Exhumation history of the Andean broken foreland revisited

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ABSTRACT

The Andean broken foreland in west-central Argentina, located 400–800 km from the Peru-Chile Trench is associated with flat subduction linked to collision of the oceanic Juan Fernandez Ridge. While the conditions associated with flat subduction would be expected to produce increases in rock uplift and exhumation, where thrusting and dynamic forces work together, a prevalence of pre-Cenozoic apatite fission track (AFT) cooling ages suggests that there is no such link. The lack of Cenozoic cooling ages is at odds with structural reconstructions and basin studies along the foreland that show several kilometers of exhumation. This paradox can be reconciled by taking into account the thermal effects of flat subduction that removed the mantle wedge, and a significant source of heat flow into the crust. Reinterpretation of published AFT exhumation data (>320 ages) using more realistic lower geothermal gradient values allows for substantial exhumation and explains the lack of Cenozoic exhumation ages across the foreland region.

INTRODUCTION

The foreland of central Argentina exposes a prominent Miocene–Pleistocene basement-thrust province, the Sierras Pampeanas (Fig. 1), considered to be the modern analogue of the ancient U.S. Laramide province (e.g., Jordan and Allmendinger, 1986). Despite extensive study (e.g., Sobel and Strecker, 2003), questions remain about the timing and magnitude of deformation in this region and the extent of associated rock uplift and exhumation.

In the Central Andes, thermochronometers have been widely used to understand deformation and the rise of the Altiplano-Puna plateau (e.g., Barnes and Pelletier, 2006); however, few studies (Jordan et al., 1989; Coughlin et al., 1998) have used low-temperature cooling ages to understand regional denudation patterns along the foreland. Despite considerable local relief, to 4 km, these studies have not yielded many Cenozoic apatite fission track (AFT) cooling ages (see Table DR1 in the GSA Data Repository[1]); this is at odds with structural and basin reconstructions. Geological and topographic cross sections show relief >5 km associated with Miocene or younger deformation, and vertical thrust displacements >4 km, where basement rocks override Miocene–Pliocene strata (Fig. 1) (e.g., Sobel and Strecker, 2003; Fisher et al., 2002; Ramos et al., 2002; Carrapa et al., 2008). The aim of this study is to explain this apparent paradox.

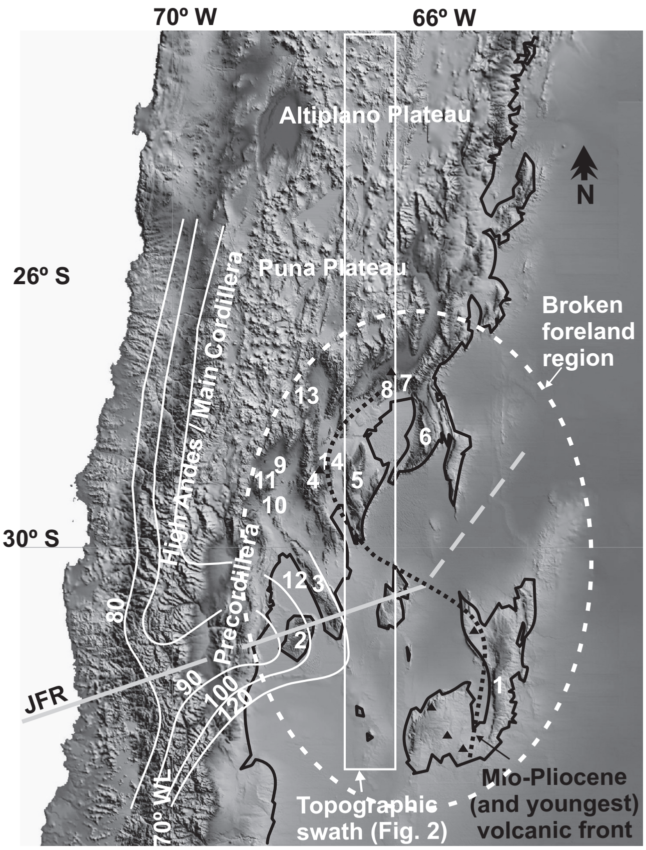

Figure 1. Digital elevation model of Central Andes showing morphostructural regions (Main Cordillera, Precordillera, and Sierras Pampeanas broken foreland), Benioff zone contour lines (thick white lines, in kilometers below surface; after Anderson et al., 2007), position of Juan Fernandez aseismic ridge (JFR, thick gray line), and 800 m elevation contour line (black thin line also shown in Fig. 3). Main regions within broken foreland: 1—Córdoba, 2—Pie de Palo, 3—Valle Fertil, 4—Famatina, 5—Velasco, 6—Ambato, 7—Capillitas, 8—Belén, 9—Vinchina, 10—Maz, 11—Umango, 12—Bermejo, 13—Fiambalá, 14—Paimán. Triangles indicate youngest volcanic activity and white rectangle is location of topographic swath illustrated in Figure 2. WL—west latitude.

GEOLOGICAL SETTING

The study area includes the Central Andean foreland of Argentina, mainly the Sierras Pampeanas basement province (or broken foreland) (Fig. 1), located hundreds of kilometers east of the High Cordillera. The foreland stratigraphy is represented by a Proterozoic to lower Paleozoic basement capped by Paleozoic to Pliocene–Pleistocene strata, locally >15 km thick (Dávila et al., 2007). The Neogene basins that developed during the main phase of the Andean orogeny are deep (locally 7–10 km) and wide, with kilometer-thick sequences at distances >500 km from the thrust front (Fig. DR2 [isopach map] in the Data Repository); this has led some to propose a long-wavelength component of dynamic subsidence (Dávila et al., 2007, 2010).

Three processes are considered to have influenced the development of the distal Andean foreland: (1) reactivation of preexisting structures (Kley and Monaldi, 1998) related to Neoproterozoic and early Paleozoic terrane accretion (Ramos, 2009); (2) subduction dynamics (Gutscher et al., 2000), by increasing and broadening of interplate frictional coupling during slab flattening (Martinod et al., 2010); and (3) thermal influences from the Cenozoic volcanic arc and backarc, which have also been viewed as a potential control on the configuration and style of deformation (Ramos et al., 2002).

[1]GSA Data Repository item 2013118, Table DR1 (cooling age data from different regions of the Argentine foreland), Figure DR1 (interpolation map of apatite fission track mean track lengths), and Figure DR2 (isopach map of Neogene basins), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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While all three processes had some influence on Cenozoic deformation and the growth of the Andean orogen, the principal control on regional deformation has been the Miocene change in the angle of the subducting slab (Jordan et al., 1983), especially flat subduction, associated with the subduction of buoyant oceanic aseismic ridges (Yañez et al., 2001; Mahlburg Kay and Mpodozis, 2002; Martinod et al., 2010; see Fig. 1). Flat subduction is an ideal setting to drive rock uplift and exhumation, where thrusting and dynamic forces work together. If the collision and dynamics of the Juan Fernandez Ridge are the main reason for slab flattening, deformation, and topographic changes cratonward, then the exhumation and denudation patterns within the Argentine foreland should show a similar evolution.

EVIDENCE FROM PREVIOUS THERMOCHRONOLOGICAL STUDIES

The first low-temperature thermochronology studies in the Sierras Pampeanas (Jordan et al., 1989) suggested that broken foreland exhumation occurred in three main intervals: (1) during a rapid cooling event before 332 Ma, as evidenced by middle–late Paleozoic granite cooling ages (see also Löbens et al., 2011); (2) between 320 and 260 Ma; and (3) after 260 Ma. No Tertiary cooling ages were reported by Jordan et al. (1989) (see Table DR1). Based on average values for geothermal gradients (~20–30 °C/km), the interpretations of Jordan et al. (1989) required modern outcrops of basement to have remained at crustal depths <~4 km since the early Mesozoic; i.e., the depth of Cenozoic exhumation of the Argentine foreland was modest throughout the Andean orogeny and collision of the aseismic ridges.

Coughlin et al. (1998) reported the first Cenozoic AFT ages along the northwestern and northern Sierras Pampeanas broken foreland (for the Famatina, Maz, Umango, and Capillitas ranges; locations in Fig. 1). The distribution of cooling ages led Coughlin et al. (1998) to propose that basement deformation shifted from west to east during the Miocene to Pliocene, in the opposite direction of growth of the Andean orogenic wedge.

More recent thermochronological studies in the northernmost Sierras Pampeanas, close to the Andean plateau (e.g., Sobel and Strecker, 2003; Carrapa et al., 2008), proposed that surface uplift occurred in the Miocene–Pliocene, coeval with the latest stage of basement deformation in the Sierras Pampeanas. In the easternmost broken foreland, at the leading edge of the flat-slab segment, the westernmost Cordoba range (Fig. 1) has yielded only Triassic to Cretaceous (ca. 253–77 Ma) ages; no Cenozoic cooling ages have been found (Jordan et al., 1989; Löbens et al., 2011).

Figure 2 plots published AFT ages against elevation along the strike of the foreland (Fig. 1). The youngest exhumation ages occur at the highest elevations (>4000 m above sea level, a.s.l.) to the north and the oldest ages are at the lowest elevations <1000 m southward. This implies a lack of connection between the two regions; the high-elevation region underwent considerable vertical denudation during and after surface uplift in comparison to the foreland region to the south. Although this area has a similar crustal structure (Whitman et al., 1996), the data imply that it has undergone comparatively little erosion. This combination of old AFT ages and interpreted low amounts of exhumation could suggest that slab flattening did not produce significant surface uplift and exhumation across the broken foreland region, and might also imply that low rates of denudation dominated the main Andean orogeny in the Neogene (e.g., Löbens et al., 2011). However, such interpretations have generally used idealized geothermal gradient values and have not fully taken into account the evidence from the regional geology.

Thermobarometric studies on igneous basement of the Sierras Pampeanas (e.g., Saavedra et al., 1998) suggest that ~10 km of crust (today the broken foreland) has been eroded since 336–325 Ma, based on an average geothermal gradient of ~25 °C/km. Linear exhumation would give an exhumation rate of 0.01–0.03 mm/yr. However, such values are unrealistic given the likelihood that over the past 300 m.y. exhumation was periodically interrupted by reburial as well as by episodes of uplift associated

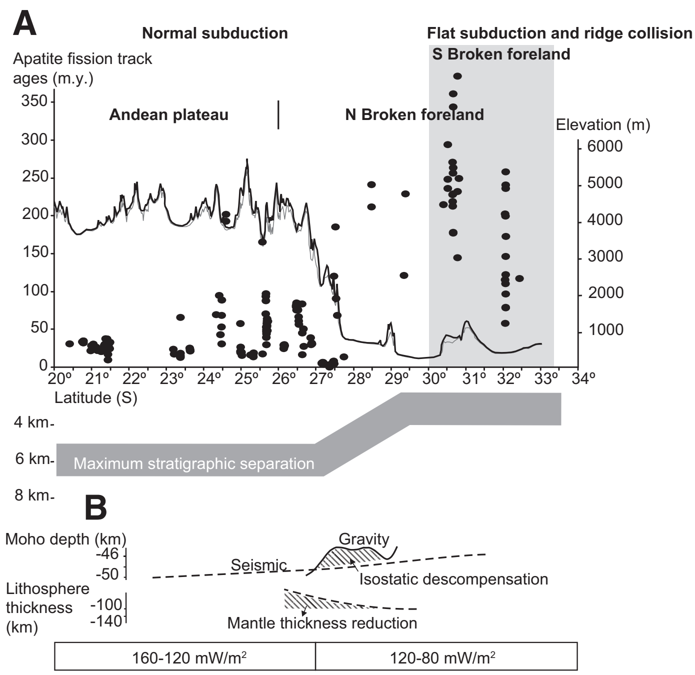

Figure 2. A: North-south, ~1300-km-long, ~44-km-wide topographic swath centered along ~66.5°W. Elevation is relative sea level. Thick black curve is average elevation, whereas thinner gray lines are maximum and minimum elevations. Black dots are apatite fission track (AFT) ages projected to swath profile (see the Data Repository [see footnote 1] for details). Note that oceanic Juan Fernandez ridge collision coincides with oldest AFT ages (and shortest mean track lengths; Fig. DR1). B: Moho depth and lithosphere thickness. Northern Sierras Pampeanas is located in zone where long-wavelength topography changes abruptly, which correlates with lithospheric mantle thinning in same direction (Whitman et al., 1996). Noncompensation area is derived from comparison between gravity and seismic data. Modern heat flow values were taken from Hamza et al. (2005).

with discrete tectonic events. The key question, in the context of understanding the impacts of subduction and Andean orogenesis, is when did most of the exhumation take place?

The contour map of cooling ages (Fig. 3) shows that the Andean foreland appears to have been relatively unaffected by increased denudation since the major reorganization of the Cenozoic plates and the collision of the Juan Fernandez Ridge (from ca. 23 Ma; Yañez et al., 2001) that would have increased plate coupling and deformation. A clear increase in recent exhumation to the west and north is coincident with the highest Andean elevations (High Cordillera and plateau). A similar trend is seen in the distribution of AFT mean track length values (n = 171; Fig. DR1 [mean track length map]), which are a more useful representation of the thermochronometry data in that they also reflect the rate of cooling; the longer the mean track length, the faster the rate of cooling and the more simple the cooling path. The shorter the mean length, the more likely the sampled rock underwent punctuated rock uplift and/or reburial throughout its history. Therefore, to better understand the timing and rate of exhumation, the published data that contained adequate individual track length measurements (>75) were inversely modeled using the HeFty program (Ketcham, 2005).

Figure 4A shows the best-fit thermal histories for each of the modeled data sets; there is no clear trend. An analysis by region (Figs. 4B–4E) is more illuminating and reveals distinct patterns, especially along strike. In the northern broken foreland, exhumation paths (Fig. 4B) show a mix of rapid Cenozoic exhumation and more protracted histories with long-term residence at shallow crustal levels throughout the Mesozoic followed by a pulse of rapid cooling in the Cenozoic. In contrast, the thermal histories from rocks of the southern broken foreland (Fig. 4D) do not show any

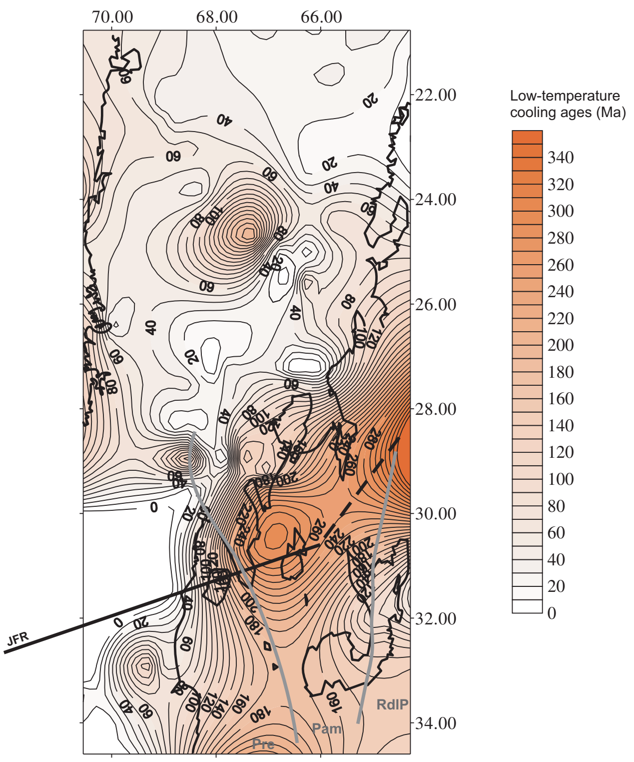

Figure 3. Contour map of published apatite fission track cooling ages (data from Table DR1; see footnote 1). Contour lines are in 10 m.y. intervals. Gray lines depict location of major sutures (after Ramos, 2009). Pre—Precordillera terrane, Pam—Pampia terrane, RdlP—Rio de la Plata terrane. Black line marks track of Juan Fernandez Ridge (JFR), and (similar to Fig. 2) oldest cooling ages cluster along this axis.

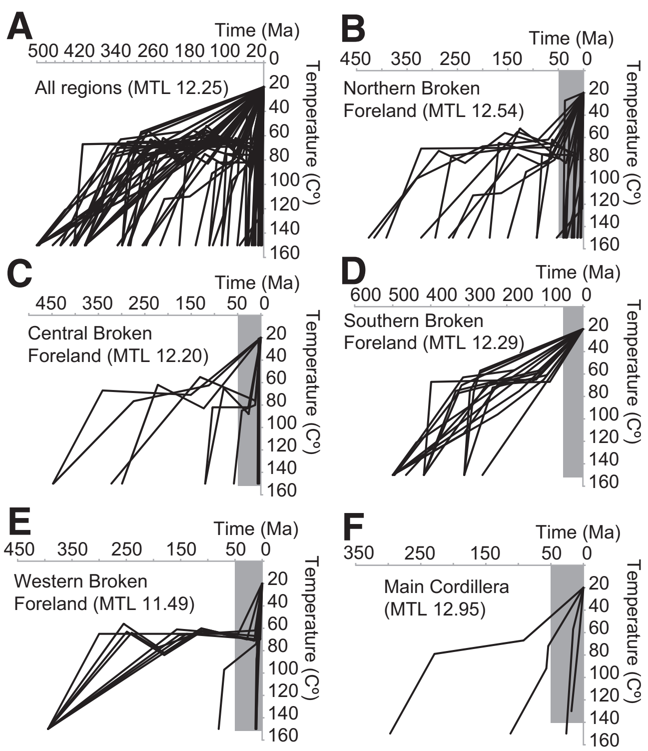

Figure 4. A–F: Apatite fission track thermal history modeling results using HeFTy software (Ketcham, 2005). Gray shaded areas highlight past 50 m.y. MTL—mean track length.

rapid exhumation in the Cenozoic. The central and western broken foreland (Figs. 4C–4F), at the foothill of the Main Andes, also records some flatter time-temperature histories, although there are fewer modeled samples from these areas. In summary, thermal history modeling shows that most of the broken foreland basement remained in the fission track partial annealing zone (~60–120 °C) until accelerated cooling in the Cenozoic.

DISCUSSION

The age compilation shows that only two areas in the Sierras Pampeanas broken foreland have late Tertiary AFT ages; both areas are located in the north (Figs. 2 and 3). The best evidence for late Neogene exhumation (ages younger than 7 Ma) within the entire foreland region come from crystalline basement samples collected from the Capillitas and Aconquija ranges at >3000 m a.s.l. (Fig. 1; Coughlin et al., 1998; Sobel and Strecker, 2003). The other young cooling ages come from the high plateau or detached basement along the Cordilleran thrust belt (e.g., Sierra de Maz, Fig. 1; Coughlin et al., 1998).

This localization of Neogene AFT ages is at odds with the geological evidence, which points to more widespread exhumation of rock from depths >4 km. The foreland geology includes thrust offsets (crystalline basement overriding Miocene or Pliocene rocks) well in excess of 4 km (Dávila et al., 2012). For example, the Sierra de Velasco (Fig. 1), at elevations of ~5 km a.s.l., contains basement thrusts that expose on their backlimb a rotated planation surface (the Pampean peneplain described by Jordan et al., 1989, and references therein). The paleosurface is a paraconformity locally covered by Late Miocene strata (Dávila et al., 2012) (see Fig. DR2). Basin seismic sections show 2–3 km of Miocene sedimentary rocks (Fisher et al., 2002); this would mean that exhumation on the fault scarp on the eastern flank of Velasco is between 6.5 and 7.5 km (based on 5 km for the highest peaks, less 0.5 km in the valleys, +2–3 km of Miocene sedimentation). At normal geothermal gradients rocks from the base of this section would yield Cenozoic AFT ages (Jordan et al., 1989), but this is not the case. Why are Cenozoic exhumation ages largely absent from the broken foreland region when the geologic evidence indicates substantial depths of erosion?

AFT ages from the basal sections of the Lower Miocene to Pliocene Vinchina Basin (Fig. 1), buried to a depth of >7–10 km, do not produce reset Neogene ages (Collo et al., 2011). Under global average geothermal gradient conditions such depths would be associated with temperatures of 200–250 °C, well above the normal 100–120 °C required to reset the AFT chronometer. Part of the explanation relates to the Arrhenius relationship between time and temperature, which defines the conditions for total fission track annealing. Rapid burial, followed by rapid exhumation, results in short exposures times to heating. Shorter exposure to elevated temperatures would increase, by ~20 °C, the total annealing temperature approximately equivalent to a 1 km increase in the depth for total track resetting. In addition, the short duration of burial and exhumation would not have allowed sufficient time for thermal equilibration with regional heat flow (typically >30 m.y.); this would depress the geothermal gradient by 10%–20% (Husson and Moretti, 2002).

Most published apatite thermochronometry studies have not taken these factors into account and have interpreted the Argentine broken foreland by assuming normal geothermal gradient values (i.e., ~30–25 °C/km), translating to exhumation from crustal depths of between 3 and 4 km (e.g., Jordan et al., 1989; Coughlin et al., 1998; Carrapa et al., 2008). However, recent mineralogical studies (illitization process analysis; Collo et al., 2011) have estimated a Late Miocene geotherm across the Andean foreland of between 15 and 18 °C/km.

Although rapid burial and subsidence have depressed local geotherms in the foreland basins, the regional heat flow has also been affected by the local mean angle of slab dip. For the northern to southern Andes the average dip is ~23.15° ± 1.46°, which is much lower than the world average of ~47.35° ± 2.05° (calculated from the global compilations of Syracuse

and Abers, 2006, using slab geometries contoured from the top surface of Wadati-Benioff zones over depth intervals of between 0 and 200 km). Thermal studies have shown that thinning and loss of the mantle wedge associated with slab flattening cuts off an important source of heat flow into the overlying crust, leaving radiogenic decay of minerals as the primary source of heat (40 mWm^{-2}; see Collo et al., 2011). Under such conditions total heat flow is unlikely to exceed 50 mWm^{-2}; rocks with typical thermal conductivity values (2.2–2.8 $W\ m^{-1}K^{-1}$) give maximum geothermal gradients in the range of 23–18 °C/km. Rapid burial and exhumation may also be linked to the relationship between oceanic ridge subduction and slab flattening. Paleomagnetic reconstructions show that the Juan Fernandez Ridge would have migrated 1300 km southward in 22 m.y. (i.e., ~60 km/m.y.; Yañez et al., 2001), suggesting that the influence of the ridge on the foreland region could have lasted only for a few million years.

CONCLUDING REMARKS

Since the major plate reorganization in South America in the Early Miocene, exhumation data have traditionally been explained as a response to shortening and crustal thickening. This study reinforces the idea of fast exhumation (see Figs. 3 and 4) along the Andean front, coincident with crustal growth. We were able to reconcile the rapid and large denudation recorded by the geology of the Sierras Pampeanas with exhumation data and interpretations that have argued for no significant crustal thickening in this part of the foreland by reinterpretation of the exhumation data using more realistic lower regional geothermal gradient values. Previous studies underestimated the magnitude of rock uplift and exhumation across the foreland region by failing to take into account the thermal consequences of flat-slab subduction and, for basin samples, short exposure to heating due to rapid burial and uplift.

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