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Eocene exhumation of the High Andes at ∼30°S differentiated by detrital multimethod U-Pb-He thermochronology

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ABSTRACT

The southern Central Andes (∼25–40°S) exhibit a complex tectonic history, crucial for understanding orogenic processes in subduction-related orogens, yet debate on the timing and mechanisms of early Cenozoic topographic growth persists. We present double-dated detrital zircon U-Pb and (U-Th)/He thermochronology data from the early Oligocene–Miocene Bermejo Basin at ∼30°S to investigate source unroofing during development of the High Andes. (U-Th)/He results yield dates of ca. 565–16 Ma (n = 73), with distinct detrital modes that indicate a mixing of sediment sources characterized by variable cooling and exhumation histories. We employ a novel approach for modeling detrital thermochronology data that leverages the shared basin subsidence history of multiple detrital modes to resolve provenance and source unroofing histories. Results from the lower Oligocene Vallecito Formation (northwestern Argentina) reveal that detritus was sourced from Permian–Triassic Choiyoi Group rocks that underwent rapid late Eocene cooling, indicated by short lag time (2–5 m.y.) between source cooling and deposition. Our findings are consistent with bedrock studies of Eocene exhumation in the High Andes and establish source-to-basin connectivity during this time. Other detrital modes with pre-Cenozoic cooling histories were derived from Carboniferous Elqui-Colangüil and Choiyoi Group rocks or recycled from Paleozoic basins. We propose that an early Oligocene drainage divide in the High Andes was located west of the Punilla–La Plata fault, an active thrust front at ∼30°S. These findings challenge Paleogene neutral stress-state models for the Andes and underscore the importance of improved knowledge of erosion and deformation histories for refining models of Andean orogenesis.

INTRODUCTION

The Central Andes are an archetypal subduction-related orogen (Ramos, 1988), with a tectonic history that underpins geodynamic models of Cordilleran orogenesis and debate on the timing and mechanisms of topographic growth (Coira et al., 1982; DeCelles et al., 2015; Quade et al., 2015; Giambiagi et al., 2022). In the southern Central Andes (∼25–40°S), the Miocene–recent tectonic history is increasingly well-understood as a time of major orogenic wedge development (Giambiagi et al., 2022). In contrast, the early Cenozoic record remains contentious even after decades of work in developing tectonic reconstructions, stress state, and surface response to subduction dynamics (Coira et al., 1982; Ramos, 1988; Giambiagi et al., 2022). The paucity of Paleogene basin records has been interpreted as a period of tectonic stasis and diminished plate coupling during subduction (Horton and Fuentes, 2016). However, new basin studies suggest initiation of distal retroarc deposition starting in Eocene time and point to a sediment source in the High Andes (e.g., Fosdick et al., 2017; Suriano et al., 2023; Ronemus et al., 2024). Recent work from the High Andes (Fig. 1) documents late Eocene shortening and rapid rock cooling at 30°S (Lossada et al., 2017; Rodríguez et al., 2018; Mackaman-Lofland et al., 2023). These studies suggest an earlier history of Andean orogenic development similar to that observed farther north at the latitude of the Puna Plateau (22–26°S) (DeCelles et al., 2011; Carrapa and DeCelles, 2015).

Detrital thermochronology using multiple chronometers has enabled major advances in understanding sediment provenance, hence advancing our knowledge of orogenic erosion and orogen-to-basin routing systems (e.g., Reiners et al., 2005; Carrapa, 2010). We present double-dated detrital zircon (U-Th)/He thermochronology and time-temperature (*t-T*) history modeling from the Huaco section of the Bermejo foreland basin (Fig. 1) that test conflicting models of Paleogene plate coupling and regimes, identify basin-bounding eastward draining hinterland catchments, and quantify the timing of Andean source unroofing. Detrital zircon U-Pb age spectra and eastward paleoflow in these strata point to the High Andes and Argentine Precordillera as sediment sources (Fosdick et al., 2015, 2017). We differentiate distinct detrital modes with unique *t-T* histories that document rapid syndepositional cooling of detritus derived from the High Andes during the latest Eocene–early Oligocene, indicating rock unroofing during hinterland deformation. Our findings highlight a novel modeling approach of detrital thermochronology datasets that leverages the shared basin subsidence history of mul-

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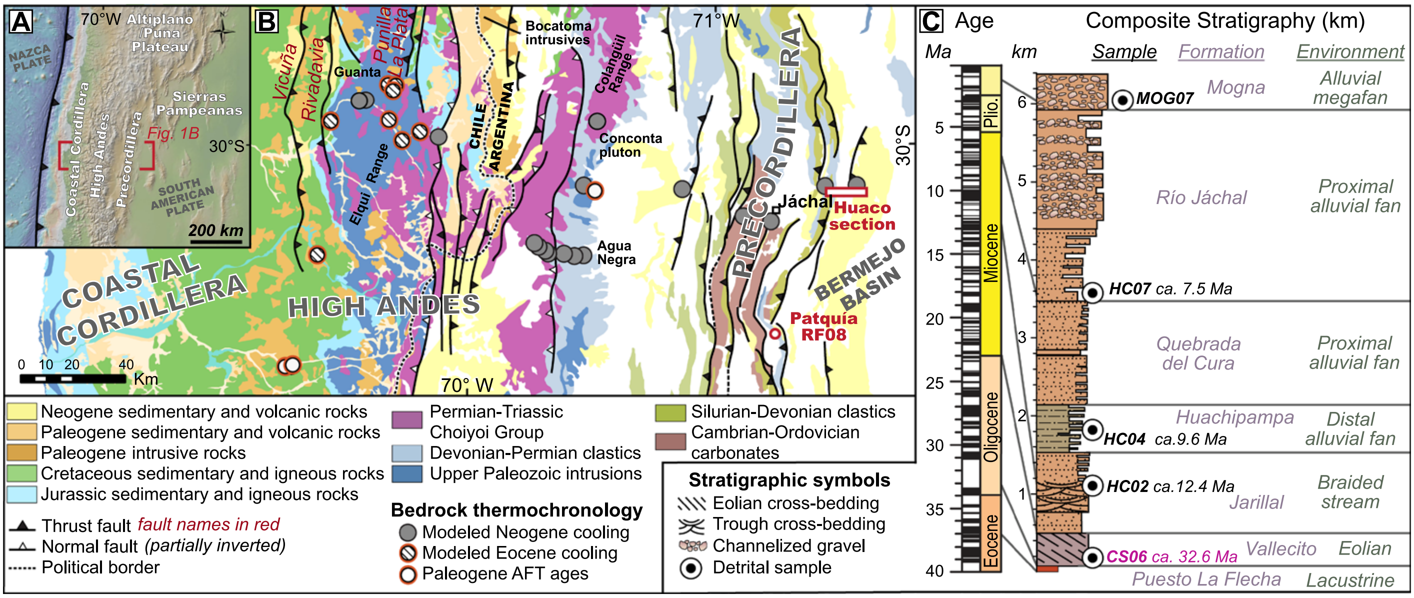

Figure 1. **(A) Tectonic setting in the southern Central Andes. Bathymetry and topography are from GeoMapApp v.3.7.1. (https://www.geomapapp.org; Ryan et al., 2009). (B) Geology at 30°S showing the Huaco section sample locality in the Bermejo Basin and thermochronology localities in the High Andes and Argentine Precordillera that exhibit Eocene cooling (orange circles with hatched pattern) or only Neogene cooling (gray circles) from time-temperature history modeling (Fosdick et al., 2015; Lossada et al., 2017; Rodríguez et al. 2018; Mackaman-Lofland et al., 2023). Sample RF08 (this study) is from the Permian Patquía Formation. Geology after Furque et al. (2003), SERNAGEOMIN (2003), and Murillo et al. (2017). AFT—apatite fission-track. (C) Huaco section composite stratigraphy modified from Johnson et al. (1986) and Fosdick et al. (2017). Plio.—Pliocene.**

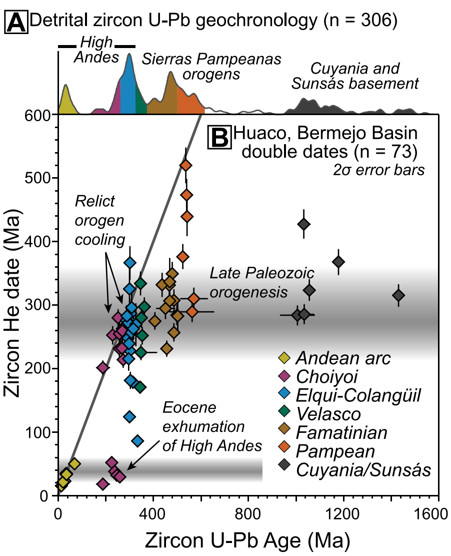

Figure 2. **(A) Detrital zircon U-Pb data from the Huaco section of the Bermejo Basin in the southern Central Andes (see Fig. 1 for location) showing primarily Andean-derived sediment and recycled Sierras Pampeanas and Cuyania/Sunsás sources. (B) Zircon U-Pb (published; see Supplemental Material [see text footnote 1]) and (U-Th)/He (ZHe; this study) data colored by U-Pb age mode and source association (after Fosdick et al., 2017). Diagonal line shows equivalent U-Pb and (U-Th)/He ages indicative of rapid cooling.**

tiple detrital modes to resolve provenance and *t-T* histories of upland sources.

METHODS AND RESULTS

(U-Th)/He thermochronology is based on retention or diffusive loss of ^{4}He produced during decay of radioactive U, Th, and Sm (e.g., Farley, 2002). In zircon, ^{4}He is lost via volume diffusion at ~50–200 °C, depending on grain size, chemical zonation, radiation damage, and cooling rate (e.g., Reiners et al., 2004; Guenthner et al., 2013). We collected 73 zircon (U-Th)/He (ZHe) dates from four Oligocene–Miocene Bermejo Basin sandstone samples that were dated previously by U-Pb laser ablation–inductively coupled plasma–mass spectrometry (Fosdick et al., 2015, 2017; Val et al., 2016). Zircon grains for ZHe analysis, extracted from U-Pb mounts, were chosen from the seven primary U-Pb age groups represented in published detrital U-Pb age spectra: Andean Arc, Choiyoi, Elqui-Colangüil, Velasco, Famatinian, Pampean, and Cuyania/Sunsás. Analytical methods and data are provided in the Supplemental Material[1].

Double-dated detrital zircon U-Pb and ZHe analysis of the Bermejo Basin yields 565–16 Ma ZHe dates (Fig. 2; Fig. S1 in the Supplemental Material). Cenozoic Andean Arc zircons exhibit 51–16 Ma ZHe dates that overlap with their U-Pb crystallization ages. Permian–Triassic Choiyoi Group zircons exhibit two distinctive ZHe modes at 280–202 Ma (Choiyoi I) and 52–18 Ma (Choiyoi II). Zircons within the older ZHe mode overlap with their U-Pb ages (Fig. 2). The Carboniferous–Permian Elqui-Colangüil zircons display 581–87 Ma ZHe dates, with a pronounced mode at 387–178 Ma. Latest Neoproterozoic–early Paleozoic zircons recycled from Gondwanan orogens (Pampean, Famatinian, Velasco) display 497–180 Ma ZHe dates, with most dates 424–238 Ma. The Mesoproterozoic Sunsás/Grenville zircons yield 422–285 Ma ZHe dates.

Inverse thermal history modeling explores plausible *t-T* histories that are compatible with measured analytical data and prescribed geologic constraints (Ketcham, 2005; Murray et al., 2022; Ketcham, 2024). We used HeFTy 2.0 software (Ketcham, 2024) to model the *t-T* histories of four detrital "U-Pb-ZHe modes," defined here by coupled U-Pb and ZHe data (Fig. 2), from the lower Oligocene Vallecito Formation (Fig. S3). These four modes represent zircons with sources originating in the Andes (Elqui-Colangüil, Choiyoi I, Choiyoi II, and Andean Arc) and specifically test the connections between High Andes cooling and inferred source exhumation (Fig. 3A; Fig. S3). The Vallecito Formation represents early foredeep sedimentation and flexural subsidence during Andean growth

[1]Supplemental Material. Methods and analytical data. Please visit https://doi.org/10.1130/GEOL.S.25987918 to access the supplemental material; contact editing@geosociety.org with any questions.

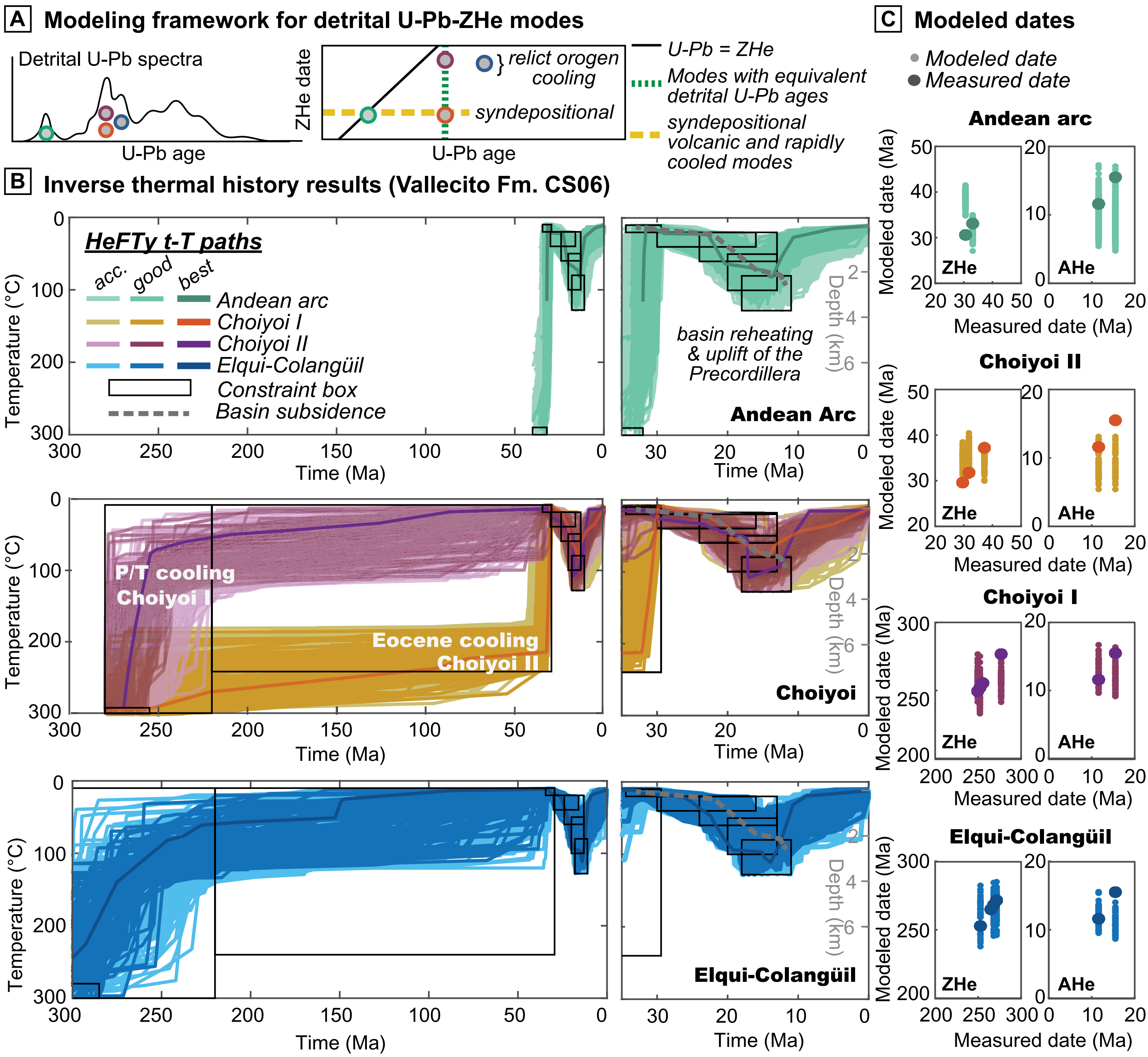

Figure 3. (A) Interpretive framework for modeling detrital zircon U-Pb-ZHe modes [ZHe—(U-Th)/He]. (B) HeFTy (software; Ketcham, 2024) Model 3 inversion results for the High Andes U-Pb-ZHe detrital modes from the Vallecito Formation (Fm.) (sample CS06 in Figure 1C) showing distinct time-temperature (*t-T*) histories of the Elqui-Colangüil, Choiyoi, and Andean Arc zircons. Gray dashed line shows basin subsidence data from Fosdick et al. (2017). acc.—acceptable. (C) Measured ZHe and apatite (U-Th)/He (AHe) dates (large circles) versus modeled dates (small circles) generated from HeFTy *t-T* paths (see Supplemental Material [see text footnote 1]).

(Jordan et al., 2001; Fosdick et al., 2017). For detrital samples with double-dated zircon U-Pb and ZHe data sets, we employed an approach for modeling distinct U-Pb-ZHe modes that leverages their shared burial history, with the assumption that each mode comprises detritus from upland sources with similar *t-T* histories.

We conducted three inverse thermal history models for each detrital mode with a progressively more tightly defined Bermejo Basin post-depositional heating constraint to show the combined improvement on inversion results when using the shared basin history of detrital modes. Model 1 uses a broad basin reheating box spanning depositional age to recent. Model 2 incorporates constraints from basin subsidence history (Fosdick et al., 2017). Model 3, our preferred model, discussed below, is further refined by restricted post-depositional reheating conditions required by thermochronologic data for all four U-Pb-ZHe modes (Fig. 3). All models also incorporate published apatite (U-Th)/He (AHe) data (Fosdick et al., 2015) that constrain post-depositional burial and exhumation. Modeling details are provided in the Supplemental Material.

Model 3 inverse *t-T* history results of the Elqui-Colangüil mode indicate cooling from initial conditions at ca. 300–280 Ma followed by residence below 120 °C prior to deposition at the surface (Fig. 3). Between 280 Ma and 38 Ma, some paths remain near surface conditions, while paths that underwent a lower magnitude of early cooling exhibit a second phase of cooling from <120 °C toward the surface. Modeling results from the two Choiyoi modes capture distinct source *t-T* histories with rapid Permian–Triassic (Choiyoi I) or Eocene (Choiyoi II) cooling (Fig. 3). The Andean Arc mode

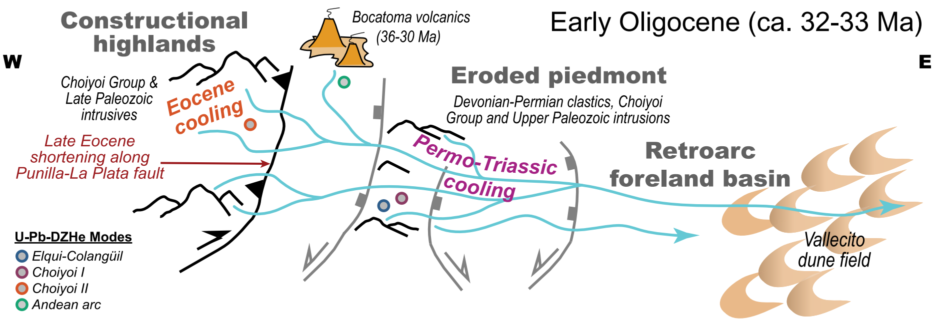

Figure 4. Schematic paleogeography of the Bermejo Basin in the southern Central Andes during deposition of the lower Vallecito Formation at ca. 33–32 Ma, showing headwaters in the High Andes. Our study suggests a drainage divide located west of the Punilla–La Plata fault (see location in Fig. 1B) and erosion of Eocene-cooled Choiyoi Group (Fig. 1B) rocks. Additional sediment sources include volcanic rocks related to Eocene Bocatoma magmatism and Late Paleozoic intrusives and recycled sources in low-lying piedmont hills.

yields *t-T* paths that indicate rapid cooling to surface conditions.

All detrital modes allow for post-depositional reheating of the Vallecito Formation as constrained by both ZHe and AHe dates (Figs. S4–S7). Given the well-established subsidence history within the Bermejo Basin (Jordan et al., 2001; Fosdick et al., 2017), we narrowed this range of basin *t-T* histories by using constraint boxes that impose the observed foreland-type subsidence history with an accelerating rate of burial heating during increased subsidence. Basin *t-T* histories inverted from all modes yield peak basin heating to an average of 95–110 °C at ca. 16–15 Ma (Fig. S7).

Leveraging Basin History to Quantify Source Exhumation

Thermal history modeling of multiple detrital U-Pb-ZHe modes provides a powerful tool to quantify source *t-T* histories (Fig. 3; Figs. S6–S8). In the Bermejo Basin, the four modeled modes require post-depositional reheating, although the timing and extent of heating are variable among modes. Remarkably, the region of overlapping reheating *t-T* path segments, particularly the more restrictive results from the Andean Arc mode, form a unique thermochronometric constraint during shared basin evolution (Fig. S7). We use this result to refine the range of plausible *t-T* histories for all age modes (Fig. 3). By requiring the *t-T* paths of detrital modes to conform to the same well-constrained basin history, the broad range of source *t-T* path segments are reduced. Notably for the Choiyoi-II mode, a more restrictive basin history results in more tightly controlled cooling histories that suggest rapid late Eocene cooling and short thermochronologic lag times; i.e., the difference between detrital thermochronologic closure age and depositional age of the sample (Fig. S8). In cases where the basin subsidence is unknown, the overlapping results that satisfy all modes may serve as a powerful guide for defining the basin *t-T* history.

Rapid Late Eocene Exhumation in the High Andes at 30°S

Double-dating zircon U-Pb-ZHe data from the early Oligocene–Miocene basin infill indicate a mixing of sediment sources characterized by variable exhumation histories. Elqui-Colangüil grains in the Vallecito Formation exhibit ZHe dates and source *t-T* histories comparable to Elqui-Colangüil detrital zircon ZHe dates recycled from the Carboniferous–Permian Agua Negra and Patquía Formations (Fig. 1; Table S2; Fosdick et al., 2015; Mackaman-Lofland et al., 2023). Similarly, Choiyoi I grains record Permian–Triassic cooling that suggests their source is either the Choiyoi Group rocks or recycled strata. These findings are consistent with reworking of relict orogen low-lying piedmont sources (Fig. 4).

In contrast, the Choiyoi II mode exhibits onset of rapid cooling at ca. 38–35 Ma, requiring rapid cooling through the ZHe closure window to surface conditions by ca. 32.6 Ma (Fig. 4). We propose that the Choiyoi II mode was sourced from the High Andes or similar intrusions in the Colangüil Range, suggesting early Oligocene drainage connectivity between the Bermejo foreland and the hinterland (Fig. 4). These findings are consistent with structural and thermochronological evidence from the Guanta Plutonic Complex (Fig. 1) that indicate rapid cooling and exhumation of the High Andes during a late Eocene (ca. 40–35 Ma) shortening along the Punilla–La Plata thrust (Lossada et al., 2017; Rodríguez et al., 2018; Mackaman-Lofland et al., 2023). Based on similar crystallization ages and thermal histories, we contend that the Guanta Plutonic Complex and nearby Choiyoi Group (Pankhurst et al., 1996; Martin et al., 1999) are viable sources for Choiyoi II zircons. Using the *t-T* inversion results for onset of cooling—which are guided by diffusion kinetics and geologic constraints—we compute thermochronologic lag times of ~2–5 m.y. for the Choiyoi II mode, suggesting rapid source unroofing. The High Andes were a locus of arc magmatism for hundreds of millions of years (e.g., Haschke et al., 2006), and thermal effects from Cenozoic magmatism on Choiyoi II ZHe sources cannot be fully ruled out. However, given the sparse extent of mapped intrusions of this age (Coira et al., 1982; Murillo et al., 2017) and a well-documented structural and thermal record, we suggest minimal reheating of hinterland Choiyoi II sources from Eocene intrusions. Localized arc-derived sources to the Vallecito Formation include volcanic rocks related to Eocene Bocatoma magmatism (Bissig et al., 2001).

Growing evidence of late Eocene shortening, exhumation, and retroarc sedimentation in the Central Andes at 30°S suggests a phase of Andean construction (Giambiagi et al., 2022) that was contemporaneous with orogenic wedge development farther north in the Puna Plateau (Fig. 1) where substantial shortening took place in the early Cenozoic, consistent with development of high elevation as early as late Eocene time (DeCelles et al., 2015; Quade et al., 2015; Henríquez et al., 2023). Absolute constraints on Cenozoic paleotopography at 30°S are absent; however, our results point to a drainage divide located west of the Punilla–La Plata fault by ca. 33 Ma (Fig. 4). Proximal foredeep deposits associated with early Cenozoic shortening were largely removed by subsequent Neogene thrust-belt propagation in the western Frontal Cordillera and Argentine Precordillera.

CONCLUSIONS

Our thermal history modeling of coupled detrital zircon U-Pb and ZHe dates from the Bermejo Basin document distinct sediment sources within the High Andes. Modeling results from Permian–Triassic Choiyoi Group zircons (Choiyoi II) in the Vallecito Formation document rapid late Eocene cooling, indicating a short lag time between ZHe cooling and deposition. This work is consistent with structural and thermochronological evidence from the High Andes that suggests rapid cooling of the Choiyoi Group during late Eocene shortening along the Punilla–La Plata fault (Lossada et al., 2017; Rodríguez et al., 2018; Mackaman-Lofland et al., 2023). Our findings are difficult to reconcile with a neutral Paleogene stress-state model (Horton and Fuentes, 2016), and instead suggest an active phase of shortening, exhumation, and sediment routing to the distal foreland at 30°S in late Eocene–early Oligocene time. Improved knowledge of the timing and duration of erosion and deformation is important to evaluate models of Andean cyclicity (DeCelles et al., 2015) and evolutionary stages of orogenic wedge growth (Giambiagi et al., 2022; Ronemus et al., 2024). As double-dating detrital thermochronology capabilities expand (e.g., Horne et al., 2016), a modeling approach for discrete detrital U-Pb-ZHe modes may prove a powerful tool to better resolve source-to-sink *t-T* histories.

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