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NEW THERMOCRONOLOGICAL DATA OF THE CRETACEOUS-CENOZOIC CLASTIC SEQUENCES FROM THE VINCHINA BASIN: LINKAGE BETWEEN BURIAL, EXHUMATION AND THERMAL FLOW VARIATIONS.

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ABSTRACT

New apatite fission track (AFT) and (U-Th)/He (AHe) data from two sections recording Cretaceous-Cenozoic clastic successions (La Flecha - La Troya Sur creeks) in the northern sector of the Central Precordillera of Argentina are presented. The results show that the Ciénaga del Río Huaco, Puesto la Flecha and Vallecito Fms. would have crossed the 60 °C isotherm during burial, while the middle sector of the Vinchina Fm. would not have reached temperatures higher than 55 °C. Multimethod inverse thermal modeling suggests that the AFT ages of all the studied levels would not have been completely reset and allow inferring that the partial retention zone for the AHe system (AHe-PRZ) would have been reached during the Miocene in levels between the Vallecito and Vinchina Fms. Our 1D-modeling results for the Ciénaga del Río Huaco, Puesto la Flecha and Vallecito Fms. show that the maximum temperature would have been reached at ~ 15 Ma, with a sedimentary thickness of ~ 2750 m and a heat flow of 65 mW/m². From these data, a geothermal gradient of ~ 27 °C/km at this time could be inferred. In turn, the Vinchina and Zapallar Fms. would have reached their maximum temperature at ~ 2 Ma, under a cooler thermal regime (20 mW/m²) and with an estimated geothermal gradient of <15 °C/km. Thus, a complex time-temperature trajectory is proposed. Maximum and cooling temperatures reached by each unit do not correspond in all cases to the maximum burial and exhumation times. Comparison of the thermal modelling from this work with those carried out by other authors for sections immediately to the north allows us to infer that the thermal regime within the Vinchina basin has important lateral variations. Finally, AFT and AHe analyzes carried out in this work constitute a baseline database of the thermal regime, which is necessary for future multiproxies studies that are being done to evaluate the preservation of

primary thermal signals, and thus check their reliability for paleoclimatic and paleoenvironmental interpretations.

Keywords: AFT, (U-Th)/He, inverse thermal modeling, thermal regime, Vinchina basin, Cretaceous-Cenozoic sedimentary basin.

1. INTRODUCTION

Post-depositional thermal histories of sedimentary basins are of broad interest in various geological fields. In this regard, low temperature thermal proxies are used in a wide variety of sedimentary records to make inferences regarding the temperatures associated with preserved paleoclimatic and diagenetic processes. Classic proxies used in this type of studies are analysis of clay minerals, fluid inclusions, organic matter maturity, and isotopic and thermochronological indicators, among others. Although these proxies are applied in many and varied contexts, they are usually used individually (a single analytical method or a single proxy; Thiry and Dupuis, 2000; Birks and Birks, 2006; Fagel, 2007) and to solve specific problems without weighing the influence of the variety of superimposed processes that affect the sedimentary units from their deposition, lithification, to their deep burial. As an example, studies based on associations of clay minerals to establish either paleoclimatic and paleoenvironmental conditions or post-depositional processes could be mentioned. Although some studies of paleoclimatic and paleoenvironmental conditions of different geological periods based on this proxy take into account the influence of diagenetic processes (eg. Daoudi et al., 2010), many others do not consider such influence or subjectively assume that diagenesis can be negligible (e.g., Thiry, 2000; Net et al., 2002; Ruffell et al., 2002; Daoudi et al., 2008; Raucsik and Varga, 2008; Bauluz et al., 2014). Similarly, many studies that attempt to establish paleothermal conditions, geodynamic contexts and geothermal gradients do not take into account possible compositional variations related to paleoenvironmental changes or primary source variations (e.g., Hower et al., 1976; Merriman and Peacor, 1999; Collo et al., 2011; Clauer and Lerman, 2012). For this reason, in order to make inferences regarding the temperatures associated with different processes coexisting during the evolution of a basin, it is necessary to perform detailed studies that allow discriminating the primary signals from those linked to the processes of shallow and deep diagenesis. A first step in this direction is to know the thermal-temporal regime that affected a sedimentary basin during its post-depositional history.

Thermochronological analysis constitute one of the most widely used techniques by the geological community in recent decades for the reconstruction of time-temperature burial histories of sedimentary basins (e.g. Naeser et al., 1989; Armstrong and Chapman, 1998; Armstrong, 2005; Tagami and O'Sullivan, 2005; Ketcham 2012; Mahoney et al. 2019; Pujols et al., 2020). In particular, apatite fission tracks (AFT) and (U-Th)/He in apatites (AHe) have been used to establish thermal histories at temperatures between $\sim 60^{\circ}\text{C}$ and $110\text{-}140^{\circ}\text{C}$, and $\sim 60^{\circ}\text{C}$ and $75\text{-}80^{\circ}\text{C}$, respectively, intervals known as "partial annealing zone" and "partial retention zone" (PAZ and PRZ; Ketcham et al., 1999; Farley, 2002). These proxies are considered as systems almost exclusively affected by thermal and temporal factors associated with post-depositional processes, which allows us to rule out the influence of factors associated with paleoenvironmental dynamics, such as primary composition and early mineral neof ormation. Moreover, the post-depositional thermal history of a

sedimentary basin may not be as simple as it is interpreted in most cases from thermochronological studies, i.e. considering a stable thermal regime through time and maximum temperatures and cooling ages related with maximum depths and exhumation stages, respectively. Actually, this history can be much more complex.

In this work, we present thermochronological analysis of two geological sections (La Flecha - La Troya; Fig. 1) within the northern limit of the Argentine Precordillera and the Western Sierras Pampeanas. These sections are located on the eastern flank of the syncline that constitutes the La Flecha range, in La Rioja province, and preserve a thick and relatively continuous Cretaceous-Cenozoic strata. Although several authors have carried out studies characterizing and modeling the evolutionary history of these sections (Ciccioli, et al., 2010; Collo et al., 2015), no AFT analyses have been performed. In this region, a transition from normal to flat subduction regime during the Cretaceous-Cenozoic time interval has been interpreted (Kay et al., 1991; Gutscher et al., 2000; Jordan et al., 2001; Kay and Mpodozis, 2002; Ramos et al., 2002; Yañez et al., 2002; Ramos and Folguera, 2009; Gans et al., 2011; Collo et al., 2018) and discrepancies exist regarding the associated thermal regime (see Collo et al., 2011 and Stevens Goddard and Carrapa, 2018), both at regional and local scales (Stevens Goddard and Carrapa, 2018). So, it constitutes an ideal scenario to make inferences regarding the effects of a changing thermal regime on the post-depositional history. Specifically, the AFT and AHe carried out in this work allows decipher the temperatures reached after deposition, their relationship with the basin thermal regime and its variations between the Cretaceous and Cenozoic and, consequently, to improve the understanding of the relations between the thermal field and the geodynamics in this region.

Furthermore, as these strata records paleoclimatic, paleoenvironmental (Ciccioli et al., 2005, 2010) and lithological variations, clay minerals, fluid inclusions and isotopic analyses are being carried out. In this context, this study will also constitute a baseline of knowledge of the thermal regime necessary for future evaluation of the preservation of the primary signals of these proxies, and thus define their reliability for future paleoclimatic and paleoenvironmental interpretations.

2.GEOLOGICAL FRAMEWORK AND THERMOCHRONOLOGICAL BACKGROUND

The sections studied in this work include the sediments belonging to one of the depocenters associated with the extension that affected the central-western region of Argentina during the Cretaceous (Franzese et al., 2003), and the overlapping synorogenic deposits of the Cenozoic Vinchina foreland basin (eg. Jordan et al., 1993). These Cretaceous-Cenozoic sequences were affected by Andean deformation during the Cenozoic and are exposed in the northern frontal zone of the fold and thrust belt (Allmendinger and Judge, 2014).

The study area is in the northern boundary of the Argentine Precordillera with the Western Sierras Pampeanas (La Rioja province, Fig.1 a, b), approximately 20 km north-northwest to the town of Guandacol. It forms part of the eastern flank of the La Flecha syncline, which is composed of a relatively continuous Cretaceous-Cenozoic sedimentary succession (Fig.1c) overlying the Triassic-Jurassic Santo Domingo Fm. (Ciccioli et al., 2005; Tedesco et al., 2007).

The Cretaceous strata correspond to the upper-middle part of Ciénaga de Río Huaco Fm. (Ciccioli et al., 2005; Limarino et al., 2000; Tedesco et al., 2007), which

consists of ~120 m thick fluvial and playa lake deposits. This formation lies conformably on the red strata of the Triassic Santo Domingo Fm. and are superseded by Cenozoic units of the Vinchina foreland basin above a paraconcordance surface (Limarino et al., 2001; Ciccioli et al., 2010). The Cenozoic levels preserve sediments characteristic of fluvial, ephemeral lacustrine and aeolian environments associated in general with arid and semiarid climate conditions (Ciccioli et al., 2010), corresponding to the Puesto la Flecha (Caselli et al., 2002), Vallecito (Tripaldi, 2012), Vinchina (Turner, 1964), Zapallar (Furque, 1972) and El Corral Fms. (Furque, 1963). In the La Flecha range, the entire section has an approximate thickness of ~6 km.

Precise ages are unknown for the Ciénaga del Río Huaco, Puesto la Flecha, and Vallecito Fms. in the La Flecha and La Troya creeks (Fig.1). For the top of the Ciénaga del Río Huaco Fm. (northern La Flecha range; Nacimientos) Tedesco et al. (2007) obtained a K-Ar age in a tuff of 108.1 ± 4.4 Ma. One hundred km to the south in the Huaco anticline section (Fig.1), Fosdick et al. (2017) obtained detrital zircon U-Pb maximum depositional age (MDA) of 93.6 ± 7.3 Ma for the top of the same unit (~ 150m thick), 36.8 ± 1.7 Ma for the Puesto la Flecha Fm. (~ 95m thick) and between 32.6 ± 1.5 and 30.1 ± 0.5 Ma for the base of the Vallecito Fm. (~ 300 m thick). In the Valle Hermoso section (~122 Km to the north, see Fig.1), Stevens Goddard and Carrapa (2018) obtained a MDA of 16.0 ± 0.3 Ma for the Vallecito Fm. (~300m thick) based on U-Pb detrital zircons. In the same section, these authors propose for the Vinchina Fm. (~ 5500m thick) MDA ages of 18.6 ± 0.4 Ma (U-Pb detrital zircons at the base of the unit), 13.8 ± 1.7 Ma (1000m above the base), 9.2 ± 0.5 Ma. (at ~ 3220m from the base) and 9.3 ± 0.4 Ma (top of the unit). Ciccioli et al. (2014) reported a MDA U-Pb age of 15.6 ± 0.4 Ma obtained from detrital zircons collected from a thick tuffaceous interval of the Lower Member of the Vinchina Fm. at La Cueva (Precordillera) and a depositional U-Pb age of 9.24 ± 0.034 Ma from a thin tuff bed in the Upper Member of this unit at Quebrada de Los Pozuelos (Northwestern Sierras Pampeanas). Within the La Flecha creek, Collo et al. (2015) published a MDA of 16.3 ± 1.2 Ma based on U-Pb analysis in detrital zircons of a tuff collected close to the base of the Vinchina Fm.

Farther to the north in the Vinchina section (see Fig.1), Stevens Goddard and Carrapa (2018) document an age of 8.9 ± 2.5 Ma from the base of the overlying Toro Negro Fm. (~ 1400m thick), correlated with the Zapallar Fm. in our study area. In the same section, U-Pb zircon ages from tuffs were used by Amidon et al. (2016) and Ciccioli et al. (2018) to propose depositional ages between ~ 6.9 ± 0.1 Ma at the base and 2.4 ± 0.03 Ma at the top of the Toro Negro Fm., and a MDA age $<1.4 \pm 0.5$ Ma for the El Corral Fm., which discordantly lies immediately above the Toro Negro Fm.

Available thermochronological data of the Vinchina basin in the studied transect are scarce (Figs.1, 2). Stevens Goddard and Carrapa (2018) published single-grain AHe ages between 3.4 and 5.7 Ma for the base of the Vinchina Fm. and between 17 and 114.2 Ma for its middle part. For the same section, Collo et al. (2015) published single-grain AHe ages between 3.3 and 7.4 Ma for one sample at ~ 300m from the base of the Vinchina Fm. In addition, Reynolds et al. (1990) published a central ZFT age tuff of 12.1 ± 2.8 Ma for the top of the Vinchina Fm. (Las Juntas section in their work). Location of complementary AFT and AHe data from the Vinchina and Valle Hermoso sections is shown in Fig. 1b.

3. MATERIALS AND METHODS

Twelve samples were taken from sandstones corresponding to Cretaceous-Cenozoic sedimentary units in the La Flecha and La Troya sections in order to perform AFT and (U-Th)/He analyzes. Apatite grains suitable for fission track dating and (U-Th)/He analyzes were concentrated and separated from their host rock samples by conventional mineral separation techniques. Overall, these minerals are naturally concentrated in sandstone and these kinds of rocks can be found throughout the entire studied section.

Each sample was stratigraphically located based on previous detailed studies (Caselli et al., 2002; Ciccioli et al., 2005; Collo et al., 2015). Sample location in the stratigraphic column and their coordinates are shown in Fig. 2 and Table 1, respectively.

3.1. Apatite (U-Th)/He analysis (AHe)

To carry out (U-Th)/He analyses, three to five apatite grains per sample were analyzed from four samples (TG011T, TG014T, TG016T and TG018T, see Fig. 2 and Table 1). Apatite concentration was performed at the Low Temperature Thermochronology Laboratory of the University of São Paulo. Each apatite grain was photographed and packed in 1 mm Pt tubes using an Olympus SZX16 stereoscopic microscope, following the procedure proposed by Farley (2002). The grain dimensions and the number of crystal terminations were determined to calculate the correction factor associated with alpha ejection (Ft, Farley et al., 1996). Helium measurements were performed at the University of Potsdam, Germany. The platinum tubes were loaded into a 25-hole sample chamber of an ASI Alphachron He analysis and extraction system, equipped with a 978nm 30W coherent diode laser and a Pfeiffer Prisma 200 Quadrupole mass spectrometer. The abundance of ^4He in the purified gas was measured by isotope dilution using a ^3He tracer, calibrated against a gauged ^4He standard. A second analysis or re-extraction was performed for each sample to ensure that the grain was completely degassed. Following degassing, the analysis of U, Th and Sm was carried out at the GFZ Potsdam by isotope dilution using a Thermo Element 2 XR ICP-MS equipped with a CETAC ASX-520 automatic sampling system, and was run in the low resolution mode to maximize ion transmission. Age calculation followed the procedures of Meesters and Dunai (2005). An uncertainty of 2σ is reported for all ages. The potential effect of radiation damage on the AHe data was evaluated by comparing the effective uranium ($e[U] = U + 0.235 * \text{Th}$) and the grain size with individual ages (see Fig. 3) as a proxy for radiation damage, following the model by Flowers et al. (2009).

3.2. Apatite Fission Track analysis (AFT)

AFT analyzes were performed on 12 samples (see Fig. 2 and Table 1) following procedures described in Tagami and O'Sullivan (2005). The grinding and concentration of heavy minerals were carried out in the Heavy Minerals Grinding and Concentration laboratory of CICTERRA and in the Low Temperature Thermochronology Laboratory of the University of São Paulo. Two aliquots of each sample were prepared. One aliquot was analyzed for age determination by the External Detector Method (Gleadow and Duddy, 1981), using an Olympus BX51 microscope with a digitizing tablet and the FTStage 4.05 software (Dumitru, 1993) at the Low Temperature Thermochronology Laboratory of the São Paulo University. Ages and errors were calculated using the zeta calibration method (Hurford and

Green, 1983), using a zeta calibration factor of 79.6 ± 1.8 (CN1 glass; Cecilia Wunderlin) obtained by analyzing a total of 9 Durango and Fish Canyon Tuff age standards. An uncertainty of 1σ is reported for all ages. The other aliquot was irradiated with ^{252}Cf fission-fragments in order to make visible a greater number of confined tracks for length measurements (table SM2 in supplementary material). The AFT counting was performed on an average of 20 grains per sample (see table 2 and table SM1 in supplementary material). The potential effects of variations in track annealing kinetics were evaluated by measuring Dpar values.

3.3 Multimethod thermochronological modeling

Multimethod inverse thermal modeling was applied in samples with AHe and AFT data. TG011T, TG014T, TG016T and TG018T samples were modeled using the QTQt v5.7.0R software (Gallagher, 2012), considering all AHe aliquots and AFT ages (this is justified in section 4.4), track lengths and angles to the C-axis and using the Dpar measurements as a kinetic and compositional parameter. This allows probable thermal histories to be extracted using Bayesian transdimensional statistics. At least 500,000 interactions were performed. For the fission track annealing parameters, we used the kinetic model of Ketcham et al. (2007); for the AHe system, we used the radiation damage model of Flowers et al. (2009).

Taking into account the geological configuration of the modeled samples, we applied restrictions to the model based on geological information that includes the depositional age of each level (Table 1), an approximate exhumation age of the sections (~ 2 Ma according to Amidon et al., 2016) and the depositional (20 ± 5 °C) and current (20 ± 5 °C) temperatures. Maximum ages of ~ 200 Ma and maximum temperatures of 140 °C were used for the search space, considering that this is large enough not to influence the model.

3.4 1D thermal modeling

Simplified reconstructions of the post-depositional and thermal history of the studied section were performed using the 1D-Petromod® software package. The main assumptions for modeling are: (1) because it is an entirely siliciclastic section, rock decompaction factors proposed by Sclater and Christie (1980) was used, (2) variations in seawater depth over time are assumed to be irrelevant, because all deposits involved in this study are continental and thermal evolution is mainly affected by sediment thickness rather than depth of the water; (3) a surface temperature of 20 °C is assumed and (4) variable heat flow values over time are assumed following the proposal of Collo et al. (2011). The 1D model was performed to obtain variations in heat flow values through time, allowing the maximum QTQt modeled temperatures to be reached. The thicknesses and ages of the stratigraphic units are shown in Table 1.

4. RESULTS

4.1. AHe analyses

The results obtained for the four samples analyzed are shown in Table 2 and Fig. 2. Apatite grains had an equivalent spherical radius between 42.7 and 65.8 μm and eU contents between 2.9 and 70.8 ppm. AHe ages range from 5.7 ± 0.8 to 109.2 ± 2.2 and show an upsection increase in dispersion, so that some aliquots are older than

the depositional ages and therefore represent partially reset ages (Fig. 2 and 4). The overall negative linear correlation between eU vs. AHe ages (Fig. 3) for most samples measured shows that the more commonly used models of radiation damage (Flowers et al., 2009; Gautheron et al., 2009), which predict enhanced He retentivity and hence older ages for damaged (i.e., eU-rich) grains, cannot explain the dispersion in AHe ages obtained (Fig. 3). It is likely that this dispersion is caused by samples with very different provenance histories and the effect of preservation of radiation damage from the source area. Therefore, used all aliquots for each sample in the model calculation. For the Puesto la Flecha Fm. (TG011T), five AHe ages between 5.7 and 9.7 Ma were obtained. These ages are younger than the depositional age of 37 Ma (Fig. 4), suggesting either total or partial resetting of the AHe system after sediment accumulation. For the Vallecito Fm. five AHe ages ranging between 7.4 and 32.0 Ma were acquired in sample TG014T. For the Vinchina Fm. four aliquots yield AHe ages between 8.2 and 109.2 Ma in sample TG016T, collected at 550m from the base, and three aliquots from sample TG018T, collected at 1100 m above the base, yield ages between 13.1 and 70.9 Ma. Ages from all samples show a large dispersion, although for most of the samples, this is unrelated to variations in the effective uranium concentration (Fig. 3). As AHe ages from the Vinchina Fm. are older than the depositional ages (see Fig. 4), it is concluded that they were not reset during burial.

4.2. AFT analysis

The AFT central ages obtained are shown in Table 3 and Fig. 2. Mean track lengths (MTL) were obtained in 4 samples based on a variable amount of 4 to 99 confined tracks available (Tables 2 and SM2 in Supplementary Material).

In the deepest sample, at the base of the Fm. Ciénaga de Río Huaco (TG002T), no apatite grains were identified. For the top of this unit (TG010T), AFT central ages of 122.2 ± 19.4 Ma and 76.2 ± 13.7 Ma were measured in two aliquots (A and B), respectively. TG010T-A is the only sample analyzed that passes the χ^2 test, but just 4 grains could be measured in it (see Table 3 and Fig.5). About 10 m up section, at the base of the Puesto la Flecha Fm. (TG011T), an AFT central age of 60.7 ± 4.6 Ma (n=18) and an MTL of 14.7 ± 1.4 μm (n=4, Fig. 5d) were obtained. For the Vallecito Fm., sample TG014T yielded an AFT central age of 39.0 ± 3.3 Ma (n=15) with a MTL of 11.3 ± 0.2 μm (n=12, Fig. 5c). For the Vinchina Fm. two AFT central ages were obtained. A sample collected at 550 m from the base (TG016T) yielded an age of 119.3 ± 6.5 Ma (n=24) and an MTL of 11.3 ± 0.3 μm (n=43, Fig. 5b) and a sample at 1110 m from the base (TG018T) yielded an age of 137.9 ± 6.1 Ma (n=24) and a MTL of 13.6 ± 1.2 μm (n=99, Fig. 5a).

A slightly bimodal track-length distribution (see Fig. 5), χ^2 test values <5% (except sample TG010T-A) and the relationship between the obtained ages and the time of deposition (see Fig. 4) for all samples suggest that the AFT ages are unreset or, at most, partially reset.

Samples TG020T, TG021T, TG022T, TG023T and TG024T, collected stratigraphically up-section, were processed but, considering that all the samples analyzed at deepest levels do not show evidence of a complete resetting, were not analyzed (see Fig. 2 for location of the samples).

4.3. Multimethod thermochronological thermal modeling

The results of the multimethod QTQt modeling are shown in Fig. 6 and Table 4. In general, a decrease in the peak temperatures is observed upsection. In the deepest analyzed sample (TG011T, Puesto la Flecha Fm.) the modeled maximum temperatures are between 95 and 105 °C, showing partial reset AFT ages and total reset AHe ages (Figs. 4 and 7). Maximum temperatures gradually decrease to TG0014T (~ 95-105 °C) and TG016T (~ 90-100 °C) and, according to the model, these temperature peaks were reached in a time interval between 30 and 12 Ma (Table 4). The shallowest sample (middle section of the Vinchina Fm.) shows a maximum temperature of ~55 °C, which is consistent with a lack of resetting in the two systems analyzed (see Figs. 4). This temperature is achieved, according to the model, in a time interval between 15 and 1.5 Ma (Table 4).

The obtained models cannot reproduce all aliquots adequately, as some of them are only partially reset and the thermal history in the source area is most likely different for each aliquot. However, we decided to include them in the models because if the older aliquots are discarded, the models can overestimate the maximum temperatures reached by considering a total reset of the AHe system.

4.4. Petromod 1D thermal modeling

The results of the 1D Petromod thermal modeling (Fig. 7, Table 4, supplementary material SM3) shows that for the Ciénaga del Río Huaco, Puesto La Flecha and Vallecito Fms. the maximum temperatures obtained from thermochronological models (95 and 70°C, respectively) would have been reached at ~15 Ma, with a sedimentary thickness of approx. 2750 m and a basal heat flux of 65 mW/m². After the temperature maximum was reached (from ~11 Ma) these units would have experienced cooling associated with a reduction of the basal heat flux to 20 mW/m², consistent with the AHe ages (between 5.3-9.6 Ma) obtained from the TG011T sample, despite the basin being in a subsidence stage. This cooling would be reinforced by a blanketing effect associated with an increment in the sedimentation rates during the deposition of the Vinchina Fm. (See Fig. 7). Furthermore, our 1D forward thermal model shows that the Vinchina and Zapallar Fms. experienced the entire heating and cooling history in a cooler regime, with peak temperatures (64 and 60°C, respectively) reached at approximately 2 Ma, at the moment when the units would experience the maximum burial within the basin.

5. DISCUSSION AND CONCLUDING REMARKS

Thermochronological analysis together with 1D modeling allow inferring a complex relation between maximum temperatures and timing in the studied sections (Fig. 7 and table 4). According to the models, the Ciénaga del Río Huaco, Puesto la Flecha and Vallecito Fms. would attain resetting temperatures for the AHe system (>80 °C) during the early Miocene, and they would have crossed the ~60 °C isotherm during the cooling trajectory between ~16 and 6 Ma. The Vinchina and Zapallar Fms. did not reach total resetting temperatures for the AHe system at any time during their burial. The thermal models (QTQt) show that the middle part of the Vinchina Fm. reached a maximum temperature of ~55°C at ~5 Ma, that is, after the deposition of the part of the Cenozoic sediments. The deepest modeled sample (TG011T, Puesto La Flecha Fm.) would not have reached temperatures above the AFT closure temperature (>120 °C). Taken together, the data allows us to approximate the base of the Miocene PRZ for the AHe system (~80 °C, Farley,

2002) in this region to lie within the upper section of the Vallecito Fm. and the base of the Vinchina Fm. (Fig. 4).

Through the 1D Petromod thermal modeling we could associate the maximum temperatures reached, the burial and exhumation histories of the basin and the variations in heat flow that would have taken place in the region during the Miocene. Before ~15 Ma a thermal gradient of ~27 °C/km is estimated, while for the Pliocene we propose a geothermal gradient of <15 °C/km (both based on basal temperatures, sedimentary thicknesses and a surface temperature of 20°C). The temporal gap between Miocene and Pliocene-Pleistocene maximum temperatures is interpreted as strongly associated with thermal flow variations (65 and 20 mW/m², respectively, see Fig. 7) likely associated with the installation of the flat slab subduction in the region (Gutscher et al., 2000; Collo et al., 2015), and also with the blanketing effect, and allow explaining the abrupt decrease in maximum temperatures modeled for the TG018T sample (~55°C).

The complex time-temperature trajectory modeled in this work reinforces the hypothesis of a change in heat flow during the installation of the flat slab and also support the thermal regime proposed by Collo et al. (2015) for the Vinchina basin based on AHe ages and clay minerals analysis, whose model considers a thermal flux of 65 mW/m² before to 15 Ma and a gradual decrease from that age to 20 mW/m² since 11 Ma to present. Likewise, these results are also consistent with the extremely low gradient in this foreland basin proposed by authors such as Dávila and Carter (2013), Richardson et al. (2013), Bense et al. (2014), Hoke et al. (2014) and Collo et al. (2018), as well as with those recorded for other flat slab regions (eg. Dumitru, 1990, Dumitru et al., 1991, Gutscher 2002, Manea and Manea 2011).

It should be noted, however, that the paleotemperature distribution in the studied sections is substantially different from that observed by Stevens Goddard and Carrapa (2018) for the Vinchina section, immediately to the north, which estimated Mio-Pliocene gradients of 25-35 °C/km. These authors record AFT ages which are interpreted as reset at approximately 5400m from the surface of the Cenozoic section (middle section of the Vinchina Fm.; MDA: 9.2 ± 0.5 Ma; AFT age: 8.9 ± 3.5 Ma, Sample VN3-2020). Although track lengths for the analyzed samples are not available, the ages allow modeling and thus to discern whether they are completely or partially reset. The simple comparison between the ages obtained for levels with comparable maximum attained burial depths in our sections allows substantial differences to be corroborated. Sample VN3-4032 in the Vinchina section, located ~3400m below from the base of the El Corral Fm., has an AFT age of 6.6 Ma (Stevens Goddard and Carrapa, 2018), while sample TG018T in the La Flecha section (this work), located ~3750m below from the base of the El Corral Fm., yields an AFT age of 138.9 Ma and AHe ages between 13.1 and 70.9 Ma. Based on this comparison, it is likely that these substantial differences reflect local-regional variations in the thermal regime.

Lastly, it should be noted that the results obtained in this work allow us to sketch a complex thermal history for the Cretaceous-Cenozoic clastic successions in the La Flecha and La Troya Sur Sections, in which burial, exhumation and changes in the thermal regime are combined. The maximum time-temperature relationships records a cooling mechanism associated with the change in thermal flux, which does not correspond with the traditional concept in which the onset of cooling is directly related to the onset of exhumation and, at the same time, constitutes an advance in the understanding of the paleothermal regime of this particular Andean sector. Moreover, it is a solid baseline from which to move forward in future studies

concerning the degree of preservation of primary thermal signals from clay minerals, fluid inclusions and isotopic analyses and define their reliability for paleoclimatic and paleoenvironmental interpretations.

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FIGURE CAPTIONS

FIGURE 1

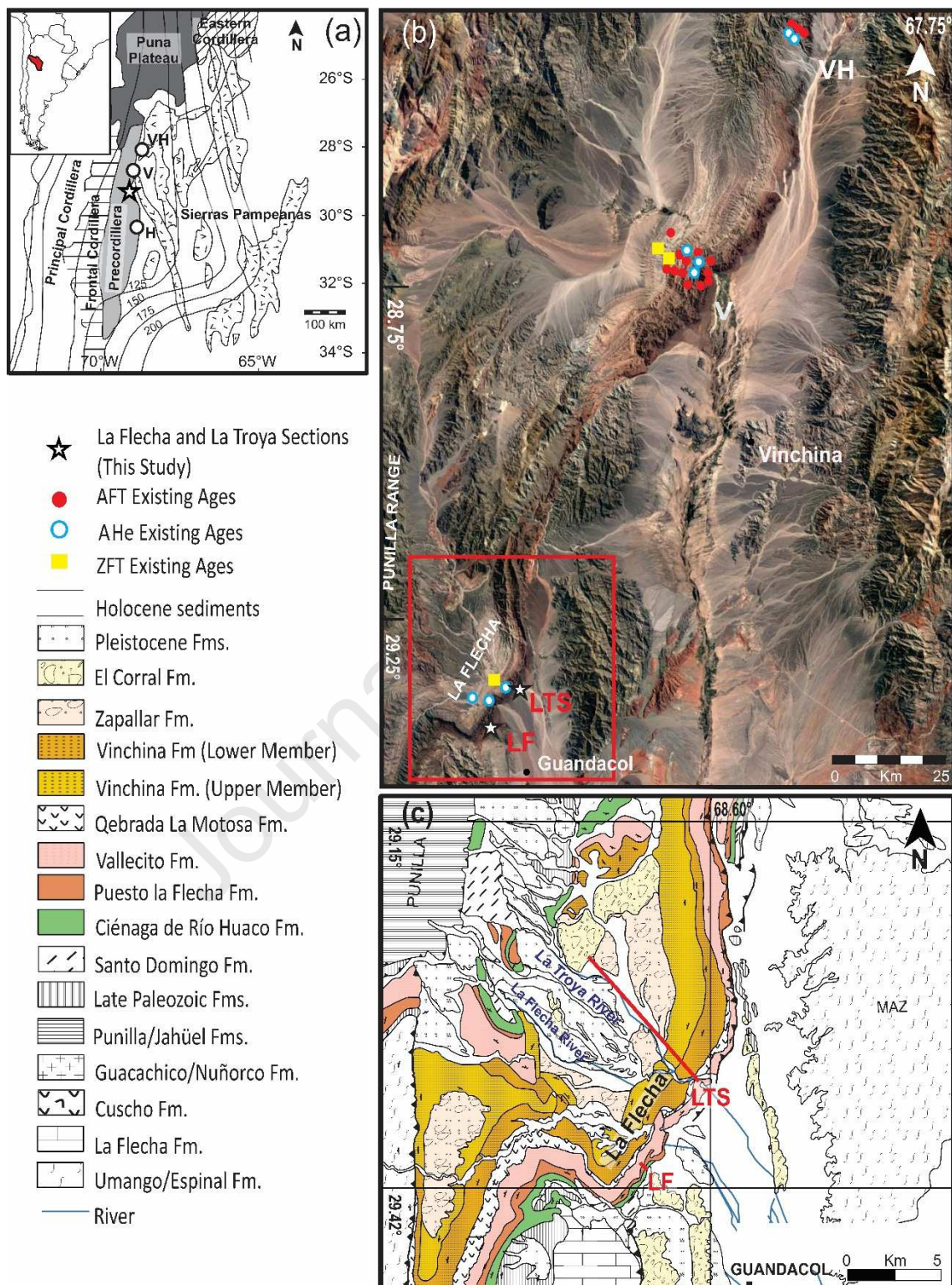


Figure 1. (a) Tectonomorphic setting of the central Andes adapted from Stevens Goddard and Carrapa (2018). (b) Satellite image (Google Earth) with locations of published thermochronologic data (Tabbutt, 1986; Reynolds et al., 1990; Coughlin, 2000; Collo et al., 2015 and Stevens Goddard and Carrapa, 2018). The study area is

indicated with the red box. **(c)** Geological map of the La Troya-La Flecha depocenter (modified from Ciccioli et al., 2014). The study sections are also shown with red lines. VH: Valle Hermoso; V: Vinchina; H: Huaco; LF: La Flecha, HC: Huaco anticline, VN: Vinchina, VH: Valle Hermoso. AFT: Apatite Fission Track; AHe: Apatite (U-Th)/He; ZFT: Zircon Fission Track. LF: La Flecha section; LTS: La Troya section.

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FIGURE 2

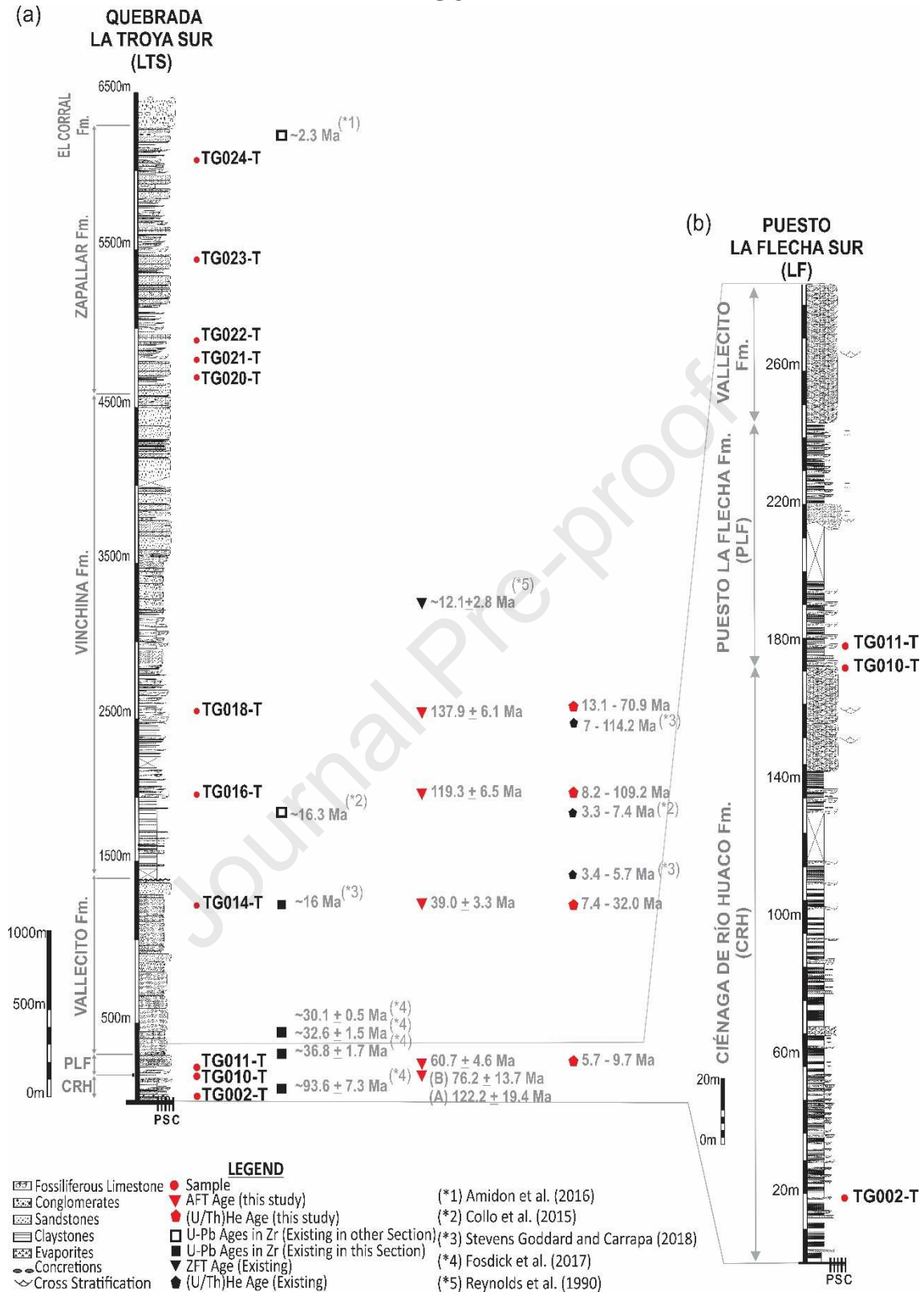


Figure 2. (a) Stratigraphic columns of La Troya and La Flecha sections, modified from Caselli et al. (2002) and Collo et al. (2015). Sample positions, the respective AHe and AFT thermochronological ages, and UPb maximum depositional ages from this and previous works are indicated. Extrapolated depositional ages from other sections are shown with empty boxes. (b) Detailed stratigraphic column from La Flecha section.

FIGURE 3

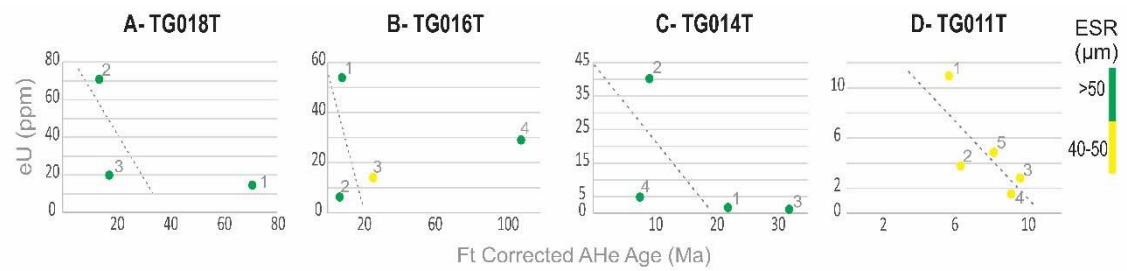


Figure 3. eU ($eU = U + 0.235Th$) plotted versus Ft corrected AHe ages for single grains in samples TG018T, TG016T, TG014T, TG011T. The color of the marker indicates the grain size and the dotted lines delineate trends. The negative linear correlation between eU and AHe ages shows that radiation damage is not the main factor responsible for the age dispersion.

FIGURE 5

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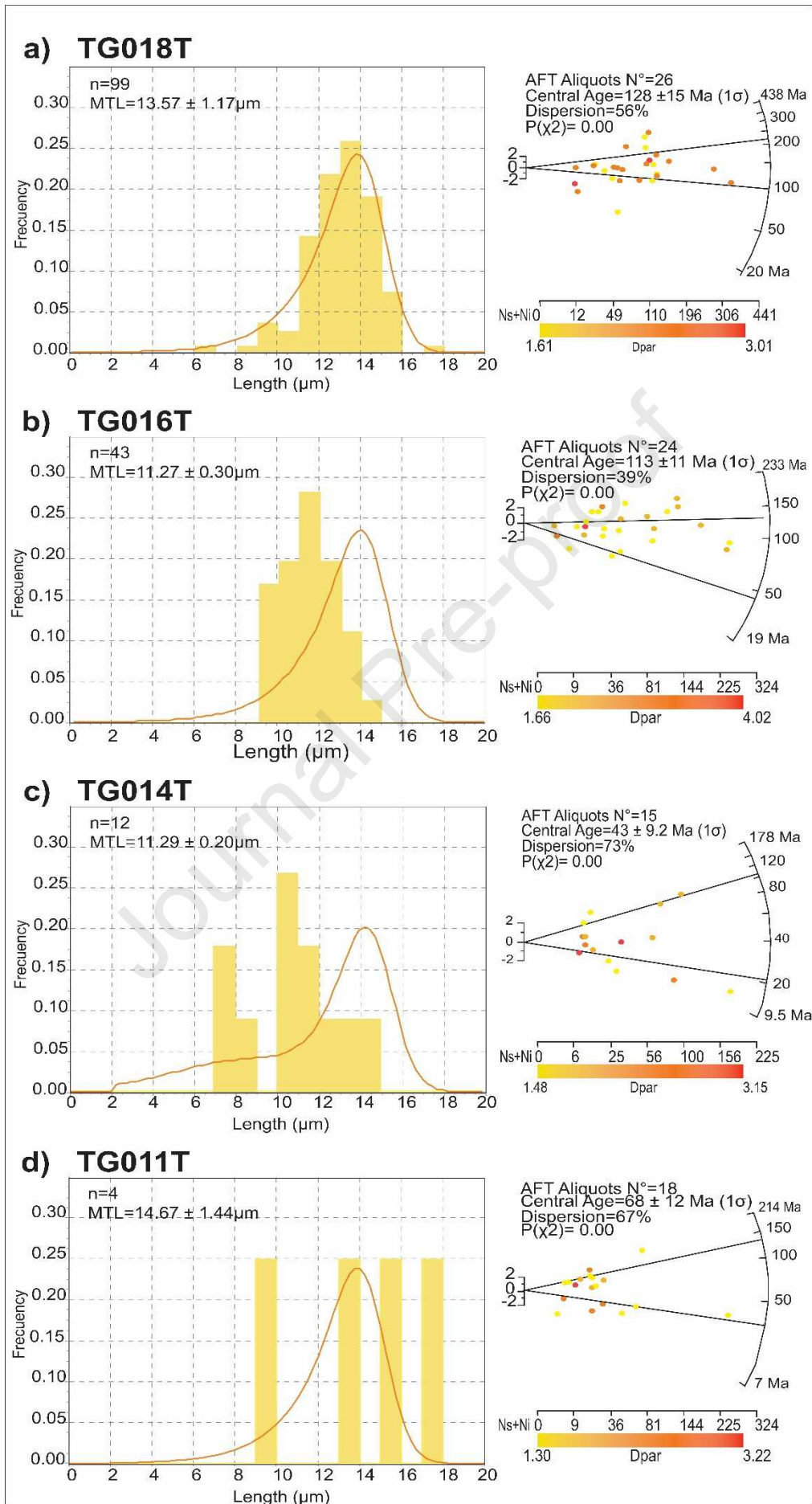


Figure 5. Frequency histograms showing the distribution of track lengths and radial plots from AFT data in the four samples analyzed in this work (A-TG018T, B-TG016T, C-TG014T, D-TG011T). $P(\chi^2)$: Chi-square probability. Values greater than 5% are considered to pass this test and represent a single population of ages. MTL: median confined track length.

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FIGURE 6

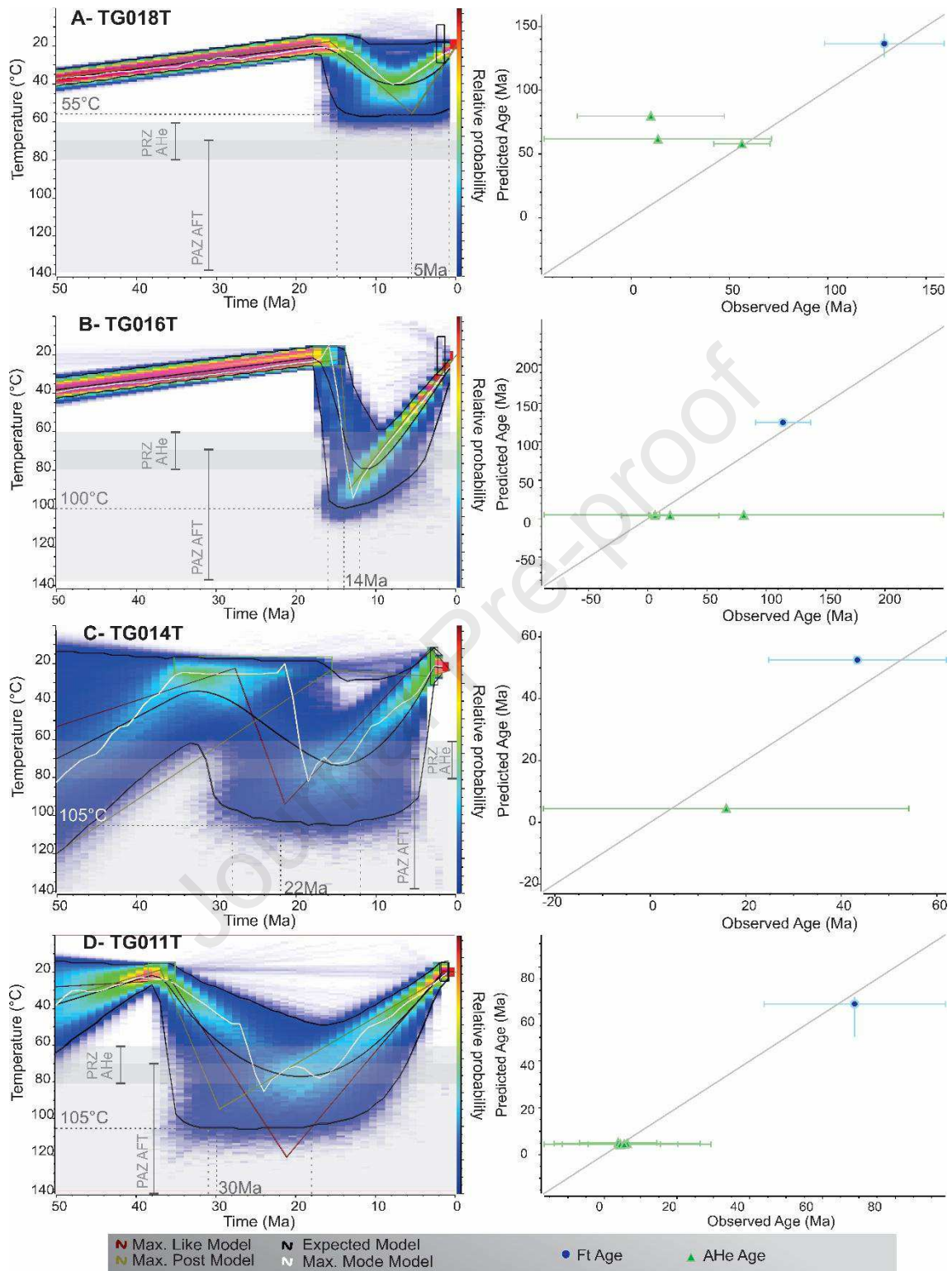


Figure 6. QTQt multi-method inverse thermal modeling showing the t-T histories to the left and individual predictions (predicted ages vs. measured ages) to the right. The AHe and AFT results were modeled considering the depositional ages of each sample and the exhumation of the sections at ~ 2 Ma (Amidon et al., 2016). Light brown lines: maximum posterior models or best fit; red lines: maximum likelihood models; black

lines: expected models; white lines: maximum mode models (further information can be found in Gallagher, 2012). Green triangles: AHe ages; blue circles: AFT ages.

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FIGURE 7

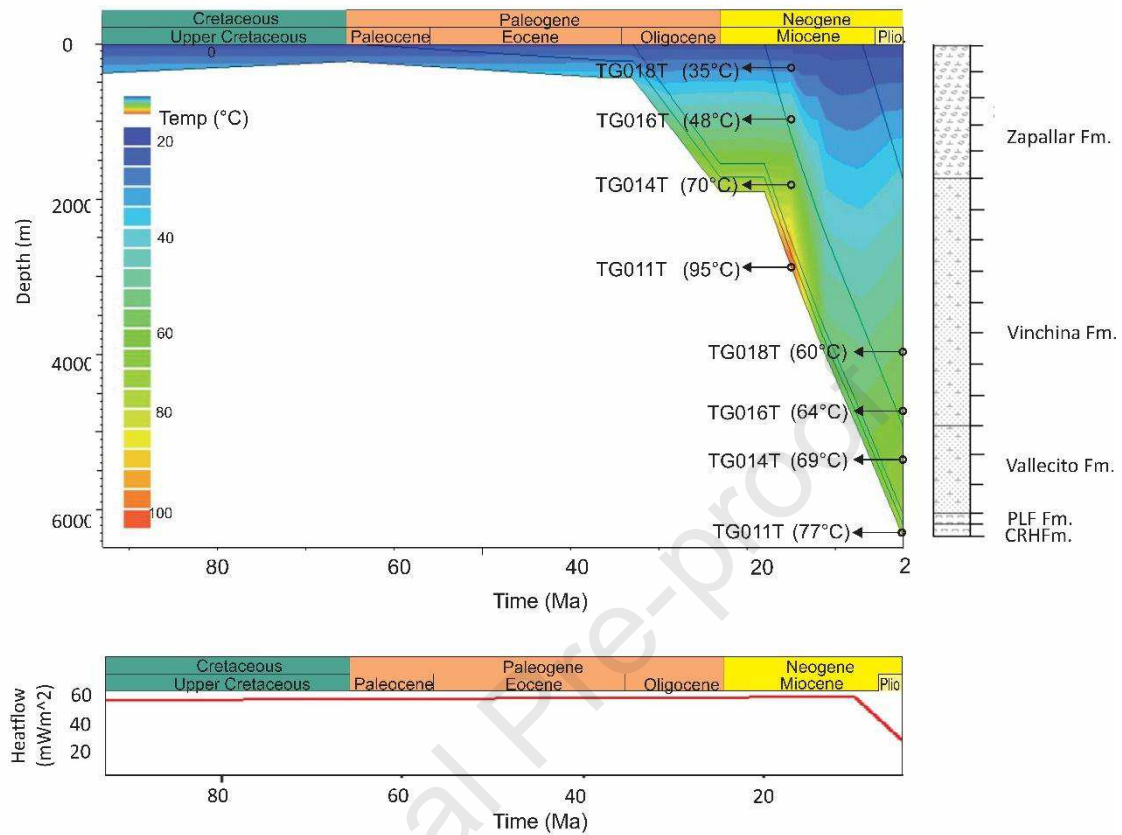


Figure 7. a) 1D thermal modeling for the Cretaceous-Cenozoic units in the studied sections using PetroMod 1D Express software. A heat flux of 65 mW/m² until 15 Ma and a gradual decrease to 20 mW/m² from 11 Ma to the present are considered according to the model proposed by Collo et al. (2015) for the Vinchina basin. The model shows that maximum temperatures are reached at ~15 Ma for the Ciénaga del Río Huaco (CRHF), Puesto la Flecha (PLF) and Vallecito Formations and at ~2 Ma for the Vinchina and Zapallar Fms. Black circles show sample location. It can also be observed the blanketing effect from ~10 Ma and the recovery of a steady state for the last 5 My. **b)** Heat flux input conditions, (for more details see table SM3 in supplementary material).

TABLE CAPTIONS
Table 1

Sample	Longitude (W)	Latitude (S)	Depth (m)	Stratigraphic section	Unit	Depositional age	U-Pb MDA (Ma)	Thermochronologic Ages		
								AHe	AFT	Cf
TG024 T	68° 40' 30.50"	29° 17' 21.63"	~200			Upper Miocene	~2.3 (*1)			(*5)
TG023 T	68° 39' 20.35"	29° 18' 21.17"	~850			Upper Miocene (~10 Ma)				(*5)
TG022 T	68° 38' 43.64"	29° 19' 42.71"	~135 0		Zapallar Fm.	Upper Miocene (~12 Ma)				(*5)
TG021 T	68° 38' 36.28"	29° 19' 43.48"	~170 0	Qda. La Troya Sur		Upper Miocene	~6.9 (*1)			(*5)
TG020 T	68° 37' 44.57"	29° 21' 02.49"	~335 0			Upper Miocene (~13 Ma)				(*5)
TG018 T	68° 37' 18.12"	29° 21' 22.04"	~355 0		Vinchin a Fm.	Upper-Mid Miocene (~15 Ma)		•	•	
TG016 T	68° 37' 05.35"	29° 21' 19.15"	~425 0			Upper-Mid Miocene	16.3 (*2)	•	•	•
TG014 T	68° 36' 17.75"	29° 21' 30.82"	~510 0		Vallecito Fm.	Oligocene	16 (*3) 33 (*4)	•	•	•
TG011 T	68° 40' 11.30"	29° 25' 39.09"	~612 2			Eocene	~37 (*4)	•	•	•
TG010 TA	68° 40' 10.7940"	29° 25' 39.68"	~612 7	Puesto La Flecha Sur	Puesto La Flecha Fm.	Eocene	~37 (*4)		•	
TG010 TB	68° 40' 10.79"	29° 25' 39.68"	~612 7			Eocene	~37 (*4)		•	
TG002 T	68° 39' 53.06"	29° 25' 47.21"	~628 0		Ciénaga de Río Huaco Fm.	Upper Cretaceous	~94 (*4)		NA G	•

Table 1. Sample location, depths (from the base of the El Corral Fm.) and U-Pb MDA (maximum depositional ages) for the studied units. (*1) Amidon et al. (2016), (*2) Collo et al. (2015), (*3) Stevens Goddard and Carrapa (2017), (*4) Fossdick et al. (2017). A detail of the analysis carried out in this work is shown in black circles. (*5) samples processed but not measured. NAG: samples without Apatite grains; AFT: Apatite Fission Track; AHe: Apatite (U-Th)/He; Cf: Californium irradiation.

Table 2

Sample	Aliquot N°	FT corrected Age ^a (Ma)	1 σ error Ma	Raw Age	U (ppm)	Th (ppm)	Sm (ppm)	Ue ^b	Th/U	He (nmol/g)	Mass (ug)	FT ^c	ESR ^d (μ m)	Terminations
TG018T	1	70.9	0.7	56.4	7.6	30.0	44.2	14.6	4.1	4.6	4.83	0.80	65.8	0
	2	17.4	0.2	13.6	14.4	23.3	54.5	19.9	1.7	1.5	3.41	0.78	62.2	1
	3	13.1	0.1	10.0	46.0	105.7	27.5	70.8	2.4	3.8	3.91	0.77	59.8	0
TG016T	1	8.2	0.1	6.1	51.3	9.8	49.2	53.6	0.2	1.8	1.80	0.74	53.1	1
	2	6.9	0.2	5.3	4.3	7.6	109.4	6.1	1.8	0.2	3.03	0.76	60.2	1
	3	25.8	0.6	18.9	8.9	21.6	54.2	14.0	2.5	1.5	2.14	0.73	49.6	0
	4	109.2	1.1	81.1	19.0	42.5	70.3	29.0	2.3	13.1	3.17	0.74	59.2	1
TG014T	1	22.0	1.3	15.9	0.5	5.3	24.4	1.7	11.7	0.2	3.15	0.73	56.2	0
	3	9.4	0.1	6.9	21.5	79.7	39.2	40.2	3.8	1.5	2.99	0.73	58.1	1
	4	32.0	3.4	22.3	0.5	1.0	0.3	0.7	1.9	0.1	1.84	0.70	50.5	1
	5	7.4	0.4	5.5	2.4	10.2	25.0	4.8	4.3	0.2	2.67	0.75	53.4	0
TG011T	1	5.7	0.4	3.8	4.3	27.9	74.6	10.8	6.7	0.2	1.49	0.66	44.3	0
	2	6.5	0.9	4.4	2.3	6.2	16.7	3.8	2.8	0.1	1.38	0.68	42.7	0
	3	9.7	1.6	6.4	1.0	7.7	21.1	2.9	7.6	0.1	1.43	0.66	43.4	0
	4	9.2	1.3	6.3	0.8	3.4	9.4	1.6	4.5	0.1	1.78	0.68	47.3	0
	5	8.2	0.6	5.5	2.2	11.2	23.8	4.9	5.3	0.1	1.40	0.66	43.7	0

Table 2. AHe analysis data.Notes: ^a Age corrected using the grain geometry and ejection factor FT, error at 1 σ .^b effective uranium concentration.^c geometric correction factor for age calculation.^d equivalent spherical radius.

Table 3

Sample	Stratigraphic Age (Ma)	N° of grains	Area (cm ²)	NS ^a	ND ^b	NI ^c	ρS^d (cm ²)	ρD^e (cm ²)	ρI^f (cm ²)	Dpar (μ m)	N° of Dpar	Age ^g (Ma)	$\pm 1\sigma$ Error	U (ppm)	P(χ^2) ^h	MTL ⁱ (μ m)	Error (μ m)	SD ^j (μ m)	N° of length
TG018 T	~15	26	1.26E-03	1642	16308	1241	1.30E+06	2.65E+06	9.81E+05	2.21	104	137.9	6.1	13.95	0	13.57	1.17	1.68	99
TG016 T	~18	24	5.84E-04	909	16308	791	1.56E+06	2.63E+06	1.36E+06	2.24	96	119.3	6.5	19.37	0	11.27	0.30	1.92	43
TG014 T	~16-33	15	5.39E-04	205	16308	547	3.81E+05	2.62E+06	1.02E+06	2.3	60	39.0	3.3	14.58	0	11.29	0.20	1.27	12
TG011 T	~37	18	3.75E-04	314	16308	534	8.38E+05	2.61E+06	1.42E+06	1.91	72	60.7	4.6	20.56	0	14.67	1.44	2.87	4
TG010 T A	~37	4	1.16E-04	89	16308	74	7.69E+05	2.58E+06	6.39E+05	3.08	16	122.2	19.4	9.32	0	-	-	-	-
TG010 T B	~37	6	1.95E-04	55	16308	74	2.82E+05	2.59E+06	3.79E+05	2.69	24	76.2	13.7	5.51	98.9	-	-	-	-

Table 3. AFT analysis data. Zeta for WC analysis = 79.6 ± 1.8 . Stratigraphical ages are approximated (see Fig. 2 for more details).

Notes: ^a spontaneous track numbers.

^b number of induced tracks counted in the mica for estimating RhoD.

^c induced tracks number.

^d spontaneous tracks density.

^e induced track density measured in the external mica detector attached to CN1 dosimetry glass.

^f induced tracks density.

^g Central (Pooled) age for samples passing (failing) the χ^2 test.

^h Chi-square probability. Values greater than 5% are considered to pass this test and represent a single population of ages.

ⁱ Median confined track length measure.

^j Standard deviation of measured lengths.

Table 4

Sample	Depth (m)	QtQt Max. Temp. ^a (°C)	Time Interval ^b (Ma)	QtQt Best Fit Max ^c Temp. (°C)	Time ^d (Ma)	1D Modeling Max. Temp. ^e (°C)	Time interval ^f (Ma)
TG018T	-3950	55	1.5-15	55	5	60	2
TG016T	-4450	100	12-16	90	14	64	2
TG014T	-5300	105	12-28	95	22	70	15
TG011T	-6320	105	18-30	95	30	95	15

Table 4. 1D Thermal modeling data.

Notes: ^a Maximum temperature reached by all tested t-T path in QtQt models.

^b Time interval in which maximum temperatures are observed from all tested t-T path in QtQt models.

^c Maximum temperature reached by best fit QtQt model. See Max. Like model line of Figure 6.

^d Time in which maximum temperatures for best fit are observed.

^e Maximum temperature from 1D Petromod model.

^f Time interval in which maximum temperatures are observed in 1D Petromod model.

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- New apatite fission track (AFT) and (U-Th)/He (AHe) data from Cretaceous-Cenozoic clastic successions in Precordillera of Argentina.
- A complex time-temperature trajectory is proposed. Maximum and cooling temperatures reached by each unit do not correspond in all cases to the maximum burial and exhumation times
- A geothermal gradient of ~ 27 °C/km at ~ 15 Ma and <15 °C/km at ~ 2 Ma could be inferred.
- This study will constitute a baseline of knowledge of the thermal regime necessary for future multiproxy evaluation of the preservation of the primary signals of other thermal proxies.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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