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The state of the art of low-temperature thermochronometry in Brazil

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Abstract

Low-temperature thermochronology focuses on the comprehension of the upper crust's thermal history, where morphotectonic processes take place. We present a robust compilation (1120 data in almost 30 years of research) of fission-track and (U-Th)/He studies and their implications to the understanding of Brazilian geomorphology development. Brazil has a complex geological evolution, involving multiple orogenic and taphrogenic episodes that shaped cratons, orogens, and basins together through time. The thermochronology data set is inconsistently distributed, most of it is concentrated in coastal regions, mainly in the southeastern region; while the intracontinental portions lack studies. The available data set suggests a complex reactivation scenario near the coast to a more stable situation inland. The Mantiqueira and Borborema provinces show a great Early Cretaceous denudation event and a less important Permian to Jurassic, and Paleogene denudation events. The cratonic areas show different patterns, with denudation related to the Devonian to the Jurassic. The data suggest that elastic thickness, structural network, and drainage system play an important role in the morphotectonic control of Brazilian landscape evolution.

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1 - Introduction

Low-temperature thermochronology is a branch of isotope geology that focuses on the comprehension of the upper crust thermal history, which can be used to reconstruct the timing and rate of heating and cooling at temperatures ~50ºC to ~320ºC (Chew and Spikings 2015; Tagami 2005). It includes a set of thermochronometric systems, being fission track analysis and (U-Th)/He thermochronometry (both in apatite and zircon crystals), the most consolidated and employed methods for investigating the cooling and unearthing processes. Such systems can reveal the temporal and thermal of geological aspects, and give insights into the duration and rates of denudation processes. As fission-track and (U-Th)/He thermochronometry have different closure temperature (Fig.1), the combination of those methods leads to the comprehension and interpretation of the upper crust thermal evolution allowing connections between superficial processes (that acted in erosion and denudation) and tectonic processes (that act in epeirogenic movements).

The thermochronology approach is used to clarify several geological problems such as exhumation rates in orogenic systems, provenance studies of sedimentary basins, understanding of mineral deposits for mineral exploration, maturation of kerogen petroleum for hydrocarbon exploration, and continental margin development. In this paper, we bring the state of the art of low-temperature thermochronology in Brazil, aiming to help future research on the topic. Based on a robust data compilation we show the contributions of fission-track and (U-Th)/He studies to the understanding of the morphotectonic processes that shaped the Brazilian territory. Therefore, we will not propose new interpretations in this work, but bring a compilation of the data and interpretations that already exist. Due to the specificity of the subject, we initiate with a brief introduction to the low-temperature thermochronology methods. Complete reviews can be found in Reiners et al. (2017), Braun et al. (2006), and Reiners and Ehlers (2005). The compiled data is available in Appendix 1 (electronic supplementary material).

1.1. Fission-track thermochronometry

The fission-track thermochronometry is based on the U^{238} fission decay, in which the parent isotope splits into two

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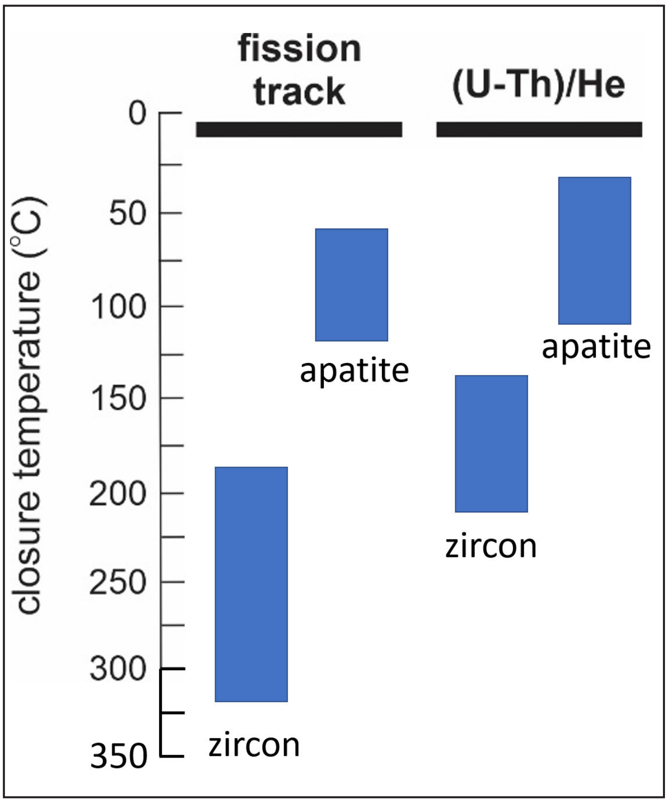

FIGURE 1. Closure temperature for fission-track and (U-Th)/He methods applied in apatite and zircon (modified from Ault et al. 2019).

positively charged high-energy nuclei (Price and Walker 1963, Fleischer et al. 1975). The heavy ionized particles travel at high velocity through the insulating solid (detector) and shape an amorphous damaged channel. These defects in the crystal lattice are the fission tracks, and each one represents a fission-decay event. In uranium-rich mineral grains (e.g., apatite, zircon, titanite), it is possible to determine the density of accumulated track under an optical microscope after polishing and acid etching procedures. For dating, parent isotope concentration is acquired through direct (i.e., laser ablation inductively coupled plasma mass spectrometry - LA-ICP-MS method, Hasebe et al. 2004) or indirect methods (i.e., external detector method, Gleadow and Duddy 1981).

In the fission-track thermochronometry, the heat diffusion can gradually shorten the fission tracks (annealing) until the total disappearance (e.g. Ketcham 2005). Therefore, just below a certain temperature the tracks can accumulate. This temperature highly impacts the closure temperature (CT) (Dodson 1973) which also varies according to the mineral, the cooling rate, and the crystal chemistry (Carlson et al. 1999; Green et al. 1986; Ketcham et al. 2007; Ketcham et al. 1999; Tagami et al. 1998). For example, if the fission-track thermochronometry is applied in apatite (AFT) or zircon (ZFT), the CT will be different. To the AFT, the CT ranges approximately between 120ºC to 80ºC and in ZFT between ~50ºC to ~320ºC (Fig. 1). Thus, apatite is a lower temperature thermochronometer than zircon, and its analysis deals with shallower portions in the crust.

Over the years, knowledge about track annealing has become a powerful tool to interpret rock cooling. The track-length analysis added to dating provides a better constraint in the time-temperature path (Gleadow et al. 1986).

1.2. (U-Th)/He thermochronometry

This method is based on the production of an alpha particle (4He) from U^{238}, U^{235}, Th^{232} and Sm^{147} (limited contribution) isotopes decay and the loss of He due to thermal diffusion (e.g., Farley 2000; Strutt 1909; Wolf et al. 1996; Zeitler et al. 1987). In the conventional analysis, the daughter's content is determined by extracting He from samples by laser heating, fusion, and resistance furnace. The measurement is performed by a noble gas quadrupole or magnetic sector mass spectrometer. The parent content (U, Th, and Sm) are mainly measured using LA-ICP-MS in acid dissolved samples.

The understanding of He heat diffusion has been evolving in recent years (e.g., Farley 2000; Flowers et al. 2009; Gautheron et al. 2009; Guenthner et al. 2013; Shuster et al. 2006), and it is not well understood as the annealing in the fission-track thermochronometry. As in the fission-track thermochronometry, the CT in (U-Th)/He thermochronometry is dependent on several factors, including the mineral, grain size, rate of cooling, and radiation damage. In apatite (AHe), it is suggested that CT is approximately between 70ºC to 40ºC (Farley 2000). In this case, AHe thermochronometry would be the lowest temperature technique and better to constrain changes in the uppermost crust than other approaches. However, a robust published AHe data set shows an excess of dispersion and/or AHe ages older than AFT ages. Thus, the first calculations of CT in the AHe system probably overestimate the diffusion process; as an approximation, the CT is considered to be between 120ºC to 30ºC (Ault et al. 2019; Fig. 1). The diffusion processes in (U-Th)/He thermochronometry in zircon (ZHe) is even less understood. In general, zircon appears to be more retentive than apatite to He (Reiners et al. 2002; 2004) and then its CT can range from 220ºC to 140ºC (Guenthner et al. 2013, Fig.1). Despite uncertainties, the carefully applied AHe and ZHe method, combined with other thermochronological techniques, form an ideal device to reconstruct time-temperature (t-T) paths through inverse modeling in the shallow crust (Ketcham et al. 2007; Gallagher 2012).

2 - Brazil thermochronology data set

Brazil is a country with continental proportions and complex geological evolution, involving multiple orogenic and taphrogenic episodes that shaped cratons, orogens, and basins together through time. The data set is distributed in a heterogeneous way, mainly spread in coastal regions, while the inland portions lack studies. We choose to exhibit the dataset divided according to geotectonic domains (Figure 2). That is because the tectonic evolution of a given area directly reflects its properties, such as flexural strength (response to tectonic stress) and structural framework, thus characterizing large areas with reasonably similar thermochronological patterns, i.e., the Archean to Proterozoic São Francisco and Amazonian craton, the Proterozoic Mantiqueira, Tocantins and Borborema provinces, and the Phanerozoic Syneclises, Marginal Basins, and alkaline intrusions.

2.1. São Francisco craton

The São Francisco craton (SFC) is located in central-eastern Brazil, limited by orogenic systems, being Borborema at northbound, Tocantins at westbound, and Mantiqueira in the

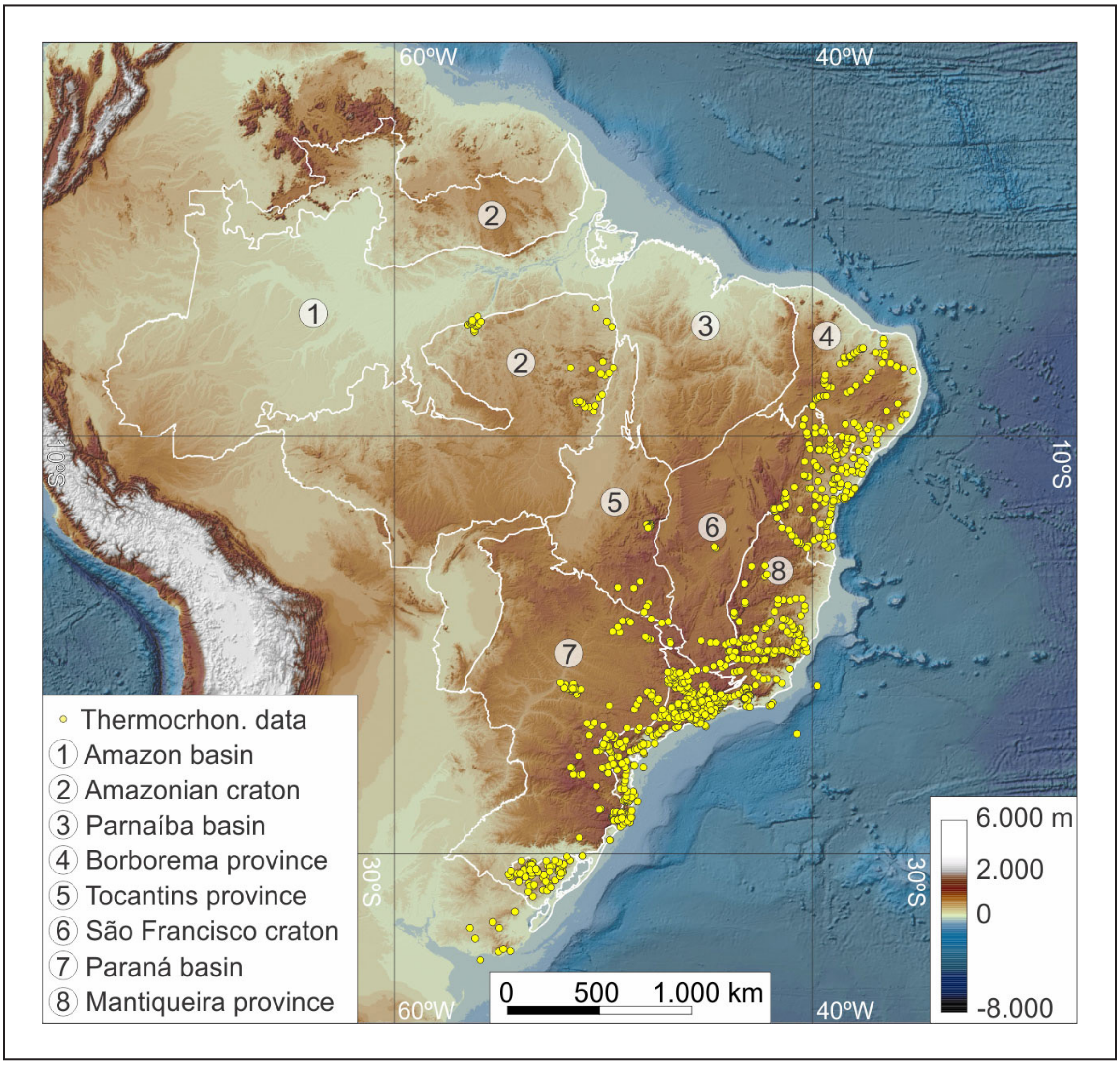

FIGURE 2. Thermochronological data set available for Brazil. The white lines divide the different geotectonic domains (1 to 8).

eastern portion (Fig. 2 and 3). It represents the paleocontinent São Francisco-Congo formed during Rhyacian times through the amalgamation of Archean and Paleoproterozoic blocks. The SFC stayed together with the Congo craton (its African counterpart) from the Paleoproterozoic to the late Cretaceous, when it broke apart to form the South Atlantic Ocean (Porada 1989). As a cratonic entity, the SFC has a cold, stronger, and relatively less dense lithosphere, as well as deeper and cold lithospheric roots (Jordan 1978; Assumpção et al. 2017; Alkmim 2004). The SFC basement is formed mainly by TTG and greenstone terrains (Heilbron et al. 2017; Alkmim 2004), partially covered by intracratonic and passive-margin sedimentation (Martins-Neto et al. 2001; Reis et al. 2017). The Meso-Cenozoic marginal basins developed in the cratonic extended area were controlled by the rift-resistant crystalline basement (Mohriak et al. 2008). That prompted the formation of a relatively narrow platform with sparse magmatism and the inland Recôncavo-Tucano-Jatobá Basin.

Thermochronological data in SFC are intensely concentrated in its northeastern portion which corresponds to a segment of the Brazilian passive margin (Amaral et al. 1997; Harman et al. 1998; Japsen et al. 2012; Jelinek et al. 2014; Jelinek et al. 2020; Turner et al. 2008; Fig. 3). Amaral et al. (1997) reported a few pioneering data showing Permo-Triassic AFT ages. Near the border with Borborema province, Harman et al. (1998) and later Turner et al. (2008) introduce a more robust set of analyzed samples. The data adjacent to the passive margin shows younger AFT ages (Upper Cretaceous) with long mean track lengths (MTL). In contrast, the samples from the countryside exhibit older (Lower Cretaceous to Permian) ages with decreasing MTL. The results indicate two phases of denudational cooling. According to Harman et al. (1998), the first cooling event (c.a. 130 to 95 Ma) was related to the generation of local relief and change in the base level due to the rifting process, which is mainly recorded by coastal samples. Turner et al. (2008) also highlight the possible influence of the relaxing geothermal gradient in this phase. The second cooling event (c.a. 70 to 55 Ma) is interpreted as a denudation response to a post-rift tectonic reactivation. The inversion of intracontinental rift basins close to the area (Harman et al. 1998) is pointed as geological evidence to the inferred event. This phase seems to be widespread, affecting the craton interior. In the central African shear zone system, a late Cretaceous tectonic event is synchronous with the discussed uplift, which suggests major changes in the relative plate motions as the driving force.

Japsen et al. (2012) and Jelinek et al. (2014; 2020) explore the craton coastal margin spanning their sampling to the borders with the Mantiqueira and Borborema provinces, the central portion, and also the interior of the craton (~ 500 km to the continental hinterland). The large AFT data set published by these authors is consistent with the previous works. Japsen et al. (2012) infer a complex thermal history with four post-rift stages, evolving cycles of burial, and erosion phases. Like the previous works (Harman et al. 1998; Turner et al. 2008), the widespread effects of plate motion (mainly due to lateral resistance; Japsen et al. 2012) are evoked as post-rift uplifts cause. On the other hand, Jelinek et al. (2014) cast doubt on the intervening periods of widespread sedimentation proposed by Japsen et al. (2012). Even though periods of reheating can be a solution for the inversion model based on their thermochronological data, it is not unique. Jelinek et al. (2014) points to the lack of evidence in the existence of the sedimentary cover and advocate the erosion of the crystalline basement rather than sedimentary rocks. The several uplifts episodes are also challenged as the exhumation origin and the effects of isostasy aided by magmatic underplating are taken as an alternative hypothesis (Jelinek et al. 2014; 2020). The pre-rift history of SFC was not the scope of these papers, despite a late Paleozoic to Early Mesozoic cooling phase is reported (Japsen et al. 2012; Turner et al. 2008; Jelinek et al., 2014). The inverse models inferred from these samples indicate a limited effect of the thermal and tectonic processes related to the rifting processes. Jelinek et al. (2014) correlate this cooling phase to the final stages of the Gondwanides orogeny, which settled in the south in the paleocontinent during that time. Jelinek et al. (2020) show data focused on the Recôncavo-Tucano-Jatobá Rift and detail cooling stages in the Permian-Triassic, Cretaceous and Cenozoic. The authors point out that the regional warming that began in the Cretaceous resulted in the uplift and erosion of the current continental margin.

Fonseca et al. (2021) present AFT dating results from the continental interior segment of SFC, mainly in its southern portion far from the Atlantic Ocean. The authors discuss two cooling phases revealed by the data: (i) firstly during the Paleozoic, and (ii) then between Late Cretaceous to Paleocene. The Paleozoic cooling phase seems to have affected several West Gondwana basement areas besides the SFC (e.g. Brasília Orogen, Fonseca et al. 2020), thus the authors argue for a far-field mechanism responsible for inducing widespread erosion during this time. The Gondwana geodynamic cycles are probably connected with high Paleozoic subsidence rates of adjacent depocenters (e.g. Paraná basin) and other intracontinental sags basins in the West Gondwana interior. These geodynamic cycles probably triggered basement tectonic readjustments leading to the erosion and cooling events of the paleohighs, such as SFC. This hypothesis is also suggested by Jelinek et al. (2014) for the late Paleozoic to Early Mesozoic cooling phase in the marginal portion of SFC. The second cooling phase is revealed between the Late Cretaceous to Paleocene and it affected the narrow weak zones (e.g. Recôncavo-Tucano-Jatobá rift) and at the cratonic borders. The proposed driving mechanism for the post-rift erosional event is reactivations prompted by far-field stress transmitted from the plate boundaries.

2.2. Amazonian craton

This province is located in the northwest Brazilian territory extent and is limited by Parnaíba Basin and Tocantins provinces at its eastern border (Fig. 2). It contains the Amazonas basin which separates this cratonic area into two provinces, the Rio Branco province in the northern extent and the Rio Tapajós province in the south. Although it covers almost half of the Brazilian territory, the Amazonian craton is the less geologically-known area (Hasui 2012). It comprises multiple terrains elongated according to NW direction with a complex Archean-Proterozoic tectonic history (Santos et al. 2000; Tassinari and Macambira 1999). During Neoproterozoic Era, the region of the Amazonian province participated in the Brasiliano/Pan African orogenic cycle with other paleocontinents, such as São Francisco-Congo and Paranapanema, was amalgamated to compose the West Gondwana paleocontinent. The Phanerozoic history of the Amazonian craton and nearby regions is well registered by the sedimentary record of the Phanerozoic intracontinental basins.

Despite the small amount of thermochronological data, locally scattered in the southeastern portion of the craton (Figs. 2 and 4), they corroborate with the sedimentary evidence. The Amazonian craton passed through a substantial amount of denudation assigned by the main pulses of exhumation and cooling. ATF in Paleoproterozoic crystalline rocks showed three cooling stages (Pina 2010): i) a mid to late-Paleozoic cooling episode (between 392 and 270 Ma); ii) followed by Triassic heating event (between 260 and 180 Ma); iii) and then another cooling process in the Cretaceous (100 Ma). Furthermore, in the eastern border of the Amazonian craton, Harman et al. (1998) identified ages from Upper Carboniferous (309 Ma) to Lower Cretaceous (137 Ma). Both works relate the Paleozoic ages to a substantial amount of denudation in the craton interiors, apparently, uncorrelated with the tectonic process. The Cretaceous ages are consonant with the convergent movement of the Andean subduction zone and the opening of the eastern equatorial Atlantic. The models point to a young denudational cooling in the Late Cretaceous interpreted as a result of differences in the relative plate motions between South American and African plates implying reactivation of the Proterozoic shear zones resulting in intracontinental deformation over the cratonic area by this time.

2.3. Mantiqueira province

The Mantiqueira province configures a strip along the Brazilian coastal region between southern Bahia and Rio Grande do Sul states, with an extension to Uruguay. It is about 3,000 km long, 200 km wide in the south, and 600 km in the north (Figs. 2 and 5). To the west, it borders the São Francisco craton, the southern end of the Brasília belt (Tocantins province) and the coverage of the Paraná basin (Almeida et al. 1981). To the east, it borders the Atlantic coast. The Mantiqueira province is a Neoproterozoic orogenic system developed during Western Gondwana amalgamation. The orogeny starts with the consumption of the Adamastor ocean when subduction processes generate arc-related rocks. Diachronic collisional episodes put together terrains formed by basement rocks (older than 1.7 Ga), arc-related rocks, and sedimentary successions. During the Cambrian to Ordovician, a regional orogenic collapse occurs (Trouw et

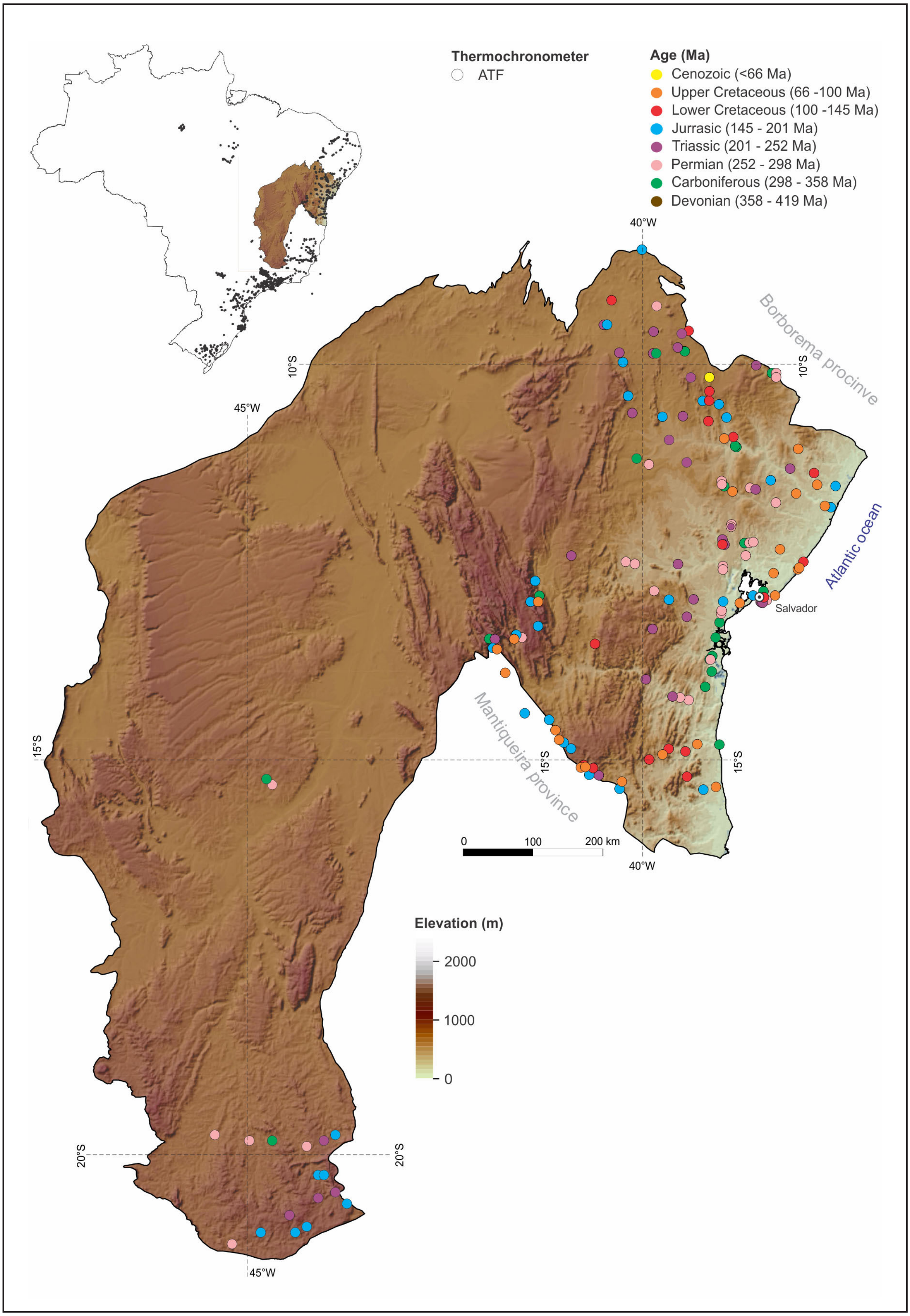

FIGURE 3. Thermochronological data set published in the São Francisco craton. The detailed map highlights the northeast portion of the craton where thermochronological data are concentrated.

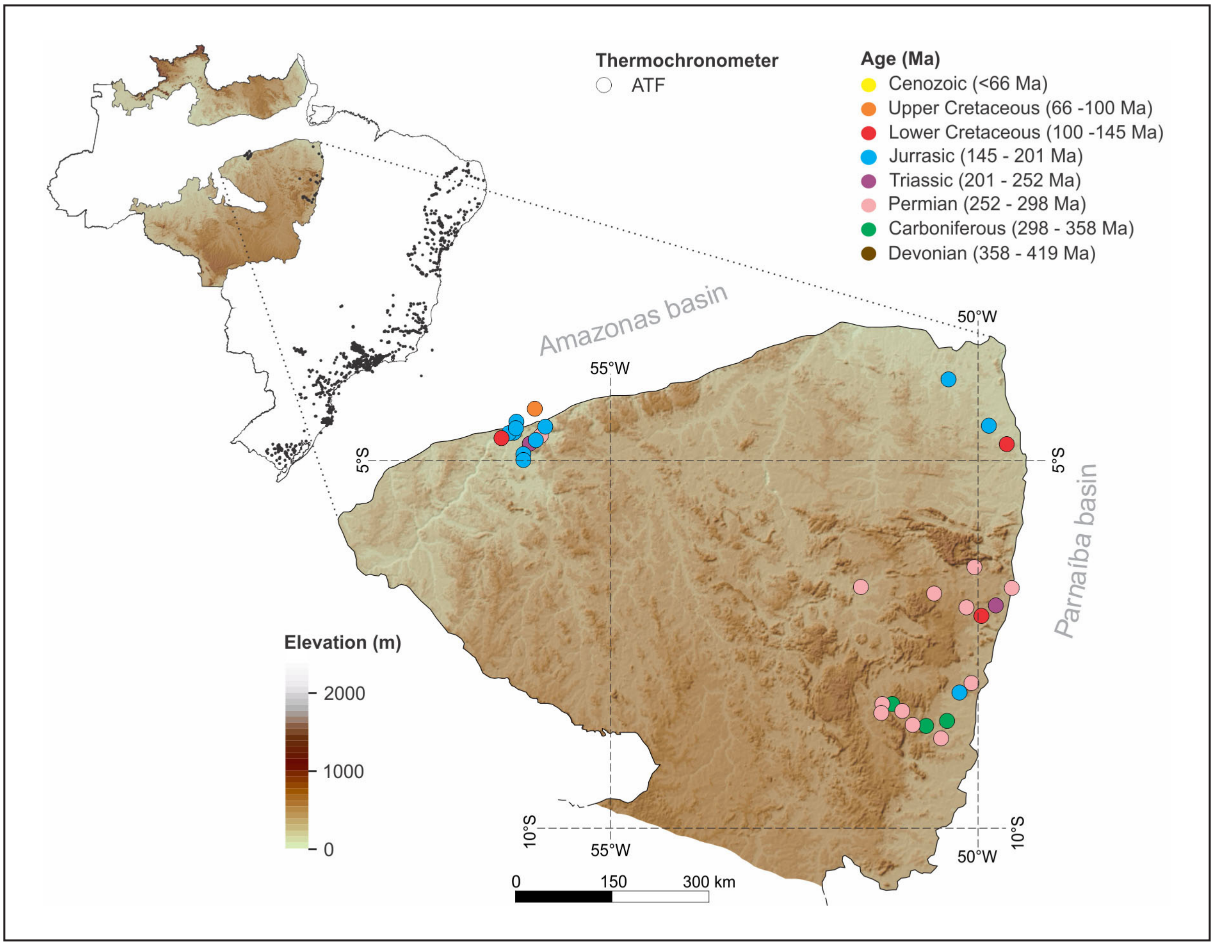

FIGURE 4. Thermochronological data set published in the Amazonian craton.

al. 2000; Pedrosa-Soares and Wiedemann 2000; Pimentel et al. 2000). In the late Cretaceous, the Atlantic opening marks the Gondwana break-up; apparently, this is the last regional tectonic event that affects Mantiqueira province.

Thermochronological studies in the Mantiqueira province started in the early '90s, with the pioneering work of Ariadne Fonseca (Fonseca 1994), nowadays it is the best-studied area in Brazilian territory, highlighting the Serra do Mar range region, that concentrates the most fission-track and (U-Th)/He data set (Fig. 5). During the '90s, few studies were made in Brazil, but they already bring great contributions to thermochronology. Gallagher et al. (1994) and Gallagher et al. (1995) already made aware that a lato sensu passive margin rift does not explain the present-day topography, suggesting control by basement structures. In the late '90s Jelinek et al. (1999) applied for the first time AFT in mineral prospecting. The authors dated hydrothermal fluids in fluorite ore veins in the southernmost portion of Mantiqueira province.

In the '2000s and '2010s, many thermochronological studies were made in the Mantiqueira province, mainly in the Serra do Mar and Mantiqueira mountain ranges aiming to quantify its thermal histories and timing of epeirogenic and tectonic processes (e.g. Oliveira et al. 2000; Tello Saenz et al. 2003; Borba et al. 2003; Tello Saenz et al. 2005; Hackspacher et al. 2004; Cogné et al. 2012; Karl et al. 2013; Hueck et al. 2018; Van Ranst et al. 2019; Fonseca et al. 2021). The studies describe a long stabilization from Cambrian to Mesozoic times. Locally it described a Carboniferous cooling event (Oliveira et al. 2016b; Krob et al. 2019) recorded mainly by zircon fission-track and associated with the final stages of the Gondwanides orogeny. From Permian to Jurassic a major cooling phase is registered in the Southern portion of the Mantiqueira province, probably related to pre-rift lithosphere thinning (Machado et al. 2019). An early Cretaceous uplift is widely registered associated with the south Atlantic opening. Paleogene denudation is also described, related to reactivation in the coastline and plate adjustment. Due to the variability of the structural network, drainage system, and lithosphere elastic thickness across the Mantiqueira province, spatial variations of the denudation rate are expected.

The Serra do Mar mountain range recorded a Late Cretaceous uplift, probably linked to its genesis, but Tello Saenz et al. (2005) and Hackspacher et al. (2004) highlight that Serra do Mar thermal history probably is much more complex. Oliveira et al. (2000) already alert that the Serra do Mar region went through several vertical and horizontal movements from the Cretaceous to nowadays. Hiruma et al. (2010) made one of the greatest contributions to thermochronology in the Brazilian scenario during the 2010s. Studying the highest part of the Serra do Mar, they model the exhumation of the Bocaina plateau. Agreeing with other authors (e.g. Genaro 2008; Hiruma et al. 2010) Cogné et al. (2011) point out that the late Cretaceous uplift could be related to the alkaline magmatism. There is an agreement that denudation and uplift rates have been intensified during the Cretaceous, and the alkaline

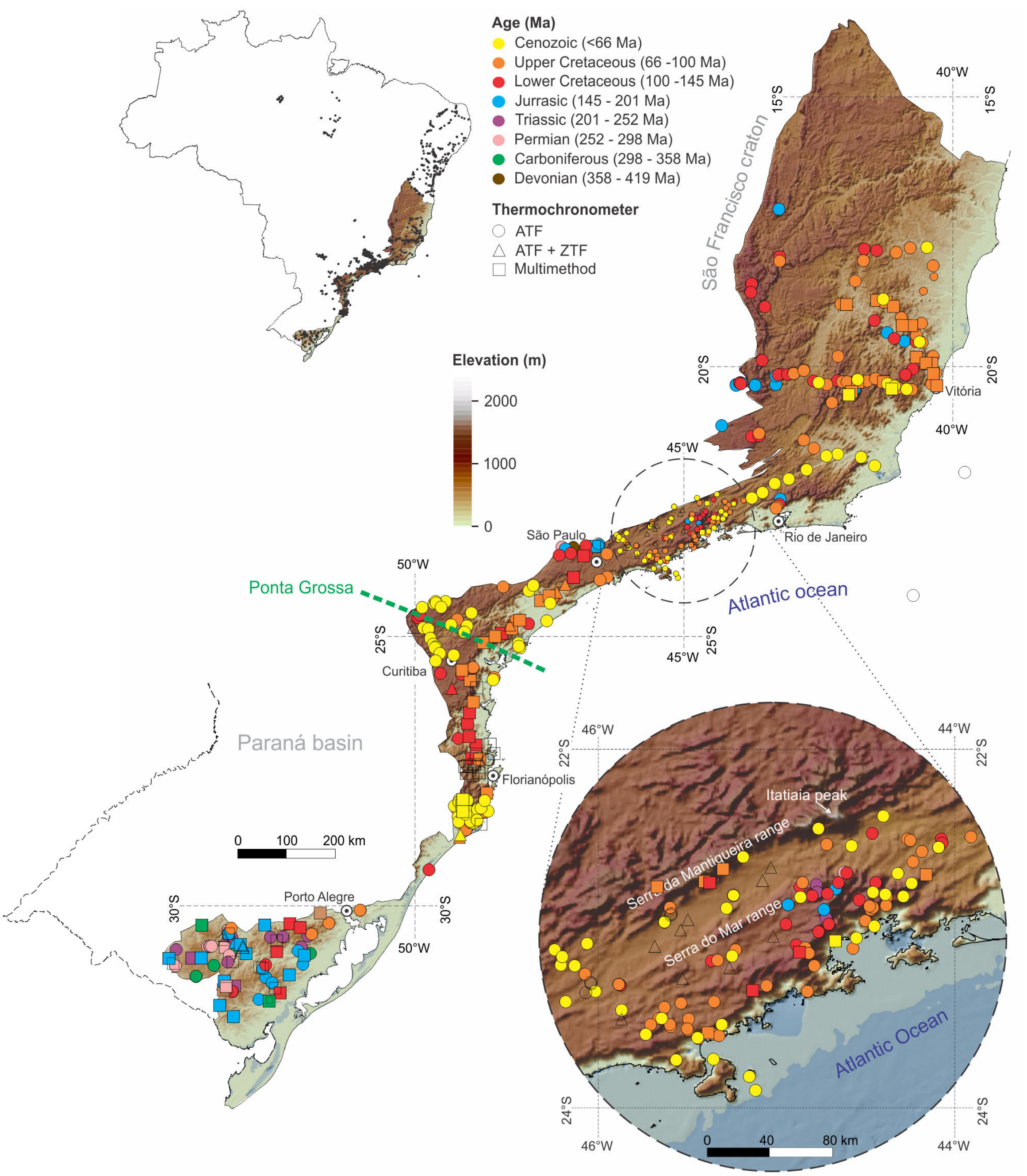

FIGURE 5. Thermochronological data set available for the Mantiqueira province, the circle below is a zoom highlighting the Serra do Mar range region.

magmatism could generate thermal weakening of the lower crust improving those rates.

Hueck et al. (2018; 2019) and Gomes and Almeida (2019) draw attention that besides the thermal weakening, LIPs could overprint thermochronology systems; e.g. Z(He) overprinting due to the Serra Geral magmatism in southern Mantiqueira Province, or the alkaline magmatism associated with the post-rift stage.

Godoy et al. (2006) studied the Pitanga dome, emphasizing the importance of reactivation of basement structures in the Meso-Cenozoic tectonics. Ribeiro et al. (2005a), Ribeiro et al. (2005b), and Ribeiro et al. (2011) also pointed out the importance of the recognition of brittle deformation (pseudotachylytes, cataclasites, and fault gouges) to correlate with the AFT and (U-Th)/He data. Besides the above mention events, Ribeiro et al. (2005b) and Hiruma et al. (2010) recognize a late Triassic uplift, suggesting that Serra do Mar mountain range was a long-lived source of sediments for the Paraná, Bauru, and Santos basins. Oliveira et al. (2016a) studying boreholes of the Santos basin basement, suggest that Serra do Mar mountain range denudation is related to late Cretaceous uplift.

In the last decade, several studies using multi-method thermochronology were made aiming to model the pre-, syn- and post-rift exhumation events in the Mantiqueira province (Cogné et al. 2011; Cogné et al. 2012; Karl et al. 2013; Franco-Magalhães 2014; Oliveira et al. 2016b; Hueck et al. 2017; 2018; 2019; Krob et al. 2019; Van Ranst et al. 2019; Machado et al. 2019, 2021; Gomes and Almeida 2019; Curvo et al. 2013; Souza et al. 2020; Gezatt et al. 2021; Fonseca et al. 2021). Karl et al. (2013) bring for the first time zircon and apatite fission-track and (U– Th–Sm)/He data in a regional view across the Mantiqueira province. The exhumation history varies in the Mantiqueira province due to the variability in the elastic thickness, structural network, and drainage system; being the Serra do Mar and Serra Geral regions the places with the most intense reworking from the Cretaceous to the Paleogene. Souza et al. (2020) performed thermal modeling based on ^{10}Be-derived erosion rates and topographic and climatic parameters. The authors highlight that modern erosion is focused on the escarpments and the incised rivers, pointing out that reactivations of the inherited Precambrian shear zone and transfer zone are the biggest controllers of the relief. According to Karl et al. (2013), three events can be registered in the whole Mantiqueira province: the Paraná– Etendekka event; the alkaline intrusions event; and the evolution of the continental rift basins.

Japsen et al. (2012) suggest a different approach for denudation history on the Brazilian northeast coast. As mentioned in the “São Francisco craton” section, the authors suggest a series of burial and uplift stages taking into account the variability of base level and the lateral resistance to plate motion. Alternatively, other authors assign the exhumation events to far-field stress (related to Gondwanides orogeny), a rift to post-rift tectonism, climate, and underplating (Jelinek et al. 2014; Bicca et al. 2013). According to Jelinek et al. (2014), the idea of burial and uplift cannot be sustained with the thermochronological data set; besides, the material accommodation and surface preservation are hard to explain by a simple burial and uplift model.

Cogné et al. (2011; 2012) using apatite and Franco-Magalhães et al. (2014) and Curvo et al. (2013) using zircon and apatite, present an inverse thermal history modeling based on FT and (U-Th)/He data, providing more detail on the rift to post-rift cooling history. The (U–Th)/He data suggests a Neogene compression event in the South American plate, between the Andean subduction zone (Peruvian phase) and the mid-Atlantic ridge, reactivating Precambrian shear zones. The authors highlight that this reactivation was concentrated in specific places where the reheating seems to be robust (e.g. Taubaté Basin).

The countryside portion of Mantiqueira province lacks studies. Hackspacher et al. (2004) argue that three main stages of denudation control the region, one during the Jurassic, another in Early Cretaceous, and the last one from the Late Cretaceous to the Miocene, involving several reactivations of brittle basement structures. Amaral-Santos et al. (2019) show evidence of a cooling episode starting in the late Devonian to early Permian in the boundary between São Francisco craton and Mantiqueira province. Van Ranst et al. (2019) and Fonseca et al. (2021) bring a great contribution to countryside studies, the authors describe a major phase of uplift and accelerated denudation during the late Cretaceous to early Paleogene. The authors agree that sensu strictu rifting process could not be the only one responsible for the configuration of the relief on the coast. Van Ranst et al. (2019) highlight that the basement structural framework of the northern Mantiqueira province controlled the differential denudation rates, and it directly affects its drainage network. Also, this framework shows a major influence on the small-scale denudation, which has led to the formation of the inselberg landscape, and the persisted role of the Mantiqueira range as a watershed.

It is a fact that the landscape evolution of the Brazilian continental margin cannot be explained by the predicted simple models of continental-margin development. Besides tectonics, the climate directly affects the denudation history of the Mantiqueira province, from the glaciation during a long-term stabilization in Paleozoic times to its breakdown in Early Mesozoic creating variable denudation due to block rearrangement. In the Late Cretaceous, the uplift of the Serra do Mar and Mantiqueira mountain ranges generated a climate barrier in the Brazilian southeast coastline, causing progressive denudation towards the continent related to scarp retraction.

2.4. Tocantins province

Tocantins province (Almeida et al. 1981) is located between the Amazonian and São Francisco cratons and is bounded to the north and south by Parnaíba and Paraná basins, respectively (Fig. 2). It comprises the remnants of a Neoproterozoic orogenic system, generated due to a convergence between Amazonian, São Francisco, and Paranapanema paleocontinents during the Brasiliano/ Pan African cycle (Pimentel et al. 2004). The continental collision was preceded by the consumption of a large ocean crust between ca. 900 and 600 Ma and attachment of minor continental fragments and magmatic arcs. Three large fold belts compose the province: the Brasília belt, situated on the western margin along with the São Francisco craton; and the Araguaia and Paraguay belts, established on the eastern and southeastern margin of the Amazonian craton. The end of the orogeny and then the transition through a relatively stable area inside the West Gondwana was followed by the development of large Paleozoic syneclises (Brito Neves 2002; Milani and Thomas 2000). Widespread post-Paleozoic alkaline magmatism intruded the province’s basement mainly in areas surrounding the Paraná basin. The Brasília belt hosted several alkaline magmatic pulses in the late Cretaceous (Riccomini et al. 2005); more information about the alkaline intrusions in the topic “Alkaline provinces”. Evidence of the Phanerozoic sedimentation is limited to sedimentary beds in Água Bonita graben and Cretaceous and Cenozoic continental covers, standing out the Pantanal (with thickness up to 500 m) and Araguaia plain (Almeida et al. 1981).

Thermochronological studies in the Tocantins province are strongly concentrated in the southern portion of Brasília belt (Cogné et al. 2011; Doranti et al. 2008; Doranti-Tiritan et al. 2014; Gallagher et al. 1994; Hackspacher et al. 2004; 2007; Oliveira 2000; Ribeiro et al. 2005a; 2005b; Tello Saenz et al. 2003; 2005; Fonseca et al. 2020; Fig. 6). Only one study, applying ZFT analysis, was made in the Araguaia belt (Dias et al. 2017; Fig. 6). In this work, based on four bedrock samples, three distinct ZTF age populations are recorded. The older one (498 ± 8 to 489 ± 15 Ma) was interpreted as the orogenic collapse. The intermediate population (345 ± 13 to 331 ± 8 Ma) was related to a reactivation event due to the Gondwanides orogeny and then erosion of Parnaíba sedimentary deposits that could cover the area. Finally, the younger age population (208 ± 10 to 197 ± 3 Ma) was associated with a possible reheating linked with the Lower Jurassic Mosquito magmatism.

In the Brasilia belt region, the Poços de Caldas plateau is an elevated region that was cut by Cretaceous alkaline intrusions and investigated by thermochronometers. Doranti-Tiritan et al. (2014) using new and previous (Doranti et al. 2008; Cogné et al. 2011; Gallagher et al. 1994) AFT data verified that the thermal effect of the magmatism emplacement was not strong enough to affect the close basement portions and leave any impression on AFT data. Thus, the pre-Cambrian rocks could keep registered its ancient thermal history. The authors associated the oldest cooling phase with the glacial erosional process during the Carboniferous. Afterward, several collisions in the south of Gondwana during the Triassic may have generated widespread uplift, decreasing the cooling rate. The erosion of this raised terrain may have resulted in the Gondwana pediplanation surface (King 1956) generating another cooling cycle. Fonseca et al. (2020) reveal a Devonian to Permian cooling period and correlate it to the final exhumation of the Brasília Belt, associated with the orogenic collapse and sediment influx to Paraná basin.

In a transect starting from Poços de Caldas plateau towards the border with Mantiqueira province, Gallagher et al. (1994) analyzed basement rocks through the AFT method. Years later, Cogné et al. (2011) reanalyzed the same samples through the (U-Th)/He approach. Using both methods was possible to greatly improve the data set and understand in more detail the post-rift cooling history. Only a few samples record an early cooling episode related to the South Atlantic opening (~120 Ma). Most of the results implied two main phases of cooling. The first one during the late Cretaceous with higher rates and regional extent, and subsequently the second one during Cenozoic with lower rates and concentrated along pre-existing shear zones. Together, the cooling events imply exhumation from depths between 2 and 5 km. Cogné et al. (2011) attribute the post-rift cooling history to the compression of the South America plate between the Andean subduction zone and the mid-Atlantic ridge.

In the convergence zone between Tocantins and Mantiqueira provinces, which encompasses the Ituverava shear zone, several analyses investigated the Jundiaí plain and High Mantiqueira mountain range domains (Hackspacher et al. 2004; 2007; Oliveira 2000; Ribeiro et al. 2005b; Tello Saenz et al. 2003). According to Ribeiro et al. (2005b), the Jundiaí plain AFT data are related to the Late Triassic formation of the Gondwana surface (King 1956) and can also be associated with the Paraná basin subsidence. On the other hand, the High Mantiqueira mountain range domain records the Early Cretaceous cooling, which was linked to the Mantiqueira mountain range uplift due to the opening of the South Atlantic Ocean (Hackspacher et al. 2004; 2007; Oliveira 2000; Tello Saenz et al. 2003; 2005). During Late Cretaceous until Oligocene some samples from the region record a heating period that Hackspacher et al. (2007) associate with a thermal anomaly resulted from the mantle plume passage and crustal thinning. The ensuing cooling period was related by the same author with the Japi/Sul-American pediplanation surface (King 1956; Almeida 1964). Ribeiro et al. (2005a), also studying in the southern portion of the Brasília belt, found ATF ages ranging from Ordovician, right next to Paraná basin, to Cenozoic, next to the High Mantiqueira mountain range. The authors suggest that the differential cooling stories are probably connected to basement reactivation during the tectonic subsidence periods of the Paraná Basin.

Martins-Ferreira et al. (2020) show the first fission-track data in zircon and apatite detrital grains in the northern Brasilia belt. ZFT age range from Neoproterozoic to Triassic. The authors suggest that the older ages are related to the West Gondwana assembly exhumation, while the younger ages are linked to the Gondwanide orogeny. The apatite data are Cretaceous to Paleogene age; the authors related it to Pangea breakup.

2.5. Borborema province

The Borborema province in northeast Brazil is limited to the west by the Parnaiba basin and the south by the São Francisco craton. It comprises a long system of strike-slip shear zones, that juxtaposed Archean/Proterozoic blocks and Neoproterozoic metasedimentary rocks during the Brasiliano/Pan African orogenic cycle (Dantas et al. 1998; Neves et al. 2000). These structures represent the main crustal discontinuities which played an important role during the Gondwana fragmentation and later Phanerozoic tectonic events. From Cretaceous times onwards, the Borborema province underwent significant uplift. The main topographic expression is the Borborema plateau which elevates a sequence of continental sediments up to 1200 m above sea level. It has been an intriguing point of discussion in the past four decades. Another point of discussion that needs more analytical data to evaluate is the onshore and offshore evolution of the hydrocarbons deposits.

Morais Neto et al. (2009) made the greatest contribution to thermochronology in the Borborema Province (Fig. 7). Based on AFT and ZFT the authors pointed to two main Phanerozoic denudational/cooling events. One between 100 and 90 Ma, related to post extension lithospheric processes. And further, a 20-0 Ma event probably due to climate change rather than a tectonic source. According to the authors, the late Cretaceous event seemed to be a generalized uplift instead of the denudation slope retreat classic style observed on the Brazilian southeast continental margin.

2.6. Phanerozoic syneclises and Marginal basins

The Phanerozoic syneclises developed during Gondwana stabilization to its break up, passing from a stable to an activated platform in syn to post-rift stages, when the marginal basins formed. It lacks thermochronology studies, being the Paraná basin the only studied Phanerozoic syneclise, and the Campos and Santos basins the marginal basins with thermochronology data. The Campos and Santos basins host large, world-class oil reservoirs. The data set related to the basement of the basins is described in the "São Francisco craton", "Mantiqueira Province" and "Borborema Province" sections.

2.6.1. Paraná basin - Bauru basin

Bauru basin is the top succession of the Parana basin, located in south-central Brazil (Fig. 8). It is formed by thermal subsidence after an Early Cretaceous volcanic event, and it is mainly composed of sandstones, mudstones, and

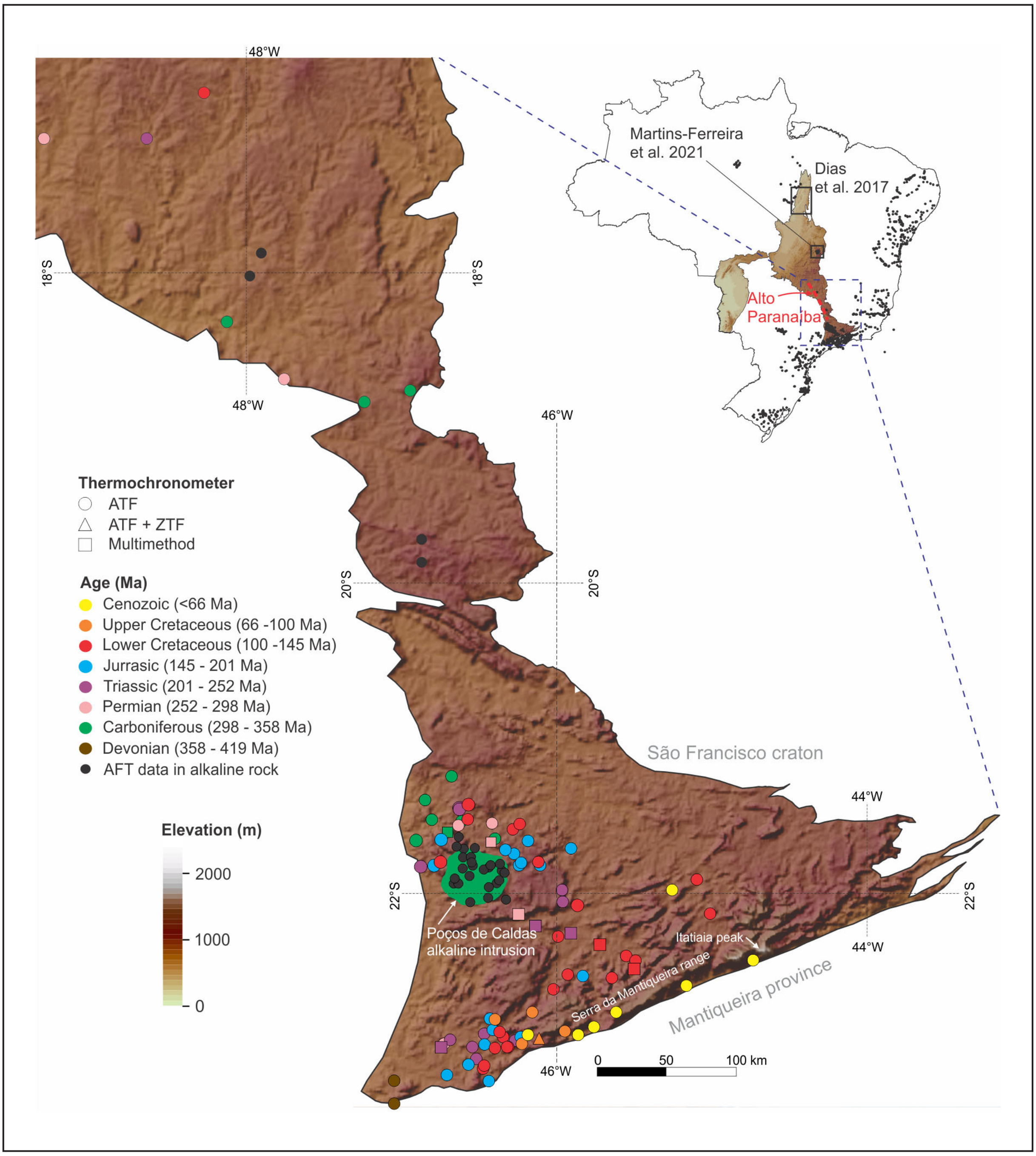

FIGURE 6. Thermochronological data set published in the Tocantins province. In the Brazil map, the study of Dias et al. 2017 is highlighted. In the bottom, the southern portion of the Brasília belt where thermochronological data are concentrated. Poços de Caldas alkaline intrusion is drawn in green and the analyses from its rocks in black; The data of the Poços de Caldas alkaline intrusion is shown in the "Alkaline provinces" section.

conglomerates (Batezelli and Ladeira 2016). Dias et al. (2011) analyzed detrital zircons from Vale do Rio do Peixe Formation, in the Bauru Basin, and obtained ZFT ages varying from 239 Ma to 825 Ma, reflecting the main denudation processes of the South American Plate from Neoproterozoic to Early Triassic, like those related to orogenic cycles of early Brasiliano, Famatinian/Cuyanian and Gondwanides. Dias et al. (2018; 2021a) analyzed detrital zircons from the Bauru basin and the fission-track data record ages from the Neoproterozoic to Late Cretaceous, which were interpreted as uplift and exhumation due to tectonic events along the western margin of the South American platform; like the denudation of Brazilian and Gondwanides and the Serra Geral magmatism.

2.6.2. Campos and Santos basins

In the Campo basin, Oliveira et al. (2018) analyzed the thermotectonic history of the Maastrichtian oil reservoir and obtained a minimum AFT age of 45.9 ± 5.5 Ma. Two phases of heating were distinguished, one after the deposition of Carapebus Formation until 65 Ma, and one during the late Eocene, reflecting subsidence. The phases are separated by a cooling event (65-37 Ma), which is correlated to subaerial

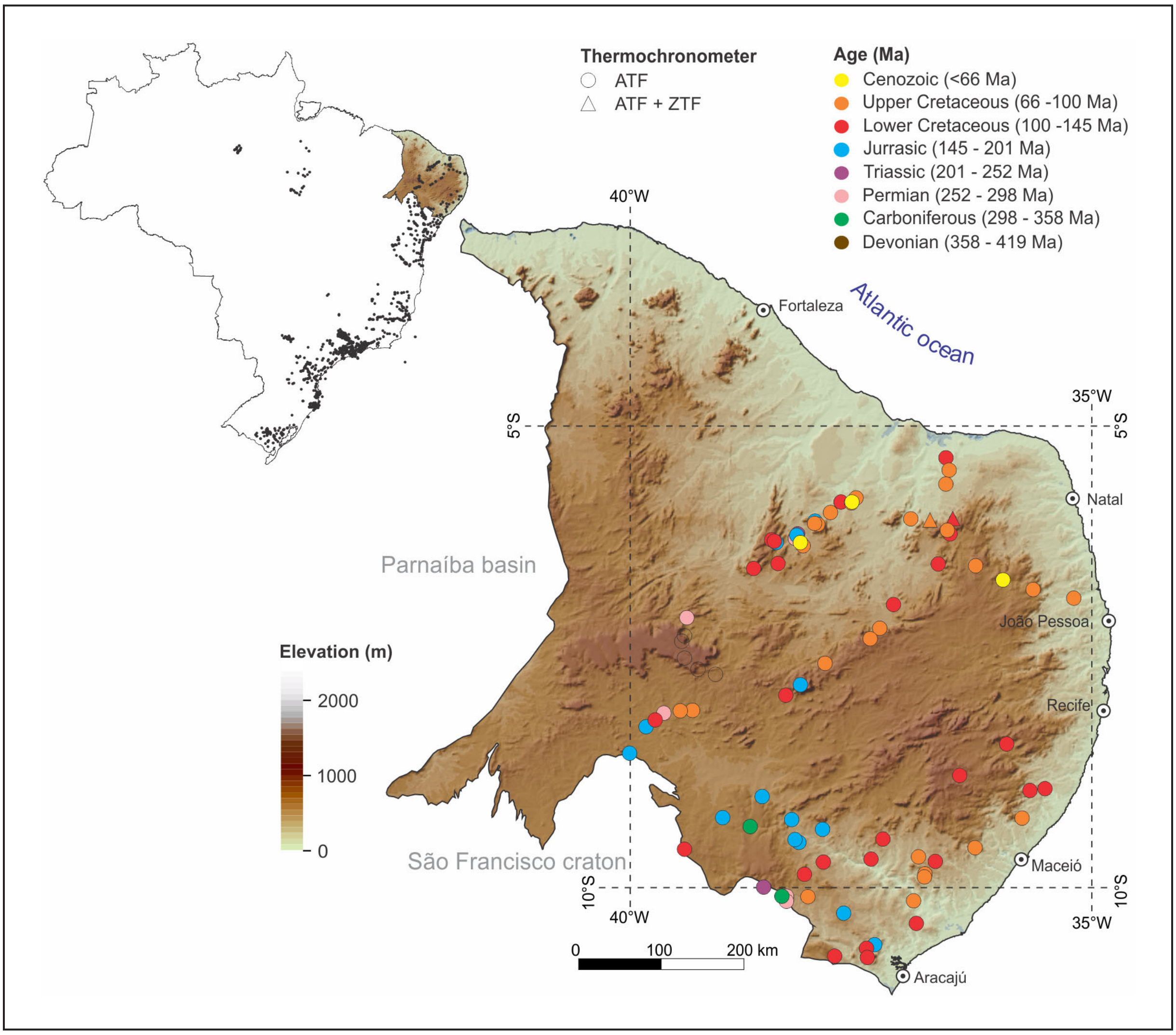

FIGURE 7. Thermochronological data set published in the Borborema province.

unconformity and thermal uplift coeval with volcanic pulses of Trindade plume.

Oliveira et al. (2016b) analyzed apatite fission-track from borehole samples from the Santos basin. The central ages obtained for the basement range from 21.0 ± 1.8 to 157.0 ± 35.0 Ma, and the central ages for borehole samples vary from 6.5 ± 1.1 to 208.0 ± 11.0 Ma. From thermal modeling, an early thermotectonic event is recorded during the late Cretaceous related to uplift and denudation of the Serra do Mar and Serra da Mantiqueira, and also indicates that the oil generation started at 55–25 Ma and continued until the Pliocene-Pleistocene. Besides that, during the Neogene, fast cooling is linked to the reactivation along Precambrian shear zones, which also changed the drainage system of Paraíba do Sul.

2.6.3. Barreiras Formation

Dias et al. (2021b) show ZFT ages from the Barreiras Formation; a Neogene deposit in the Brazilian continental margin. The data range from the Silurian to Late Cretaceous. The authors recognize four groups (429 to 358 Ma, 351 to 274 Ma, 270 to 171 Ma, and 167 to 127 Ma) that reflect the Gondwana and Pangea agglutination and break-up.

2.7. Alkaline provinces

Almeida (1983) defined alkaline provinces as chrono-correlated clusters of alkaline bodies with similar petrographic and geotectonic features. This section brings the main contributions of thermochronology studies in alkaline provinces (Ponta Grossa Arch, Alto Paranaíba, and Poços de Caldas) and Trindade island, in the Brazilian territory (Fig. 8). The data set related to the host rocks of the alkaline intrusions is described in the “Tocantins province” and “Mantiqueira province” sections.

2.7.1. Ponta Grossa arc province

Ponta Grossa arc alkaline province is located at the eastern border of Paraná basin, in southeastern Brazil. Jacupiranga is one of its alkaline bodies, composed of mafic and ultramafic rocks associated with carbonatite (Almeida 1983; Riccomini et al. 2005). The crystallization age of the Jacupiranga alkaline body ranges from ca. 130 to 133 Ma (Renne et al. 1993; Sonoki and Garda 1988; Roden et al. 1985; Amaral 1978; Amaral et al. 1967). Amaral et al. (1997) obtained similar ages with AFT, confirming an early Cretaceous heating period from 130 to 70 Ma, followed by continuous cooling since 70 Ma. The heating

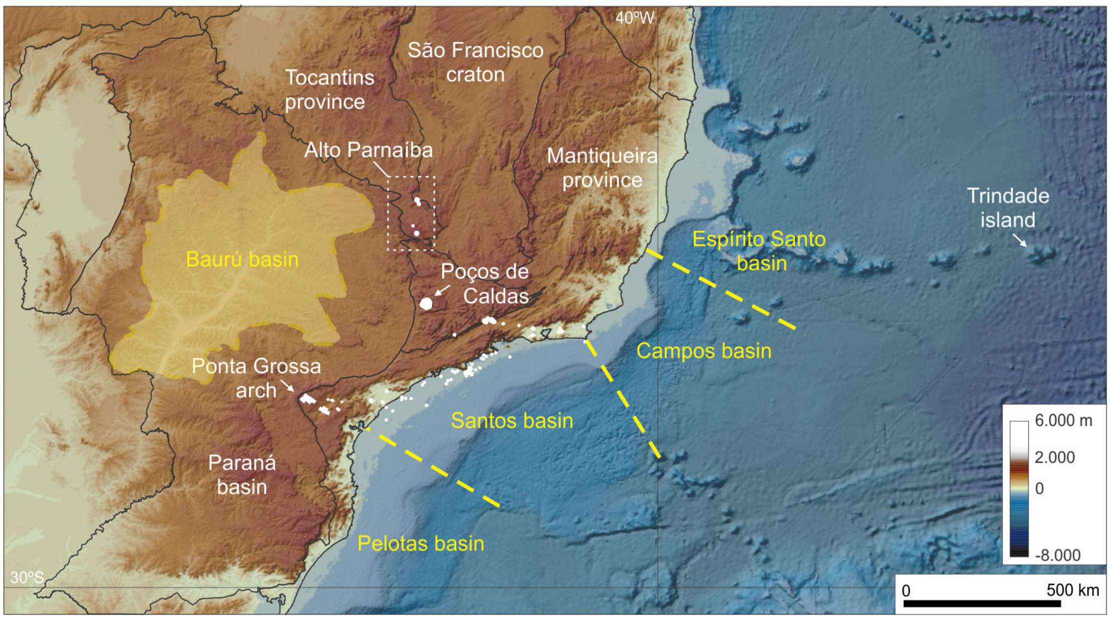

FIGURE 8. Phanerozoic syneclises, marginal basins, and Alkaline provinces (indicated in white).

event suggests the influence of Upper Cretaceous alkaline intrusions or due to the increase of heat flow during crustal thinning during the Santos basin rift event.

Soares et al. (2016) obtained AFT ages from Ipanema (69.1 ± 6.5 Ma), Barra do Itapirapuã (98.2 ± 12.7 Ma) and Jacupiranga (94.9 ± 8.0 Ma) bodies, with modeling indicating a Late Cretaceous fast cooling event. The difference between the crystallization age (ca. 130 Ma) and the AFT age is attributed to the compressive Andean collision, which caused rising and erosion on the boundary of the Paraná basin (Lima 2000), increasing the temperature and resetting the fission-track ages in Jacupiranga, and inducing a slower cooling in Barra do Itapirapuã and Ipanema bodies. Tunas, a felsic alkaline body from the Early Cretaceous (110 Ma K/Ar age), yields an AFT age of 16.95 ± 1.05 Ma. (Gomes et al. 1987; Sonoki and Garda 1988; Ulbrich and Gomes 1981; Franco-Magalhães et al. 2010).

2.7.2. Alto Paranaíba province

The Alto Paranaíba province (Almeida 1983) or the southeastern portion of the Minas–Goiás Alkaline province (Sgarbi and Gaspar 2002) is located in central Brazil, in the northeast border of the Paraná Basin. The apatite fission-track thermochronometry data were analyzed by Eby and Mariano (1992) and compared with the K/Ar data set from Amaral et al. (1967), Hasui and Cordani (1968), and Sonoki and Garda (1988). The alkaline bodies detailed here are Araxá, Catalão II, Tapira, Serra Negra, Salitre I, and II, which yielded ages from the Upper Cretaceous while Catalão II yielded ages from the Lower Cretaceous. For the Araxá body, the AFT mean age for carbonatite/glimmerite rock is 84.4 Ma, phosphate rock is 81.9 Ma and pyrochlore-mineralized carbonatite is 84.4 Ma. K/Ar ages from the glimmerite yielded older values as 89.4 ± 10.1 and 97.7 ± 6.1 Ma and carbonatite (77.4 ± 1.0 Ma), which can indicate that the glimmerite were emplaced earlier than the carbonatite, or that thermal closure for the AFT system did not occur until about 5-13 Ma after the complex's emplacement. At Catalão I, AFT ages range from 110.6 to 116.1Ma, with a mean age of 114 Ma, while for Catalão II, the AFT age is 87.1Ma. The K/Ar dating of an alkali-syenite from Catalão I yielded an age of 85.0 ± 6.9 Ma and Eby and Mariano (1992) suggested that the alkali syenite may be related to Catalão II. For Tapira body, AFT ages are 81.7 ± 7.9 Ma (bebedourite) and 78.6 ± 9.0 Ma (carbonatite) and the K-Ar biotite age of 71.2 ± 5.1 Ma (bebedourite), 87.2 ± 1.2 Ma (phonolite) and 85.6 ± 5.1 Ma (jacupiranguito). Conceição et al. (2020) dated $^{40}Ar/^{39}Ar$ in phlogopite, which indicate at least two magmatic events during the emplacement, the first at > 96.2 ± 0.8 Ma and the second at 79.15 ± 0.6 Ma. Amaral et al. (1997) also analyzed the thermal histories on apatite from Catalão II and Tapira Complex which presents single cooling history since the annealing temperature, characterized by a slow cooling from 95º to 85ºC between 90 and 60 Ma and faster cooling from 85º to 27ºC for the last 60 Ma. Soares et al. (2016) dated apatite fission tracks from Catalão (82.6 ± 5.3 Ma) and Tapira (88.9 ± 7.4 Ma) in agreement with values from other radiometric methods which can be associated with post-magmatic cooling and the confined track length distributions can be related to fast cooling.

The Serra Negra body was dated by K/Ar of biotite from the peridotite and yielded ages of 83.7 - 83.8 ± 2.5 Ma, while AFT age is 79.1 Ma of an apatite-calcite carbonatite. Salitre I was dated by AFT phosphate-rich carbonatite (87.1 Ma) and sanidine trachyte (89.8 Ma) and at Salitre II the bebedourite has an AFT age of 82.6 Ma. Biotite from bebedourite of Salitre was also dated by K/Ar and yielded 86.3 ± 5.7 and 82.5 ± 5.6 Ma and phonolite yielded ages from 79.0 ± 1.2 to 94.5 ± 1.5 Ma. In general, K/Ar dating and AFT dating are in good agreement and they all were emplaced between 88-79 Ma, except for Catalão I. This supports that the alkaline complexes were emplaced relatively close to the surface and also had a fast cooling at temperatures that the fission tracks were retained in apatite. Besides that, the results suggest that there are two moments of activity, the first one at ca. 80 Ma with the emplacement of Salitre II, Serra Negra, and Tapira; and the second one at ca. 88 Ma refers to the emplacement of Catalão II and Salitre I. (Eby and Mariano 1992; Gomes et al. 1990).

2.7.3. Trindade island

Trindade Island is located in the South Atlantic Ocean, 1170 km from the Brazilian coast. Pires et al. (2016) present new Ar/Ar ages and also a re-evaluation of K/Ar data. The volcanism has a peak between 3.9-2.5 Ma (Trindade Complex) and completely ceased at ca. 0.25 Ma (Paredão Formation). Apatites from the lava flow and dikes from the basal unit

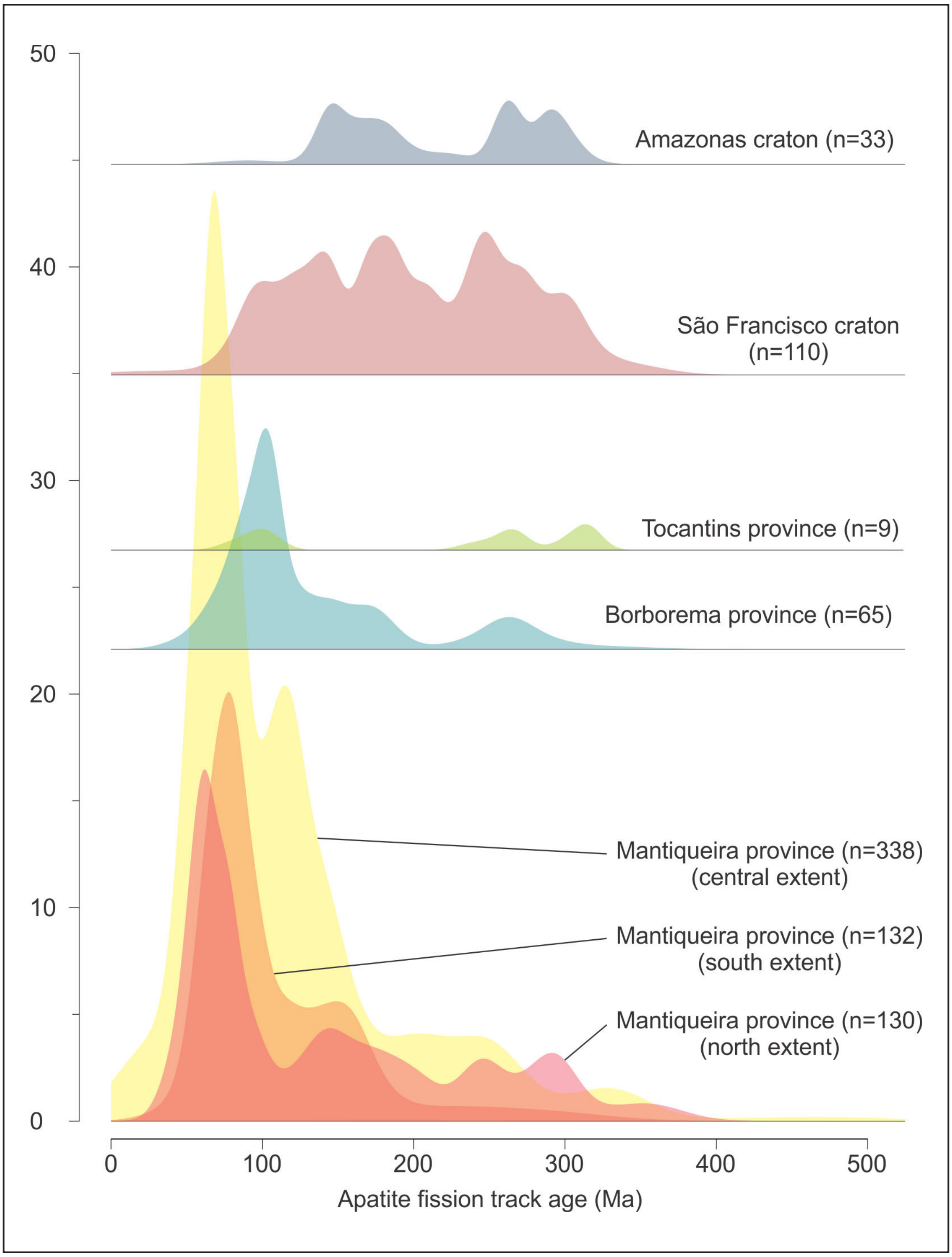

FIGURE 9. Apatite fission-track samples dating histograms for Brazilian tectonic domains. Due to a large amount of data, Mantiqueira province was divided into three sectors: North (13°S to 20°S), Central (20°S to 26 °S), and South (26°S to 33 °S).

(Trindade Complex) yielded ages of 3.53 - 3.0 Ma and the modeling showed cooling between 3.9 and 3.0 Ma, followed by relatively slow erosion rates (Hackspacher et al. 2017).

2.7.4. Poços de Caldas province

In southeastern Brazil, the Serra do Mar magmatism migrated progressively approximately 500 km from Poços de Caldas to Cabo Frio, between 80 and 55 Ma (Thompson et al. 1998; Sonoki and Garda 1988; Amaral et al. 1967). Poços de Caldas alkaline massif is located on the boundary between São Paulo and Minas Gerais. Cogné et al. (2011) combined AHe and AFT ages from samples of the Poços de Caldas alkaline body. The AHe ages suggest slow cooling between 90-60 Ma related to exhumation during Late Cretaceous followed by a fast cooling during Neogene (although this result is in the limit of the method resolution). On the other hand, Silva et al. (2011) showed apatite grains yielding AFT ages from 69.0 ± 4.4 to 42.7 ± 3.4 Ma, with magmatic crystallization age ranging from 89.1 ± 7.1 Ma to 83.6 ± 6.7 Ma. The thermochronological history reveals that shortly after the intrusion, the faster cooling and main exhumation occurred, which lasted for about 11 Myr. Doranti-Tiritan et al. (2014) agree with Silva et al. (2011) and interpreted the data as fast cooling at 80 Ma with the thermal stability of 40°C until approximately 50 Ma when heating occurs from 40° to 75°C until 5 Ma, followed by a fast cooling event to 20°C. Souza et al. (2014) get Eocene to Paleocene AFT ages in the region, and compared with published data (Godoy 2003; Franco et al. 2005; Doranti 2006; Silva 2010; Doranti-Tiritan 2013), highlighting the importance of past tectonic and magmatic events for the regional relief development.

3. Final Remarks

On one hand, the data highlight the importance of the elastic thickness, structural network, and drainage system in the morphotectonic control. On the other hand, the lack of data leaves a series of unsolved questions: i) which forces act in the Brazilian morphotectonic evolution? Compressive, extensional, and plume-related tectonic events could lead to blocks adjustment? What is the role of climate in this interaction? And what could be the implications of a robust data set for gas, oil, and metal deposit studies?

For a more in-depth and robust discussion, it is necessary to acquire a regional fission-track and (U-Th)/He database in zircon and apatite. Brazil still has large areas with no thermochronology data. Advances in the method, like the uranium content reading by mass spectrometers, would exponentially change this scenario. Besides basic data acquisition, an integrated, multi-method, transdisciplinary study is recommended, including sedimentology, geophysics, geomorphology, structural, and tectonics. Complete research like this could lead to an understanding of Brazilian tectono-thermal evolution.

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