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Key Points:

- Structural analysis and multi-thermochronometry constrain the thermal-structural evolution of the Agrio FTB, in the Southern Central Andes
- From ~85–75 Ma to ~55–50 Ma, a slow cooling event has occurred in the inner Agrio FTB, driven by the growth of basement-involved anticlines
- From ~15–10 Ma to 0 Ma, a faster cooling event has affected the entire Agrio FTB through the development of basement-involved blind thrusts

Supporting Information:

Supporting Information may be found in the online version of this article.

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Structural Evolution of the Northern Agrio Fold and Thrust Belt (~37°30'S), Neuquén Basin, Argentina, Derived From Low-Temperature Multi-Thermochronometry

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Abstract The Agrio Fold and Thrust Belt (FTB), situated in the Southern Central Andes at 37–39°S, underwent two phases of contractional deformation: Late Cretaceous-Eocene and middle-late Miocene. Despite advances in understanding its tectonic history, many questions persist regarding the timing and activity of specific structures during these deformation phases. By combining low-temperature multi-thermochronometry, inverse thermal models and field structural data, we present a new thermal-structural history for the northern Agrio FTB. Our findings unveil an initial cooling event between approximately 85–75 Ma and 55–50 Ma, involving cooling rates of 1.1–2°C/Ma and vertical displacement rates from 0.07 to 0.12 km/Ma. This slow event, confined to the inner zone, is associated with the growth of the basement-cored Manzano anticline. Additionally, still in the inner zone of the Agrio FTB, a second and faster cooling event from ~15–10 Ma to 0 Ma, marked by a cooling rate of 7°C/Ma and a vertical displacement rate ranging from 0.11 to 0.17 km/Ma, results from in-sequence thick-skinned thrusting at depth. In the outer zone of the FTB, only the younger cooling event from 15–10 Ma to 0 Ma is evident, with a cooling rate of 8.8°C/Ma and a vertical displacement rate ranging from ~0.14 to 0.26 km/Ma, attributed to displacement along the basement-involved Las Yeseras thrust. Furthermore, Apatite Fission Track (AFT) ages of detrital grains in the Tralalhué conglomerates support the maximum depositional age for these synorogenic strata to be between 14.1 and 9.2 Ma.

1. Introduction

Fold-and-thrust belts (hereafter referred to as FTBs) are tectonic features located at the boundary between an orogen's hinterland and foreland. FTBs are key element in orogenic systems, as they record the temporal migration of deformation in response to the development of the orogenic wedge. Consequently, the structural analysis of FTBs, which involves the examination of individual contractional structures such as folds and thrust faults, and the determination of the timing of their formation and activity, provides essential insights into the style and rates of crustal shortening processes inherent in mountain-building dynamics (e.g., Lacombe & Beau-doin, 2024 and references therein).

The integration of structural data and multi-thermochronometric techniques has been used to characterize and quantify the thermal and kinematic development of FTBs in different orogens across the globe (e.g., Castelluccio et al., 2015; De Celles et al., 2020; Hernandez et al., 2020; Lock & Willett, 2008; McQuarrie & Ehlers, 2017; Mora et al., 2015). In particular, the utilization of thermochronometric methods, such as apatite fission track analysis (AFT), along with (U-Th)/He dating methods (AHe and ZHe, respectively) enables the reconstruction of thermal histories within the uppermost approximately 10 km of the continental crust. These methods serve as valuable tools to identify and measure distinct burial and exhumation cycles associated with orogenic deformation. In this study, we use this integrated approach to investigate and refine the conflicting timing of the main compressional episodes that have shaped the Southern Central Andes of Argentina and Chile.

The Central Andes (4°S–46°30'S) stretching for almost 5,000 km along the western margin of South America (Figure 1a), result from the subduction of the oceanic Nazca plate beneath continental South America along an eastward-dipping subduction zone (e.g., Barazangi & Isacks, 1976; Cahill & Isacks, 1992). Within this orogenic region, variations in tectonic deformation can be attributed to a multitude of geodynamic factors, such as the absolute trenchward motion of the South American plate, the rate of subduction, the obliquity and angle of the

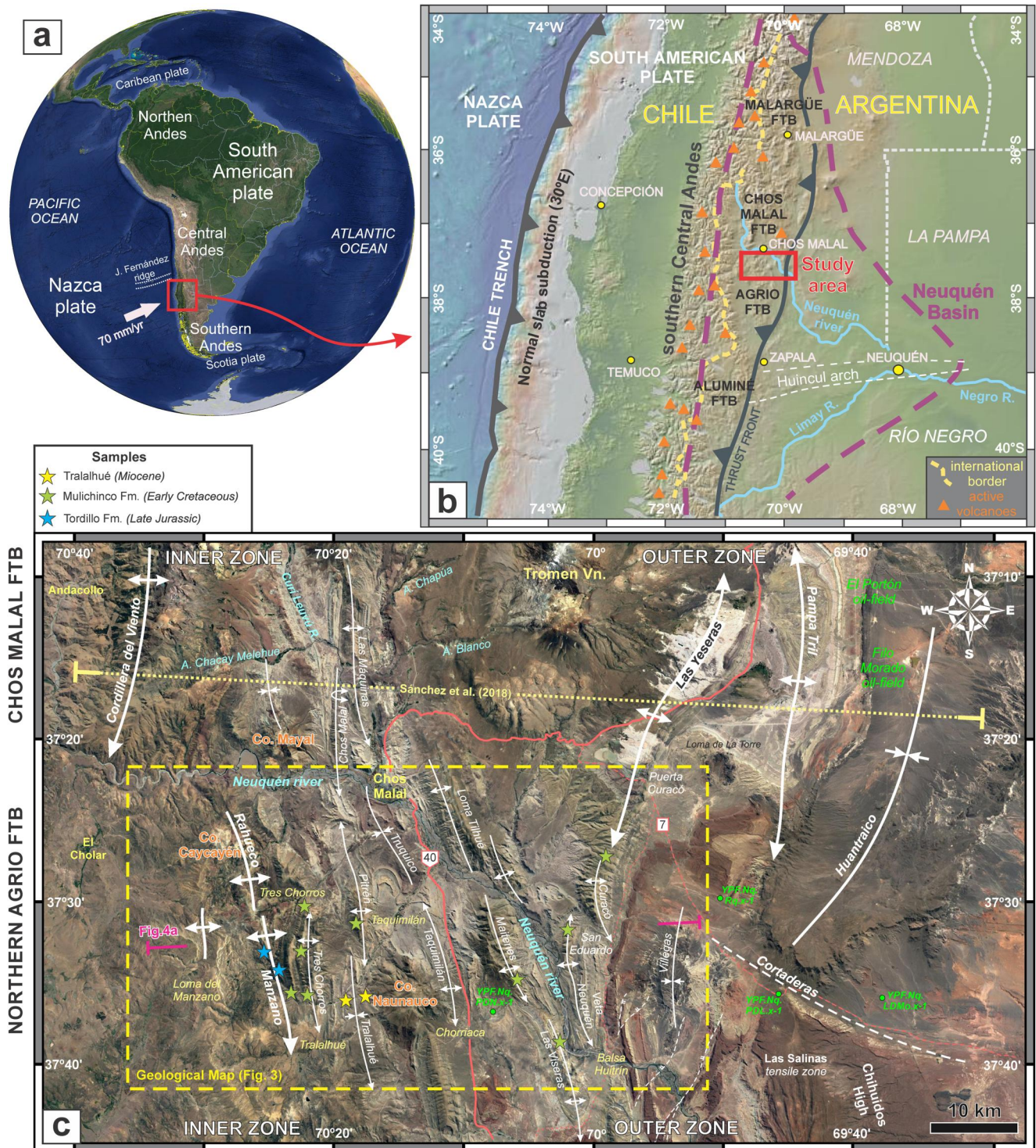


Figure 1. (a, b) Location of the Fold-and-Thrust Belts (FTB) formed on the western flank of the Mesozoic Neuquén Basin, Argentina, due to the convergence between the Nazca and South American plates. The topography/bathymetry data is derived from the Shuttle Radar Topography Mission (SRTM, 90 m). (c) Satellite image (taken from Google Earth) showing the main thick and thin-skinned folds (thick and thin white lines, respectively), within the FTBs. Stars of different colors denote the sampling locations for different geological units examined in this study.

subducted slab, as well as rheological factors including upper-plate strength and inherited structures, and climatic factors like surface erosion and sediment accumulation in the trench. (e.g., Giambiagi et al., 2012, 2022; Hilley & Coutand, 2010; Horton, 2018; Lamb & Davis, 2003; Oncken et al., 2006; Ramos, 1999, 2010; Ramos

et al., 2014; Sobolev & Babeyko, 2005; Stalder et al., 2020 and references therein). Pioneering geologists such as Schiller (1912), Windhausen (1914), Keidel (1925), Groeber (1929), Steinmann (1929), and Wichmann (1924), among others, recognized different phases of deformation along the Andes based on field, structural and stratigraphic studies. These different phases were named by Steinmann (1929) for the Peruvian Andes as: Peruvian (Late Cretaceous), Incaic (Eocene), and Quechua (Neogene to Recent). During the last two decades, new field, geochronological and thermochronological data helped refine the timings of these pulses of Andean contractional deformation. The Southern Central Andes, spanning approximately 34°–41°S (Figure 1b), are situated above a typical subduction zone, with an east-dipping plunging slab currently at 30°, and an active magmatic arc (Ramos & Kay, 2006). Fore-arc and back-arc basins, characterized by sequences of marine and continental sediments, developed to the west and east of the magmatic arc, respectively, from the Jurassic to the Early Cretaceous periods (Charrier et al., 2007; Howell et al., 2005; Legarreta & Uliana, 1991). Compressive deformation in these sedimentary rocks initiated during the Late Cretaceous, documented in both Chile (Boyce et al., 2020; Charrier et al., 2007) and Argentina (Cobbold & Rossello, 2003; Fennell et al., 2020; Ramos & Folguera, 2005; Ramos & Kay, 2006). Specifically, in the back-arc region, contractional deformation impacted the western margin of the Mesozoic Neuquén Basin, leading to the formation of various fold-thrust belts (FTBs), as shown in Figure 1b. The formation of contractional structures within these FTBs, noted for their mix of thick and thin-skinned deformation, occurred across two principal shortening phases: one from the Late Cretaceous to the Eocene, and another from the mid to late Miocene (Ramos & Folguera, 2005; Ramos & Kay, 2006). Despite the recent application of low-temperature thermochronology in studying these FTBs, debates persist regarding the precise timing of their tectonic uplift and exhumation. Between Malargüe and Chos Malal (35°30′–37°S, Figure 1b), using AFT data Folguera et al. (2015) propose that exhumation occurred in two distinct stages within the FTB: the Campanian-Paleocene period (75–55 Ma) and the middle Miocene period (15–10 Ma). These exhumation events coincided with phases of mountain-building attributed to a shallowing of the subducted slab at the time (Folguera et al., 2015). In a structural transect north of Chos Malal (37°15′S), utilizing multi-thermochronometry methods (AFT, ZHe, and AHe), Sánchez et al. (2018) propose that tectonically induced exhumation occurred between 93 and 55 Ma ago in the inner (western) zone and between 15 and 7 Ma ago in both the inner and outer (eastern) zones of the FTB (Figure 1c). To the north, near 36°30′S, Galetto et al. (2021) employed multiple low-temperature thermochronometers (ZFT, AFT, ZHe, and AHe) in the inner zone of the FTB, and identified two primary episodes of rapid cooling events that occurred during the Albian-Campanian (~110–75 Ma) and the Eocene (~55–35 Ma), which they attributed to exhumation resulting from two major contractional tectonic phases.

The Agrio FTB, situated approximately between 37° and 39° S, covers the region from Chos Malal to Zapala in the western part of the Neuquén province (Figure 1b). Existing geological and geochronological data suggest that the tectonic structuration of the Agrio FTB results from at least two main phases of orogenic contraction. The first occurred during the Late Cretaceous-Eocene period (~100–40 Ma), and the second took place during the middle-late Miocene (Cobbold & Rossello, 2003; Ramos, 1998; Ramos & Folguera, 2005; Zamora Valcarce et al., 2006; Zapata & Folguera, 2005). In the past decade, studies using AFT data to assess the timing of formation and/or activity of specific structures within the central segment of the Agrio FTB (at 38°S) identified these same two major contraction episodes (Rocha et al., 2018; Rojas Vera et al., 2015).

Several unresolved questions persist regarding the tectonic evolution within the Agrio FTB. These include:

1. Was the initial deformation event in the Agrio FTB continuous from the Late Cretaceous to the Eocene, or did it occur in discrete phases of contraction, as recently recognized north of the Chos Malal FTB by Galetto et al. (2021)?
2. Which structures were active during this initial phase of deformation, and for how long?
3. Did the Cretaceous-Paleogene deformation front extends to the current outer or eastern zone of the Agrio FTB, as suggested for the Malargüe FTB to the north (e.g., Borghi et al., 2023; Fennell et al., 2020; Folguera et al., 2015)?
4. Did the Miocene contraction affect the entire FTB with uniform intensity?
5. Did the two primary orogenic contraction phases, Late Cretaceous-Eocene and Miocene, produce comparable amount of deformation, or was one more significant than the other?

The overarching objective of this study is to constrain the Mesozoic-Cenozoic spatio-temporal structural evolution of the Agrio FTB. To address these questions, we investigate the thermal-structural evolution of the

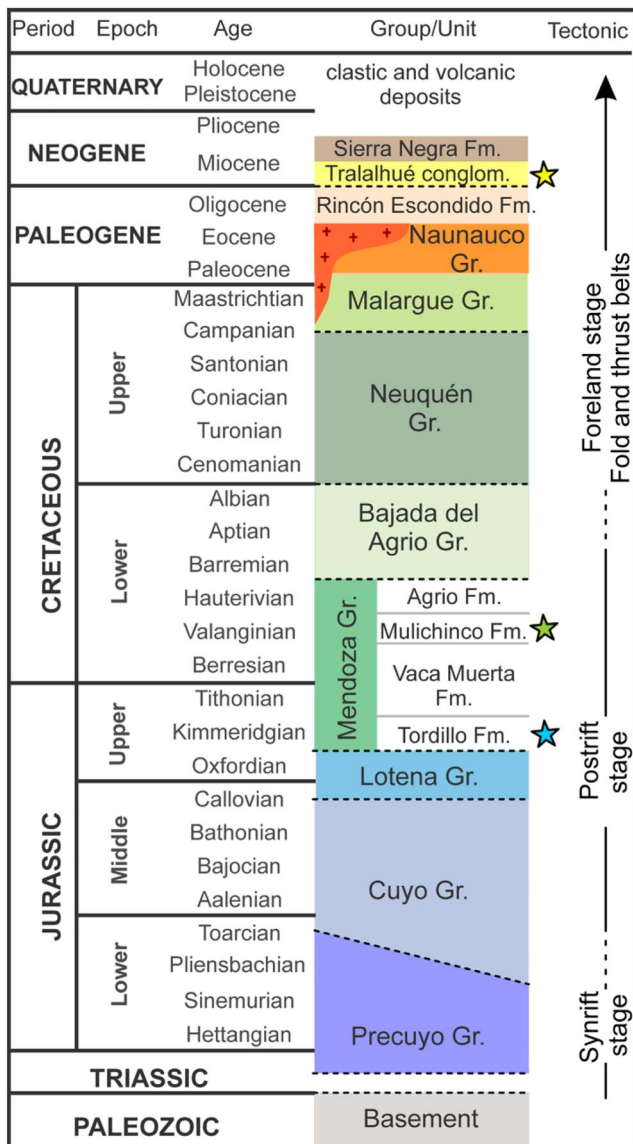


Figure 2. Stratigraphic chart summarizing the nomenclature, age and tectonic setting of units in the Neuquén Basin region (adapted from Gulisano and Gutiérrez Pleimling, (1995), Howell et al. (2005), Llambías et al. (2007), and other sources). Further references and detailed explanations are provided in the text. Stars denote the geological units sampled in this study.

northern Agrio FTB (approximately 37°20′–37°40′S, as shown in Figure 1c), an area devoid of prior thermochronological information. This investigation combines detailed structural analysis with inverse modeling of new low-temperature multi-thermochronological data (AHe, ZHe, and AFT). Using recent detailed structural studies in this region (e.g., Aramendia et al., 2019; Lebinson et al., 2015, 2018, 2020; Turienzo et al., 2022), we have constructed a regional balanced cross-section that illustrates the structural architecture of the FTB and facilitates the calculation of vertical displacement along major thick-skinned structures. In addition, we collected 13 sandstone samples along a ~64 km-long E-W trending transect across the FTB (Figure 1c), comprising two from Upper Jurassic sandstones, nine from Lower Cretaceous sandstones, and two from Miocene conglomerates. Among these, only three samples, situated in the western, central, and eastern sectors of the study area, yielded thermochronological ages for all three methods and were subsequently modeled using the Hefty software (Ketcham, 2005). The derived time-temperature paths provide insights into the cooling histories of these samples in distinct sectors of the northern Agrio FTB. The integration of structural and thermochronological data sets enables us to elucidate the tectonically driven exhumation history of the northern Agrio FTB and explore its relationship with the thermal-structural development of neighboring regions.

2. Geological Framework

The Andean region of northern Neuquén province exposes Paleozoic to Quaternary rocks representing multiple tectonic, sedimentary, and magmatic cycles, which have produced a complex morphotectonic configuration in the southwestern margin of South America (Ramos & Folguera, 2005; Ramos & Kay, 2006; Ramos et al., 2011). Most of the exposed rocks form part of the Mesozoic sedimentary infill of the Neuquén Basin, which contains significant hydrocarbon resources (i.e., Howell et al., 2005; Vergani et al., 1995; Veiga et al., 2020).

The Paleozoic basement of the Neuquén Basin is visible northwest of the study area in the Cordillera del Viento (Figure 1c). The opening of the basin occurred through NW-oriented half-grabens that received primarily volcanic synrift sequences during the Late Triassic to Early Jurassic extension (Precuyo Group, Figure 2, Carbone et al., 2011; D'elia et al., 2020; Franzese & Spalletti, 2001; Gulisano, 1981; Llambías et al., 2007). During the Early Jurassic to Early Cretaceous, sediment accumulation in the Neuquén Basin was primarily influenced by back-arc thermal subsidence, coupled with eustatic fluctuations, resulting in periodic connections and disconnections with the Paleo-Pacific Ocean (Howell et al., 2005; Legarreta & Uliana, 1991; Vergani et al., 1995). Sediments accumulated in this context formed three

major marine-continental sequences: the Cuyo, Lotena and Mendoza Groups (Figure 2). The Early Middle Jurassic Cuyo Group (~900 m) is completely exposed at Chacay Melehue creek, east of the Cordillera del Viento (Figure 1c), where it mainly consists of fossiliferous black shales, covered by a thin evaporitic bed (Gulisano & Gutiérrez Pleimling, 1995). In our study area, the upper part of the Cuyo Group is exposed in the core of the Rahueco anticline, and these are the oldest rocks in the northern Agrio FTB (Figure 3). The overlying Lotena Group (Figure 2) is formed by siliciclastic sediments, carbonates and evaporites accumulated during the Late Jurassic (Arregui et al., 2011). The thickness of the Lotena Group is ~180 m at the Rahueco anticline (Figure 3), but it is over 300 m at Las Yeseras anticline (Figure 1c) where thicker successions of laminated gypsum are exposed (Gulisano & Gutiérrez Pleimling, 1995). The Mendoza Group includes the Tordillo, Vaca Muerta, Mulichinco and Agrio formations, which were accumulated between the Late Jurassic and the Early Cretaceous (Figure 2) and are widely exposed in the study area (Figure 3). The Tordillo Formation, cropping out between the

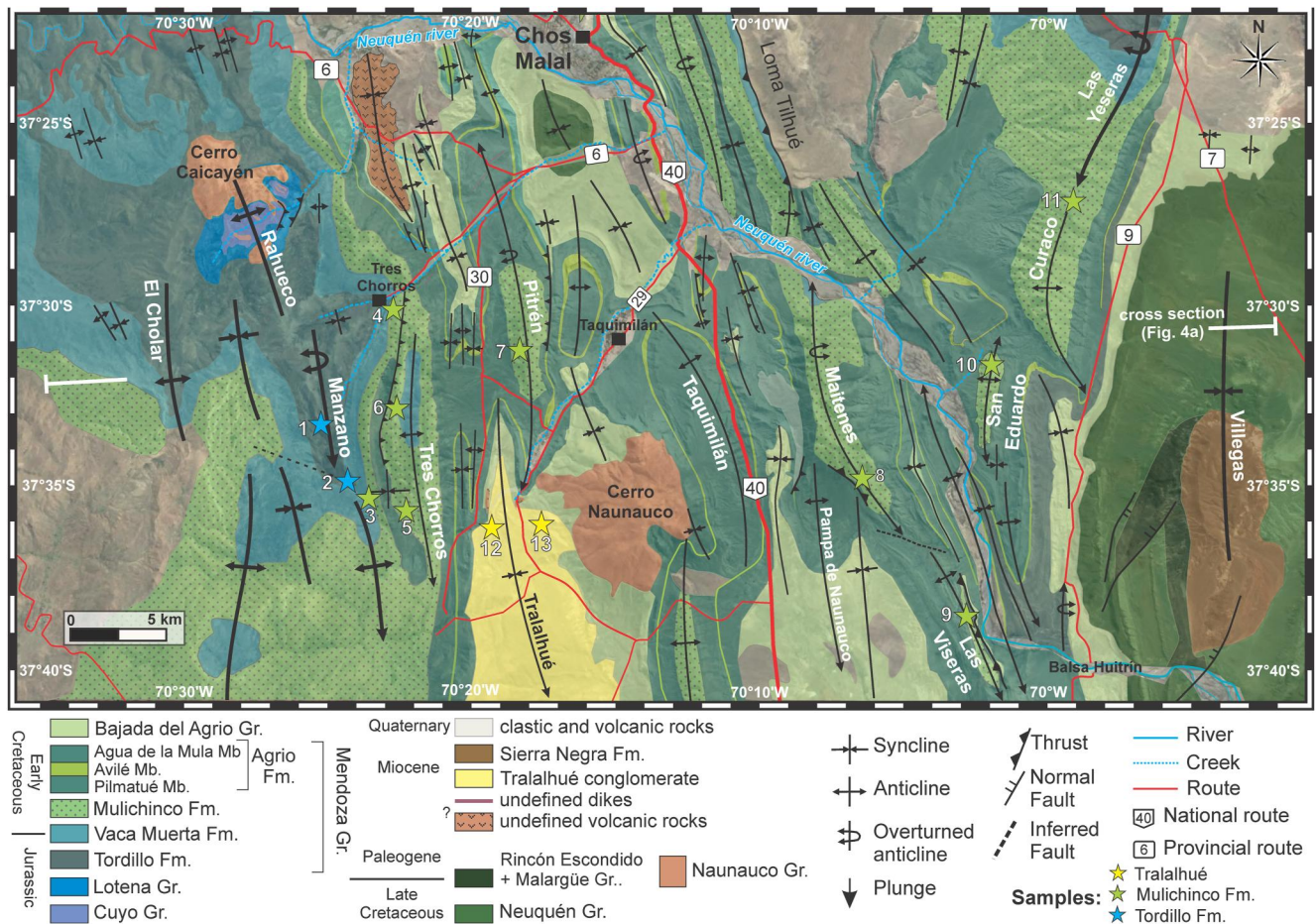


Figure 3. (a) Geological map of the northern Agrio FTB (based on Lebinson et al., 2018, 2020; Turienzo et al., 2022). The color stars show the location and number of the studied samples.

Cordillera del Viento and Tres Chorros (Figures 1c and 3), is mainly composed of fine-grained reddish clastic deposits, with a thickness around 500–600 m, formed in an arid fluvial-dominated system (Spalletti & Colombo Piñol, 2005; Spalletti, Arregui, & Veiga, 2011). The thickness of this unit decreases to 215 m in the YPF.Nq.PDN. x-1 well and to 130 m in the YPF.Nq.Rq.x-1 well, located to the east of the study area (Figure 1c). U-Pb detrital zircon ages for the Tordillo Formation suggests a maximum depositional age ranging from 151 Ma to 143 Ma (Naipauer et al., 2015). A recent high-resolution U-Pb age in zircons from an ash horizon interlayered near the top of the Tordillo Formation in the Las Yeseras area (Figure 1c), constrains the age of this part of the section at 147.11 ± 0.07 Ma (Lena et al., 2019). The Vaca Muerta Formation is formed by marine dark bituminous shales and limestones, and based on its abundant fossil content it spans from Early Tithonian to Early Valanginian (i.e., Aguirre-Urreta et al., 2019; Kietzmann et al., 2016). Its thickness is ~600 m in the Tres Chorros area and ~500 m in the Las Yeseras area (Figure 1c). The overlying Mulichinco Formation, in this sector of the Neuquén Basin, contains ~230–340 m of marine siliciclastic and carbonate rocks (Schwarz et al., 2011). Based on integrated biostratigraphy and U-Pb zircon ages from the underlying Vaca Muerta Formation (Aguirre-Urreta et al., 2019) and the overlying Agrio Formation (Aguirre-Urreta et al., 2017), the Mulichinco Formation is Valanginian in age (~139.5–137.5 Ma, Schwarz et al., 2011). Finally, the Agrio Formation (Figure 2) is a thick, complex and heterogeneous marine-continental sequence (Pazos et al., 2020; Spalletti, Veiga, et al., 2011), classically divided into three members: (a) the Pilmatué Member mostly comprises marine dark shales, with subordinate limestones and sandstones; (b) the Avilé Member is dominantly formed by fluvial and aeolian sandstones, interbedded with fine-grained floodplain deposits (Veiga et al., 2011); (c) the Agua de la Mula Member predominantly consists of black shales, with subordinate carbonates, accumulated in a low energy marine environment (Spalletti et al., 2001, 2011b). This formation spans from Late Valanginian to Early Barremian, and it includes U-Pb zircon ages since

130.4 Ma to 127.4 Ma (Aguirre-Urreta et al., 2015, 2017). The complete thickness of this formation in the zone between the Chacay Melehue stream and the Neuquén River (Figure 1c) is ~1,050 m (Zöllner & Amos, 1973). In the area of San Eduardo, the Agrio Formation reaches the maximum thickness of ~1,290 m, while it is 942 m-thick in the YPF.Nq.PDL.x-1 well (Figure 1c). On top of the Mendoza Group, the Bajada del Agrio Group (Figure 2) contains sandstones, evaporites and limestones representing the final connection between the Neuquén Basin and the Pacific Ocean during the Lower Cretaceous (Barremian), which are covered by reddish clastic deposits, recording the continentalization of the basin (Leanza, 2003). The thickness of this group is variable, mainly because evaporitic deposits are not uniformly distributed, but southward of Las Viseras it is ~605 m-thick (Leanza, 2003) while north of Balsa Huitrín (Figure 1c) it only reaches ~490 m. The accumulation of continental sediments continued in the Late Cretaceous with the Neuquén Group (Figure 2), which contains up to ~1,200 m of reddish silicoclastic deposits of fluvial, aeolian and shallow lacustrine origin developed between the Early Cenomanian and the Middle Campanian (Garrido, 2010). Provenance studies and U-Pb detrital zircon geochronology record a sharp change in the source of sediments, from the eastern foreland basement of the Bajada del Agrio Group and from the western magmatic arc at the base of Neuquén Group (Di Giulio et al., 2017; Tunik et al., 2010). This shift in clastic sediments' provenance is interpreted as resulting from active rock uplift and exhumation within the Cordillera to the west, in response to compressional tectonics in the Cenomanian (ca. 100 Ma) (Di Giulio et al., 2017; Fennell et al., 2020; Tunik et al., 2010) and the growth of the magmatic arc (Fuentes & Horton, 2020). Additionally, at this time, the eastward migration of the Late Cretaceous magmatic arc, associated with the surface uplift of the main Andes and the development of a foreland basin, were interpreted as resulting from the shallowing of the dip angle of the plunging Pacific plate underneath South America (Ramos & Folguera, 2005; Ramos & Kay, 2006). The Neuquén Group is unconformably covered by the Malargüe Group, which includes fossiliferous limestones that represent the first marine transgression from the Atlantic Ocean during the Maastrichtian-Danian (Figure 2). These sediments were deposited in a foreland basin in response to the advancing Andean FTB (Aguirre-Urreta et al., 2011), influenced by dynamic subsidence (Gianni et al., 2018), and concurrent with a global sea-level rise (Barrio, 1990).

The Malargüe Group is exposed in the southeastern portion of the study area, east of the provincial route 9 (Figure 3), where it reaches a thickness of ~250–300 m (Barrio, 1990; Ramos, 1981). The Late Cretaceous-Paleocene magmatism, named as the Naunaucó Group (Figure 2), consists of andesitic sills, microdioritic laccoliths and andesitic extrusive facies, which bear a calc-alkaline signature (Franchini et al., 2003; Iannelli et al., 2020; Llambías & Aragón, 2011; Zamora Valcarce et al., 2006). In the study area, the main exposures of these rocks (Figures 1c and 3), are the laccoliths forming the Cerro Caicayén (^{40}K - ^{40}Ar age on amphibole of ~44.7 Ma, Llambías & Rapela, 1989), the Cerro Naunaucó (^{40}Ar - ^{39}Ar age on amphibole of ~65.5 Ma, Zamora Valcarce et al., 2006) and the Cerro Mayal (^{40}Ar - ^{39}Ar age on whole rock of ~39.7 Ma, Cobbold & Rosello, 2003). The Rincón Escondido Formation (Figure 2), comprises only 31 m of conglomerates, sandstones, claystones and pyroclastic materials, and contains fossil mammals remains from the Oligocene period (Garrido et al., 2012). It unconformably overlays the Malargüe Group on the western flank of the Villegas syncline (Figure 3). These rocks are unconformably covered by ~850 m of volcanic and volcanoclastic rocks of the Sierra Negra Formation (Garrido et al., 2012), mostly composed of olivine-bearing basaltic flows with ^{40}Ar - ^{39}Ar (groundmass) ages of ~14.8 Ma (Kay & Copeland, 2006) in the vicinity of the Villegas syncline (Figure 3) and 17–18 Ma (Dyhr et al., 2013) in the Huantraico syncline located ~15 km to the northeast (Figure 1c). The Tralalhué syncline, situated to the west of Cerro Naunaucó (refer to Figure 3), contains approximately 210 m of conglomerates (Leanza et al., 2005). These conglomerates rest in angular unconformity atop folded Mesozoic units and are interpreted as synorogenic deposits associated with Neogene contraction within the Agrio FTB (Ramos, 1998; Zamora Valcarce et al., 2006, 2009, 2011; Zapata et al., 2002). Most of the clasts within these conglomerates consist of andesites, sandstones and limestones from nearby areas (Zamora Valcarce, 2007), with a likely middle Miocene age estimated based on a fragment of fossil mammal (Leanza et al., 2005). Finally, Quaternary magmatic activity generated basaltic flows, rhyolitic to andesitic domes and pyroclastic deposits in the surroundings of the Tromen volcano (Galland et al., 2007) (Figure 1c).

3. Structure of the Northern Agrio FTB

The Agrio FTB is a 160 km long and 60 km wide north-south trending deformed belt, developed in the Southern Central Andes between ~37°–39°S (Figures 1b and 1c). The structural style is dominated by thrusts and folds of variable orders resulting from the interaction between thick and thin-skinned deformational processes (Figure 4a).

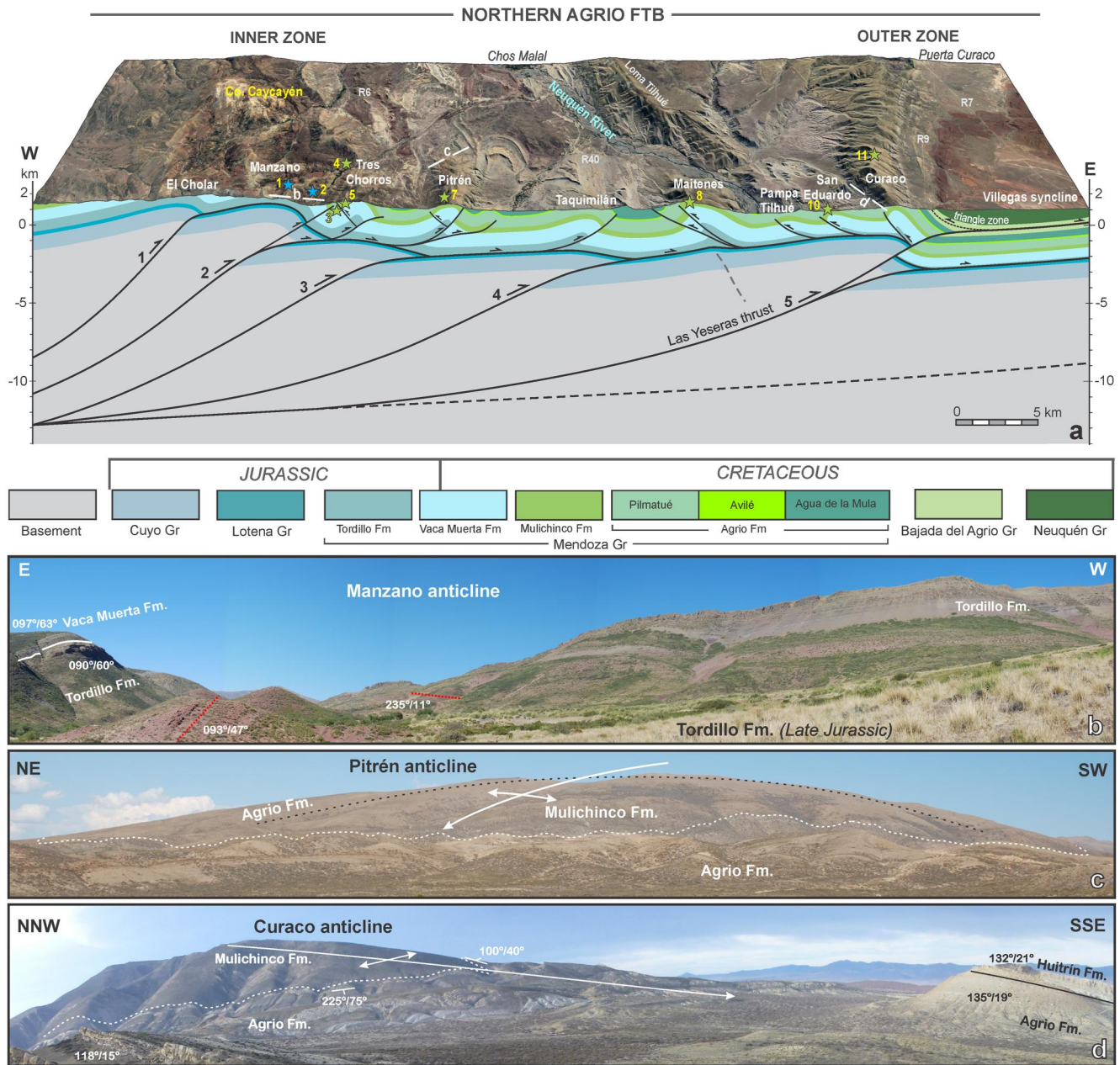


Figure 4. (a) Structural cross-section through the northern Agrio FTB ($\sim 37^{\circ}30'S$) adapted from Lebinson et al. (2015, 2018, 2020). The colored stars indicate the positions and numbering of the studied samples (b–d) Panoramic photographs of three fault-related folds from which samples (1, 7, and 11) were obtained (see locations in Figure 3). (b) Southward view of the first order Manzano anticline, exposing the red beds of the Late Jurassic Tordillo Formation in its core. (c, d) Pitrén and Curaco anticlines, second-order folds that expose the Early Cretaceous Mulichinco and Agrio Formations.

These contratraccional structures involve both Paleozoic to Triassic basement rocks and Jurassic to Cretaceous sedimentary sequences of the Neuquén Basin. While the basement is not directly exposed along the Agrio FTB, thick-skinned structures have been identified using seismic data and field mapping (e.g., Lebinson et al., 2018; Turienzo et al., 2022; Zamora Valcarce et al., 2009; Zapata et al., 2002). These structures have given rise to large-scale folds with wavelengths exceeding approximately 8 km. Basement-involved structures are prominently developed in the western (inner) zone of the Agrio FTB, leading to the exposure of Early Jurassic rocks. In contrast, their presence in the eastern (outer) zone is inferred primarily from subsurface data (e.g., Irastorza et al., 2019; Rojas Vera et al., 2014; Turienzo et al., 2020; Zapata & Folguera, 2005). To elucidate these basement-involved structures within the Chos Malal and Agrio FTBs, two main mechanisms have been

proposed: positive inversion of preexisting normal faults (Rojas Vera et al., 2014, 2015; Zamora Valcarce et al., 2006, 2009; Zapata & Folguera, 2005; Zapata et al., 1999) and newly formed thrusts faults that generate basement-involved wedges (Kozłowski et al., 1998; Lebinson et al., 2015, 2018, 2020; Sánchez et al., 2014, 2015, 2018; Turienzo et al., 2014, 2018, 2020). There is a consensus that these basement-involved faults connect with an upper detachment rooted within the sedimentary cover, typically situated within the Jurassic evaporites atop the Lotena Group (Figure 4a). Thereby, the thick-skinned structures (first-order) transfer deformation to produce thin-skinned thrust-related folds (second-order). These second-order folds affecting Late Jurassic-Cretaceous sequences, exhibit N to NNW trends (referring to their hinge line orientation), wavelengths of approximately 3–6 km, and have been interpreted as fault-propagation folds, fault-bend folds, or as a combination of both mechanisms (Lebinson et al., 2015, 2018; Zamora Valcarce & Zapata, 2015; Zapata et al., 2002).

The northern segment of the Agrio FTB extends south of the Neuquén River and Chos Malal city, approximately from 37°20' to 37°45'S (Figure 1c). Three large ~N-S anticlines, with kilometer-scale wavelengths and vergence to the east, characterize the western portion of the study area (Figure 3). The Rahueco anticline is a doubly plunging fold, exposing the Early Middle Jurassic Cuyo and Lotena groups in its core. Within these Jurassic strata, igneous rocks from the Cerro Caicayén intrude, utilizing a system of backthrusts as feed channels within the forelimb of the Rahueco anticline, showing a structural influence on magmatism (Lebinson et al., 2018). To the south, the El Cholar and Manzano anticlines (Figure 3) are cored by Upper Jurassic red beds of the Tordillo Formation (Figure 4b). Both anticlines exhibit gently dipping backlimbs (approximately 15°–30°W) and steeply dipping forelimbs (around 50°–60°E), and they are interpreted as thick-skinned fault-bend-fold with eastward vergence (Figure 4a). The El Cholar anticline displays minor structural relief of about 0.8 km in vertical displacement, whereas the Manzano anticline exhibits a more significant structural relief of approximately 2.4 km. These first-order structures, together with others basement-involved wedges interpreted at depth, form a thick-skinned duplex system that allows the exhumation of Jurassic rocks in the inner zone of the Northern Agrio FTB and transfers deformation to the sedimentary cover creating thin-skinned structures toward the east (e.g., Aramendia et al., 2019; Lebinson et al., 2018, 2020). Such second-order structures have a basal detachment located in the evaporites of the Lotena Group and form fault-related anticlines of variable vergence in the overlying Mendoza Group (Figure 4a). The Tres Chorros anticline (Figure 3), is a N-S double-vergence fold that resembles a pop-up structure (Figure 4a). South of the cross-section, this anticline is asymmetric, westward-directed, and affects the Lower Cretaceous Mulichinco Formation (Aramendia et al., 2019). The Cerro Pitrén anticline (Figure 3) is a north-trending, doubly plunging fold, which in its central part exposes the Mulichinco Formation (Figure 4c). Lebinson et al. (2015) reconstructed this anticline in two stages: first, as a fault-bend fold with displacement along an upper decollement within the Vaca Muerta Formation shales, forming a third-order anticline, and subsequently, a thrust propagated upward, shifting the anticline eastward (Figure 4a). The Taquimilán anticline (Figure 3) is a wide east-vergent fold with low structural relief, which exposes mostly the Agrio Formation. On the contrary, the Maitenes anticline (Figure 3) has a marked vergence to the west and shows a significant structural relief, related to a set of imbricated backthrusts, exposing the Mulichinco Formation at a high topographic elevation (Figure 4a). Both the Maitenes and Las Viseras anticlines, located toward the south (Figure 3), have an oblique NNW trend, probably influenced by underlying pre-existing rift faults (Turienzo et al., 2022). The easternmost thin-skinned structures are the San Eduardo and Curaco anticlines (Figure 3). These north-trending folds are cored by the Mulichinco Formation (Figure 4d) and have a vergence to the west (Figure 4a). All anticlines with opposite vergence in this region are associated with a backthrust system that accommodates the horizontal shortening transferred from prominent east-directed basement-involved thrusts formed in the inner zone (Lebinson et al., 2020). These thin-skinned folds are located in the hangingwall of the basement-involved Las Yeseras thrust, which flattens into a subhorizontal detachment on the Early Cretaceous evaporites of the Bajada del Agrio Group creating a triangle zone in the outer zone of the Agrio FTB (Figure 4a). Some of the fault's displacement may have been accommodated by passive backthrusting within the triangle zone, while the rest was transmitted to the east, leading to the formation of minor-scale duplexes and backthrusts involving the overlying Cretaceous sequences (Starck et al., 2022; Turienzo et al., 2020, 2022). The related first-order Las Yeseras anticline exposes the Tordillo Formation near Route 7 in the Puerta Curaco region (Figure 3). To the north, it exposes the Lotena Group resulting in extensive evaporitic outcrops along Route 40 (as shown in Figure 1c). At this latitude, the basement-involved deformation at the mountain front creates a structural relief of approximately 2.1 km relative to the subhorizontal layers beneath the Villegas syncline (refer to Figure 4a; Turienzo et al., 2020, 2022).

4. Low-Temperature Thermochronology

Low-temperature thermochronological methods have the ability to constrain rocks thermal histories through the upper 10 km of the crust making them potent tools to investigate the thermo-kinematic evolution of FTBs (e.g., Ault et al., 2019; Reiners et al., 2018 and references therein). In the next sections, we briefly outline the theoretical foundations of (U-Th)/He dating on apatite and zircon (AHe and ZHe, respectively) and Fission Track dating on apatite (AFT), the three dating methods that were used in this study.

4.1. Methods

4.1.1. (U-Th)/He

(U-Th)/He chronology is based on the production of ^4He atoms resulting from the radioactive alpha decay of ^{235}U , ^{238}U , ^{232}Th , and ^{147}Sm within a crystal lattice (e.g., Farley, 2002; Reiners, 2005). These ^4He atoms are subject to variable retention or loss through thermally activated volume diffusion. The kinetics of ^4He diffusion are influenced by factors such as radiation damage, crystal size, major element chemistry, and crystal defects, all which impact closure temperatures (Flowers, Zeitler, et al., 2023; Flowers, Ketcham, et al., 2023). These dating techniques exhibit sensitivity within specific temperature ranges, approximately 120–30°C in apatite (AHe) and about 200–20°C in zircon (ZHe). For a comprehensive review, (see Flowers, Zeitler, et al., 2023; Flowers, Ketcham, et al., 2023 and references therein).

4.1.2. Fission-Track

The AFT method is based on the spontaneous radioactive decay of ^{238}U , into two positively charged nuclei repelling each other in opposite directions and leaving behind their trajectory an ionized trail in the crystal lattice called a fission track (Fleischer et al., 1975). Fission tracks are unstable features that shorten (anneal), fade, and segment (e.g., Ketcham, 2005) by thermal and time-dependent recrystallization processes (e.g., Wagner & Van den haute, 1992). In apatite crystals, this dating technique has a sensitivity range of 120–80°C depending on the cooling rate and the composition of the crystal (e.g., Donelick et al., 2005; Green et al., 1985; Ketcham et al., 1999). This temperature range is referred to as the Partial annealing zone, (PAZ) in which pre-existing tracks are progressively annealed and new tracks are formed. Determining the density of spontaneous fission tracks and the concentration of ^{238}U yields a single-grain fission track age (For a comprehensive review of the method, see Donelick et al., 2005; Gallagher et al., 1998; Tagami & O'Sullivan, 2005).

4.2. Sampling Strategy

We collected sandstone samples along an approximately ~45 km-long west-east transect, perpendicular to the strike of the structures and covering both the inner and outer zones of the northern Agrio FTB (Table 1 & Figure 1c). Samples 1 and 2 were collected from the Upper Jurassic Tordillo Formation in the core of the first-order Manzano anticline (Figure 3). Samples 3 to 11 were collected from the Lower Cretaceous Mulichinco Formation, in the hinge zones or on the flanks of the second-order Tres Chorros, Pitren, Los Maitenes, San Eduardo, Las Viseras and Curaco anticlines (Figure 3). Finally, samples 12 and 13 were collected from Miocene synorogenic strata in the limbs of the Tralalhue syncline (Figure 3). All the samples were processed for AFT analyses. The samples that passed the statistical χ^2 test were then processed for AHe (four samples; number 1, 7, 8, and 11) and ZHe (three samples; number 1, 7, and 11). Details of each thermochronometer analytical procedures used for data acquisition are given in the Texts S1 and S2 in Supporting Information S1.

4.3. Results

4.3.1. Apatite Fission Track (Table 2)

Out of the 13 samples analyzed for AFT thermochronology (Tables 1 and 2, Figure 5), two were from the Tordillo Formation (151–147 Ma, Naipauer et al., 2015), nine from the Mulichinco Formation (~139.5–137.5 Ma, Schwarz et al., 2011), and two from the Tralalhue conglomerate (middle Miocene?). We processed the maximum number of datable grains we could find, resulting between 17 and 51 grains for each sample (Table 2). Each single-grain age distribution was decomposed using the binomial peak method (Figure 6; Galbraith & Green, 1990) incorporated into the *Binomfit* software (Brandon, 1992, 1996, 2002) to identify discrete

Table 1
Sample Identification and Location

Sample	Latitude (S)	Longitude (W)	Stratigraphic unit	Stratigraphic age (Ma)	Applied method			Modeled
					ZHe	AFT analysis	AHe	
1	37° 17' 38.08"	69° 41' 26.20"	Tordillo	[~151–147.0]	✓	✓	✓	✓
2	37° 26' 3.7"	70° 17' 9.7"	Tordillo	[~151–147.0]		✓		
3	37° 22' 45.12"	69° 55' 49.08"	Mulichinco	[139.5–137.5]		✓		
4	37° 15' 27.36"	70° 26' 57.16"	Mulichinco	[139.5–137.5]		✓		
5	37° 15' 54.00"	70° 25' 30.04"	Mulichinco	[139.5–137.5]		✓		
6	37° 17' 31.56"	69° 41' 42.36"	Mulichinco	[139.5–137.5]		✓		
7	37° 21' 58.32"	70° 16' 1.56"	Mulichinco	[139.5–137.5]	✓	✓	✓	✓
8	37° 22' 4.08"	70° 11' 30.12"	Mulichinco	[139.5–137.5]		✓	✓	
9	37° 21' 45.36"	70° 21' 3.96"	Mulichinco	[139.5–137.5]		✓		
10	37° 20' 19.36"	70° 1' 54.16"	Mulichinco	[139.5–137.5]				
11	37° 20' 11.04"	69° 58' 44.08"	Mulichinco	[139.5–137.5]	✓	✓	✓	✓
12	70° 26' 47.08"	37° 15' 23.08"	Tralalhue	Middle—Late Miocene		✓		
13	37° 18' 3.28"	70° 18' 2.16"	Tralalhue	Middle—Late Miocene		✓		

Note. ✓ indicate the samples processed for each thermochronometer.

populations subsequently referred to as P_1 to P_n (where the age of the population increases with n). The distribution of fission-track grain ages (FTGA) generally shows a wide range, from 3.3 Ma to 304 Ma, with AFT dates ranging from 12.9 ± 1.4 and 74.0 ± 8.4 Ma. Ages are reported as the central age when the sample pass the Chi test $P(\chi^2) < 5\%$, and are reported as the pooled age when they do not pass it (Table 2). These ages are consistently younger than the stratigraphic ages of the strata from which they were collected indicating partial to full resetting, except for samples 12 and 13 from the synorogenic Tralalhue conglomerate, for which AFT ages are older than the Miocene, suggesting these two samples were unreset. Samples 1, 2, 5, 7, and 11 have pooled ages of 14.6 ± 1.9 , 26.4 ± 5.4 , 74.0 ± 8.7 , 27.0 ± 3.5 , and 12.9 ± 1.4 Ma, respectively. The remaining samples fail the χ^2 test (Galbraith, 1981; Green, 1981) with $P(\chi^2) < 5\%$ (Table 2 and Figure 5) indicating that FTGA distributions are non-poissonian and represent a mixture of components or peak ages (Brandon, 1992, 1996, 2002). In general samples from the Mulichinco and Tordillo Formations show a younger population P_1 between $12.1 \pm 4.4/7$ Ma to $20.2 \pm 3.7/4.5$ Ma representing between 32% and 95% of the dated grains (Figure 5). A second population P_2 ranging from $31.9 \pm 13.8/24.4$ Ma to $44.8 \pm 13.6/19.6$ Ma, and a third population P_3 between $61.1 \pm 29.7/191.4$ Ma to $94.9 \pm 50/105$ Ma were identified. In samples 12 and 13 of the Tralalhue conglomerate, two populations were differentiated, a younger population compatible with P_2 varying from $40.9 \pm 8.9/11.3$ to $41.5 \pm 8.9/11.3$ Ma with ~94% occurrence and an older population that we label P_4 ranging from $191.4 \pm 121/323$ to $224.81 \pm 27/299$ Ma, with 6% occurrence. The populations recognized in each sample and their associated percentages are shown in Figure 6 and a more exhaustive analysis is provided in Section 5.4.

A total of 32 confined horizontal track lengths were measured in the sample set (Table 2). However, both the low-number of track lengths measured in each sample (between two and 10 tracks) and the unknown track length distribution in the grains at the time of deposition precludes drawing any conclusions from this part of our data set. With exception of sample 1, all samples have mean Dpar values $< 3 \mu\text{m}$ and do not display a clear relationship between grain age and this parameter (see Supporting Information S2).

4.3.2. Zircon (U-Th)/He (ZHe, Table 3)

Three samples that successfully passed the Chi-squared test were deemed fully reset for the AFT thermochronometer, which was further supported by vitrinite reflectance data (see Section 5.4). Subsequently, these samples were processed for (U-Th)/He analyses on apatite and zircon, to serve as input data for thermal inversions. These three samples are from Tordillo (sample 1) and Mulichinco Formations (samples 7 and 11). ZHe mean ages were calculated using five to four aliquots (Table 3 and Figure 5). For sample 1, five aliquots yielded

Table 2
Apatite Fission-Track Results

Sample	Latitude (S)	Longitude (W)	Stratigraphic unit	Stratigraphic age (Ma)	No of grains	Spontaneous track density $\rho_s \times 10^6 \text{ cm}^{-2}$ (N_s)	Induced track density $\rho_i \times 10^6 \text{ cm}^{-2}$ (N_i)	Dosimeter track density $\rho_d \times 10^6 \text{ cm}^{-2}$ (N_d)	$P(\chi^2)$	Pooled age $\pm 1\sigma$ (ppm)	Number of tracks length counted per sample	Mean track length ($\pm 1\sigma$) (μm)	Mean track length SDT (μm)	Dpar (μm)
1	37° 17' 38.08"	69° 41' 26.20"	Tordillo	[151–147]	28	0.1668 (126)	1.9835 (1,535)	9.4970 (10,283)	6.77	13.5 $\pm$ 1.6	2	18.07	3.1	2.4
2	37° 26' 3.7"	70° 17' 9.7"	Tordillo	[151–147]	17	0.1708 (44)	1.0119 (315)	9.4225 (10,283)	9.69	22.7 $\pm$ 4.0	2	-	-	5.0
3	37° 15' 54.00"	70° 25' 30.04"	Mulichinco	[139.5–137.5]	32	0.2229 (256)	2.0319 (2,378)	9.6087 (10,283)	0.25	17.9 $\pm$ 1.8	3	13.24	1.5	3.0
4	37° 17' 31.56"	69° 41' 42.36"	Mulichinco	[139.5–137.5]	26	0.3526 (264)	3.2562 (2,089)	9.7205 (10,283)	1.64	21.2 $\pm$ 2.1	4	11.21	-	2.7
5	37° 15' 27.36"	70° 26' 57.16"	Mulichinco	[139.5–137.5]	51	0.1415 (185)	2.866 (387)	9.199 (10,283)	89.32	74.0 $\pm$ 8.7	2	12.79	-	2.4
6	37° 21' 45.36"	70° 21' 3.96"	Mulichinco	[139.5–137.5]	23	0.2615 (123)	1.8738 (960)	9.9812 (10,283)	0.04	22.1 $\pm$ 2.7	3	13.10	3.4	1.8
7	37° 20' 19.36"	70° 1' 54.16"	Mulichinco	[139.5–137.5]	24	0.2848 (155)	1.9941 (1,044)	10.3165 (10,283)	6.42	27.0 $\pm$ 3.5	34	-	1.9	3.0
8	37° 22' 45.12"	69° 55' 49.08"	Mulichinco	[139.5–137.5]	26	0.2878 (203)	2.4201 (1,816)	9.1245 (10,283)	0.0	17.6 $\pm$ 1.9	4	12.7	1.8	1.9
9	37° 21' 58.32"	70° 16' 1.56"	Mulichinco	[139.5–137.5]	21	0.3185 (94)	2.0472 (750)	9.7950 (10,283)	0.47	21.2 $\pm$ 2.8	4	-	3.4	1.9
10	37° 22' 4.08"	70° 11' 30.12"	Mulichinco	[139.5–137.5]	33	0.2556 (109)	1.9025 (861)	9.8685 (10,283)	0.0	21.6 $\pm$ 2.7	3	-	-	2.8
11	37° 20' 11.04"	69° 58' 44.08"	Mulichinco	[139.5–137.5]	35	0.1822 (174)	2.5300 (2,413)	10.3910 (10,283)	55.45	12.9 $\pm$ 1.4	23	-	3.4	2.9
12	37° 15' 23.08"	70° 26' 47.08"	Tralalhué	Middle - Late Miocene	30	0.1652 (159)	0.5904 (563)	9.2735 (10,283)	3.39	45.3 $\pm$ 5.3	2	-	-	2.9
13	37° 18' 3.28"	70° 18' 2.16"	Tralalhué	Middle—Late Miocene	22	0.2519 (151)	1.2051 (545)	9.3480 (10,283)	0.13	44.7 $\pm$ 5.3	4	13.2	4.0	2.5

Note. N , number of individual grains dated per sample; ρ_s , spontaneous track density; ρ_i , induced track density; N_s , number of spontaneous tracks counted; N_i , number of induced tracks counted; ρ_d , induced track density in external detector adjacent to dosimetry glass; N_d , number of tracks counted in determining ρ_d ; $P(\chi^2)$, χ^2 probability.

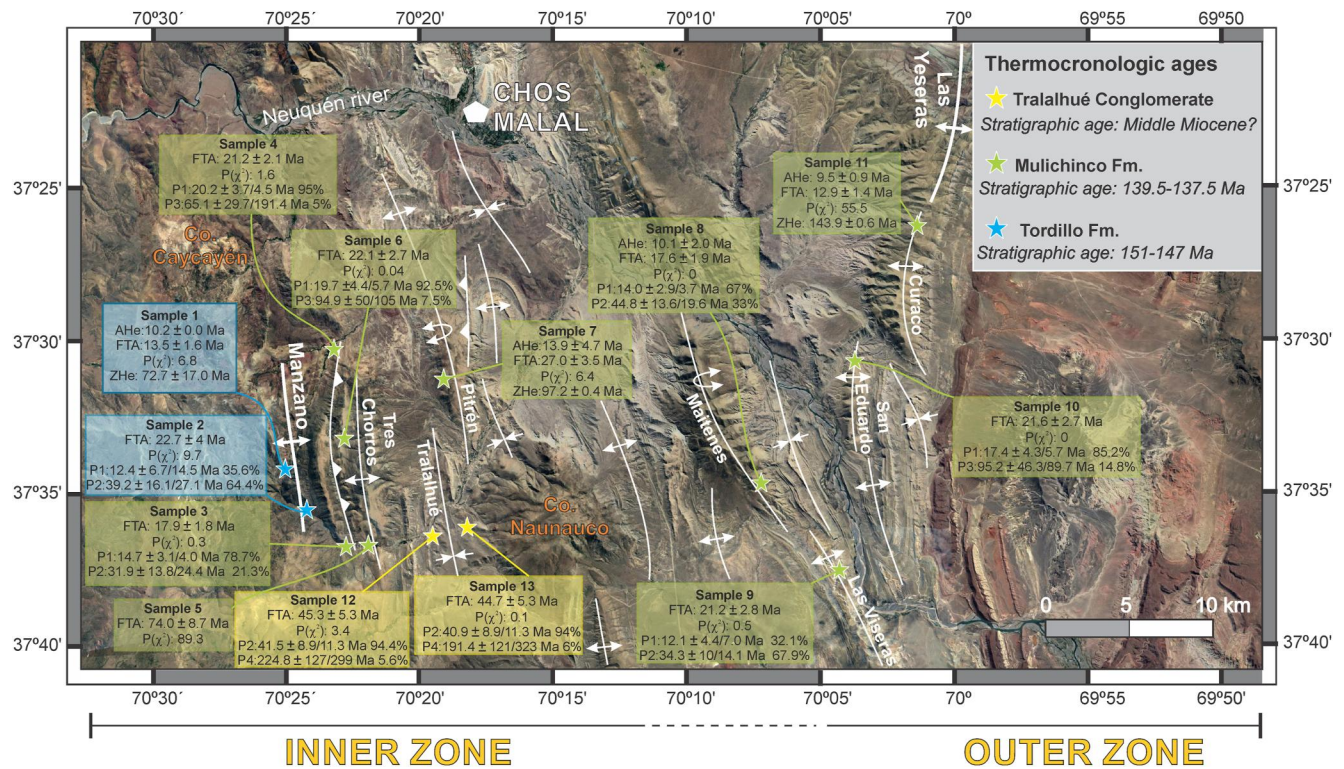


Figure 5. Thermochronological results in the northern Agrio FTB. The AFT ages are pooled ages associated 1σ error (Table 2). P_1 , P_2 , P_3 , and P_4 indicate the AFT ages and associated 95% confidence level errors of the populations extracted with the software *Binomfit* (Brandon, 1992, 1996, 2002) from the samples failing the χ^2 test ($P(\chi^2) < 5\%$ in Table 2 and Figure 6). The samples 1, 7 and 11, which include the three thermochronological methods used in this work (AFT, ZHe and AHe), were modeled with *Hefty* (Ketcham, 2005).

ages ranging from 54.4 to 95.0 Ma, all younger than its stratigraphic age (151–147 Ma, Naipauer et al., 2015), with a mean of 72.7 ± 17.0 Ma. Four out of five aliquots dated for sample 7 yielded younger ages than its stratigraphic age (~ 139.5 – 137.5 Ma, Schwarz et al., 2011), varying between 110.9 and 84.7 Ma (mean age of 97.2 ± 10.8 Ma). This sample has a positive correlation between ZHe data and eU (See Text S2 in Supporting Information S1) which could be due to the effect of radiation damage on He diffusion kinetics at low damage levels in zircon crystals (Guenther et al., 2013). As our goal is to constrain the maximum heating temperatures during burial and the subsequent cooling/exhumation histories, the aliquot z7-1 with age of 158.9 Ma was discarded in the calculation of the mean age because it is older than the stratigraphic age of the Mulichinco Formation suggesting it hasn't been reset for the method. For sample 11, five aliquots were dated ranging from 125.2 to 174.3 Ma. In this case, all the aliquots are older or close to the stratigraphic age (~ 139.5 – 137.5 Ma, Schwarz et al., 2011). This sample has a mean age of 143.9 ± 21.1 Ma (see Text S2 in Supporting Information S1).

4.3.3. Apatite (U-Th)/He (Table 4)

Four sedimentary samples from the Tordillo (sample 1) and Mulichinco (samples 7, 8, and 11) Formations were processed for AHe dating. Five aliquots were measured for each sample and included in the mean age calculation. However, in the case of sample 7, only four aliquots were utilized since one outlier was discarded because of its dissimilar age to the other aliquots and the absence of linear correlation between age/eU and age/ESR (See Text S2 in Supporting Information S1). Five aliquots were dated from sample 1 and yielded ages ranging from 7.3 to 16.5 Ma. The mean age obtained for this sample is 10.2 ± 3.8 Ma. For sample 7, the aliquots range from 9.1 to 18.8 Ma in age, resulting in a mean age of 13.9 ± 4.7 Ma. For sample 8 the dated aliquots range from 8.6 Ma to 13.5 Ma and the mean age for this sample is 10.1 ± 2.0 Ma. Finally, the aliquots for the sample 11 range from 8.5 to 10.9 Ma with a mean age of 9.5 ± 0.9 Ma (Table 4). All the AHe ages are consistently younger than AFT ages (see Text S2 in Supporting Information S1).

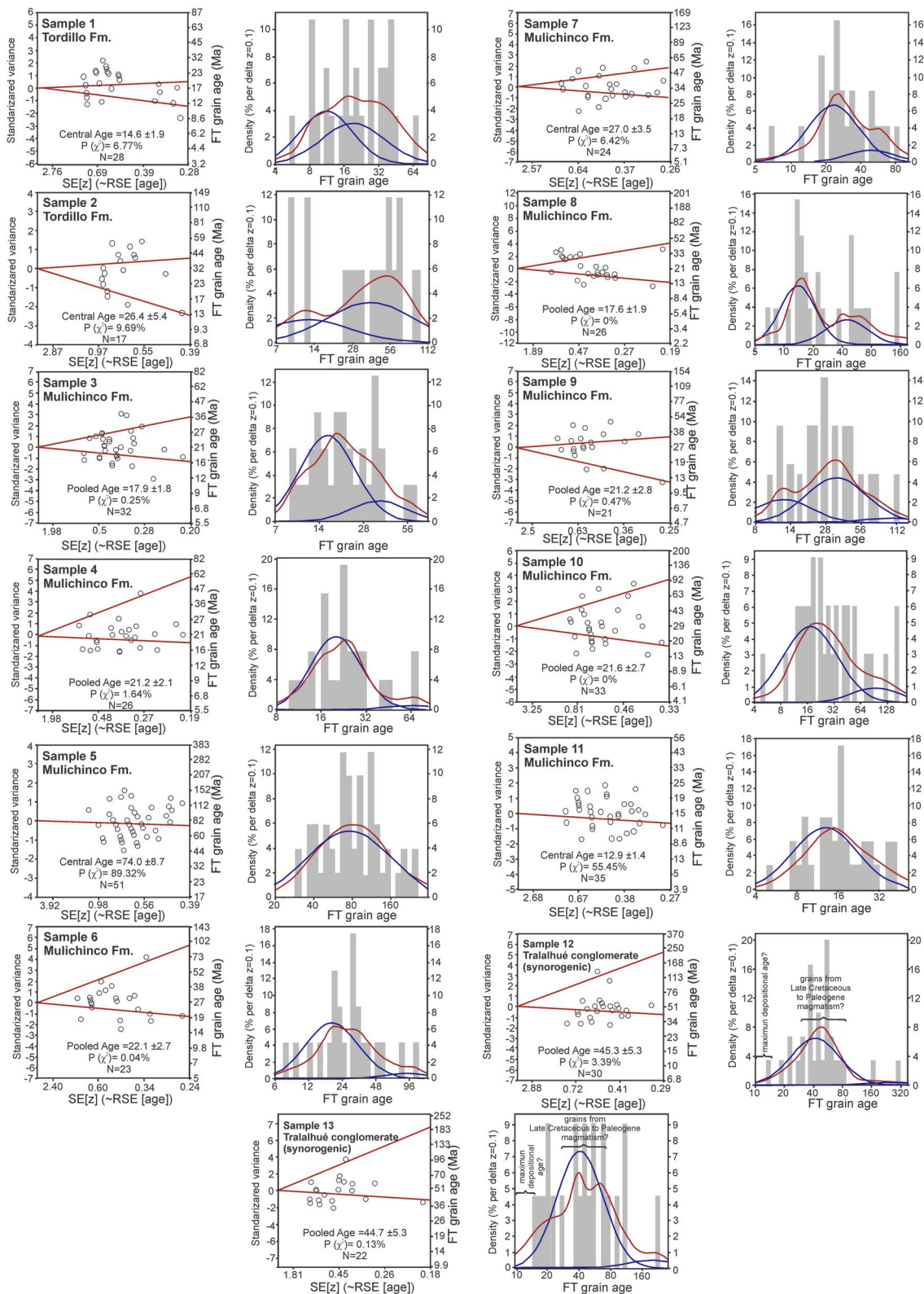


Figure 6. Apatite fission-track results. For each sample, the left column is a radial plot of the single-grain age data and the right column is the probability density plots of fission-track grain age distributions (Brandon, 1996, 2002). Red lines indicate probability density distributions and blue lines indicate component distributions estimated by the binomial peak-fit method (Galbraith & Green, 1990).

Table 3
Zircon (U-Th)/He Data

Samples	He (pmol)	U(ppm)	Th(ppm)	Th/U	Rs (μm)	Raw age	Age error (1σ) (Ma)	Ft	Corrected age (Ma)	Mean age (Ma)
z1-1	64.16	223.79	174.82	0.78	45.89	44.74	0.26	0.74	60.22	72.74 ± 17.0
z1-2	59.85	125.04	217.86	1.74	45.40	62.58	0.32	0.74	85.12	
z1-3	146.22	321.49	236.72	0.74	47.57	71.45	0.41	0.75	95.05	
z1-4	35.38	110.14	88.87	0.81	42.37	49.83	0.29	0.72	68.88	
z1-5	22.23	80.65	63.32	0.79	57.06	42.98	0.23	0.79	54.42	
z7-1	309.45	380.91	340.00	0.89	53.28	123.20	0.67	0.78	158.93	97.21 ± 10.8
z7-2	84.52	138.81	158.56	1.14	59.57	88.31	0.45	0.80	110.93	
z7-3	26.48	53.48	41.70	0.78	55.34	77.07	0.42	0.78	98.33	
z7-4	48.52	107.67	66.37	0.62	50.20	72.55	0.42	0.76	94.86	
z7-5	38.85	92.98	79.64	0.86	48.95	64.13	0.36	0.76	84.69	
z11-1	41.84	66.45	55.47	0.83	48.06	96.79	0.54	0.75	128.50	143.92 ± 21.1
z11-2	134.49	234.64	63.32	0.27	43.91	99.14	0.63	0.74	134.17	
z11-3	133.07	159.74	125.80	0.79	45.19	128.89	0.74	0.74	174.34	
z11-4	104.02	146.66	90.67	0.62	41.92	113.72	0.69	0.72	157.37	
z11-5	145.76	256.77	164.14	0.64	42.41	90.82	0.55	0.73	125.21	

Note. Five aliquots were processed per sample. Ft is the alpha ejection correction factor (Farley, 2002; Farley et al., 1996). Numbers in italic indicate outliers that were discarded before mean age calculation. Mean ages are the mean of each selected aliquot, and the age error is the standard deviation between selected aliquots divided by the square root of the number of aliquots.

5. Inverse Thermal Modeling

The three samples 1, 7, and 11, were selected for modeling because their AFT ages passed the statistical χ^2 test and are younger than their stratigraphic ages (indicating that these samples have been fully reset after deposition, hence can be treated as bedrock samples and are therefore, suitable for modeling) (Figure 6). Furthermore, they could be dated using the three different thermochronometers (AFT, AHe, and ZHe). T-t paths were calculated using thermal inverse modeling from the *HeFTy* program (Ketcham, 2005). Three inversions representative of the crustal cooling history of the study area below 200°C were run (Figure 7, see Table 1 in Text S3 in Supporting Information S1). Using a Monte Carlo random search, each model run had 50,000 iterations. Each T-t constraint is evenly spaced by two half-segments. We used intermediate monotonic consistent (2i) path segments for all samples except for an episodic monotonic consistent (2e) path for the first segment of sample 11 because that model starts before the deposition of the Mulichinco Formation and more freedom was allocated to this first segment.

For AFT data we input the c-axis projected tracks lengths, the individual grain age, Dpars (etch pit size), and we chose the annealing model from Ketcham et al. (2007). For AHe and ZHe systems, we input parameters such as U, Th, Sm, He concentrations, the mean radius of each aliquot, the effective Uranium value, and the diffusion kinetics. We chose the kinetic models from Flowers (2009) and Guenther et al. (2013) for AHe and ZHe data, respectively. The software allows a maximum of seven input age data per model. To select AHe and ZHe aliquots for the models, we have tested as many combinations as possible and retained the best outputs. For each thermochronometric system, the range of closure temperatures that we used to determine some of our T-t constraints (see Sections 5.1–5.3) are from Ault et al. (2019) and references therein: 30–120°C for AHe (Farley, 2000; Flowers, 2009; Gautheron et al., 2009; Shuster & Farley, 2009; Shuster et al., 2006), 75–125°C for AFT (e.g., Ketcham et al., 2007), and 20–200°C for ZHe (Guenther et al., 2013; Reiners et al., 2004). We found that adding these constraints facilitate the Monte Carlo search and yield a higher number of good solutions. To increase the degree of freedom of the search, initial T-t boxes were set much larger than they appear on Figure 7; they were then progressively reduced to optimize the search for best outputs. For each model run, the program determined good and acceptable fit solutions (light and dark gray lines respectively), using merit values of 0.5 and 0.05, respectively (Ketcham, 2005; Ketcham et al., 2009), and from which the best fit path (black bold line) and the mean weighted path (yellow bold line) for each model were identified. In this paper, we chose to present the

Table 4
Apatite (U-Th)/He Data

Samples	²³⁸ U(ppm)	²³² Th(ppm)	¹⁴⁷ Sm(ppm)	⁴ He(fmol)	Mean R (μm)	Raw age (Ma)	Error (Ma)	Ft	Corrected age	Mean age (Ma)
a1-1	48.33	53.87	86.34	2.0	45.15	6.0	0.04	0.67	8.98	10.2 ± 3.79
a1-2	3.08	18.31	125.38	0.3	46.33	7.2	0.04	0.66	10.83	
a1-3	3.59	14.15	96.62	0.4	31.91	8.8	0.07	0.54	16.50	
a1-4	3.56	17.06	229.19	0.2	36.13	4.3	0.03	0.58	7.45	
a1-5	6.16	30.55	439.73	0.4	34.62	4.1	0.03	0.56	7.32	
a7-1	20.09	56.09	200.71	1.0	37.90	5.47	0.03	0.60	9.09	13.9 ± 4.71
a7-2	9.85	4.49	44.40	0.6	35.50	10.12	0.08	0.60	16.88	
a7-3	54.97	64.63	89.81	4.7	43.52	12.34	0.08	0.66	18.82	
a7-4	15.32	14.69	188.90	0.7	35.01	6.26	0.05	0.59	10.69	
a7-5	3.16	17.27	104.17	0.7	34.24	16.63	0.12	0.56	29.71	
a8-1	36.18	54.30	241.53	1.6	37.83	5.8	0.04	0.61	9.61	10.1 ± 1.99
a8-2	7.26	54.06	164.76	0.6	34.39	4.8	0.03	0.56	8.58	
a8-3	14.26	10.20	70.10	0.7	63.34	7.6	0.04	0.76	10.05	
a8-4	6.46	6.23	60.76	0.4	38.80	8.4	0.06	0.62	13.52	
a8-5	5.29	27.21	187.55	0.4	42.32	5.6	0.03	0.63	8.85	
a11-1	4.29	30.21	157.52	0.4	42.59	6.40	0.04	0.63	10.09	9.5 ± 0.95
a11-2	8.87	26.57	147.23	0.5	42.78	5.81	0.03	0.64	9.06	
a11-3	11.84	75.15	292.80	0.9	38.03	5.09	0.03	0.60	8.52	
a11-4	40.91	75.79	50.75	2.2	40.05	6.79	0.04	0.62	10.87	
a11-5	21.07	37.38	41.53	1.1	55.33	6.50	0.03	0.72	9.03	

Note. Five aliquots were processed per sample. Ft is the alpha ejection correction factor (Farley, 2002; Farley et al., 1996). Numbers in italic indicate outliers that were discarded before mean age calculation. Mean ages are the mean of each selected aliquot, and the age error is the standard deviation between selected aliquots divided by the square root of the number of aliquots.

models for which we obtained the highest number of good T-t paths. The aliquots used in the best models are shown in Table 1 of the Text S3 in Supporting Information S1.

Because of the diversity of output T-t paths from the inverse models (see modeling results sections), we applied the Path Family Approach described by Murray et al. (2022) to samples 1 and 7. A Python script was developed to identify T-t paths at different time intervals using the spreadsheet output generated by *HeFTy*. This analysis focused exclusively on the oldest cooling event (Late Cretaceous–Paleogene), which exhibits a wider range of path dispersion. The filtering process began by selecting T-t paths with Cretaceous cooling events older than 80 Ma for sample 1 and 110 Ma for sample 7. Subsequently, paths with cooling events younger than these thresholds were included in 10-million-year time increment windows until reaching the post-80 Ma period for sample 1 and the post-90 Ma period for sample 7 (Figure 7). After applying the filtering procedure, the resulting data was exported to preferred graphic design software for further analysis and visualization.

5.1. Modeling Parameters and Results for Sample 1

Five Time-temperature (T-t) constraints were used for this sample: (a) 0–20°C between 151 and 147 Ma based on the stratigraphic age of Tordillo Formation determined from detrital zircon U-Pb dating (Naipauer et al., 2015). The constraints derived from our thermochronometric data (ZHe, AFT and AHe) are centered on the mean (or pooled) age ± 20% of that age (b) 20–200°C between 87 and 58 Ma (based on ZHe mean cooling age); (c) 75–125°C between 16.2 and 10.8 Ma (based on AFT pooled age); (d) 30–120°C between 12.2 and 8.2 Ma (based on AHe mean cooling age) and (e) 20°C as the modern surface temperature (Table S1 and Text S3 in Supporting Information S1).

The model returned 2058 acceptable paths and 346 good paths (Figure 7a). We describe the resulting T-t history using the weighted mean path (bold yellow line) which suggests this sample underwent progressive heating at a

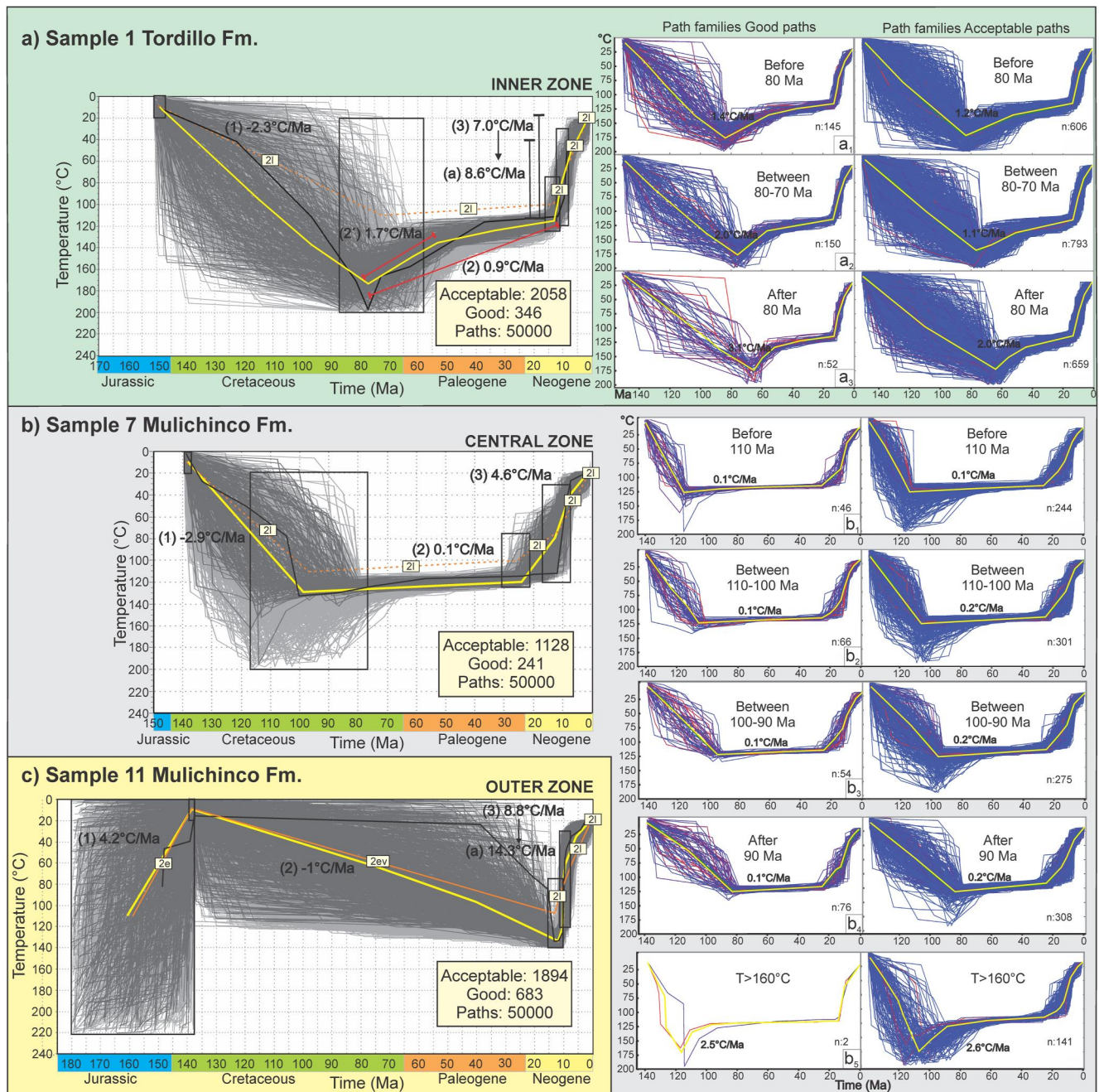


Figure 7. Representative *HeFTy* inversion results. Models' T–t constraints (black boxes) are centered on cooling ages and associated errors obtained for the different thermochronometers (see Section 5 and Table S1 in Supporting Information S1 for details). For every model run, the program determined the best-fit path (black bold line), the weighted mean path (yellow line) and good and the acceptable fit solutions (dark and light gray lines respectively) (Ketchum, 2005). In the right-hand side of (a, b) display Path Families for “good” (left column) and “acceptable” (right column) fit solutions for samples 1 and 7. The filtering commences with Cretaceous cooling events older than 80 Ma (110 Ma) for samples 1 and 7 and advances in 10 Myr time increment windows until the post-80 Ma period for sample 1 and the post-90 Ma period for sample 7 are reached. The color palette from red to blue is weighted according to each path's Goodness-of-Fit (GOF): redder signifies higher GOF, while more blue indicates lower GOF. Further explanations in Section 5.

rate of $\sim 2.3^{\circ}\text{C}/\text{Ma}$ after 151–147 Ma (deposition of the Tordillo Formation) and reached the peak burial temperature of 180°C at ~ 77 Ma. Then the sample experienced a slow ($\sim 0.9^{\circ}\text{C}/\text{Ma}$) and steady cooling between 77 Ma and 13.5 Ma (Figure 7a). Between 77 and 53 Ma a steeper segment of the T–t path suggests a slightly faster cooling rate ($1.7^{\circ}\text{C}/\text{Ma}$). From 13.5 Ma to the present, the sample was cooled at a rate of $\sim 7.0^{\circ}\text{C}/\text{Ma}$. However, it should be highlighted that there is a wide range of possible cooling paths, different from the weighted mean path,

mainly between the Late Cretaceous and the Paleogene time range of the paths. We apply the Path Family Approach strategy (Murray et al., 2022) to evaluate alternative cooling rates of path families whose cooling began at different times within this period. We separated the good and acceptable paths cooling before 80 Ma, between 80 and 70 Ma, and after 70 Ma. Before 80 Ma, there are 145 good paths with a cooling rate of 1.4°C/Ma from ~85 to 55 Ma (considering the weighted mean path of this group of trajectories, drawn as a yellow line) and 606 acceptable paths with a cooling rate of 1.2°C/Ma (Figure 7a1). There are 150 good paths with a cooling rate of 2°C/Ma from ~75 to 55 Ma and 793 acceptable paths with a cooling rate of 1.4°C/Ma (Figure 7a2). After 70 Ma, there are 52 good paths with a cooling rate of 3.1°C/Ma from ~65 to 50 Ma and 659 acceptable paths with a cooling rate of 1.4°C/Ma (Figure 7a3).

5.2. Modeling Parameters and Results for Sample 7

Five constraints were used for modeling sample 7: (a) 0–20°C between 139.5 and 137.5 Ma according to the stratigraphic age of Mulichinco Formation, which is constrained from the underlying Vaca Muerta Formation (depositional age determined from ammonites, nannofossils and zircon U/Pb dating; Aguirre-Urreta et al., 2019) and the overlying Agrio Formation (depositional age determined by ammonoids, nannoplankton, palynology and zircon U-Pb age from interlayered tuffs; Aguirre-Urreta et al., 2015, 2017). The constraints derived from our thermochronometric data (ZHe, AFT and AHe) are centered on the mean (or pooled) age $\pm$ 20% of that age. (b) 200–20°C between 117 and 77 Ma (based on ZHe mean cooling age); (c) 125–75°C between 31 and 21 Ma (AFT pooled age); (d) 120–30°C between 10.2 and 7.2 Ma (based on AHe mean cooling age) and (e) 20°C as the modern surface temperature Table S1 and Text S3 in Supporting Information S1).

The model yielded 1,128 acceptable paths and 241 good paths (Figure 7b). The output weighted mean path suggests a progressive and steady heating episode at a rate of 2.9°C/Ma between 139.5 and 137.5 Ma, the time of deposition of the Mulichinco Formation and ~98 Ma when a peak temperature of 130°C is reached (Figure 7b); it is followed by a steady, continuous and slow cooling episode at a rate of 0.1°C/Ma lasting until around 23 Ma, a time at which a rapid cooling event initiates at a rate of 4.6°C/Ma and lasts until the present. In this model, although it is not evident from the weighted mean path, there are many possible paths that reached a higher peak temperature and show a Late Cretaceous cooling event (Figure 7b). We use the Path Family Approach (Murray et al., 2022) initially to distinguish the start and end of cooling from these different groups of trajectories, filtering the paths into discrete time intervals before 110 Ma, between 110 and 100 Ma, between 100 and 90 Ma, and after 90 Ma (Figures 7b1–7b4). This cooling event is recognized primarily from the acceptable paths, which show hundreds of possible trajectories in each of those time intervals, starting approximately between 115 Ma and 85 Ma and ending around ~80–70 Ma. In all cases, the weighted mean path in each family (yellow line) remains with a flat trajectory in the late Cretaceous, which suggests that most of the individual paths follow that trend. Then, to obtain more information about the paths that show a Late Cretaceous cooling, we filtered the trajectories that, according to the model, reached a temperature greater than 160°C. From this approach, we found 2 good paths with a cooling rate of 2.5°C/Ma from ~115 to 95 Ma and 141 acceptable paths with a cooling rate of 2.6°C/Ma from ~107 to 90 Ma (Figure 7b5).

5.3. Modeling Parameters and Results for Sample 11

For this last modeled sample, five constraints were used. (a) 20–200°C between 180 and 137 Ma (ZHe mean cooling age) (b) 0–20°C between 139.5 and 137.5 Ma according to the stratigraphic age of Mulichinco Formation; (c) 125–75°C between 15.4 and 10 Ma (AFT pooled age); (d) 120–30°C between 11.4 and 7.6 Ma (AHe mean age) and (e) 20°C as the modern surface temperature (Table 2 in Text S3 in Supporting Information S1).

The model yielded 2358 acceptable paths and 911 good paths (Figure 7c). After the deposition of the Mulichinco Formation, most of trajectories show a peak temperature of ~130–140°C at ~15–10 Ma, with a heating rate of 1°C/Ma (from the weighted mean path). From 15 to 10 Ma to the present, the model exhibits a rapid cooling. As the shape and distribution of the paths is highly homogeneous, we used the weighted mean path to estimate a cooling rate of 8.8°C/Ma from 13 Ma to the present, which is even faster (14.3 °C/Ma) on the steeper portion of the curve between 13 and 6 Ma (Figure 7c).

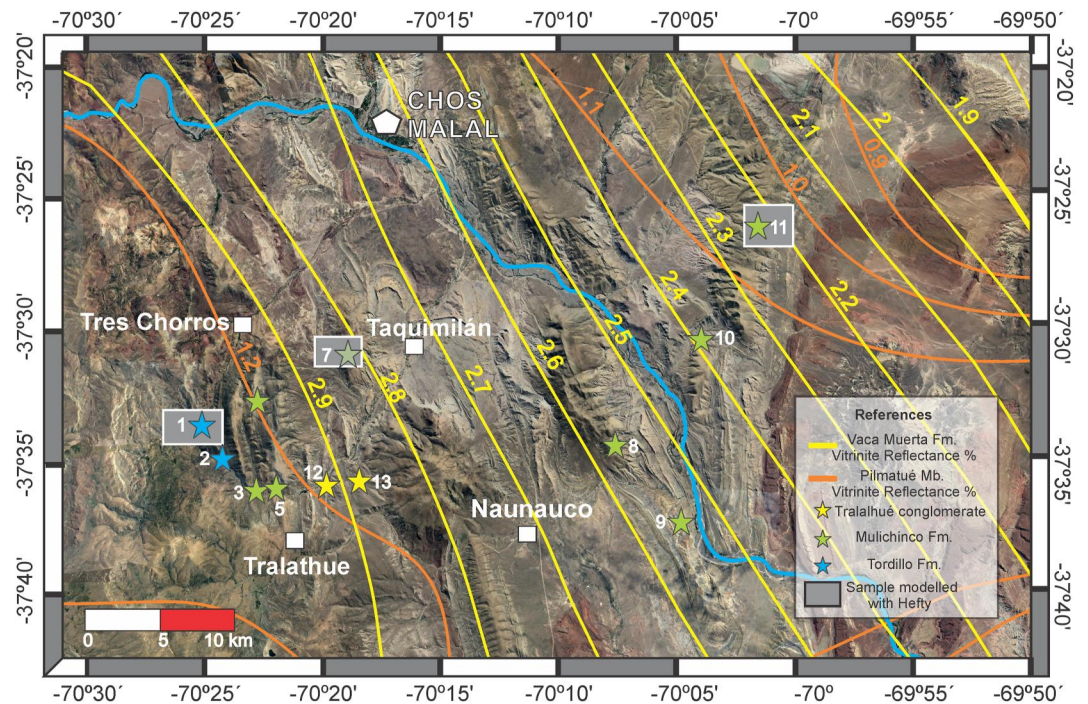


Figure 8. Vitritine Reflectance (% R_0) values from the Vaca Muerta Formation (yellow) and from the Pilmatué Member, Agrio Formation (orange) in the study area. The % R_0 curves are based on the open thematic maps published by the Subsecretaría de Minería e Hidrocarburos de Neuquén (<http://hidrocarburos.energianeuquen.gov.ar/mapa>).

5.4. Interpretation of the Models and Data

According to the model and the cooling rates observed in the Manzano anticline (sample 1), the inner zone of the Agrio FTB was affected by two cooling events (Figure 7a). We used the vitritine reflectance maps of the Vaca Muerta and Agrio Formations, available online from the Subsecretaría de Minería e Hidrocarburos de Neuquén (<http://hidrocarburos.energianeuquen.gov.ar/mapa>), to estimate the maximum temperature (T_{max}) at which our samples were heated in the sedimentary basin. The vitritine reflectance (R_0) at the base of the Vaca Muerta Formation around sample 1, to the south of Tres Chorros, is higher than 2.9 (Figure 8). This reflectance value is equivalent to at least a temperature of $\sim 222^\circ\text{C}$ (Barker & Pawlewicz, 1994, see Table S2 and Text S4 in Supporting Information S1). This indicates that the underlying Tordillo Formation reached the ZHe annealing temperature, and consequently that sample 1 is fully reset for all the thermochronometric methods used in this study. This is confirmed by the fact that the ZHe age in the sample 1 is younger than the stratigraphic age of the Tordillo Formation. Sample 1 is localized above the first order (basement-cored) Manzano anticline, which is related to a west-dipping thrust (structure number 2 on Figure 4a). If we interpreted that this sample's cooling results from tectonically driven exhumation, then structure number 2 might have been active from ~ 85 –75 to ~ 55 –50 Ma (considering the weight mean path and the path families with good and acceptable trajectories) when sample's 1 T-t path transitioned from heating to cooling (Figures 7a and 9a). The second cooling event was faster starting around ~ 15 –10 Ma, 13.5 Ma according to the weight mean path, and also supported by the samples around the Tres Chorros anticline (2, 3, 4, 6). These samples show AFT ages with two populations (Figures 5 and 6), suggesting that they underwent partial annealing. Following Garver et al. (1999) we consider that the youngest fission track grain age (FTGA) population (P_1) might represent a maximum cooling age, ranging from 20.2 to 12.4 Ma, for the last cooling episode this sample has experienced. We interpret this cooling event associated with the development of two other basement-involved thrusts (number 3 and 4) underneath the Tres Chorros and Pitrén anticlines (Figure 9b). In the absence of additional chronological or structural constraints, we interpret thrusts 3 and 4 as having formed in sequence with respect to thrusts 1 and 2. The displacement along this thrust system produced horizontal shortening in the sedimentary cover toward the east, creating the second-order (thin-skinned) fault-related folds between Taquimilán and San Eduardo (Figures 4a and 9b). During this stage, the previously

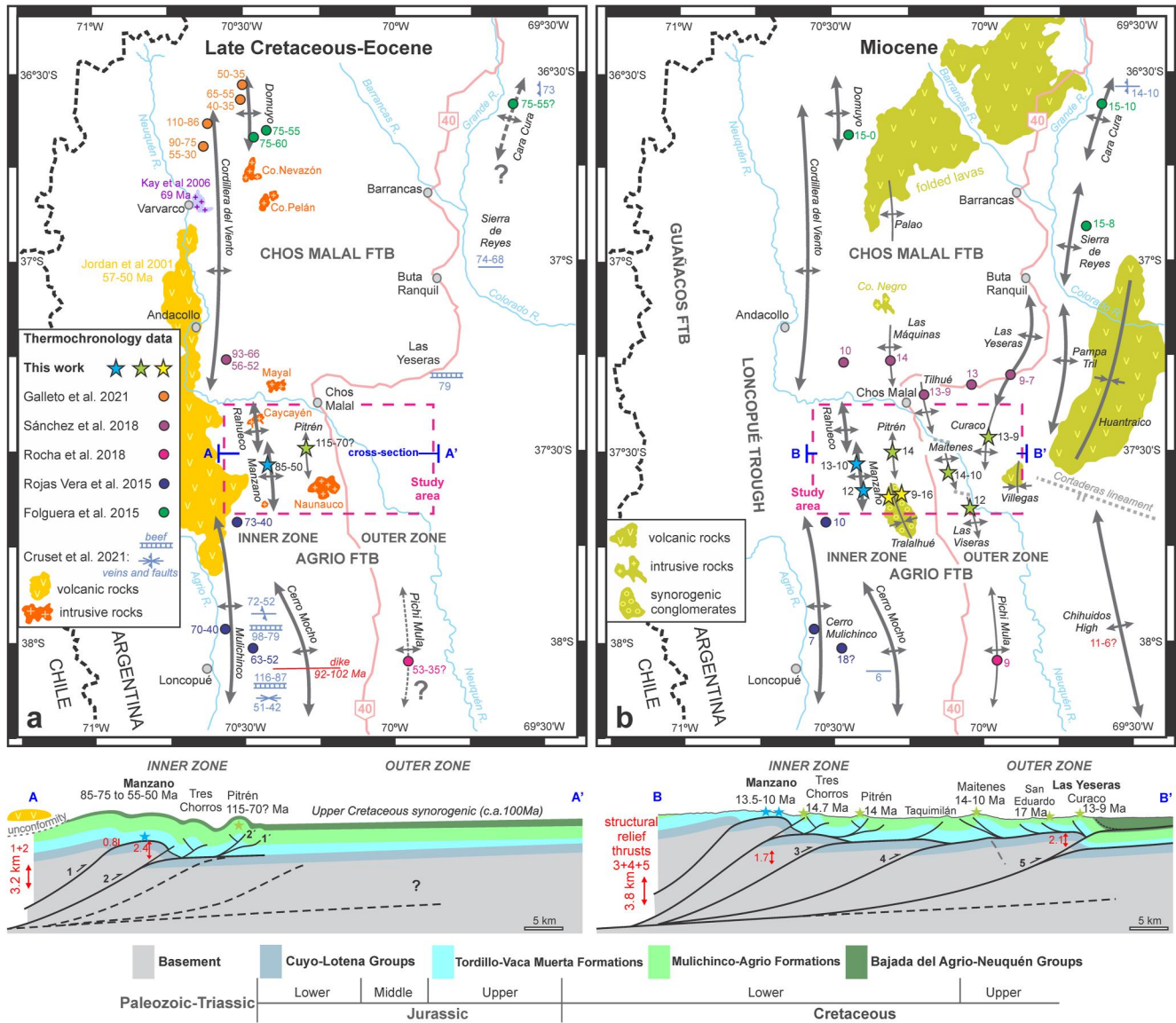


Figure 9. New (this study) and published thermochronological and geochronological data in the Chos Malal and Agrio FTBs supporting the two deformational stages: (a) Late Cretaceous–Eocene (b) Middle–Late Miocene. Schematic cross-sections showing the structural evolution of the northern Agrio FTB interpreted during each stage (based on Figure 4a).

formed Manzano anticline, located in the hangingwalls of thrusts 3 and 4 (Figure 9b), was uplifted and translated to its present-day location.

Sample 7 was collected at the top of the Mulichinco Formation, close to the contact with the overlying Pilmatué Member of the Agrio Formation, in the western flank of the Pitrén anticline (Figures 3, 4a, and 9b). In this area, according to the vitrinite reflectance map (Figure 8), the rocks have a R_0 value of ~ 1.2 suggesting that this sample could have reached a peak temperature of 150 °C (Barker & Pawlewicz, 1994, for details see Table S2 and Text S4 in Supporting Information S1). In the thermal model (Figure 7b), the weighted mean T-t path indicates that this sample has reached a maximum temperature of 130 °C at around 100 Ma, and consequently, this sample could be partially reset for ZHe, close to fully reset for AFT and it is completely reset for AHe. Sample 7 is located in the Pitrén anticline (Figures 3 and 4a), which we interpreted as a second-order fold formed by the shortening transmitted by the first-order basement wedges of the El Cholar and Manzano anticlines (thrusts 1 and 2, Figure 9a). In the thermal model of sample 7 (Figure 7b), the output weighted mean path indicates heating of the

Mulichinco Formation up to circa 98 Ma, followed by a phase of burial at a consistent temperature from 98 Ma to 23 Ma. Nonetheless, a considerable number of the acceptable paths reached maximum temperatures falling within the range of 150–200°C and then began to cool from ~115 to 85 Ma to ~80–70 Ma (Figure 7b5). Although this possible cooling event based on some acceptable paths should be taken with caution, it would have started a little earlier and partially overlapped the cooling history of sample 1. The stratigraphic location of sample 7 (Early Cretaceous Mulichinco Fm.) above sample 1 (Late Jurassic Tordillo Fm.) may explain its relatively earlier onset of cooling. Additionally, the initial development of the Pitrén anticline (sample 7) could be linked to the displacement of thrust 1 and then culminating its evolution associated with the displacement in sequence of thrust 2 (Figure 9a). Subsequently, the T-t paths show a cooling event starting between 25 and 10 Ma, but most of the trajectories have a steeper T-t path segment (constrained by AHe data) that suggests a faster cooling between ~15 Ma and 7 Ma (Figure 7b). Accelerated cooling after ~15–10 Ma agrees with the younger cooling event documented for sample 1, on the Manzano anticline, and the youngest FTGA populations observed from the samples around the Tres Chorros anticline (14.7 Ma, Figure 5). These observations collectively support the occurrence of a substantial middle Miocene cooling event, which we interpret as linked to the formation of the underlying thrusts system (faults number 3 and 4 in Figure 9b) across the entire inner zone of the northern Agrio FTB. In such scenario, the Pitrén anticline (sample 7) and the other previously formed structures were passively uplifted and translated in the hanging wall of these thrusts.

Sample 11 was collected near the top of the Mulichinco Formation, in the eastern sector of the study area (Figures 3 and 4a), where the value of vitrinite reflectance for the overlying Pilmatué Member is 1.05 (Figure 8) equivalent to a maximum temperature of ~146°C (Barker & Pawlewicz, 1994, see Table S2 and Text S4 in Supporting Information S1). The fact that the individual ZHe ages in sample 11 are older or close to the stratigraphic age suggests that, in this sample, such temperature was not enough to reset completely the grains for ZHe. On the other hand, young ages obtained with AFT (12.9 Ma) and AHe (9.5 Ma) thermochronometers, indicate that the sample is completely reset for these methods. The output T-t path reach maximum temperatures of 130–140°C and then show a rapid cooling from 15 to 10 Ma to the present, which could have been even faster between 14 and 6 Ma (Figure 7c). We interpret this cooling episode as being associated with the growth of the basement-involved structure related with the Las Yeseras thrust (number 5, Figure 4a), which generated the exhumation of the Curaco anticline in the outer zone of the Agrio FTB (Figure 9b). Samples from the Mulichinco Formation (8, 9, 10) in others second-order folds located on the hangingwall of the Las Yeseras thrust, have a youngest FTGA populations (P_1) ranging in age from 17.4 to 12.1 Ma (Figure 5). Additionally, sample 8 from the Maitenes anticline has an AHe mean age of 10.1 ± 2 Ma. Collectively, these observations converge toward the occurrence of a significant cooling event affecting the range front at about 14–9 Ma (middle-upper Miocene) that we attribute to tectonically driven exhumation in response to displacement on thrust 5.

The samples from the Tralalhué conglomerate (12, 13, Figures 3 and 5) contain unreset apatites derived and/or recycled from different sources from neighboring areas. Upon analysis using the *Binomfit* software (Brandon, 1992, 1996, 2002), the grains present two age populations, with a dominant population (P_2) comprising approximately 94% of the data set, featuring mean ages of 41.5–40.9 Ma (Figure 5). However, it is important to note that these dominant populations comprise highly dispersed datapoints, displaying individual grain ages spanning from 83 Ma to 33 Ma (Figure 6). On one hand, these ages overlap the well-documented Late Cretaceous to Eocene magmatic episode in the area. Paleocurrent data from conglomerate beds on the Tralalhué syncline flanks (Zamora Valcarce, 2007) indicated transport directions originating from both the NW and NE. These directions correspond with the positions of the Caycayén (44.7 Ma, ^{40}K - ^{40}Ar on amphibole, Llambías & Rapela, 1989) and Naunaico (65.5 Ma, ^{40}Ar - ^{39}Ar on amphibole, Zamora Valcarce et al., 2006) intrusive bodies, as illustrated in Figure 3 pointing them as potential source for this grain population. On the other hand, these grains could come from the erosion of the adjacent folds that contain older populations (P_2 – P_3) formed by partially reset apatites (Figure 5). Collectively in samples 12 and 13, there are six young grains with AFT ages ranging from 14.1 to 9.2 Ma (see light gray bars on Figure 6 for these two samples); these ages represent the unique information we have on the maximum depositional age for these synorogenic strata and are concordant with the middle Miocene age estimated from fossil mammal remnants for the Tralalhué conglomerate (Leanza et al., 2005). Such young grains could come from the erosion of some of the neighboring folds, which contain a population (P_1) with comparable AFT ages (Figure 5).

6. Discussion: Regional Analysis About the Age of Compressive Deformation

In the following section, we examine the ages of some contractional structures within the FTBs spanning from 36° 30' to 38°30'S, integrating our findings with previously published geochronological and thermochronological data (Figure 9).

6.1. Late Cretaceous—Eocene Contraction

The onset of contractional deformation and rock uplift along the Andean margin of the Neuquén Basin, produced the subsidence that led to the synorogenic accumulation of Late Cretaceous red beds of the Neuquén Group (Cobbold & Rossello, 2003; Di Giulio et al., 2017; Fennel et al., 2020; Gómez et al., 2019; Ramos & Folguera, 2005; Tunik et al., 2010). Provenance analysis and U-Pb dating of detrital zircons in the basal strata of the Neuquén Group reveal a shift in sediment sources compared to the upper section of the underlying Bajada del Agrio Group (in which the grains came from basement rocks located east). Notably, a series of younger zircon peaks ranging from 98.6 to 130 Ma suggests a direct origin from the Early Cretaceous magmatic arc that was exposed during Late Cretaceous deformation along the western Chilean slope of the Andean cordillera (Di Giulio et al., 2017; Tunik et al., 2010). Sedimentologic and structural analysis of mid-Cretaceous deposits in Central Chile (32°50'S) reveals sustained compressional deformation throughout the latest Early and Late Cretaceous, from 105 to 83 Ma (Boyce et al., 2020). Thermal model of apatite fission track ages from the Coastal Cordillera at ~33°S, show cooling from 106–98 Ma to 70 Ma (Gana & Zentilli, 2000) and 94–90 Ma (Parada et al., 2005) interpreted as tectonic exhumation. A 19-km-long dike, oriented in an E-W direction, crosscuts the Cerro Mocho anticline (Figure 9a). The ^{40}Ar - ^{39}Ar obtained from plagioclase and ground mass samples are 101.9 ± 0.69 Ma and 91.97 ± 4.06 Ma, respectively (Zamora Valcarce et al., 2006). These ages establish a minimum age for the initial folding episode. In the north of the Cordillera del Viento anticline and Domuyo volcano (Figure 9a), inverse thermal modeling of AFT, ZFT and AHe data from Paleozoic granitoids (with U-Pb zircon ages of ~288 Ma) and Upper Jurassic sedimentary rocks, reveals two main episodes of rapid cooling constrained to ~110–75 Ma and ~55–35 Ma that have been attributed to exhumation driven by contraction along N-S striking structures (Galletto et al., 2021). Folguera et al. (2015) performed AFT analysis and they interpreted a cooling episode from ~75–55 Ma in the Domuyo area, but also in the Cara Cura anticline located in the outer zone (Figure 9a). Nonetheless, the authors acknowledge the method's limitations in constraining the older deformation phase, which need to be substantiated using alternative lines of evidence. In four samples from Late Triassic-Early Jurassic rocks south of the Cordillera del Viento anticline (Figures 9a), Sánchez et al. (2018) obtained fully reset ZHe cooling ages ranging from 93.3 ± 3.9 to 66.0 ± 6.1 Ma and AFT ages between 56.5 ± 10.7 and 51.7 ± 3.2 Ma, interpreted as associated with tectonically driven exhumation resulting from thrusting. Significant displacement along this first-order structure is necessary to account for the minimum ~5–6 km of rock uplift and denudation required to generate the angular unconformity observed between the Paleogene volcanics and the Paleozoic basement rocks in the vicinity of Andacollo (Figure 9a) (Kozłowski et al., 1996, 1998). This pre-Eocene exhumation episode of the inner zone of the FTB must have occurred before ~57–50 Ma, the time at which Paleogene volcanics were emplaced as indicated by ^{40}Ar - ^{39}Ar dating on hornblende (Jordan et al., 2001). Kay and Copeland (2006) reported ^{40}Ar - ^{39}Ar age of 69.09 ± 0.13 Ma for biotites for the Varvarco pluton located in the western flank of the Cordillera del Viento anticline (Figure 9a), which they interpreted as a cooling age associated with the exhumation of this basement-involved structure. Late Cretaceous to Eocene intrusive rocks, spanning from Cerro Nevazón to Cerro Naunauco (Figure 9a), provide evidence for the emplacement of a magmatic arc within the FTB.

Cobbold and Rossello (2003) obtained an ^{40}Ar - ^{39}Ar age of 39.7 ± 0.2 Ma for a sill at Cerro Mayal, and noted that these rocks intruded pre-existing folded Mesozoic formations. The Cerro Caycayén has a ^{40}K - ^{40}Ar on amphibole age of 44.7 ± 2.2 Ma (Llambías & Rapela, 1989), and these rocks were intruded along a backthrust located in the forelimb of the Rahueco anticline (Lebinson et al., 2018). Field relationships consistently indicate that those igneous rocks were intruded along pre-existing structures, suggesting that deformation might predate magmatic activity. On the other hand, the temporal overlap between the ages of the igneous rocks and the proposed contractional events in this region implies a potential coexistence of magmatism and deformation. However, further comprehensive petrological and structural investigations are required to establish the syntectonic nature of the intruded rocks. At ~38°S in the inner zone of the Agrio FTB, Rojas Vera et al. (2015) made thermal models based on AFT analysis from three samples of Jurassic-Early Cretaceous sandstones, which show a cooling episode ranging from ~70 to 40 Ma (Figure 9a). Cruset et al. (2021) recently conducted a study that integrated

structural analysis with 22 U-Pb age measurements in fracture-filling carbonate cement from various geological features, including bed-parallel fibrous calcite veins (known as “beef” veins), conjugated veins, and faults within the Vaca Muerta Formation. U-Pb dating in mineral fibers from the inner zone of the beefs indicate ages ranging from 116.7 ± 17.7 to 78.8 ± 10.2 Ma at Cerro Mocho and La Yesera areas (Figure 9a). Cruset et al. (2021) interpret that mild late Cretaceous tectonic pulses associated with Andean compression may have contributed to the growth of these bed-parallel veins. Mineral fibers in the outer zone of the beefs, bed perpendicular veins and filled faults register a long period of east-directed layer-parallel shortening from ~ 72 to 42 Ma in the Cerro Mocho area and from ~ 74 to 68 Ma in Sierra de Reyes-Cara Cura area (Figure 9a) (Cruset et al., 2021). From a sample of the Early Cretaceous Agrio Formation in the Pichi Mula anticline, located in the outer zone of the Agrio FTB, Rocha et al. (2018) proposed a cooling event between ~ 53 –35 Ma (Figure 9a). To summarize, evidence from diverse sources indicates significant Late Cretaceous to Eocene contractional deformation, primarily affecting the inner zone of the fold-and-thrust belt (FTB) from approximately 110 to 50 Ma. Some studies suggest this period extended up to 40–35 Ma (Figure 9a). However, Horton and Fuentes (2016) utilized geochronologic, provenance, and sediment accumulation data from the Andean retroarc basin (34° – 37° S) to propose a post-Late Cretaceous phase of diminished sediment accumulation between ~ 60 and 40 Ma, followed by a hiatus from ~ 40 to 20 Ma. Furthermore, structural, stratigraphic, geochronologic, and geochemical evidence from the Chilean Andes around 35° S supports the extrusion of volcanic rocks aged 80–65 Ma in an intra-arc basin setting during a phase of extension and crustal thinning (Muñoz et al., 2018). While alternating phases of shortening-induced flexure and tectonic quiescence appear to be a common pattern throughout the Andes, Horton and Fuentes (2016) caution that these discrete phases are not necessarily synchronous or consistent along the entire margin.

According to our thermal modeling results, sample 1 from the Late Jurassic Tordillo Formation shows a slow and long Late Cretaceous–Paleogene cooling event (Figure 7a). Location of this sample in the first-order Manzano anticline led us to interpret the exhumation of the inner zone of the Agrio FTB, related to a basement-involved thrusts at depth (fault 2), between ~ 85 –75 Ma and ~ 55 –50 Ma (Figure 9a). This interval of deformation aligns closely with the extensive evidence presented in the northern and southern regions surrounding the study area, indicative of a regional contractional deformation. Nevertheless, considering the available data from adjacent areas (e.g., Cruset et al., 2021; Galletto et al., 2021; Zamora Valcarce et al., 2006), it is highly likely that exhumation within this segment of the Agrio FTB commenced earlier, approximately around 110 million years ago. In this regard, some acceptable paths (141) and 2 good paths from our thermal model of sample 7 (Mulichinco Fm.), are consistent with Late Cretaceous cooling from ~ 115 –85 Ma to ~ 80 –70 Ma (Figure 7b₅). This potential age of cooling should be taken with caution, but it can be interpreted considering that the Pitren anticline (sample 7) was initially formed in association with displacement from thrust 1 and reached its final configuration by in sequence development of thrust 2 (Figure 9a). On the other hand, from our thermochronological data was not possible to detect Late Cretaceous–Paleogene cooling in the outer zone of the Agrio FTB, as it was proposed in the Sierra de Reyes-Cara Cura (Cruset et al., 2021; Folguera et al., 2015) or in the Pichi Mula anticline (Rocha et al., 2018).

Thermochronological studies in FTBs allow calculating exhumation rates, by combining the cooling rates obtained from inverse thermal modeling and the paleo-geothermal gradients (known or assumed) for the region (e.g., Galletto et al., 2021; Hernandez et al., 2020; Lossada et al., 2023). In the Domuyo region ($\sim 36^{\circ}$ 30'S, Figures 9a), Galletto et al. (2021) estimated exhumation rates between 0.2 and 0.5 mm/yr using their cooling rates of 12–23°C/Ma and considering a geothermal gradient of $\sim 51^{\circ}$ C/km in the modern easternmost region of the Neuquén Basin (extracted from Sigismondi & Ramos, 2009) as an analogue to the pre-Andean tectonic scenario. However, it is difficult to accurately know the paleo-geothermal gradients in deformed areas with a complex tectono-magmatic evolution because the crustal thermal field is deformed (isotherms can be compressed and then relaxed when deformation stops), the gradient is dynamic (it changes through time) and superimpose magmatism probably further distorts the thermal field (e.g., Malusà & Fitzgerald, 2019). Because the paleo-geothermal gradients in our study area are unknown, we prefer to calculate the amount of vertical displacement of the hangingwall relative to the footwall of thrust to compare the relative magnitude of deformation related with each contractional stage and between different sectors of the northern Agrio FTB. From our interpreted cross-section we measured the difference in elevation of the Tordillo Formation between the hangingwall and the footwall of the basement-involved thrusts (2–5, Figure 4a). From our thermal models (Figure 7), we estimate the duration of each cooling event at the inner and outer zones of the belt. The thermal model of sample 1 (Figure 7a) shows a cooling from ~ 85 –75 Ma to ~ 55 –50 Ma and the vertical movement on thrust 2 from our structural reconstruction

is ~ 2.4 km (Figures 4a and 9a). The vertical displacement rates calculated from these data, ranges between 0.07 km/Ma to 0.12 km/Ma, which suggest a slow process of deformation.

6.2. Middle—Late Miocene Contraction

Primary evidences of Neogene contraction are derived from direct field observations of folded Miocene volcanic rocks, located to the north and east of the study area (Figure 9b). In the region of the Barrancas River, lavas and ignimbrites with ^{40}Ar - ^{39}Ar ages in plagioclase and amphibole of 14.51 ± 0.12 Ma and 14.8 ± 8.0 , respectively (Spagnuolo et al., 2012) not only unconformably overlay pre-existing folded Mesozoic rocks, but are themselves involved into broad folding around the Palao anticline (Folguera et al., 2007). Basaltic lava flows in the western flanks of Huantraico and Villegas synclines (Figure 9b), with ^{40}Ar - ^{39}Ar ages ranging from ~ 18 to 15 Ma (Dyhr et al., 2013; Kay & Copeland, 2006) have been deformed and currently dip toward the east.

In the Tralalhué syncline (Figure 9b), synorogenic conglomerates dominantly composed of clasts from andesites, dacites and limestones, unconformably overlie the Cretaceous strata and the igneous rocks of Cerro Naunaucó (Zamora Valcarce et al., 2006). In samples 12 and 13 from this unit, most individual apatite grains (approximately 94% of the data set) yielded a dominant population with an average AFT age of 41.5–40.9 Ma (Figure 5). Single-grain ages exhibited a wide distribution spanning from 83 to 33 Ma (Figure 6). Paleocurrent data from the Tralalhué syncline conglomerate beds (Zamora Valcarce, 2007) combined with AFT single grains ages indicate a likely source from the Caycayén (44.7 Ma, ^{40}K - ^{40}Ar analysis on amphibole, Llambías & Rapela, 1989) and Naunaucó (65.5 Ma, ^{40}Ar - ^{39}Ar analysis on amphibole, Zamora Valcarce et al., 2006) intrusive bodies for these grains. Younger apatite grains dated with the fission track method, ranging from 14.1 to 9.2 Ma (Figure 6) suggest a maximum depositional age for these conglomerates. Given the absence of nearby magmatic bodies of similar ages, it is plausible that these grains originated from the erosion of adjacent folds that were contemporaneously growing and possessed apatites falling within this age range (Figure 5). In the Chos Malal FTB, dikes and sills at Cerro Negro, with U-Pb ages on zircon around ~ 11.6 Ma, were emplaced during the contraction along fractures caused by stretching of layers at the hinge zone of the Las Máquinas anticline (Gürer et al., 2016) (Figure 9b). Syn- to post-folding fracturing is evident in E-W oriented calcite veins with U-Pb dates ranging from 13.9 ± 2.6 to 6.2 ± 1.1 Ma, intersecting folded rocks within the Cerro Mocho and Cara Cura anticlines (Cruset et al., 2021).

Most of the low-temperature thermochronology data and models in the region identified a Miocene cooling event, recorded both in the inner and outer zones of the FTBs (Figure 9b). North of 37°S , Folguera et al. (2015) identified a post-15–10 Ma cooling episode from inverse modeling of AFT data in the Domuyo, Cara Cura and Sierra de Reyes anticlines (Figure 9b). South of 37°S , Sánchez et al. (2018) obtained similar results from AFT data and proposed that tectonically driven exhumation through basement-involved thrusting has occurred at ~ 15 –7 Ma in the entire Chos Malal FTB. In the inner zone of the Agrio FTB, Rojas Vera et al. (2015) obtained cooling ages ranging from ~ 18 to 7 Ma from inverse modeling of AFT data in the Cerro Mulichinco and Cerro Mocho anticlines (Figure 9b). Toward the east, Late Miocene cooling was recognized from AFT data in the Pichi Mula anticline (~ 9 Ma, Rocha et al., 2018) and in the Chihuidos High (~ 11 –6 Ma, Zamora Valcarce et al., 2009).

Our thermal models reveal a rapid cooling event spanning from approximately 15 to 10 Ma to the present, in both the inner and outer zones of the northern Agrio FTB, (Figure 7). This event accounts for all our AHe mean ages ranging from 13.9 to 9.5 Ma (Table 4) and is consistent with most of our AFT data, including the younger population (P_1) of partially reset samples, which exhibit ages ranging from 20.2 to 12.1 Ma (Figures 5 and 6). We proposed a structural interpretation wherein the Neogene exhumation of samples in the inner zone is attributed to displacement along basement-involved thrusts 3 and 4, whereas exhumation at the mountain front is associated with thrust 5, responsible for the formation of the Las Yeseras anticline (refer to Figure 9b). The striking similarity between the thermochronological data in both zones suggests that middle-late Miocene deformation was widespread across the entire FTB, consistent with prior thermochronological investigations in neighboring regions (Folguera et al., 2015; Rojas Vera et al., 2015; Sánchez et al., 2018). The cumulative vertical displacement on thrusts 3 and 4 is estimated to be approximately ~ 1.7 km over the time interval of 15–10 to 0 Ma, resulting in a vertical displacement rates ranging from 0.11 km/Ma to 0.17 km/Ma within the inner zone of the Agrio FTB. In the outer zone, thrust 5 (Las Yeseras) generates a vertical displacement of around 2.1 km over the same period (Figure 7c), leading to estimated vertical displacement rates ranging from approximately 0.14 km/Ma to 0.21 km/Ma. We interpret the rapid cooling episodes detected in thermal inversions as the outcome of tectonically induced exhumation processes occurring throughout of the northern Agrio FTB since approximately 14 Ma.

7. Conclusions

The objective of this study was to constrain the Meso-Cenozoic spatio-temporal structural evolution of the northern part of the Agrio FTB using an integrated approach combining detailed structural analysis with inverse thermal modeling of new low-temperature multi-thermochronological data (AHe, ZHe, and AFT). We found that:

- The structural evolution of the northern Agrio FTB is characterized by two main tectonic phases of contractional deformation, the first during the Late Cretaceous-Eocene and the second in the middle-late Miocene, aligning with the pre-existing geological evidence in the area.
- The Late Cretaceous-Eocene tectonic event is exclusively recorded in the inner zone of the FTB, where inverse thermal modeling of Late Jurassic sandstones from Tordillo Formation (Sample 1) reveal a slow and continuous cooling event occurring between 85–75 Ma and 55–50 Ma, with cooling rates ranging from 1.1 to 2°C/Ma. This cooling episode is attributed to the initiation and activity of a basement-involved blind thrust, resulting in approximately 2.4 km of vertical displacement, allowing us to estimate the vertical displacement rates, of around 0.07–0.12 km/Ma for this tectonic phase.
- The middle-late Miocene tectonic event is recorded in both the inner and outer zones of the northern Agrio FTB. Inverse thermal models indicate a rapid cooling episode spanning from 15 to 10 Ma to the present, encompassing the entire width of the FTB, with cooling rates calculated at 7°C/Ma across the inner zone and 8.8°C/Ma in the outer zone. This rock cooling is tectonically induced, with the inner zone experiencing exhumation through displacement along two basement-involved blind thrusts, resulting in a structural uplift of approximately 1.7 km, while the uplift of around 2.1 km in the outer zone is attributed to displacement along the Las Yeseras thrust. The vertical displacement rates of the thrust generated by this contractional deformation are ~0.11–0.17 km/Ma in the inner zone and ~0.14–0.21 km/Ma in the outer zone.
- The detrital apatite grains in the syntectonic Tralalhué conglomerate, with AFT ages ranging from 14.1 to 9.2 Ma, support the maximum depositional age of the rocks, coinciding with late Miocene deformation in the FTB.

Data Availability Statement

All of the Supporting Information S1 have been filed at the Geochron data base http://www.geochron.org/dataset/html/geochron_dataset_2023_11_21_pil67.

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