Slab flattening, magmatism, and surface uplift in the Cordillera Occidental (northern Peru)

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ABSTRACT

The impact of subduction processes on surface uplift and relief building in the Andes is not well understood. In northern Peru, we have access to a modern flat subduction zone (3°–15°S) where both the geometry and timing of the flattening of the slab are well constrained. Some of the highest Andean peaks, the Cordillera Blanca (6768 m) and the Cordillera Negra (5187 m), are located just above the Peruvian flat slab. This is a perfect target to explore the impact of slab flattening and associated magmatism on Andean topography and uplift. We present new apatite (U-Th)/He and fission-track data from three vertical profiles in the Cordillera Blanca and the Cordillera Negra. Time-temperature inverse modeling of the thermochronological data suggests that regional exhumation in the Cordillera Occidental started at ca. 15 Ma, synchronous with the onset of subduction of the Nazca Ridge and eastward movement of regional magmatism. We propose that ridge subduction at 15 Ma and onset of slab flattening drove regional surface uplift, with an important contribution of magmatism to relief building in the Cordillera Occidental.

INTRODUCTION

The Andes are often presented as the classic example of relief building along a non-collisional convergent plate boundary, but many subduction zone processes, specifically related to surface uplift, are still not fully understood. Along the western Andean margin, topography and slab dip vary significantly, resulting in a clear segmentation along strike, with two modern flat-slab segments in northern Peru (3°–15°S; Fig. 1) and central Chile (28°–32°S) (Barazangi and Isacks, 1976). These flat-slab subduction zones influence the occurrence and location of magmatic activity along the Andean range, with the magmatic arc migrating away from the trench and even ceasing to exist during slab flattening. Slab flattening also increases coupling at the plate interface, resulting in an increase and eastward displacement of shortening in the overriding plate and consequent surface uplift in both the Andean forearc and backarc (e.g., Ramos and Folguera, 2009). However, the impact of slab flattening on surface uplift in the western part of the Andes (Cordillera Occidental) remains unclear.

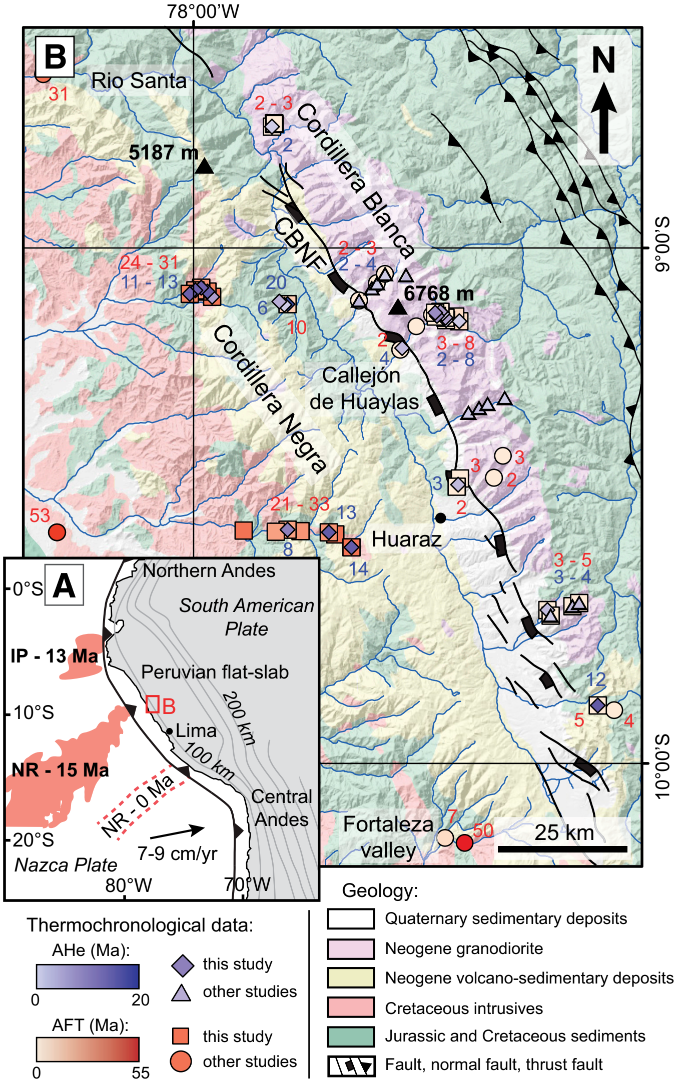

Figure 1. A: Study area location within Peruvian flat slab and South American Pacific margin (modified after Ramos and Folguera, 2009). Respective positions of Nazca Ridge (NR) at ca. 15 Ma and 0 Ma and of Inca Plateau (IP) at ca. 13 Ma (Rosenbaum et al., 2005) are represented in red. B: Geological map of Cordillera Occidental (northern Peru) showing apatite fission-track (AFT) ages (red) and apatite (U-Th)/He (AHe) ages (blue) (modified from geologic map of Ancash; INGEMMET, 1999). CBNF—Cordillera Blanca normal fault.

The geometry and timing of slab flattening in northern Peru are constrained by the subduction of two buoyant features, the Nazca Ridge and the Inca Plateau (e.g., Gutscher et al., 1999; Rosenbaum et al., 2005). In this region, the Cordillera Blanca (CB), a Miocene batholith exhumed along an ~150-km-long crustal-scale normal fault trending parallel to the range, forms the highest Peruvian peaks (Fig. 1; e.g., McNulty and Farber, 2002). In the context of flat subduction, which is expected to produce shortening, the presence of this major normal fault is surprising. Two models have been proposed to explain the Cordillera Blanca normal fault (CBNF). Dalmayrac and Molnar (1981) suggested that extension was induced by gravitational collapse of a thickened crust, whereas McNulty and Farber (2002) suggested extension due to the arrival of the Nazca Ridge beneath this region, which temporarily increased the coupling with the overriding plate. Understanding the exhumation of the CB and extension along the CBNF in this compressive regime is important for understanding the impact of ridges and flat subduction on Andean relief development.

The aim of this paper is to evaluate the relationship between changes in geodynamics and relief evolution in the Cordillera Occidental in northern

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Peru. We infer relief evolution from apatite (U-Th)/He (AHe) and fission-track (AFT) data of the CB and the Cordillera Negra (CN). We compare time-temperature inverse modeling (QTQt software; Gallagher, 2012) with the timing of the arrival of the Nazca Ridge at the subduction zone, periods of magmatic activity, and periods of uplift.

GEOLOGIC AND GEODYNAMIC CONTEXT

Reconstructions of the timing and location of the initial Nazca Ridge subduction and its subsequent southeastward migration constrain the timing of slab flattening (e.g., McNulty and Farber, 2002; Rosenbaum et al., 2005). These reconstructions are based on symmetric seafloor spreading in a hotspot reference frame, and rely on the calculation of the Nazca plate motion with respect to South America, which may contain considerable errors. Rosenbaum et al. (2005) presented a regionally refined plate circuit that suggests ridge subduction beginning at 15 Ma at 10°S and the arrival of the Inca Plateau at the trench at 5°S at 13 Ma (Fig. 1).

The CB is a 14–5 Ma granitic pluton (zircon U-Pb; Mukasa, 1984; Giovanni, 2007) intruded into Jurassic sediments. The high summits of the CB build the footwall of the CBNF, which has produced >4500 m of vertical offset since 5 Ma (Bonnot, 1984; Giovanni, 2007). The Callejón de Huaylas, a 150-km-long range-parallel intra-mountain basin, separates the CB and the CN. The 8–3 Ma Yungay ignimbrites in the northern part of the basin (Farrar and Noble, 1976; Cobbing et al., 1981; Wise and Noble, 2003) and 5.4 ± 0.1 Ma ignimbrites at the base of the stratigraphy of this basin constrain the timing of basin formation in relation to CBNF activity (Giovanni et al., 2010). The CB batholith and synchronous volcanic deposits indicate the last activity before the cessation of magmatism (Petford and Atherton, 1992) associated with slab flattening.

The Cretaceous and Paleogene plutons (73–48 Ma; Beckinsale et al., 1985) intruded into Jurassic sediments of the CN form a plateau with summits >5000 m and 1–2-km-deep valleys incised into its western flank. Some Neogene volcano-sedimentary deposits cap the CN (54–15 Ma Calipuy Formation; Cobbing et al., 1981). Few studies have addressed volcanism in the CN (Farrar and Noble, 1976; Myers, 1976; Noble et al., 1990), and no thermochronological data are currently available. In the CB, few AFT and AHe data are available, mostly from glacial valleys along longitudinal profiles (Montario, 2001; Giovanni, 2007; Hodson, 2012). Thermochronological data outside of our CB and CN study areas are limited (Wipf, 2006; Michalak, 2013; Eude et al., 2015), preventing any regional thermal modeling. Due to the absence of thermochronological data in the CN, earlier exhumation models focused on the CBNF.

METHODS

AFT and AHe thermochronology record the temperature evolution of the crust from 120 to 40 °C (e.g., Gallagher et al., 1998; Gautheron et al., 2009), which can be related to local exhumation or thermal events. Although thermochronological data do not allow direct quantification of surface uplift, with complementary information, exhumation can be interpreted to be the result of surface uplift and enhanced erosion. We determine the thermal history for a vertical profile using the QTQt software, which inverts AFT annealing and AHe diffusion parameters with the Markov chain Monte Carlo method (Gallagher, 2012; details on sample processing, analysis, and modeling are provided in the GSA Data Repository[1]). We use the multi-kinetic annealing model of Ketcham et al. (2007) to model the AFT ages and track-length dispersion, and the recoil damage model of Gautheron et al. (2009) to model AHe ages.

NEW THERMOCHRONOLOGICAL DATA

We sampled three profiles with elevations spanning 0.9–1.9 km, one in the CB batholith (>10 km from the CBNF to avoid a tectonic exhumation signal) and two in the CN, providing 33 AFT ages, track-length measurements, and single-grain AHe ages for 23 samples (Fig. 1). The AFT ages in the CB range from 1.5 ± 0.3 Ma to 7.7 ± 1.1 Ma, and AHe ages range from 1.9 ± 0.2 Ma to 13.7 ± 1.4 Ma (Fig. 1). The AHe ages are scattered and older than AFT ages, raising the question of their reliability. Indeed, ^{4}He implantation from an external U-Th source can generate 50% of excess He and cause age dispersion (Gautheron et al., 2012). In the CN, AFT ages range from 21.1 ± 1.3 Ma to 33.2 ± 1.9 Ma and AHe ages range from 1.9 ± 0.2 Ma to 32.6 ± 3.3 Ma.

TIME-TEMPERATURE INVERSION

Thermal inversion of the CB age-elevation profile indicates rapid cooling at ~200 °C/m.y. between 4.5 and 4 Ma following batholith emplacement at high temperatures (Fig. 2). This rapid cooling is bracketed by the batholith emplacement ages (14–5 Ma; Mukasa, 1984; Giovanni, 2007) and AFT ages. At ca. 4 Ma, the cooling rate decreased to 25 °C/m.y.

Inverse modeling of the northern CN suggests an initial cooling stage between 30 and 23 Ma, followed by a progressive reheating between 23 and 15 Ma (Fig. 2). Between 15 Ma and today, the rocks have cooled at 7 °C/m.y. The southern CN model indicates an initial cooling episode between 30 and 18 Ma, and then a 18–15 Ma heating event. From 15 Ma to today, the rocks have recorded a cooling phase with a rate of ~7 °C/m.y. (Fig. 2). For both CN profiles, the obtained temperature-time paths indicate slow cooling during the Oligocene followed by reheating during the early Miocene and finally monotonic cooling since ca. 15 Ma (Fig. 2).

DISCUSSION

Middle Miocene Exhumation of the Northern Peruvian Andes

Both CN profiles indicate reheating of the crust over several million years before 15 Ma and subsequent cooling. This progressive reheating likely corresponds to regional heating during emplacement of the volcanic Calipuy Formation (54–15 Ma; Cobbing et al., 1981). The presence of the Calipuy magmatic arc possibly increased the geothermal gradient in the Cordillera Occidental.

The cause of the onset of exhumation recorded by the cooling phase in the CN between 15 and 0 Ma is not straightforward. Pollen analyses constrained a maximum possible elevation of 2 km in the Peruvian Andes before the middle Miocene (Hoorn et al., 2010). At that time, the CN formed the drainage divide (Fig. 3A; Wise and Noble, 2003). McLaughlin (1924) suggested that the CN Jurassic sediments, deposited near sea level, were uplifted and eroded to a low-relief surface (Puna surface) until ca. 15 Ma, during the Quechua 1 deformation event. This surface is presently located at ~4400 m above sea level. Late Miocene volcanic rocks (7.4 Ma; Wipf, 2006) fill a paleovalley (now reincised) along the Rio Fortaleza, which has its headwaters in the CN. This morphology records a change in base level indicating that some uplift and incision occurred between 15 and 7 Ma (Farrar and Noble, 1976; Myers, 1976). Giovanni et al. (2010) showed from $\delta^{18}O$ analyses of paleolake deposits that high elevations in the Callejón de Huaylas basin (Fig. 1) were attained by latest Miocene times. Therefore, the cooling recorded at 15 Ma in the CN is likely related to erosion triggered by regional surface uplift. This scenario is consistent with previous studies bracketing the uplift of the western Andes of northern Peru between the early and late Miocene (e.g., Farrar and Noble, 1976; Myers, 1976; Giovanni et al., 2010; Hoorn et al., 2010).

Ridge Subduction, Slab Flattening, and Surface Uplift

The initiation of exhumation at ca. 15 Ma in the CN correlates with subduction of the Nazca Ridge (Fig. 3B; Rosenbaum et al., 2005). Exhumation in the CN has continued after initial ridge subduction and its southward

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[1] GSA Data Repository item 2015347, details on sample processing, analysis, and modeling; Figure DR1 (predicted *T-t* paths using the Flowers et al. [2009] He diffusion model); Table DR1 (AHe ages); and Table DR2 (AFT data), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

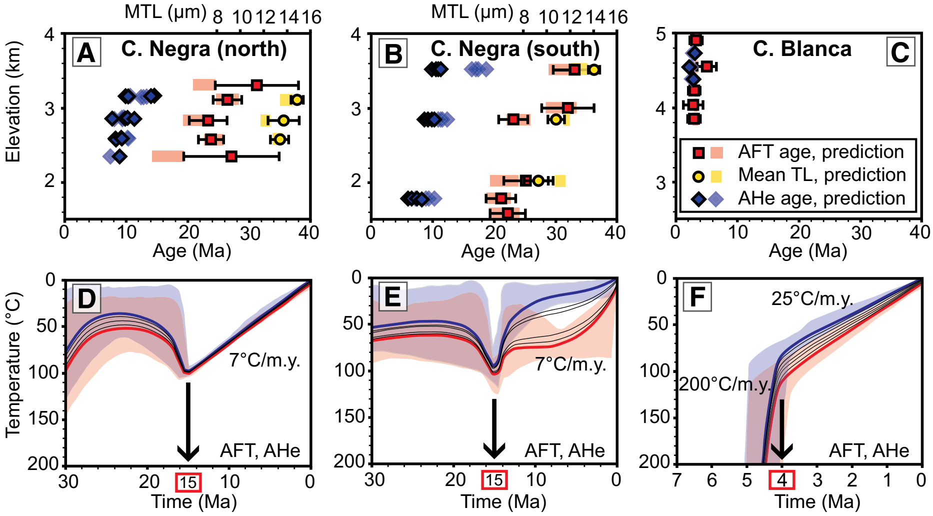

Figure 2. Age-elevation plots and temperature-time (*T-t*) paths predicted for thermochronological ages using Gautheron et al. (2009) He diffusion model. A–C: Age-elevation plots showing apatite fission-track (AFT) ages (red), mean track length (MTL; yellow) and apatite (U-Th)/He (AHe) ages (blue); ages predicted by thermal history are plotted in pastel colors. A: Northern Cordillera Negra (CN) profile.B: Southern CN profile. C: Cordillera Blanca (CB) profile. D–F: *T-t* paths for northern and southern CN and CB profiles. Each line represents *T-t* path of a sample; red line represents path of lowest-elevation sample and blue line highest, pastel shading represent uncertainties.

migration until today (Figs. 3C and 3D). The timing (15 Ma) and location (10°S) of the initial Nazca Ridge subduction proposed by Rosenbaum et al. (2005) is consistent with the middle Miocene continental shelf uplift at this latitude (von Huene and Suess, 1988), with the propagation of the orogenic front toward the east at ca. 8 Ma (Mégard, 1987) and with the shift of magmatic sources toward the east from the Calipuy Formation (54–15 Ma; Cobbing et al., 1981) to the CB magmas (CB batholith, Fortaleza and Yungay ignimbrites, 14–3 Ma; Mukasa, 1984; Wise and Noble, 2003; Wipf, 2006; Giovanni, 2007; Giovanni et al., 2010). Eakin et al. (2014) suggested that slab flattening has an influence on the evolution of the overriding plate and proposed ~1000 m of positive dynamic topography in the Cordillera Occidental after slab flattening. As no important compressive phase has been documented during the middle Miocene in the Cordillera Occidental in northern Peru (Mégard, 1987), we suggest that regional uplift resulted from positive dynamic topography above the flat slab.

Magmatism and Exhumation in the Cordillera Blanca

The CB thermal history indicates rapid cooling (200 °C/m.y.) of the batholith followed by slower cooling (25 °C/m.y.) beginning at ca. 4 Ma. The rapid cooling likely corresponds to the post-magmatic cooling of the CB batholith; coeval exhumation is not excluded. The slower cooling likely corresponds to exhumation. This cooling rate suggests higher exhumation rates in the CB than in the CN. Following McNulty et al. (1998) and Petford and Atherton (1992), we propose that strike-slip faulting facilitated the earlier stage of CB exhumation (Fig. 3C). Our data combined with previously published thermochronological data (U-Pb and Ar-Ar; Giovanni, 2007) indicate that the CB emplacement and onset of exhumation are coeval, suggesting that the crustal emplacement of low-density magma participated in the exhumation of the CB (Petford and Atherton, 1992). The presence of polished granitic clasts in Pliocene sediments indicates glacial erosion of the CB (Bonnot, 1984), placing the CB at elevations at least in excess of ~3500 m at this time. Finally, we suggest that magmatism and glacial erosion (Fig. 3D) continued to drive the local CB uplift and exhumation in a context of regional surface uplift following slab flattening.

The CB exhumation cannot be explained with models involving increased coupling at the plate interface and shortening in the upper plate. Such models are not compatible with extension related to the CBNF. The initiation of the CBNF (ca. 5.4 Ma; Giovanni et al., 2010) is ~10 m.y. after the subduction of the Nazca Ridge (15 Ma; Rosenbaum et al., 2005), demonstrating that the subduction of the ridge does not control extension on the CBNF and CB exhumation, as suggested by McNulty and Farber (2002). Collapse models (e.g., Dalmayrac and Molnar, 1981) are in contradiction with the 15–0 Ma exhumation of the CN. We suggest that the fault is accommodating the differential exhumation of the two cordilleras.

SUMMARY

Thermochronological data and temperature-time history modeling suggest exhumation since 15 Ma in the Cordillera Negra. We interpret this exhumation phase as the result of elevated erosion rates in response to regional surface uplift. This scenario is in agreement with other studies bracketing the timing of uplift of the Cordillera Occidental between the early and late Miocene (e.g., Hoorn et al., 2010), but contradicts models of extensional or gravitational collapse of thickened crust (e.g., Dalmayrac and Molnar, 1981). We propose that surface uplift in the Cordillera Occidental was driven by the Nazca Ridge subduction, slab flattening, and

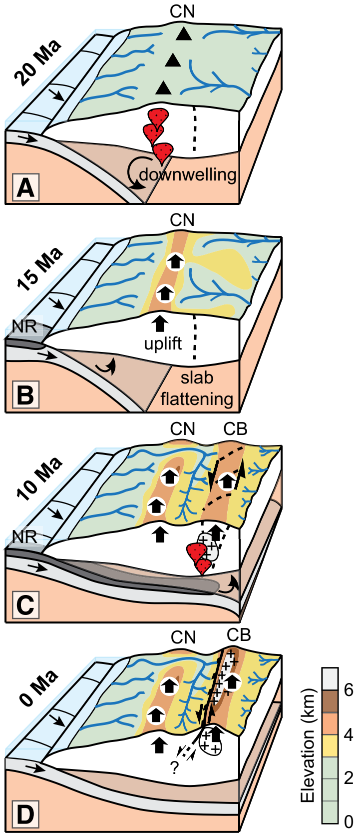

Figure 3. Block diagrams showing uplift history and paleogeography of Cordillera Occidental in northern Peru. Diagrams represent surface uplift (bold arrow), volcanism (black triangle), partial melting (red droplet), faults (dotted and continuous black lines), drainage network, and Cordillera Blanca (CB) batholith. A: Calipuy Formation emplaces in Cordillera Negra (CN) above "normal" subduction (54–15 Ma). B: Subduction of Nazca Ridge (NR), slab flattening, and corresponding surface uplift in CN at 15 Ma. C: During slab flattening, magmatism shuts down in CN and moves eastward. CB batholith emplaces at depth and is exhumed in strike-slip context. D: Cordillera Blanca normal fault accommodates recent exhumation of CB resulting in modern elevations >6 km.

associated magmatism (i.e., CB magmas). By constraining the timing of heating and cooling of upper crustal rocks from the late Oligocene to the present, this study provides new evidence linking flat subduction to the topographic evolution of the northern Peruvian Andes.

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