Regional exhumation and kinematic history of the central Andes in response to cyclical orogenic processes

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ABSTRACT

Low-temperature thermochronological ages of samples from the central Andes correlate with major tectonic events during Late Cretaceous and Cenozoic times. Apatite fission-track (AFT) ages show prominent clusters during the Early–Late Cretaceous in the Coastal Cordillera and the Cordillera de Domeyko; Paleocene–Oligocene ages in the western Puna Plateau and Cordillera de Domeyko; and latest Eocene–Pliocene ages in the Eastern Cordillera. These ages track the expansion of the Andean orogenic edifice, the eastern front of which migrated rapidly eastward ~200 km and ~150 km during late Eocene and Pliocene times, respectively. During the intervening time interval, ca. 35–5 Ma, the orogenic strain front migrated slowly eastward through the Eastern Cordillera. A second cluster of Cretaceous ages in the Eastern Cordillera and Santa Bárbara Ranges documents exhumation related to extension in the Salta rift. The highly unsteady pace of orogenic wedge propagation suggests that kinematics controlled local climate, rather than vice versa. The frequency of AFT ages is anticorrelated with magmatic production in the central Andean arc and the rate of convergence between the Nazca and South American plates. We propose a link between AFT bedrock cooling ages in the central Andes and exhumation related to cyclical processes of shortening, wedge propagation, magmatism, and removal of dense roots from beneath the magmatic arc and thickened hinterland region. In particular, periods of sustained exhumation associated with local crustal shortening alternate with periods of rapid eastward wedge propagation during which exhumation was more spatially diffuse across the high-elevation hinterland. Episodes of spatially confounded exhumation are correlated with periods of relatively low magmatic production in the central Andean arc and relatively slow or declining plate convergence rates. We speculate that shortening in the upper crust was contemporaneous with underthrusting of lower crust and mantle lithosphere beneath the magmatic arc. Because of thermal inertia, melting of these underthrust rocks lagged behind the shortening events themselves, thus producing the observed temporal anticorrelation between rapid shortening-induced exhumation and arc magmatism.
INTRODUCTION

The central Andes contain the type example of an active continental margin magmatic arc and the world’s largest noncollisional orogenic plateau (Fig. 1; Isacks, 1988). Processes responsible for the construction of the central Andes include crustal thickening in response to horizontal shortening associated with the formation of a retroarc orogenic system, magmatic processes associated with the volcanic arc, erosional processes, which are partially responsible for redistributing mass within the orogenic wedge, and geodynamic processes associated with the subducting Nazca plate oceanic slab and the overriding South American plate (e.g., Jordan et al., 1983; Isacks, 1988; Kay et al., 1994; Allmendinger et al., 1997; Kley and Monaldi, 1998; Beck and Zandt, 2002; Schurr et al., 2006; Oncken et al., 2006; Strecker et al., 2007; Pelletier et al., 2006; Drew et al., 2009; Ducea et al., 2013; Schoenbohm and Barton, 2007). Isotopic and trace-element trends toward more-evolved magma compositions in the arc accompany the high-flux events and are interpreted to reflect melting of increasingly crustal components (Ducea, 2001). Isotopic and trace-element trends toward more-evolved magma compositions in the arc accompany the high-flux events and are interpreted to reflect melting of increasingly crustal components (Ducea, 2001). Metamorphism of overthickened crust also produces eclogite beneath the hinterland. Critical taper theory (e.g., Davis et al., 1983) suggests that during the formation of high-density roots, the orogenic wedge will be forced into a subcritical state in response to slightly decreased hinterland elevation; thus, the wedge will deform internally in order to increase taper. When the eclogitic roots reach critical mass, they may form convective instabilities that are prone to delamination or dripping into the asthenosphere (Kay and Kay, 1993; Ducea and Saleeby, 1998; Ducea, 2001; Zandt et al., 2004). This process of mass removal both relieves the accommodation space problem beneath the arc (e.g., McQuarrie et al., 2005) and causes isostatic uplift of the surface, potentially driving the orogenic wedge into a supercritical state (Garzione et al., 2006; DeCelles et al., 2009). Although the magnitude of such uplift is probably low (between 500 and 1000 m; Pelletier et al., 2010), and most of the elevation in the Puna Plateau region was achieved by Eocene–Oligocene time (Quade et al., this volume; Canavan et al., 2014), such small changes in surface uplift are enough to modify the state of stress within the orogenic wedge. In response to the excess gravitational potential energy in the uplifting orogenic wedge, the wedge will propagate forward in order to reduce its overall taper and regain a minimum-work state (Dahlen et al., 1984). Thus, the rate of magma production in the arc and the rate of crustal shortening of the orogenic wedge are anticorrelated, and the system oscillates between supercritical and subcritical states. Although critical taper theory has been formulated to explain thrust-belt-scale kinematics using a variety of different rheological parameterizations, the overall concepts of the original model are independent of scale and should apply at the orogenic belt scale (e.g., Willett et al., 1993).

In this paper, we use low-temperature thermochronology (primarily apatite fission-track [AFT] ages and, in places, apatite (U-Th)/He ages) as a proxy for the timing of exhumation and explore the spatio-temporal relationships among exhumation, deformation, and basin evolution with the goal of testing predictions made by the cordilleran cycle model (DeCelles et al., 2009). The study area in the central Andes of northwestern Argentina and Chile (Fig. 1) exhibits abundant evidence of lithospheric removal based on geophysical, petrological, and neotectonic studies (Kay et al., 1994; Schurr et al., 2006; Tassara et al., 2006; Drew et al., 2009; Ducea et al., 2013; Schoenbohm and Carrapa, this volume), and a rich record of arc magmatism has been documented in numerous studies (e.g., Haschke et al., 2002, 2006; Trumbull et al., 2006; Kay and Coira, 2009). A previous
thermochronological compilation highlighted the relationships among tectonics, climate, erosion, and geomorphology (Strecke et al., 2007) but did not attempt correlations between exhumation and lithospheric-scale processes. Key questions that we address with this study are: (1) Was regional exhumation (and the kinematic activity for which we accept it as a proxy) steady or unsteady during the growth of the central Andes? (2) What linkages exist among exhumation, kinematics, magmatic activity in the arc, and other potentially controlling processes? (3) Are trends in exhumation and deformation consistent with predictions of the cordilleran cycle model?

We compile previously published and new low-temperature thermochronological bedrock data from the Coastal Cordillera, Cordillera de Domeyko, Puna Plateau, Altiplano, and Eastern

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Figure 2. Isochron map of the Altiplano, Puna, and northern Sierras Pampeanas based on data in Table DR1 (see text footnote 1). AFT—apatite fission track.

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GSA Data Repository Item 2015008, Analytical details of apatite fission-track thermochronology and thermal modeling, is available at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
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Cordillera of northern Chile, northwestern Argentina, and Bolivia. Although we present data from the Altiplano as a general comparison (Fig. 2), we focus our discussion on the region in northwestern Argentina between ~21°S and 28°S.

Given the relatively low magnitude of Cenozoic maximum exhumation (6–8 km) in the Andes (Deeken et al., 2006; Strecker et al., 2007; Insell et al., 2012), AFT thermochronology is the ideal technique for recording Cenozoic and older exhumation signals. (U-Th)/He ages on zircons are Mesozoic and older, and (U-Th)/He ages on apatite are often partially reset, especially within the Puna Plateau (Carrapa et al., 2009; Reiners et al., this volume), and/or show large age scatter and low reproducibility in places such as the Salta rift province (e.g., Carrapa et al., 2014). On the other hand, apatite (U-Th)/He ages have been particularly useful in tracking the most recent exhumation signal within the Eastern Cordillera associated with propagation of the deformation front through a region previously occupied by a thick regional foreland basin (Carrapa et al., 2012). In this paper, we include data from the northern Sierras Pampeanas, which we correlate with the Eastern Cordillera (Safi pour et al., this volume), in our general compilation (Fig. 2), but we exclude them from the age versus longitude presentation in Figure 3 and from Figure 4.

**EXHUMATION OF THE CENTRAL ANDES**

Evidence of contractional deformation since the Cretaceous has been documented to the west of the Salar de Atacama in Chile (Mpodozis et al., 2005; Arriagada et al., 2006). Syndepositional deformation in Lower Cenozoic rocks of the Naranja...
Formation suggests that this area was the site of active tectonic shortening during Cretaceous and Paleocene time (Arriagada et al., 2006). AFT data from the Cordillera de Domeyko (Mas-kaev and Zentilli, 1999; Andriessen and Reutter, 1994) and from the Coastal Cordillera (Juez-Larré et al., 2010) in Chile support active exhumation and deformation in the region since the Cre-
taceous (Fig. 2).

New AFT ages from six samples from the Salar de Arizaro region (Table 1) are Jurassic to Eocene, indicating limited exhu-
mation in the region during the Cenozoic. An Eocene AFT age (37.3 ± 4.8 Ma) from the hanging wall of a thrust to the west of the Arizaro Basin (Fig. 2) suggests moderate local exhumation and deformation at that time. A granite cobble from Miocene synor-
genetic conglomerates (Schoenbohm and Carrapa, this volume) in the footwall of the same thrust has an AFT age of 68.7 ± 4.6 Ma (sample A09-FT1). This age, together with other Cretaceous and older ages (Table 1), suggests that although some exhumation occurred during the Cretaceous, most of the region was charac-
terized by limited exhumation in the Cenozoic, in agreement with the tectono-thermal history of samples east of the Salar de Arizaro (DeCelles et al., 2014). Limited exhumation of the Puna Plateau in the Cenozoic is in agreement with a high-elevation, dry plateau since ca. 36 Ma (Canavan et al., 2014).

Figure 4. Probability density curves of apatite fission-track (AFT) and apatite (U-Th)/He ages (AHe; Tables DR1 and DR2 [see text footnote 1]) correlated with isotopic lulls (Haschke et al., 2002) and convergence rates (compiled from Sdrolias and Müller, 2006; Pardo-Casas and Molnar, 1987; Somoza, 1998; Soler and Bonhomme, 1990). High-flux events are constrained using the age of volcanic rocks after Trumbull et al. (2006). Only samples from NW Argentina are included here (Table DR1).
TABLE 1. APATITE FISSION-TRACK (AFT) DATA FROM ARIZARO

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Lithology/sample</th>
<th>Lat, long (degrees, minutes)</th>
<th>Sample No.</th>
<th>ρ(_i) (tracks/cm(^2))</th>
<th>N(_i)</th>
<th>χ(_i) (%)</th>
<th>Age (Ma)</th>
<th>ρ(_D) (tracks/cm(^2))</th>
<th>N(_D)</th>
<th>χ(_D) (%)</th>
<th>U (ppm)</th>
<th>σ(U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A09-FT1</td>
<td>Granitic clast in Granitic basement</td>
<td>25° 6.39 6.81 364.7 2387 25.2</td>
<td>15.9</td>
<td>408.2 88.7 13.7 ± 1</td>
<td>1.274</td>
<td>352 9.476</td>
<td>240.5 14.1</td>
<td>4082</td>
<td>143.7 13.2 12.2 13.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A09-FT2</td>
<td>Granitic basement</td>
<td>20° 3.655 275 7.097 534 75.6</td>
<td>15.4</td>
<td>4082</td>
<td>106.0 13.4 5.8 NA</td>
<td>3.655</td>
<td>275 7.097 534 75.6</td>
<td>143.7 13.2 12.2 13.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARB09-13</td>
<td>Granitic basement</td>
<td>20° 7.60 7.40 7.40 7.40 7.40</td>
<td>40.0</td>
<td>408.2</td>
<td>106.0 13.4 5.8 NA</td>
<td>3.655</td>
<td>275 7.097 534 75.6</td>
<td>143.7 13.2 12.2 13.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10-gr1</td>
<td>Granitic basement</td>
<td>19° 7.982 265 14.639</td>
<td>40.0</td>
<td>408.2</td>
<td>106.0 13.4 5.8 NA</td>
<td>3.655</td>
<td>275 7.097 534 75.6</td>
<td>143.7 13.2 12.2 13.2</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Note: Samples were analyzed with an Olympus microscope with drawing tube located above a digitizing tablet and a Kinetek computer-controlled stage driven by the FTStage program (Dumitru, 1993). Analysis performed with reflected and transmitted light at 1600× magnification. Samples were irradiated at Oregon State University. Samples were etched in 5.5 M nitric acid at 21°C for 20 s. Following irradiation, the mica external detectors were etched with 40% hydrofluoric acid for 45 min. The pooled age is reported for all samples as they pass the χ\(_2\) test, suggesting that they represent a single population. Error is 1σ. ρ\(_i\) and ρ\(_D\) are the spontaneous and induced track density measured in external detectors, respectively (tracks/cm\(^2\)). N\(_i\) and N\(_D\) are the number of spontaneous and induced tracks counted, respectively. χ\(_2\) is the χ\(_2\) probability (Hurford and Green, 1983). Values greater than 5% are considered to pass this test and represent a single population of ages.

The Upper Eocene Geste Formation in the Salar de Pastos Grandes area of the eastern Puna (Fig. 1) contains proximal alluvial-fan deposits within a contractional growth structure (Carrapa and DeCelles, 2008). Detrital AFT ages from triple-dated (U-Pb, AFT, and apatite [U-Th]/He) Paleozoic apatite grains in the Geste Formation indicate rapid Eocene exhumation of local western source terranes (Carrapa et al., 2009). Together, these observations indicate that the Geste Formation in this area was deposited in the proximal wedge-top portion of the foreland basin system, implying that the deformation front must have migrated into the eastern part of the Puna by no later than ca. 38 Ma. Apatite (U-Th)/He ages from the same deposits and inverse thermal modeling of AFT and (U-Th)/He data indicate Miocene–Pliocene exhumation related to subsequent basin incision (Carrapa et al., 2009).

Eocene deformation and exhumation are supported by ca. 38 Ma AFT ages recovered from the southern Puna margin (Coutand et al., 2001) and by 24–35 Ma K-feldspar multi-diffusion domain modeling of the Aguilar granite near the north-eastern margin of the Puna (Insel et al., 2012). AFT ages from crystalline basement rocks in the eastern Puna and western Eastern Cordillera in northwestern Argentina (e.g., Luracatao and Cachi Ranges) indicate that the area was actively exhuming and deforming during early to middle Miocene time (Deeken, 2005; Pearson et al., 2012). Detrital AFT data from Miocene strata preserved in the Angastaco and Monte Nieva areas (Fig. 1) support rapid exhumation of the Eastern Cordillera during the Miocene (Coutand et al., 2006; DeCelles et al., 2011). An intraformational angular unconformity in ca. 14 Ma alluvial-fan deposits of the Angastaco Formation, derived from proximal Eastern Cordillera sources, indicates that this area was the site of wedge-top deposition and uplift by middle Miocene time (Carrapa et al., 2011, 2014b). This is corroborated by apatite (U-Th)/He data from the region between the Calchaquí Valley and the Rio de las Conchas to the east; combined with crosscutting relationships and the evidence of folding of Miocene–Pliocene strata, this indicates that the Eastern Cordillera was the site of active deformation between ca. 14 Ma and ca. 4 Ma (Carrera and Muñoz, 2008; Carrapa et al., 2014b; Pearson et al., 2013). Uplift of the Eastern Cordillera was associated with deformation and crustal thickening (Carrapa et al., 2014b). Growth strata in ca. 11–9 Ma alluvial-fan deposits in the Quebrada del Toro (Fig. 1) indicate active deformation and wedge-top deposition at this time (Mazzuoli et al., 2008; DeCelles et al., 2011). New paleoaltimetry data indicate that the Eastern Cordillera was uplifting between ca. 14 and 7 Ma (Carrapa et al., 2014a). Although the Eastern Cordillera was actively deforming during the Miocene and Pliocene, Cretaceous AFT and (U-Th)/He ages indicate limited Cenozoic exhumation of Cretaceous paleorift flanks and suggest significant paleotopography inherited from the Salta rift (Carrapa et al., 2014).
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indicate overall limited exhumation since the Cretaceous (<4 km, assuming a paleogeothermal gradient of 30 °C/km).

In particular, the presence of extensive Eocene evaporites in the Puna Plateau, along with stable isotopic evidence for coeval high paleoelevation, suggests that high and dry conditions limited the magnitude of erosion in the Puna during this time frame. These data also imply that the Puna region was never buried by a thick foreland basin, unlike parts of the Eastern Cordillera that were buried beneath thick Paleocene–Miocene foreland basin deposits (Starck and Vergani, 1996; DeCelles et al., 2011; Carrapa et al., 2012, 2014b) and subsequently incised during the late Miocene–Pliocene (Carrapa et al., 2012).

REGIONAL PATTERNS IN EXHUMATION AND KINEMATIC HISTORY

Figures 2 and 4 show the spatial-temporal patterns of cooling and exhumation based on AFT and apatite (U-Th)/He ages from the entire central Andean orogenic belt. We include data from the northern Sierras Pampeanas, which we correlate with the Eastern Cordillera (Safipour et al., this volume), in our general compilation (Fig. 2).

Cooling ages shown in Figure 3 are clustered into four major time-space groups: Cretaceous ages are abundant in the Chilean Coastal Cordillera and Precordillera (including the Cordillera de Domeyko) on the west, and in the Eastern Cordillera and frontal ranges to the east. Paleocene–Oligocene ages are abundant in the western Puna Plateau and Chilean Cordillera de Domeyko, and latest Eocene–Pliocene ages are abundant in the Eastern Cordillera. Each of these clusters represents a different tectonic-exhumation signal; correct interpretation depends strongly on local structural geological context and ancillary data sets that clarify each local situation. The gray line in Figure 3 tracks the orogenic strain front, which is based on the location of dated growth structures and wedge-top deposits discussed earlier and is essential for interpreting the meaning of the various cooling age signals.

The Cretaceous ages in the Chilean Precordillera may be reasonably interpreted to represent exhumation and cooling in response to shortening, crustal thickening, and development of orogenic topography during growth of the early Andes (Mpodozis et al., 2005; Arriagada et al., 2006). These ages are likely related to uplift and erosion in the nascent western thrust belt, which was confined to Chile. Contemporaneously, the Salta rift was active in Argentina to the east (Salfity and Marquillas, 1994). Uplift and exhumation of rift footwall blocks produced widespread Cretaceous cooling ages in the Eastern Cordillera and Santa Bárbara Ranges (Carrapa et al., 2014). By Paleocene time, the Salta rift was kinematically inactive and had been mostly buried by postrift thermal sag deposits of the Balbuena Subgroup (Salfity and Marquillas, 1994; Marquillas, 2005; DeCelles et al., 2011). Paleocene–Oligocene ages in the Puna Plateau reflect local uplift and exhumation in contractional structures associated with the eastward propagation of deformation into the eastern Puna region (Carrapa and DeCelles, 2008; Carrapa et al., 2009).

The Eocene–Pliocene ages are concentrated in the Eastern Cordillera and represent local structural growth; these ages track the eastward-migrating orogenic strain front, as determined mainly from growth structures in proximal wedge-top foreland basin deposits (Fig. 4). A fifth set of ages, in the ca. 68–47 Ma range and scattered over a broad region from the Eastern Cordillera to the Chilean Cordillera, with a few ages in the Puna Plateau, is not readily associated with the Salta rift or with local shortening in the thrust belt. These ages may result from partial annealing of apatites that experienced cooling during the Cretaceous rifting episode. Alternatively, these ages may be due to minor erosion associated with the passage through the region of the flexural forebulge, for which independent sedimentological evidence has been documented (DeCelles et al., 2011). We would expect no more than a few hundred meters of rock uplift in this case, so if this is indeed the cause of the Paleocene–early Eocene ages in the hinterland region, the rocks in which the ages are recorded must have been close to the top of the partial annealing zone before the flexural wave passed through the region. Together with evidence of wedge-top deposition in the same region at ca. 38 Ma (Carrapa and DeCelles, 2008), the forebulge cooling hypothesis would suggest an ~12–27 m.y. lag time between the migration of the forebulge and the arrival of the orogenic front. The forebulge was on the order of 300–400 km wide in this region (DeCelles et al., 2011). If the forebulge passed completely through this region between 65 Ma and 50 Ma, then its rate of migration would have been ~20–26 mm/yr.

We exclude Miocene–Pliocene AFT ages in the northern Sierras Pampeanas from our discussion of Figure 3 (Carrapa et al., 2006; Safipour et al., this volume) because the front of the orogenic belt swings southwestward in the transition zone to the Sierras Pampeanas such that a plot of age versus longitude becomes distorted. Nevertheless, these data are consistent with continued eastward propagation of the orogenic strain front (Fig. 4). Farther north at the latitude range of our main study area, orogenic strain migrated into the frontal Santa Bárbara Ranges during Pliocene time (Reynolds et al., 2000; Carrapa et al., 2011), and the present-day focus of seismic activity and neotectonic deformation is located in this region (Kendrick et al., 2006; Ramos et al., 2006; Metcalf and Kapp, this volume). Older (Cretaceous) cooling ages in the Sierras Pampeanas and the Bolivian Subandes (Fig. 2) may represent areas that have only recently (Miocene–Pliocene and younger) been uplifted and eroded, such that the present level of incision is insufficient to expose thermally reset rocks. Cretaceous ages in the Eastern Cordillera of NW Argentina record limited erosion of paleorift flanks that were only partially buried by Cenozoic foreland basin deposits and later exhumed (e.g., Carrapa et al., 2014).

Although the overall pattern of AFT and (U-Th)/He cooling ages has been approximated by a roughly 10 m.y. per degree of longitude trend of eastward-decreasing ages (Reiners et al., this volume), we note that an abrupt eastward shift in the timing of rapid exhumation during late Eocene time (ca. 40 Ma) is more consistent with structural and sedimentological constraints. In
particular, Figure 3 highlights the rapid migration of exhumation mainly based on well-dated growth structures, which demonstrate an abrupt eastward jump of the orogenetic strain front from the Chilean Cordillera de Domeyko into the eastern Puna region (Carrapa and DeCelles, 2008; tracked by the gray line in Fig. 3).

The large scatter of ages between ca. 40 and 5 Ma in the Eastern Cordillera (Figs. 3 and 4) is the result of exhumation slowly migrating through the region from latest Eocene through Miocene–Pliocene time, as demonstrated by growth structures (Carrera and Muñoz, 2008; Carrapa et al., 2011; DeCelles et al., 2011). The position of the modern deformation front requires that deformation had to abruptly shift into the Santa Bárbara system after ca. 4 Ma. AFT ages from the Bolivian Eastern Cordillera and Subandean zone generally correlate with ages from northwestern Argentina and are consistent with this regional exhumation history (Barnes et al., 2013; Fig. 2).

**NATURE OF THE CONTROL**

Numerous papers have been published attempting to synthesize the many available data sets from the central Andes in order to discern the overarching controls on the history of crustal thickening and mountain building (e.g., Isacks, 1988; Allmendinger et al., 1997; Beck and Zandt, 2002; McQuarrie et al., 2005; Oncken et al., 2006; Schellart, 2008; Kay and Cofa, 2009). This paper contributes to this evolving synthesis (e.g., Barnes et al., 2013) by providing a regional-scale thermochronological analysis of the central Andes within the context of known structural and sedimentological events. The summary in this volume by Reiners et al. provides additional data, especially apatite (U-Th)/He ages. When combined with data from geochronological/geochemical compilations of magmatic arc rocks (Trumbull et al., 2006; Haschke et al., 2002, 2006), the kinematic history outlined herein may be interpreted in terms of larger controlling factors such as climate and tectonics.

Exhumation and cooling require the removal of overburden, either by tectonic processes (e.g., normal faulting) or by erosional surficial processes. Inasmuch as large-scale normal faults in the central Andes are not documented outside of the Salta rift region, we set aside this process as the main control on Cenozoic regional exhumation. Erosional surficial processes generally require precipitation, and much has been written about the potential effects of climate-induced erosion (or the lack thereof) in the central Andes (e.g., Sobel and Strecker, 2003; Lamb and Davis, 2003; Strecker et al., 2007; Pelletier et al., 2010; Reiners et al., this volume). Much of this work has focused on the role of aridity in reducing the rate at which mass can be removed by flowing water in the chronically dry central Andes. Almost all (~80%) precipitation in the central Andes is derived from Atlantic easterlies; as moist easterly air masses are lifted against the ~3-km-high eastern rampart of the Andes during the summer monsoon, this moisture condenses and rains out (Zhou and Lau, 1998; Strecker et al., 2007). Easterly air masses are largely depleted of moisture upon arrival in the Eastern Cordillera and Puna Plateau, and the western flank of the central Andes is one of Earth’s driest regions. The modern climate-orography setup in the central Andes provides an attractive modern analog for interpreting past erosional processes in the orogen. In this view, expressed eloquently by Sobel and Strecker (2003), the steep eastern orogenetic front both creates and is in turn controlled by the climatic pattern: Orographic growth sets up the monsoon front, which in turn erosionally advects rocks toward the surface, confines active tectonic uplift to the region of rapid erosion, and further enhances the rain shadow such that hinterland regions are unable to export mass. Over time, orogenic taper becomes supercritical in response to the inability of surficial processes to export mass from the hinterland; new thrust faults become active in the foreland (i.e., the orogenic wedge propagates forward), and the cycle of enhanced erosion and advection repeats, thereby enlarging the high-elevation hinterland plateau.

If the model proposed by Sobel and Strecker (2003) is operating in the central Andes, three observable phenomena—the zone of rapid erosion (as proxied by rapid bedrock cooling rates), the region of high elevation, and the region of arid climate—should track the orogenic front through time. In detail, the zone of rapid erosion should be coupled with the orogenic strain front through time, and the orogenic hinterland region should gain elevation and aridity progressively eastward through time. The relationships between cooling ages and the timing of growth structures and wedge-top deposition demonstrate a tight linkage among exhumation, active deformation, and the position of the orogenic strain front (Fig. 4).

Aridity was established by early Cenozoic time in the central Andes of northern Chile and northwestern Argentina (Strecker et al., 2007; Quade et al., this volume). Evaporites and alluvial-fan deposits have been widespread in Chile and northwestern Argentina since the Paleocene (Hartley et al., 1992) and Eocene (Jordan and Mpodozis, 2006; Adelmann, 2001; Quade et al., this volume). Eocene–Miocene alluvial-fan and eolian deposits of the Vizcachera, Quebrada de los Colorados, and Angastaco Formations (Starck and Anzótegui, 2001; Carrapa et al., 2012; DeCelles et al., 2011) in the Puna Plateau and Eastern Cordillera of northwestern Argentina also indicate at least episodically dry climate. However, the dune field deposits preserved in the Quebrada de los Colorados and Angastaco Formations developed at relatively low elevations in the regional foreland basin (Carrapa et al., 2012; DeCelles et al., 2011), whereas those in the Vizcachera Formation formed at high elevation in the Puna Plateau (DeCelles et al., this volume; Quade et al., this volume). This suggests that, at least during the early Miocene, aridification in the central Andes may have been controlled by larger-scale climatic processes, rather than local tectonic orography (Starck and Anzótegui, 2001). More humid climatic conditions have been proposed in basins around the eastern perimeter of the Puna Plateau during the late Miocene (since ca. 7 Ma; Kleinter and Strecker, 2001). Sustained aridity was established at ca. 5 Ma in the Angastaco area within the Eastern Cordillera
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Recent stable isotope paleoaltimetry studies in the central Andes suggest that high elevations were achieved in the Puna Plateau region by the late Eocene (Canavan et al., 2014; Quade et al., this volume). Dry climate and high elevation in the central Andes would predict limited exhumation since the Eocene within the Puna and since at least the late Miocene–Pliocene within the Eastern Cordillera; these observations are consistent with the AFT ages (Fig. 4) and with data from Sobel and Strecker (2003). However, the unsteady eastward advance of the orogenic strain front cannot be explained simply as a response to steady-state orographic, precipitation-induced erosion along the eastern flank of the orogenic belt, nor is the kinematic history consistent with erosional pacing of kinematics (Sobel and Strecker, 2003). Rather, a more profound tectonic process seems to be at work here. To be clear, we find that the linkage between rapid erosion and local tectonic activity along the orogenic strain front (as envisioned by Sobel and Strecker, 2003) is strong, but that rapid erosion probably did not control the position of the strain front. Instead, we suggest that orography was first controlled by tectonic processes, and in turn possibly controlled local rain-out-driven rapid exhumation. The question becomes: What controlled the regional kinematic history? Alternative controls could include magmatism in the arc and back-arc regions (Haschke et al., 2002), changing angles of Nazca plate subduction (e.g., Kay and Coira, 2009), alongside changes in the rate of plate convergence (Pardo-Casas and Molnar, 1987). It is understood that these are not necessarily independent processes (e.g., Martinod et al., 2010). In particular, Martinod et al. (2010) suggested that periods of flat slab subduction under southern Peru and northern Chile during Eocene–Oligocene times resulted in a stronger interplate coupling and in a concentration of shortening within the upper plate away from the trench. In Bolivia and Argentina, flat slab subduction has been suggested for the early Miocene (Oncken et al., 2006; Coira et al., 1993; Kay et al., 1994).

Figure 4 illustrates the frequency distributions of apatite (U-Th)/He and AFT ages for NW Argentina. Apatite (U-Th)/He ages cluster in the time intervals 50–38 Ma and 20–5 Ma, consistent with the timing of arc high-flux events documented by trends in $^{143}$Nd/$^{144}$Nd and magmatic age data from Haschke et al. (2002) and Trumbull et al. (2006) (gray shaded areas in Fig. 4). This correlation may indicate that (U-Th)/He ages reflect thermal perturbations associated with the high-flux magmatic events rather than cooling associated with erosion. The AFT ages are less clustered than the apatite (U-Th)/He ages, but they do show a broad peak during the interval 40–15 Ma. The AFT ages are generally anticorrelated with the times of magmatic high-flux events. A relative lull in magmatic activity took place between ca. 35 Ma and 15 Ma (Fig. 4; Haschke et al., 2002; Trumbull et al., 2006), broadly coincident with the peak in AFT ages. As discussed already, the late Eocene AFT ages are mainly associated with exhumation in the Chilean Coastal Cordillera and Precordillera (including the Cordillera de Domeyko) and the eastern part of the Puna Plateau, whereas the Oligocene–Miocene ages are from samples in the Eastern Cordillera. In general, the AFT ages track the development and erosion of local structural features and indicate times of rapid erosion owing to local crustal shortening and thickening, which are also supported by structural, sedimentological, and provenance data sets (e.g., Carrapa and DeCelles, 2008; Carrapa et al., 2012, 2014b). Thus, crustal shortening was, in general, out of phase with magmatism. On the other hand, eastward jumps in the location of the orogenic strain front took place during late Eocene and Pliocene time, at the ends of the magmatic high-flux events.

Coira et al. (1993) and Kay et al. (1994) argued that a magmatic lull at the latitude of the Puna Plateau calls for flat subduction of the Nazca plate during the period 26–17 Ma. Yáñez et al. (2001) used plate reconstructions of the position of the Juan Fernandez aseismic ridge (which currently is associated with flat subduction outboard of the Sierras Pampeanas to the south of our study area) to argue for flat subduction during the interval ca. 20–9 Ma in the Puna region. Oncken et al. (2006) employed the flat subduction mechanism to explain rapid shortening in the Bolivian central Andes (19°S–22°S) as a response of the upper plate to increased coupling with the flat subducting lower plate. Although both timings (late Oligocene–early Miocene and early–middle Miocene) proposed for flat subduction are roughly coincident with the broad peak in AFT ages (Fig. 4), these ages are mainly confined to the Eastern Cordillera, which continues north for >500 km into Bolivia and has a similar kinematic (Oncken et al., 2006) and exhumation (Barnes et al., 2013) history over a much broader region than the proposed flat subduction region. We also note that the data assembled by Trumbull et al. (2006) do not show a deep magmatic gap over either of these time intervals; rather, the greatest gap in magmatic activity was ca. 32–26 Ma. Also, there is no evidence for a Sierras Pampeanas–style (Laramide-style) basement uplift event during either of the proposed flat subduction intervals. Although we do not discount the potential importance of flat subduction in the central Andes during middle Cenozoic time, we suggest that it was not the primary control on regional exhumation patterns.

The AFT ages are also not well correlated with the Nazca–South America plate convergence rate (Fig. 4), implying that the timing of crustal shortening (as proxied by the AFT ages) was not directly tied to rates of plate convergence. Shortening rates in the Bolivian sector of the central Andes show a similarly poor correlation with plate convergence rates (Elger et al., 2005; Oncken et al., 2006).

Given the shortcomings in alternative explanations for the regional exhumation signal in the central Andes, we turn to the Cordilleran cycle model as a means of integrating the history of magmatism, shortening, wedge propagation, and bedrock cooling ages. This model predicts that shortening and magmatism should be out of phase, with minimum rates of shortening correlating with periods of maximum magmatic productivity. This is postulated to result from the growing accommodation space
problem as underthrusting foreland lithosphere continues to accumulate beneath the arc. Melting and eclogite production beneath the arc and thickened hinterland region are delayed by 10–20 m.y. (Ducea, 2001), such that the magmatic high-flux event lags behind crustal shortening and thickening. As the dense hinterland roots become unstable and begin to founder, isostatic rebound causes the topographic surface to rise and the orogenic strain front to propagate rapidly toward the foreland. Crustal shortening accelerates as the high-flux event comes to an end. Conceivably, the AFT ages would mainly record the portion of the cordilleran cycle during which crustal shortening was relatively rapid, during and after the waning phase of the Eocene high-flux event. We refer to this as the recharge stage of the cycle (DeCelles et al., this volume).

We distinguish between rates of shortening and orogenic wedge propagation as follows: Propagation is the rate at which the orogenic wedge grows lengthwise in the tectonic transport direction, whereas shortening is the rate at which crust within the orogenic wedge reduces in length (DeCelles and DeCelles, 2001). Propagation is tracked by the orogenic strain front. Shortening and propagation rates are not necessarily coupled, and they represent different behavioral aspects of orogenic wedges. The orogenic wedge may shorten internally in order to build taper, or the wedge may propagate forward in order to reduce taper (e.g., Willett et al., 1993; DeCelles and Mitra, 1995). Thus, wedge propagation and shortening may be out-of-phase responses to different stress conditions within the wedge. In the case of the central Andes, the major propagation events took place during late Eocene and latest Miocene–Pliocene time (Fig. 4), and the major episodes of shortening-related exhumation occurred during Paleocene–middle Eocene and latest Eocene–Miocene time (Fig. 4). We suggest that the major propagation events heralded episodes of orogenic supercriticality, whereas the periods of locally controlled exhumation and shortening represent periods of time during which the orogenic wedge was subcritically to critically tapered, resulting in concentrated (stalled) exhumation (Fig. 4). The late Eocene propagation event may have been related to oroclinal bending, which predicts changes in wedge behavior and shortening (Martinod et al., 2010; Arriagada et al., 2008).

The cordilleran cycle model links these different states of orogenic wedge behavior to the history of magmatism and the growth and removal of dense lower-crustal and mantle lithospheric instabilities. Magmatic high-flux events were fueled by crustal shortening after 10–20 m.y. lag times, and periods during which dense arc and hinterland roots delaminated or dripped into the mantle both set the stage for rapid eastward propagation of the orogenic strain front and reduced arc magmatic activity to low levels. In this hypothetical context, rapid exhumation recorded by AFT dates is largely coupled with shortening during periods of slow wedge propagation and magmatic recharge. Apatite (U-Th)/He ages seem instead to correlate with high-flux events and with rapid wedge propagation (Fig. 4).

SUMMARY AND CONCLUSIONS

Our compilation of AFT and apatite (U-Th)/He ages in the central Andes demonstrates that bedrock cooling across the entire orogenic belt took place in response to several different processes. Cretaceous–Paleocene cooling ages in a relatively narrow region in Chile represent exhumation in the nascent central Andean thrust belt. Cretaceous cooling ages are also widespread in the Eastern Cordillera and frontal Santa Bárbara Ranges and are explained as the effect of Salta rift–related exhumation (Carrapa et al., 2014). An abrupt eastward shift in the locus of rapid exhumation from the Chilean thrust belt into the Puna Plateau region during late Eocene time (ca. 40–38 Ma) accompanied the development of growth structures in the eastern Puna region and is consistent with the attainment of regionally high elevation (Canavan et al., 2014; Quade et al., this volume). From late Eocene through late Miocene time, the zone of rapid exhumation was confined almost exclusively to the Eastern Cordillera, where growth structures and the sedimentology and provenance of wedge-top deposits (Carrera and Muñoz, 2008; Bywater-Reyes et al., 2010; Carrapa et al., 2012, 2014b; DeCelles et al., 2011) demonstrate a close linkage between rapid exhumation and local crustal shortening. During latest Miocene–Pliocene time, the orogenic strain front once again migrated rapidly forward into the Santa Bárbara and Subandean Ranges (Reynolds et al., 2000; Echavarria et al., 2003), but the evidence for bedrock cooling associated with this kinematic event is not yet exposed at the surface.

Our analysis suggests a strong correlation between rapid bedrock cooling/exhumation and local crustal shortening confined to relatively narrow (<100-km-wide) zones in the orogenic wedge. On the other hand, periods of rapid orogenic wedge propagation (not to be confused with shortening) are associated with regionally diffuse AFT cooling patterns (Fig. 4). Although a close linkage between rapid erosion controlled by rainout from orographically lifted moisture-laden air masses and bedrock cooling ages is plausible, the pattern of eastward migration of clusters of cooling ages (along with structural and sedimentological indicators of local thrust faulting) is highly unsteady and indicates that orographic precipitation was likely controlled by the kinematic and uplift history of the orogen, rather than vice versa.

A comparison of the cooling age spectra with published data on magmatic activity and plate convergence rate shows strong temporal anticorrelations. Bedrock AFT cooling ages, associated with local shortening, are correlated with a full in magmatic activity and overall reduced plate convergence rate (Fig. 4). We suggest that this pattern is consistent with a model for cordilleran orogenic systems in which crustal shortening feeds magmatic high-flux events, which in turn produce dense eclogitic residues and roots beneath the arc and the hinterland of the retroarc thrust belt. When these roots become unstable and begin to founder into the mantle, the orogenic wedge becomes supercritically tapered and propagates forward. Apatite (U-Th/He) ages seem to record cooling associated with deformation driven by this mechanism. Within a few million years after the propagation event, arc mag-
matism is strongly reduced as the lower crust and lithosphere underthrusting beneath the hinterland during the preceding period of shortening heats up in anticipation of the next high-flux magmatic event. This way of explaining the nonuniform, unsteady distribution of cooling ages in the central Andes is attractive because it does not require multiple episodes of flat subduction or unrealistic assumptions about the long-term kinematic behavior of the orogenic wedge.

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