 1988; Paquereau-Lebti et al., 2006), and the area of the Cotahuasi, Ocoña, and Colca canyons (this study and Paquereau-Lebti et al., 2006; Delacour et al., 2007) highlighting the significance of syn-uplift ignimbrites (dark gray, third column) and syn-incision ignimbrites (light grey, third column). Wavy lines indicate periods of erosion and/or tectonic phases, serrated lines are angular unconformities. The stratigraphy has been established on data collated from literature (e.g. Roperch et al., 2006) and from our survey in the canyon area as well as in the area of Arequipa (Paquereau-Lebti et al., 2006; Delacour et al., 2007).

To the east, the Colca catchment covers 5500 km^2 across the Western Cordillera and north of the volcanic arc. Between 130 and 170 km from the ocean, the 1.5 to 2.5 km-deep Colca valley cuts through folded Jurassic and Lower Cretaceous metamorphic and sedimentary rocks and dioritic plutons of Late Cretaceous to Early Paleogene age (Fig. 2). Seaward of the orogenic front, the river changes its name to Majes–Camaná and cuts into folded and overthrust Mesozoic sediments covered to the south by slightly folded Paleogene to Early Miocene Moquegua conglomerates, distal sand and sandstones. Near the coast, this clastic piedmont is dissected and consists of non-folded Paleogene sediments and conglomerates of the Moquegua Group unconformably overlying the metamorphic basement. Syn-uplift reverse and overthrust faults reflect only limited Neogene crustal shortening in the Western Cordillera and fore-arc regions (Fig. 2). The lower Moquegua Group has only been slightly folded and faulted (Majes–Camaná valley), and only minor erosional discontinuities are observed between the Moquegua sub-groups (Fig. 3).

3. Methods

Extensive field surveys consisted of mapping the Neogene ignimbrites, other pyroclastic deposits and lava flows, as well as determining the paleo-morphologies preserved at the valley flanks (canyon bluffs, pediments, hanging fans) and in the valley channel (fill terraces,

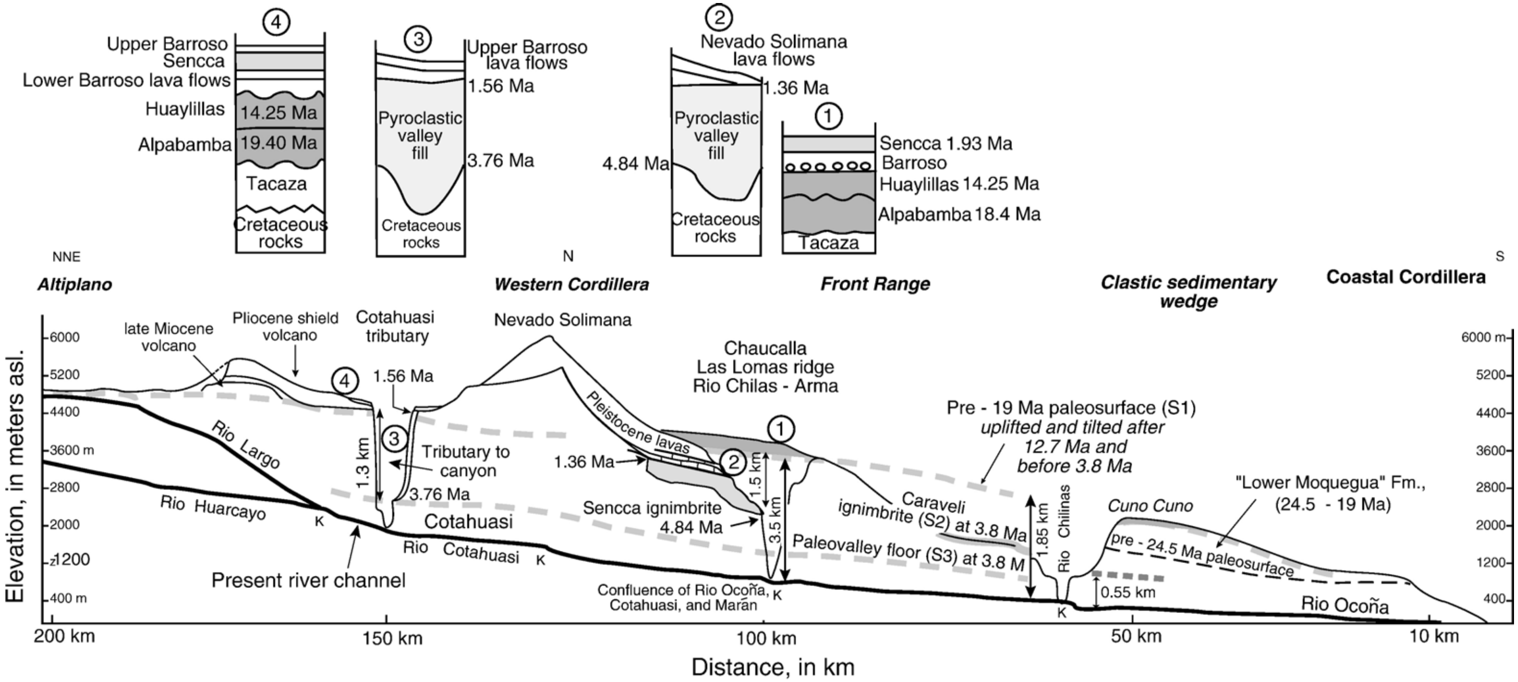

Fig. 4. Longitudinal profiles and incision history of the Cotahuasi and Ocoña canyons. The topography of the paleosurface is illustrated along the plateau edge where schematic sections show local stratigraphy and reference ignimbrites. K: knickpoint; S1: reference paleosurface, S2: pre-Caraveli paleotopography; S3: pre-Sencca paleotopography.

debris-avalanche and lahar deposits). A 20-m digital elevation model (DEM with an error of c.50 m) of the Cotahuasi–Ocoña valleys was generated from two pairs of SPOT 4 satellite images using computerized stereo-photogrammetric techniques available in the ENVI™ software package. The DEM defines the uppermost contour of the ignimbrite plateau as the initial pre-incision downwarped paleosurface (Fig. 4). It was thus used to quantify volumes of eroded material and incision rates based on elevation differences between key dated ignimbrite contours and paleovalley floors defined by the base of dated volcanic valley fills. Ignimbrites and other pyroclastic deposits were distinguished and classified in terms of stratigraphy, facies, and petrography. In order to reconstruct the position of paleothalwegs, ignimbrite and lava flow samples were collected vertically down canyon walls and throughout the drainage basins for lateral correlation. In addition to non-welded pyroclastic valley-fills, datable basal pumice-rich layers and vitrophyres of ignimbrites occurring near the present thalweg but also on the canyon edge were favoured as sampling targets. At outcrop scale, the bases and tops of ignimbrite sheets were sampled for age determination in key sections.

Forty two age determinations were made at the University of Wisconsin in addition to samples dated earlier, using the same age standard, at UMR GéoAzur (CNRS-IRD) in Nice (see Thouret et al., 2003; Delacour et al., 2007). From 15 lava flows and 27 ignimbrites sanidine, biotite, plagioclase, or groundmass samples were prepared, irradiated and aliquots of ~200-μm grains were measured using either laser fusion (single or up to 10 crystals from ignimbrites) or furnace incremental heating (50–100 mg of lava groundmass) and following protocols described in Singer et al. (2004) and Smith et al. (2006) and in the Appendix. The $^{40}Ar/^{39}Ar$ age determinations in Table 1 (keyed to locations in Figs. 1, 2, 6 and the Appendix) are based on isochrons defined by concordant single-crystal or plateau-age data and are calculated relative to 1.194 Ma Alder Creek Rhyolite Sanidine (Renne et al., 1998), using ArArCALC software (Koppers, 2002), with analytical uncertainties reported at the 2σ level (see also Delacour et al., 2007).

4. Results

4.1. A new chronostratigraphy of Neogene volcanic rocks in southern Peru

The existing stratigraphy of Neogene rocks in southern Peru (Tosdal et al., 1981, 1984; Noble et al., 1984; Sébrier et al., 1988; Quang et al., 2005; Paquereau-Lebti et al., 2006; Roperch et al., 2006) can be compared with our chronostratigraphy based on the new $^{40}Ar/^{39}Ar$ age determinations (Table 1, Fig. 3). The correlation with the broader-scale stratigraphy of southern Peru (Fig. 3) is based on age correlation (e.g. Roperch et al., 2006) and also on our surveys and mapping between this area and Arequipa (Thouret et al., 2003; Paquereau-Lebti et al., 2006; Delacour et al., 2007). These ages, which range between 24.43±0.17 and 0.34±0.05 Ma (Table 1, keyed to Figs. 1, 2, and tables in Appendix), help to distinguish six major pyroclastic deposits, including five Neogene rhyolitic ignimbrite sheets totalling >1500 km^2 in area and about 300 km^3 in volume, and six groups of lava flows. These results call for the following update of volcanic stratigraphy in the central Andes of Peru (see Fig. 3).

The thick 24.6–21.8 Ma-old *Nazca* ignimbrite sheets (No. 30 to 32, Table 1) cap extensive elevated plateaus towards the WNW of the study area (Fig. 1) as well as in southernmost Peru (Moquegua area) where they correlate with the Chilean ‘Oxaya’ ignimbrites of latest Oligocene to Early Miocene age (Wörner et al., 2000, 2002; Elger et al., 2005). They are overlain, and therefore older than, the coarse upper Moquegua conglomerates (Moquegua ‘C’ and ‘D’ intervals; Tosdal et al., 1984).

The 19.4–18.0 Ma-old *Alpabamba* (No. 28 and 29) and 14.3–12.7 Ma-old *Huaylillas* ignimbrite sheets (No. 24 to 26) are whitish to brownish welded to strongly welded cooling units that form extensive plateaus between 4000 and 4500 m a.s.l. with 350 m-high cliffs (Fig. 1C). Plateau-forming ignimbrites have been collectively termed ‘Huaylillas Formation’ (Pecho Gutierrez, 1983; Olchauski and Dávila, 1994; Quang et al., 2005) and ‘Chuntacala Formation’ (Sébrier et al., 1988). However, ignimbrites previously mapped as ‘Huaylillas ignimbrites’ were dated here at 14.25–13.19 Ma (No. 24 to 26). They are therefore younger than the 22.8–17.6 Ma-old ‘Huaylillas Formation’ of Quang et al. (2005), Tosdal et al. (1981, 1984), which we therefore infer represent a package of several ignimbrite sheets of different ages. Distal ignimbrites of 16.25 Ma to 14.25 Ma (No. 24 and 27 in Table 1) are interlayered in the fore-arc sediments towards the top of thick conglomerates of the Early to Middle Miocene Upper Moquegua Formation in the Majes, Sihuas, and Victor valleys. The top of these conglomerates (and intercalated tuff layers) are cut by the erosional surface forming the piedmont between the Western Cordillera and the Coastal Batholith (Fig. 2). The coarse conglomerates correspond to the transition between the ‘Moquegua C and D’ intervals of the Moquegua Group (Roperch et al., 2006) and the ignimbrites are distal equivalents of the Huaylillas ignimbrites. A similar series of ignimbrites overlying the thick clastic wedge are observed over an area of 1000 km on the western slope of the Andes. They are equivalent to the Chilean 'Oxaya' and 'Pica' ignimbrites of latest Oligocene to Early Miocene age (Wörner et al., 2000, 2002; Elger et al., 2005) to the south of our study area. As these ignimbrites are all largely undeformed and intercalated with the top of the Moquegua clastic wedge, they tend to form large plateaus covering the Western Cordillera and the piedmont towards the coast. We thus use the youngest of these plateau-forming ignimbrites as a reference marker which we refer to as the ignimbrite plateau of Huaylillas age (16.25 to 14.25 Ma).

We report here a previously undetected generation of 9 Ma-old ignimbrites (No. 20 to 23) which we term *Caravelí*. They fill an irregular paleotopography cut in the Huaylillas ignimbrites. The 9.4–8.8 Ma welded, 100- to 200-m thick cooling units of the Caravelí ignimbrites crown smaller and lower plateaus at 2–3 km a.s.l. that slope gently towards the WSW (Fig. 2).

The 5 to 6 Ma-old andesitic lava flows, mapped as 'lower Barroso Fm.' of the Barroso Group (Pecho Gutierrez, 1983; Olchauski and Dávila, 1994), form the core of deeply eroded shield volcanoes (Figs. 3 and 4) that once occurred on top of the Huaylillas plateau along the Western Cordillera and the western edge of the Altiplano. One of these lava flows (No. 19) has extended over the eastern edge of the upper Cotahuasi canyon (near the village of Pajcce, Fig. 2), indicating that a valley wall existed prior to 5.8 Ma at this site.

The *Sencca* ignimbrites, previously given as Pliocene (Sébrier et al., 1988), comprise two distinct sheets (4.9–3.6 and 2.3–1.4 Ma) in the study area. The 4.9–3.6 Ma-old *lower Sencca* ignimbrites (No. 16 to 18) typically occur in narrow valleys or preserved on ridges and valley flanks. The slightly welded to non-welded cooling unit usually exhibits a vitrophyre at its base. The *lower Sencca* ignimbrite is similar in age to most of the 6–5 Ma-old lower Barroso lava flows (Figs. 3 and 4).

Lava flows 2.27 Ma old (No. 14 in Table 1) overlie a member of the *upper Sencca* ignimbrites. Scattered outcrops are found on the eastern wall and benches of the lower Cotahuasi canyon upstream of Chaucalla and along the Ocoña canyon as far as Iquipi and Urrasqui (Fig. 2). The reconstructed profile of the lava flows suggests that they were sourced either from below the Nevado Solimana area and (or) other large stratovolcanoes of the Pliocene volcanic front. The 2.3–1.6 Ma-old *upper Sencca* ignimbrites (No. 7 to 13, and 42 in Table 1) often consist of non-welded pumice flows, and outcrop tops form either valley-fill benches, eroded ridges, or preserved topographic benches above tributary thalwegs. Ages show that most of the Sencca ignimbrites pre-date the Pleistocene volcanoes.

A most recent (1.56–1.36 Ma: No. 5 and 6) and thick succession of non-welded pumice flows and fall deposits leans against canyon walls or are capped in places by more recent lava flows. Lava flows ~1 Ma old (No. 40 and 41 in Table 1) form the base on which the Middle Pleistocene to Holocene volcanoes were constructed. Dated examples of these widespread lava flow fields crop out on the western flank of Nevado Solimana, and in the upper Colca canyon near Huambo (Fig. 2). Lava flows 0.6 to 0.3 Ma old were produced by parasitic cones and domes on the western flank of Nevado Solimana (No. 1 to 4 in Table 1) and mantle the eastern edge of the Cotahuasi canyon. Channeled lava flows of a similar age (No. 35 to 39 in Table 1) form high benches in the upper Colca canyon near Cabanaconde (Fig. 2). Lava flows 0.13–0.15 Ma old that belong to the Andahua–Orcopampa–Huambo monogenetic province (Delacour et al., 2007) have filled the bottom of Río Ayo (No. 33 in Table 1), a tributary to Río Colca, and in the upper course of the Colca itself (No. 34 in Table 1).

Dated lava flows in the area of the canyons indicate that three generations of volcanic edifices have crowned the Western Cordillera: the eroded Late Miocene (6–4 Ma) shield volcanoes (Barroso Group); the Late Pliocene (≤2.3 Ma) stratovolcanoes, now already deeply dissected by glacial erosion; and the Pleistocene composite cones and domes (<1.4 Ma), which are either dormant edifices (Ampato) or active cones (El Misti, Ubinas, Sabancaya) with bases no older than 0.6 Ma (Thouret et al., 2001; Gerbe and Thouret, 2004; Thouret et al., 2005).

4.2. The pre-incision paleosurface

Based on the new event chronology provided above, we now outline the uplift and incision history of the Early Miocene paleosurface. The thick Moquegua clastic wedge and its cover of plateau-forming ignimbrites have their equivalents in similar stratigraphic successions over a length of ~1500 km along the Andean slope. The wedge deposits were sourced from the NE, and record the early phase of uplift and erosion on the western margin of the Andes at ~25 Ma (Kennan, 2000; Wörner et al., 2000). The 24.6–12.7 Ma-old ignimbrite sheets are interlayered with or deposited on Late Oligocene to Middle Miocene continental conglomerate beds. This 0.4 to 1-km-thick upper Moquegua Formation contains a marine layer beneath a 24.5±0.8 Ma tuff layer (Cruzado and Rojas, 2007) situated ~100 m below the top of the sequence; see No. 32, Table 1). This formation lies now at 2.3 km a.s.l. (Cuno Cuno) and 1.8 km a.s.l. (Pampa de Gramadal), i.e. 1.8 to 1.3 km above the floor of the Ocoña canyon (Fig. 2). The general 1.6% dip of these Miocene ignimbrite sheets towards the SSW parallels the present gradient of the paleosurface. Supported by the AMS flow directions (P. Paquereau and P. Roperch, unpubl. data), this geometry defines a gently sloping surface on the western Andean slope, which already existed by 19–13 Ma. This paleosurface is erosional in the higher Western Cordillera and depositional on the western Andean slope below 2400 m a.s.l. Its topographic continuity is remarkable (cf. Figs. 2 and 4) and correlates with the 'Puna' paleosurface as defined elsewhere in Peru (Tosdal et al., 1981, 1984). The plateau surface has not been substantially eroded since its formation and today still dominates the scenery between the Western and Coastal Cordilleras (Figs. 2–4). The surface of the 19 Ma-old Oxaya ignimbrites in northernmost Chile, equivalent to the Huaylillas surface in southern Peru, has been equally inactive since about 11–12 Ma despite its westward slope, its erodible volcaniclastic cover, and elevations exceeding 3 km (Wörner et al., 2000). Such limited denudation between the times of ignimbrite deposition and much more recent valley incision may reflect a period of lower erosion rates. We attribute the longevity of this low-energy environment to the flatness of the paleolandscape sealed by thick, hard welded ignimbrites, and to arid conditions already prevalent in Miocene times. Canyon incision was thus delayed until a significant increase in runoff and/or topographic gradient enhanced erosive power and initiated valley incision.

5. Incision history of the Cotahuasi and Ocoña canyons

Based on the age of the Alpabamba and Huaylillas ignimbrites covering the sediments and their source area in the Western Cordillera, incision of the Cotahuasi and Ocoña canyons did not begin before ~13 Ma. Incision depths during the first phase between ~13 Ma and 9 Ma were limited to a few hundred meters because the ~9 Ma Caravelí ignimbrites mantle pediments on granodiorites that grade to shallow valleys cut in Paleogene sediments only 0.3 to 0.6 km below the Huaylillas ignimbrite reference surface (Fig. 4A and Electronic Supplement Fig. 1 in the Appendix). The 13 to 9 Ma pre-Caravelí valleys were thus wider and much shallower than the Late Miocene canyons.

The present-day valleys were cut mostly between 9 Ma and ~3.8 Ma (Figs. 3–5; Table 1). Evidence for this is based on outcrops of 3.76±0.14 Ma valley-filling lower Sencca ignimbrites (No. 17, Table 1) situated ~0.3 km above the present valley floor near the town of Cotahuasi and ~2 km below the paleosurface covered by the 14–12.7 Ma-old ignimbrites (Fig. 4). About 40 km downstream, the paleovalley bottom is ~0.6 km above the present valley floor at 4.84±0.07 Ma (No. 18, Table 1). This age is obtained from the base of 1-km-thick valley-filling ignimbrites that form a high ridge above the confluence of the Ríos Ocoña, Cotahuasi, and Marán (insert D, Figs. 1, 2, and Electronic Supplement Fig. 1 in the Appendix). These depths of incision suggests 2–2.5 km of uplift for the western Altiplano between ~13 and 3.8 Ma, and likewise for the Western Cordillera Front Range between 13 Ma and 4.8 Ma. The principal phase of uplift and subsequent valley cutting thus took place before the end of Miocene times (Fig. 5). The main phase of valley incision started some time after 9 Ma, when the deposition of alluvial fans in the northern Chilean fore arc and lake sediments on the Altiplano indicates a period of increased precipitation at 7 Ma (Gaupp et al., 1999 and references therein) and suggests that canyon incision peaked after 7 Ma when it became climatically enhanced.

The 3.8 Ma-old valley-filling ignimbrites (No. 17, Table 1) represent the base (at 2.8 km a.s.l.) of an extensive valley-filling sequence the top of which lies 4.06 km a.s.l. and was dated at 1.56–1.36 Ma (No. 5 and 6 in Table 1) above the town of Cotahuasi (Fig. 4). This extensive 1.3 km-thick valley fill also occurs below the west flank of Nevado Solimana and at the confluence with the Ríos Ocoña and Marán. Because they occur on both sides of the deepest canyon sections and their thicknesses increase towards the north, these pyroclastic deposits are thought to reflect a series of voluminous explosive volcanic events from a potential source caldera situated northwest of Cotahuasi (see insert Fig. 1).

The ages of valley filling volcanics at mid-elevation (3.2–3.4 km a.s.l.) between the canyon edge and the valley floors provided intermediate ages for the valley fill (No. 15 and 16 in Table 1) within the 3.8–1.4 Ma age bracket. Apparently, this poorly consolidated thick valley fill was rapidly removed after 1.4 Ma. Hanging fans and terraces that are matched on both sides of the valley reflect pauses in the re-incision process during the Pleistocene (Electronic Supplement Fig. 1 in the Appendix). Evidence for younger but more local valley fills is also provided by the staircase morphology formed by ~0.68 Ma- to 0.45–0.33 Ma-old lava flows (No. 2 to 4, Table 1) on the western flank of Nevado Solimana (Huachuy, Fig. 2), at elevations of about 1.4 to 0.6 km above the present Cotahuasi channel. Several breaks in the present (and past) longitudinal profiles indicate that incision has not been in equilibrium for much of the younger canyon history. This is due to lava flows or valley flank collapses that repeatedly filled the valley at different times and locations.

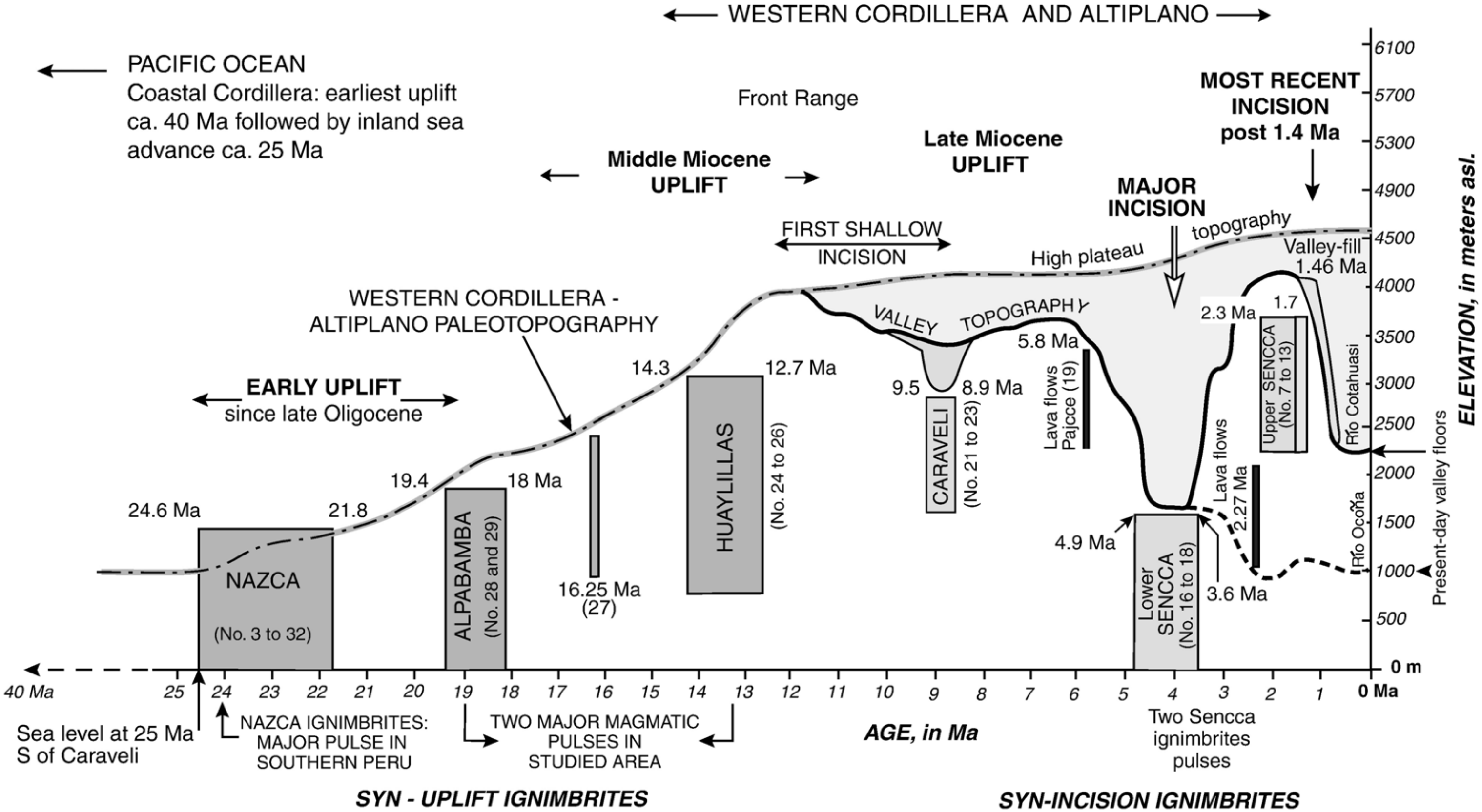

Fig. 5. Synthesis of topographic evolution since 25 Ma from the Pacific piedmont to the edge of the Altiplano based on $^{40}Ar/^{39}Ar$ age determinations, field mapping, and satellite imagery. Syn-uplift and syn-incision, dated ignimbrite sheets and/or pyroclastic deposits are shown, and phases of uplift and subsequent valley incision are indicated. Present-day valley floors of the Cotahuasi and Ocoña canyons are summarized on the basis of observations made near their confluence.

Valley-filling Sencca ignimbrites were channeled inside the deep valleys but upon reaching the western piedmont, they spread out and mantled the Miocene ignimbrites and sediments (top of the Cuno Cuno homocline, Fig. 4) or were deposited in relatively shallow (0.6 km) valleys cut in the Caravelí palaeosurface (e.g. Quebrada Pescadores, Fig. 2). Therefore, the angle of their deposition (1.6%) is at least half that of the present slope (3.3%) of the western Andean margin (i.e. the 14 Ma plateau surface) and also steeper than the present thalwegs of the canyons (1.1%). This difference must be due to tectonic tilting. The relatively lower angle of the top of the Sencca ignimbrites suggest only limited tilting and uplift since the end of their deposition (1.36 Ma).

Respectively since ~0.45 Ma (which is the age of lava flows 0.6 km above the Río Cotahuasi bed near Huachuy: Fig. 2; No. 2 in Table 1) and ~0.53 Ma (which is the age of lava flows forming terraces 0.3 km above the Colca valley floor near Cabanaconde: Fig. 5, No. 35 in Table 1), canyon incision rates have decreased. In theory, this could reflect diminished uplift rates, or the rivers approaching the minimum work conditions implied by a regular longitudinal profile (Fig. 4 and Electronic Supplement Fig. 1 in the Appendix). Present-day channel gradients, however, exhibit several knickzones close to the orogenic front (Fig. 4) and two distinct reaches: the upper course has a gradient of 2.1% upstream of a knickpoint where the river cuts into 0.4 km-thick debris-avalanche deposits (e.g. Río Cotahuasi at Cotahuasi town, and at the Ríos Arma and Ocoña confluence). Downvalley, the gentler sloping (1%) lower Ocoña and Majes valleys, with braided channels 1 km wide, have been choked by large volumes of sediment. Evidence for raised base levels and excess bedload in the Ocoña section (and in the Majes section of the Colca valley) is based on two observations: (1) given that the gradient of the 2.27 Ma-old lava flow just above the bed is steeper (2.8%) than the present-day river profile (Fig. 4), the lower Ocoña canyon reach was steeper during late Pliocene times than today and possibly related to a depressed sea level; (2) alluvial, debris-avalanche, lahar and lacustrine deposits, preserved 0.6 km above the valley floor on both sides of Río Ocoña (Urrasqui, Fig. 2), show that two thirds of the canyon had been filled to this level at some time during the early Pleistocene. Knickpoints along the channel (Fig. 4) and debris-avalanche deposits that have not been completely removed by the river suggest that the river still has a slightly disturbed thalweg profile today. However, while evidence for uplift and incision is obvious, significant tectonic displacements along discrete faults, for example at the present orogenic front, as expressed by prominent knickpoints, are lacking. This is also true for the older valley gradients as reconstructed here from the late Miocene valley fills. Absence of significant tectonic shortening in the Andean fore-arc region during the <9 My phase of uplift has been noted before and has supported a model of lower crustal flow from E to W as the main process of crustal thickening and uplift in this region (Isacks, 1988; Wörner et al., 2000; Roperch et al., 2006; Schildgen et al., 2007).

6. Recent phases of incision in the Colca canyon

The older incision history of the Río Colca is less well constrained than for the canyons of the Ríos Cotahuasi and Ocoña rivers because the pre-incision plateau is less well defined and extensively covered by Miocene volcanics of the Barroso Group. However, the more recent valley history is well documented by our new $^{40}Ar/^{39}Ar$-ages because the Río Colca, east of Rio Ocoña, flows from east to west on the northern edge of an elevated plateau capped by 2.2 Ma-old Sencca ignimbrites (No. 42, Table 1, Electronic Supplement Fig. 2 in the Appendix; Klinck et al., 1986). This young age, however, does not imply that the Colca canyon is younger than 2.2 Ma. Instead, we suggest that, as in the Ocoña canyon, the Sencca ignimbrites represent refills of an older valley, later reincised in three stages (Electronic Supplement Fig. 2 in the Appendix). The first was rapid and occurred before 1.06 Ma, as inferred from the age of lava flows now hanging 1.5 km above the valley bed near Huambo, and at mid canyon elevation (No. 11, Table 1). The second phase of re-incision was brief, and occurred when a dammed lake broke out after 0.61 Ma (No. 36, Table 1), which is the age of a lava flow capping the uppermost lake deposits near Achoma (Electronic Supplement Fig. 2 in the Appendix). Lacustrine deposits 0.3 km thick have filled the upper reach of the valley (see Klinck et al., 1986). They are related to natural dams that formed as a consequence of valley-flank collapse and lava flow fills. Thick, boulder-rich terraces down valley testify to catastrophic paleolake breakouts into the Río Majes. As in the case of the Ocoña canyon, most of the incision was achieved before the middle Pleistocene because topographic benches formed by lava flows and situated 0.3 to 0.6 km above the valley floor near Cabanaconde and Huambo, are 0.53 Ma old (No. 35, Table 1). The third and minor re-incision phase thus occurred between <0.53 Ma and 0.2 Ma, which is the age of lava flows being currently cut by the Rio Colca near the town of

Chivay. Below the preserved paleolake level, a series of terraces and hanging fans reflect repeated valley cut-and-fill episodes during the <0.4 My-long period. The left tributaries of the Colca such as the Río Ayo are entrenched by 150 m into two 0.15–0.13 Ma lava flows (No. 33 and 34 in Table 1).

7. Discussion

7.1. Timing of incision and uplift of the Altiplano and Western Cordillera

Early uplift and increased erosion have been inferred from the late Oligocene to middle Miocene “Upper Moquegua” conglomerates, and on the basis of intercalated ≥24.5 Ma-old marine strata in this Formation, now occurring at 1.8 and 2.3 km a.s.l. (Fig. 3 and Electronic Supplement Fig. 1 in the Appendix). The depositional record of this early uplift phase was punctuated by the voluminous plateau-forming ignimbrites, which sealed the land surface and appears to have remained mostly uneroded for several million years. Whereas uplift may have been more or less continuous, erosion was not. We have argued above that the Huaylillas surface was dissected between 9 and 3.8 Ma (see also Schildgen et al., 2007). This finding supports other data indicative of rapid uplift obtained for the Bolivian Altiplano between 10.3 and 6.4 Ma (Marshall et al., 1992; Ghosh et al., 2006). However, in southern Peru, as outlined earlier, significant uplift occurred prior to the eruption of the plateau-forming ignimbrites between 25 and 14 Ma and continued until Pliocene times. The evidence of a protracted uplift history weakens the case for rapid Andean uplift being restricted to a peak between 10.3 and 6.4 Ma (cf. Marshall et al., 1992; Ghosh et al., 2006), and thus casts doubt on mantle delamination as the prime cause of vertical uplift (Hartley et al., 2007).

The most recent 1.3 km-thick “Sencca” pyroclastic valley-fill (3.8–1.36 Ma) has been largely removed (Fig. 4, Table 1). This renewed phase of incision was relatively rapid (~1.05–1.2 mm yr^{-1}) because pumice-flow deposits of that valley fill were capped by 0.45 Ma lava flows at 3.2 km a.s.l. on the eastern edge of the Cotahuasi canyon near Huachuy (No. 2, Table 1). This cannot be attributed to some local effect because most of the incision was achieved before the middle Pleistocene in the middle reach of the Colca canyon, as suggested by 0.53 Ma-old lava flows forming topographic benches 0.3 to 0.6 km above the valley floor. However, accelerated erosion is detected during early to middle Pleistocene times when the vertical gradient of the canyon wall has increased due to the thick lava flows, which were added to the pre-existing canyon edges. There is no direct evidence for either tectonic uplift, increased runoff, or isostatic rebound following the deep Neogene incision phase. However, given the maximum computed rate of incision (1.7 km in 0.45 Ma, i.e. ~3.8 mm yr^{-1}), there is also no reason to assume a decline in either mean uplift rate or mean glacial meltwater supply exactly during this brief period of the middle to late Pleistocene.

7.2. Variable incision rates along canyon transects

Whereas our observations broadly coincide with recent findings (Ghosh et al., 2006; Garzione et al., 2006; Schildgen et al., 2007), with this study we provide finer resolution to show that incision (and inferred uplift) was neither uniformly fast between 13 and 3.8 Ma, nor spatially consistent across the western Central Andes. Based on the 20-m DEM (with an error of c. 50 m), a volume of ~1960 km^3 has been removed from the 160 km-long Cotahuasi–Ocoña canyons (excluding recent volcaniclastic deposits). At least 75% of that volume was removed before 3.8 Ma in the Cotahuasi valley, and before 4.8 Ma at the Ocoña–Marán confluence. The mean vertical incision rate (0.19 mm yr^{-1} in the area of Cotahuasi, Fig. 5) is inferred by computing the elevation difference between the edge of the Huaylillas plateau ignimbrite and the current river bed. The mean bedrock incision rate was moderate (0.21 mm yr^{-1}) between 13 and 9 Ma (before the Caravelí ignimbrite pulse), but it probably doubled between 9 and 3.8 Ma. This is suggested by a 1.2 km drop in elevation in the ‘Pliocene’ paleo longitudinal profile (Fig. 4) over a 30 km distance between Cotahuasi and Chaucalla (insert Fig. 1, and the Appendix).

The re-incision rate through the upper Sencca pyroclastic valley fill was ten times faster after 1.4 Ma (1.2 mm yr^{-1} near the town of Cotahuasi, Electronic Supplement Fig. 1 in the Appendix). Further downstream and since 1.36 Ma, the Río Ocoña and its Arma tributary incised the volcanic fill by as much as 1.4 km, i.e. at ~1.0 mm yr^{-1}. However, these rapid incision rates only represent valley-fill re-incision rate into young non-welded pyroclastic deposits, and not a bedrock incision rate directly correlated to tectonic uplift or increased runoff.

Incision rates have also fluctuated spatially across the western slope of the Central Andes as the canyons cut through three different structural units (Fig. 2). The Western Cordillera downstream of the Front Range and the piedmont and Coastal Cordillera were less incised than the western edge of the Altiplano in early to middle Pliocene times. For example, ignimbrites crop out 1–1.3 km above the Ocoña canyon on the SW flank of Nevado Solimana, where they form a prominent ridge (inset Figs. 3 and 5B) above the confluence at 1.6 km below the reference Huaylillas plateau ignimbrite surfaces. The pumice sole layer of the lower member of the ignimbrite pile is dated at 4.84 Ma (No. 18, Table 1) and can be traced downstream where it crops out at 0.6 km above the present valley floor at Chaucalla, 1.6 km below the reference Huaylillas ignimbrite-clad plateau surface. This 4.8 Ma-old thalweg therefore does not correlate with the ~3.8-Ma-old and relatively deeper thalweg (at 2.8 km a.s.l.) in the Cotahuasi canyon above the town of Cotahuasi. This indicates an increase in gradient of 8 m/km between the 4.8 Ma and the 3.8 Ma river paleoprofiles (Fig. 4). Canyon wall lithologies within 1 km of the valley floor are similar, so this difference may be due to renewed or faster incision between 4.8 and 3.8 Ma. It cannot be ruled out that the break in slope observed between the two river segments also reflects differential uplift landward and seaward of the Front Range. This would be the only indication of localised tectonic movements at the orogenic front.

North of Lima, deep incision occurring 5.8 Ma ago had already been inferred by Myers (Kennan, 2000) from the fact that 5.84±0.2 Ma ignimbrites were preserved 0.15 to 0.5 km above the Río Fortaleza canyon bed. Bedrock incision by drainage networks therefore took place earlier in the northern Central Andes, suggesting a faster uplift rate in the north during the Miocene. In theory, this could also suggest earlier uplift in the north. However, given that this strike-parallel gradient also reflects the present-day climatic gradient in which precipitation increases from south to north, the northward increase in the size and reach of the valleys is probably a climatic signal, tectonic uplift being assumed equal along that same gradient. Bedrock incision by drainage networks therefore took place earlier in Peru and is younger in northernmost Chile. Ignimbrites of largely equivalent age (14 to 19 Ma) are at equivalent elevations from S to N (4200–4500 m). However, the valleys in southern Peru cut significantly deeper and further east into the Altiplano than those in N Chile. This directly implies that the present climate gradient (more precipitation to the N) must have existed at least for the past 5 Ma and possibly ever since 9 Ma. Thus, whereas the incision histories of these valleys are mostly driven by tectonic uplift, morphological differences between these canyons may reflect a climatic gradient along the western margin of South America that could have been in place since at least ~9 Ma.

8. Conclusions

The deepest canyons in the Andes may be unique in providing important insight into the uplift history of the Central Andes. A chronostratigraphy of volcaniclastic formations based on 42 $^{40}Ar/^{39}Ar$ age determinations indicates that the deep valleys of southern Peru were incised into the uplifting bedrock to near their present depths as early as 3.8 Ma. This occurred on a landscape which, 13 to 14 My ago, consisted of a gently sloping paleosurface mantled by the widespread Huaylillas ignimbrites. These also cover a clastic wedge that records the first stage of Andean uplift in early Miocene times.

Initial valley incision started with the formation of broad, shallow valleys at ~9 Ma. This is interpreted as a response to continued uplift since 13 Ma, which is the age of the ignimbrites capping the plateau. The time lag between 13 and accelerated incision after 9 Ma could reflect (1) limited susceptibility to erosion of the flat paleosurface, (2) the hardness of the welded ignimbrite caprock, combined with (3) low rainfall and runoff at that time. The onset of increased downcutting after 9 Ma is attributed to (1) continued uplift, (2) breaching of the ignimbrite caprock, and (3) increased runoff. Moisture supply would have been afforded by a relatively wetter climate that has been documented for the Andes around 7 Ma (Gaupp et al., 1999). However, the main driving force for valley incision was uplift. In the absence of significant shortening along the western margin of the Andes (see also Schildgen et al., 2007), it is implied that uplift was caused by regional tilting and lower crustal flow rather than along discrete tectonic faults along the orogenic front. As far as the canyon re-incision history at the end of the Pliocene is concerned, there is no direct evidence for linking it with an increase in uplift rate after 3.8 Ma, or with isostasy due to glacial or canyon erosion after 2.7 Ma (Marshall et al., 1992).

As a result of deeper incision in Peru than Chile, the valleys of southern Peru have also cut more deeply both down and beyond the belt of the currently active volcanoes. Erosion has caused repeated catastrophic landslides and debris flows of volcanic and non-volcanic origin in the canyons of southern Peru. These pose serious threats to populated settlements. Additional hazards are also related to potential dammed lake breakouts that may trigger devastating debris flows towards the lower populated valleys and towns of the Majes and Ocoña valleys.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2007.07.023.

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