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Records of latest Triassic, mid-Cretaceous and Cenozoic uplift/exhumation phases in the Istanbul zone revealed by apatite fission-track and (U-Th)/He thermochronology

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ABSTRACT

Apatite fission-track and (U-Th)/He ages from Carboniferous to Eocene siliciclastic rocks of the Istanbul Zone (NW Turkey) range from 220 to 46 Ma, and from 46 to 18 Ma, respectively. Apatite grains from the upper Cretaceous and Eocene volcaniclastic and siliciclastic formations yielded unreset fission-track ages (85 to 65 Ma), whereas the Lower Cretaceous siliciclastic rocks yielded both reset and unreset apatite fission-track ages. This suggests the absence of substantial burial after the Early Cretaceous. The thermochronological dataset presented here in conjunction with published data defines three major deformation and uplift/exhumation phases: (i) 220–179 Ma (Late Triassic-Early Jurassic), (ii) 101–107 Ma (mid-Cretaceous), and (iii) 66–16 Ma (Palaeocene-early Miocene). The Late Triassic-Early Jurassic uplift/exhumation phase can be attributed to the Cimmeride orogeny and the uplift of the Pontides. The mid-Cretaceous uplift/deformation is also reflected in the stratigraphic record as a major unconformity, which was probably caused by the accretion of an oceanic plateau or a seamount. The Palaeocene-early Eocene uplift/deformations resulted from the closure of the Izmir-Ankara-Erzincan oceanic domain. The late Oligocene-early Miocene uplift/deformation is probably caused by extension in the Aegean region due to the suction along the Hellenic trench.

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Istanbul zone; apatite fission-track; (U-Th)/He; uplift/exhumation phases; NW Turkey; low-T thermochronology

Introduction

The current morphotectonic features of Turkey are essentially shaped by the closure of the Neotethyan oceans and subsequent convergence between the Arabian and Eurasian plates (e.g., Şengör and Yılmaz 1981; Okay and Tüysüz 1999; Bozkurt 2001; Okay *et al*. 2006, 2010; Yılmaz 2017; Figure 1). The Izmir-Ankara-Erzincan suture marks the closure of the northern branch of the Neotethys during Palaeocene-early Eocene, and the Bitlis-Zagros suture marks the closure of the southern branch of Neotethys during the early-mid Miocene (Okay and Tüysüz 1999; Okay *et al*. 2010; Cavazza *et al*. 2018). Continued convergence led to the initiation of the currently active North and East Anatolian strike-slip fault system during mid-Miocene (Serravallian) (Şengör *et al*. 1985, 2005; Figure 1). This configuration is responsible for the westward movement of the Anatolian plate (Şengör *et al*. 2005 and references therein). In the west, the Aegean region has been undergoing extension since the Oligocene due to slab rollback of the Hellenic subducting plate (Jolivet and Faccenna 2000; Okay *et al*. 2008). The present-day morphology of Turkey is reshaped by several geodynamic processes whereby the younger processes mostly overprinted the older ones. Understanding of the morphotectonic evolution of the region requires detailed low-temperature thermochronological data which became increasingly available in the last decade (e.g., Okay *et al*. 2008, 2010; Cavazza *et al*. 2009, 2012, 2018; Zattin *et al*. 2010; Espurt *et al*. 2014; Frassi *et al*. 2018; Ballato *et al*. 2018; Sunal *et al*. 2019).

Here, we present apatite fission-track and (U-Th)/He data from Carboniferous to Eocene sedimentary rocks of the Istanbul Zone in order to understand its uplift and exhumation history. Our data, together with those in literature, record three main uplift phases: (i) Late Triassic-Early Jurassic, (ii) mid-Cretaceous, and (iii) Palaeocene to Early Miocene. Such discrete episodes can be correlated with the accretion history along the southern Eurasian continental margin and the ensuing deformation pattern.

Geological framework

Within the Tethyan realm, Turkey is made up of several microplates which rifted from Gondwana and

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amalgamated to Laurasia at different times (e.g., Şengör and Yılmaz 1981; Okay and Tüysüz 1999; Stampfli and Borel 2002; Figure 1). These microplates were successively accreted to the southern margin of Laurasia. The Pontides (northern Turkey) are separated from the Anatolide-Tauride block to the south by the Izmir-Ankara-Erzincan suture, which represents the trace of a long-lived ocean at least from the Silurian to the Palaeocene/early Eocene (e.g., Okay 2000; Topuz *et al*. 2013, 2020). In turn, the Anatolide-Tauride block is separated from the Arabian Platform by the Bitlis-Zagros suture, which represents the trace of an Early Triassic to the Cenozoic oceanic domain (Şengör and Yılmaz 1981; Okay *et al*. 2010; Uzuncimen *et al*. 2011; Robertson *et al*. 2012). Turkey became a single land mass after the closure of the southern Neotethyan oceanic domain by the early-mid Miocene time. The current convergence rate between the Arabian platform and Eurasia is ~15 mm/yr (Reilinger *et al*. 2006; Figure 1). This convergence, together with the suction along the Hellenic subduction zone is responsible for the westward movement of Turkey along the North and East Anatolian fault systems at least since the mid- to late Miocene (Şengör and Yılmaz 1981; Jolivet and Faccenna 2000; Okay *et al*. 2008, 2010).

The Pontides comprise three juxtaposed continental fragments: the Istanbul, Sakarya, and Rhodope-Strandja zones separated by sutures and strike-slip faults (Okay and Tüysüz 1999; Figure 1). The Late Cretaceous stratigraphy of these three microplates are similar suggesting a pre-Late Cretaceous amalgamation (Figure 2). The Istanbul Zone of the Pontides is ca. 400 km long and 55 km wide and has a Late Neoproterozoic to Cambrian crystalline basement (e.g., Chen *et al*. 2002; Ustaömer and Rogers 1999; Ustaömer *et al*. 2005; Figure 2). This basement is unconformably overlain by a continuous sedimentary succession ranging in age from Ordovician to late Carboniferous (Özgül 2012). The Permian continental clastic series unconformably overlie the Ordovician to Upper Carboniferous sequences (Gand *et al*. 2011; Stolle 2016; Okuyucu *et al*. 2017), suggesting uplift and major erosion at the end of the Carboniferous. A few granitic bodies were also emplaced during the Permian (Okay *et al*. 2013; Aysal *et al*. 2018a). During Triassic time, there was local marine transgression in the western part of the Istanbul Zone, while the eastern part was largely erosional with minor local continental sedimentation (Alişan and Derman 1995; Tüysüz *et al*. 2004). Apart from Triassic marine deposits in its western part, there are no marine deposits of Permian to Middle Jurassic age in the Istanbul Zone. The Upper Jurassic-Lower Cretaceous shallow-marine platform carbonates lie unconformably over all the older units (e.g., Tüysüz 1999; Okay *et al*. 2018). These carbonates are the first common cover on the Istanbul and Sakarya zones, thus constrain their amalgamation in the Central Pontides. The deposition of the Upper Jurassic-Lower Cretaceous shallow-marine carbonates was followed by uplift and erosion during Valanginian-Hauterivian times. Barremian-Aptian shelf deposits and turbidites unconformably cover all the older units (Görür 1997; Tüysüz 1999; Hippolyte *et al*. 2010; Okay *et al*. 2013, 2018; Akdoğan *et al*. 2017). The Late Cretaceous is represented by thick volcanic and volcaniclastic sequences with pinkish pelagic limestone interlayers of Turonian to Campanian age (Tüysüz *et al*. 2012, 2016; Özcan *et al*. 2012; Keskin and Tüysüz 2018; Akdoğan *et al*. 2019). The volcanism occurred in a magmatic arc due to northward subduction of the northern branch of the Neotethyan Ocean. The Black Sea was opened as a back-arc basin during the Late Cretaceous (Nikishin *et al*. 2015). The volcaniclastic sequence passes upward to the upper Campanian to mid-Palaeocene calciturbidites and limestones. The lower Eocene clastic and volcanic rocks lie unconformably on the Campanian to mid-Palaeocene and locally older rock successions (Özcan *et al*. 2012, 2020). There are no records of the upper Eocene and younger marine sedimentary rocks, apart from the Thrace Basin (Okay *et al*. 2020b).

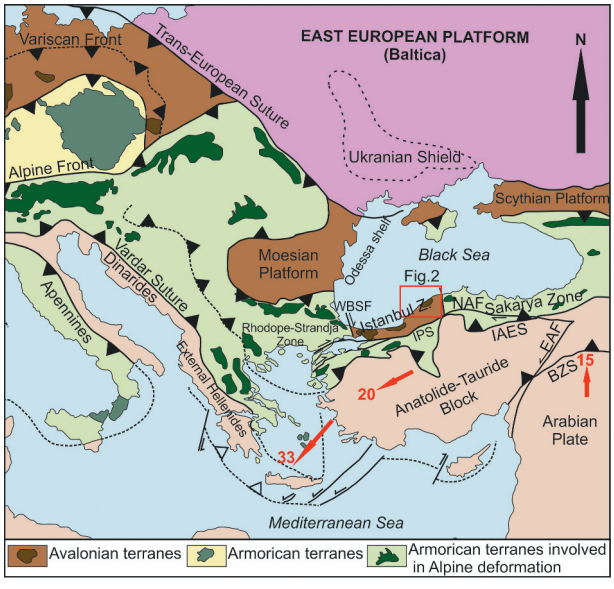

Figure 1. Tectonic map of Eastern Europe and the Black Sea region (modified after Topuz *et al*. 2020). Red arrows and corresponding numbers indicate GPS-derived plate velocities (mm/yr) relative to Eurasia after Reilinger *et al*. (2006). IPS: Intra-Pontide Suture, IAES: Izmir-Ankara-Erzincan Suture, BZS: Bitlis Zagros Suture, WBSF: West Black Sea Fault, NAF: North Anatolian Fault, EAF: East Anatolian Fault.

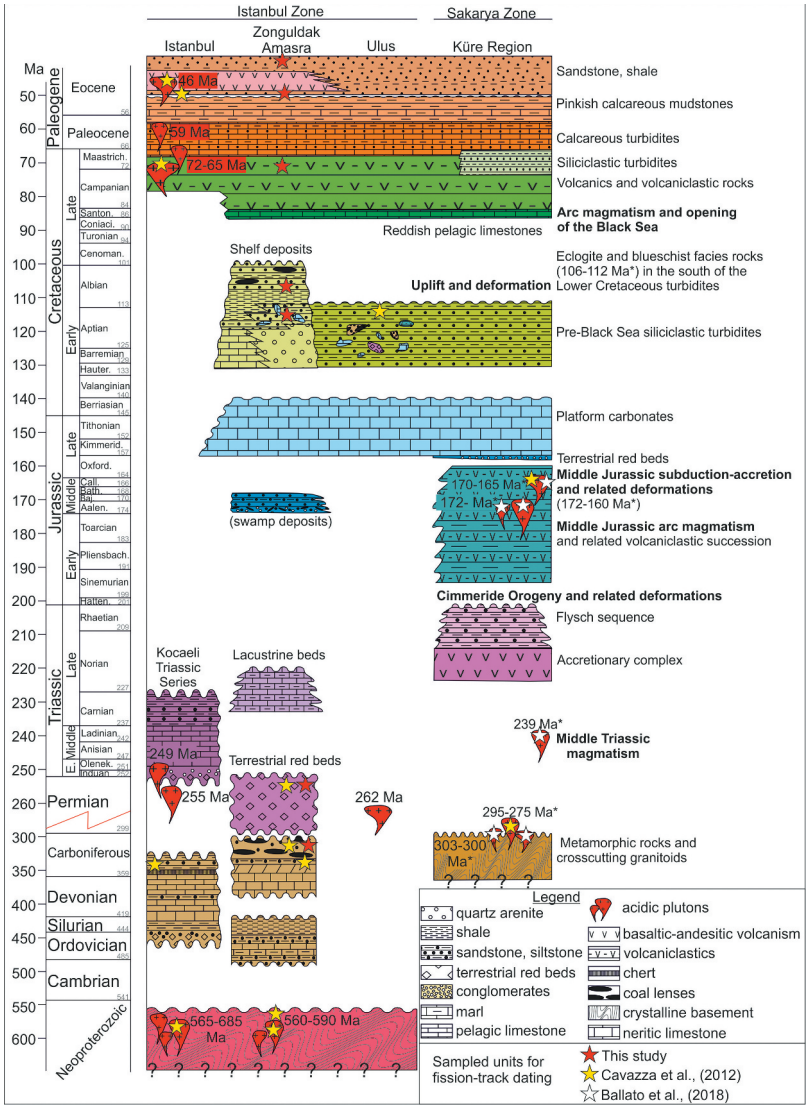

Figure 2. Generalized chronostratigraphic chart of the Istanbul and Sakarya zones (modified after Akdoğan *et al*. 2017, 2019). The time scale is from Cohen *et al*. (2020). Isotopic ages are from Chen *et al*. (2002), Ustaömer *et al*. (2005), Nzegge *et al*. (2006), Nzegge (2008), Okay *et al*. (2013), Şahin *et al*. (2012), Akbayram *et al*. (2013), Aysal *et al*. (2018a), 2018b), Ballato *et al*. (2018), Şen (2020)

Material and methods

To constrain the exhumation history of the north-eastern part of the Istanbul Zone, we used low-temperature thermochronological methods including fission-track and (U-Th)/He analyses. The investigated samples were collected from late Carboniferous to early Eocene siliciclastic and volcaniclastic sandstones of the north-eastern part of the Istanbul Zone, distributed over a distance of 100 km along the coastal region of the Black Sea (Figures 1 and Figure 3). Mineral separation was performed at the Eurasian Institute of Earth Sciences of Istanbul Technical University by standard heavy-mineral separation techniques involving crushing, sieving and magnetic and heavy-liquid separations. Apatite fission-track analysis were carried out on 14 samples, and apatite (U-Th)/He analyses on 11 samples at the GÖochron Laboratories, Geoscience Centre, University of Göttingen (Germany) (Supp. Tables 1 and 2).

Fission-track dating on apatite grains

The apatite crystals from 14 samples were embedded in epoxy resin. The mounts were polished to reveal internal structure of the apatite grains. Afterwards, the epoxy mounts were etched with 5 N HNO_3 at 21°C for 20 seconds to reveal the spontaneous fission-tracks (Donelick *et al*. 1999). Fission-tracks were counted on at least 25 grains, and on 50 grains in two samples (R-136 and R-266; Supp. Table 1). The external detector method was used (Gleadow 1981). The samples

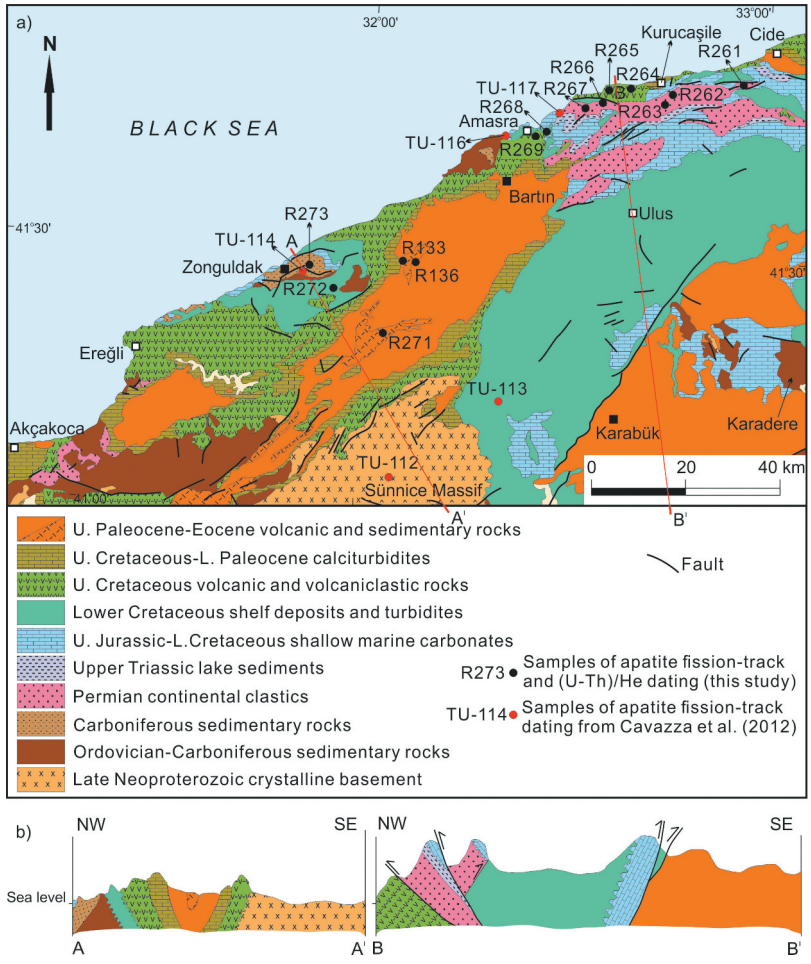

Figure 3. A) Geological map of the study area, showing the sample locations used for apatite fission-track and (U-Th)/He thermochronology. b) Structural cross-sections across A-A' and B-B' lines.

together with low-uranium muscovite mica sheets, age standards and CN-5 dosimeter glasses were irradiated with thermal neutrons at the FRM-II reactor at Munich (Germany). After irradiation, the induced fission-tracks in the mica detectors were etched by 40% HF for 40 minutes at 21°C. Track counting was carried out at the GÖochron Laboratories, Geoscience Centre, University of Göttingen (Germany) using a Zeiss Axioskop microscope-computer-controlled stage system (Dumitru 1993), with a magnification of 1000×. The size of the etch-pit (Dpar) was measured and used as a kinetic parameter for the thermal history modelling (Donelick *et al*. 2005; Ketcham *et al*. 2009). Track length analyses on apatite grains were carried out on horizontal confined tracks together with the angle between the track and the c-axis (Ketcham *et al*. 2007). The measurement of fission-track lengths gives information about thermal evolution in the temperature range of ~60 – 125°C (partial annealing zone, PAZ; Gleadow and Fitzgerald 1987). Fission-track ages were calculated using the zeta calibration method (Hurford and Green 1983; Green 1985; Hurford 1990). Calculations and plots were made by the TRACKKEY and RadialPlotter computer programs (Dunkl 2002; Vermeesch 2009). To model the thermal histories we used the HeFTy computer program (Ketcham 2005; Ketcham *et al*. 2017).

(U-Th)/He dating on apatite grains

The (U-Th)/He dating is based on the accumulation of ^{4}He produced by the decay of ^{238}U, ^{235}U, ^{232}Th, and ^{147}Sm. He concentrations were determined through extraction of He by heating the sample in a furnace or by a laser and followed by purification and analysis of emitted gases by mass spectrometry. Apatite has a low closure temperature ~70°C for (U-Th)/He system (Farley 2000, 2002). Thus, apatite (U-Th)/He ages document the latest stages of cooling in the uppermost crust. Details about the procedures and applications of the method are given in Reiners *et al*. (2017).

(U-Th)/He analyses were carried out on apatites from 11 samples which were selected out of 14 samples used for AFT analysis (Supp. Table 2). Single apatite crystals which show well-defined (ideally euhedral) external morphologies, free of cracks and inclusions were hand-picked from each sample using binocular and polarizing microscopes. The selected crystals were photographed and packed in platinum capsules. Crystal dimensions were measured on the photographs. To determine the ^{4}He content, the platinum capsules with the enclosed crystals were degassed under high vacuum by heating with an infrared diode laser. After purification of the released gas with a SAES Ti-Zr getter at 450°C, the extracted gas was analysed with a Hiden triple-filter quadrupole mass spectrometer, equipped with a positive ion counting detector. To ascertain a quantitative helium extraction, re-extraction was performed for every sample. To determine the amount of the alpha-emitting elements the platinum capsules were retrieved after He analysis and apatite grains were dissolved in nitric acid. The solutions were spiked with calibrated amount of ^{230}Th and ^{233}U, and analysed by the isotope dilution on a Perkin Elmer Elan DRC ICP-MS equipped with an APEX microflow nebulizer. An alpha-ejection correction (FT correction) was applied to all raw (U-Th)/He ages, following the procedures of Farley *et al*. (1996).

Analytical results

Apatite fission-track ages

The apatite fission-track central ages range from 220 to 46 Ma (Figures 1 and Figure 3; Supp. Table 1). Out of 14 samples, seven samples yielded unreset ages, which are older or coeval to the deposition age of the sedimentary rocks. All Upper Cretaceous and Eocene sedimentary rocks yielded unreset apatite fission-track ages. Of the two Lower Cretaceous sandstone samples, one (R268) gave an unreset age (122 ± 9 Ma), while the other (R272) has experienced thermal reset (46 ± 4 Ma). To sum up, all the sedimentary rocks with Late Cretaceous and Eocene sedimentation ages contain unreset apatite fission-track ages, while those from the Lower Cretaceous sandstones are mixed. The mean track lengths in the samples with unreset apatite fission-track ages are quite variable, ranging from 12.7 to 14.7 µm. This indicates complex time-temperature paths and long residence times in the PAZ.

The reset ages define three groups (i) 220 to 179 Ma, (ii) ca. 101 Ma and (iii) 49 to 46 Ma (Figures 3 and Figure 4 a; Supp. Table 1). All the ages from 220 to 179 Ma come from the Permian continental sandstones. The Early Cretaceous age (101 ± 6 Ma) also came from one Permian continental sandstone sample (sample R261). The Eocene apatite fission-track ages come from Upper Carboniferous and Lower Cretaceous siliciclastic sedimentary rocks (samples R273 and R272, respectively) in the southwestern part of the investigated area (Figures 3 and Figure 4 a). The samples with Late Triassic to Early Cretaceous apatite fission-track ages gave mean apatite track lengths from 11.2 to 12.2 µm, while samples with Eocene apatite fission-track ages have slightly longer mean apatite track lengths from 13.2 to 13.3 µm.

Apatite (U-Th)/He results

Apatite (U-Th)/He ages were obtained on 11 samples which are also used for apatite fission-track dating (Figure 4b; Supp. Table 2). The results represent the unweighted arithmetic mean age of several single-grain analyses. The disregarded analysis due to low degree of reproducibility are marked red in Supp. Table 2. As expected apatite (U-Th)/He ages are younger than those apatite fission-track ages for the same samples, and range from 46 to 18 Ma. Overall, the apatites from the Upper Cretaceous volcaniclastic rocks gave (U-Th)/He ages of 46 to 39 Ma, while those from the Eocene siliciclastic rocks yielded 28 to 23 Ma (Supp. Table 2). The Carboniferous and Permian siliciclastic rocks have apatite (U-Th)/He ages ranging from 32 to 12 Ma.

Discussion

Unreset apatite fission-track ages

Apatites from the Upper Cretaceous volcaniclastic and the early Eocene siliciclastic rocks yield fission-track ages nearly identical or significantly older than the age of deposition (Figure 4a; Supp. Table 1). This suggests that the Upper Cretaceous and Eocene sedimentary successions were not deeply buried after their deposition, and have not stayed in the partial annealing zone for long time. Likewise, Zattin *et al*. (2010) report an unreset apatite fission-track age of 66 ± 10 Ma from a mid-Eocene sample from the Istanbul Zone. On the other hand, apatite grains from the Lower Cretaceous siliciclastic rocks yielded both reset and unreset fission-track ages, indicating that some parts of the Lower Cretaceous successions were buried and subjected to temperatures higher than ca. 120°C.

The apatite fission-track ages in the Upper Cretaceous volcaniclastic rocks vary between 85 and 72 Ma, and those in the lower Eocene siliciclastic rocks from 71 to 64 Ma (Supp. Table 1). These ages correspond to the age of arc magmatism in the Istanbul and Sakarya zones (Şahin *et al*. 2012; Aysal *et al*. 2018b; Figure 2). The

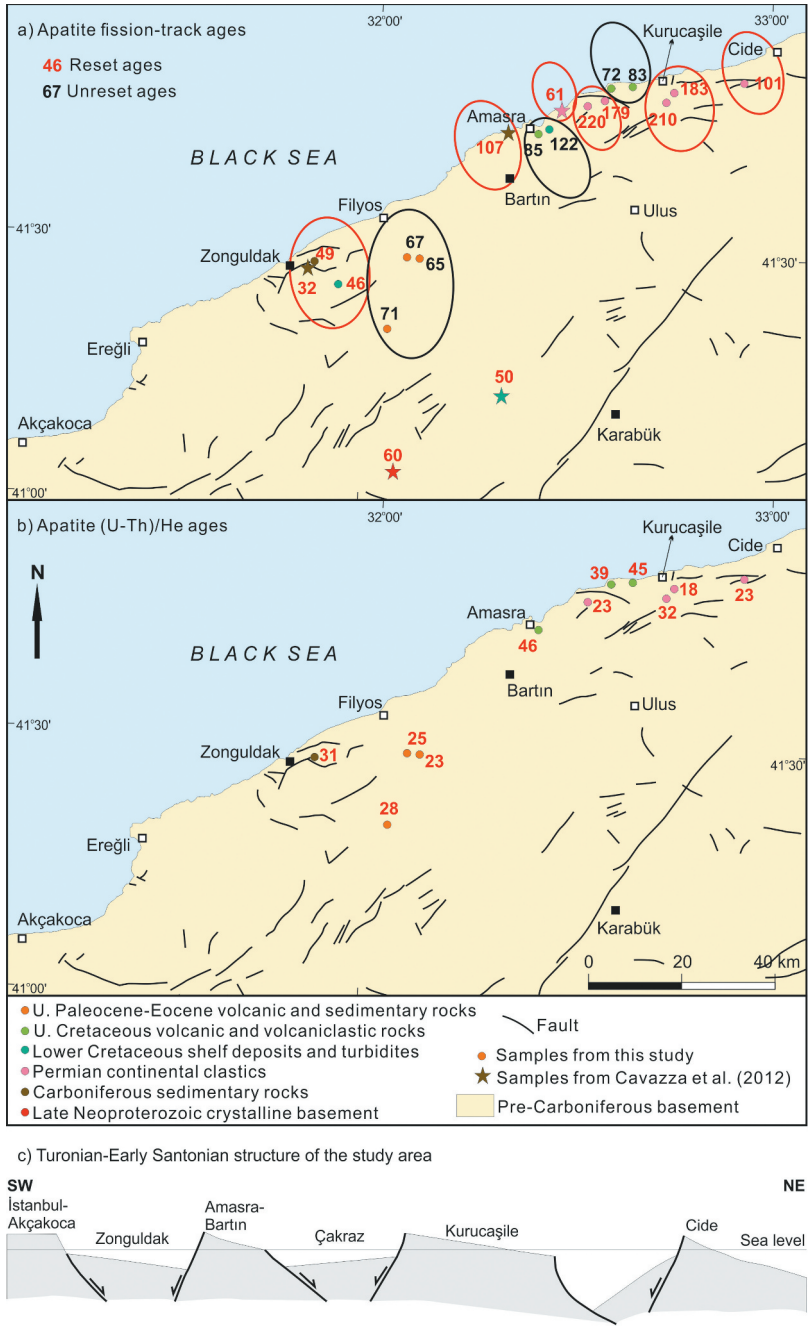

Figure 4. A) Apatite fission-track ages from this study together with those from Cavazza *et al.* (2012). Red circles represent domains with reset ages. Black circles stand the domains with unreset ages. b) Apatite (U-Th)/He ages obtained in this study. c) Schematic structural cross-section between Akçakoca and Cide, as proposed by Tüysüz *et al.* (2012)

absence of older apatite fission-track ages suggests that the source area was the magmatic arc. The apatite fission-track age in the Lower Cretaceous siliciclastic sample (R268) is 122 ± 9 Ma. Magmatic rocks with Early Cretaceous ages have not been reported from the Pontides. However, in the Central Pontides, there is a large Early Cretaceous blueschist- and eclogite-facies area, pointing to Early Cretaceous subduction (Okay *et al.* 2006, 2013).

The thermal modelling based on apatite fission track ages, track length and (U-Th)/He ages indicates that the Upper Cretaceous volcaniclastic formations (e.g., sample R264) have not experienced significant burial after their formation, and stayed near-surface conditions (Figure 7a). The track-length distributions are suggestive of rapid-cooling. On the other hand, the track-length distribution in the apatites from the early Eocene sandstones (e.g., sample R133) is suggestive of a complex

burial history. The thermal modelling indicates that the apatites were recycled from latest Cretaceous-earliest Palaeocene rocks (ca. 66 Ma) or from an older source that experienced thermal reset at latest Cretaceous-earliest Palaeocene. The early Eocene sandstones were buried between 40 and 25 Ma in the partial retention zone, and subjected to rapid exhumation at around 20 Ma (Figure 7b).

Reset apatite fission-track and (U-Th)/He ages

The data in this paper in conjunction with those in literature (Zattin *et al*. 2010; Cavazza *et al*. 2012) suggest three main cooling/exhumation phases in the Istanbul Zone (Figures 5 and Figure 6). These are (i) Late Triassic-Early Jurassic, (ii) mid-Cretaceous, and (iii) Palaeocene-early Miocene. Apart from the Late Triassic-Early Jurassic phase, the other ones are also shown by apatite fission-track and (U-Th)/He ages in the Sakarya Zone (Okay *et al*. 2008; Cavazza *et al*. 2009, 2012; Zattin *et al*. 2010; Espurt *et al*. 2014; Frassi *et al*. 2018; Ballato *et al*. 2018; Sunal *et al*. 2019). Below we discuss the inferred cooling/exhumation phases and possible underlying possible tectonic events.

The Late Triassic-Early Jurassic cooling/exhumation phase

Late-Triassic-Early Jurassic apatite fission-track ages (220–179 Ma) are the oldest ages reported so far in the Pontides (Figure 5). During the Late Triassic, most of the Istanbul Zone and the Variscan continental units of the Sakarya Zone emerged above sea level, as implied by the absence of Upper Triassic to Middle Jurassic marine deposits (except for the Kocaeli Triassic sequence). The emergence above sea level can be related to a compressional deformation event. The thermal modelling on the apatites from Permian continental sandstones (e.g., sample R266) indicates burial and cooling below 120°C during Early Jurassic (ca. 177 Ma; Figure 7c). This is followed by slow cooling through the PAZ until 20 Ma, and subsequent rapid exhumation.

In the Sakarya Zone, there are widespread exposures of the Permo-Triassic and Early to Middle Jurassic accretionary complexes (e.g., Okay 2000; Okay and Göncüoğlu 2004; Robertson and Ustaömer 2012; Okay *et al*. 2013, 2020a; Topuz *et al*. 2013, 2014, 2018). It has been suggested that the accretion of submarine topographic rises such as oceanic plateaus or seamounts led to the jamming of the Permo-Triassic subduction zone south of Pontides (the so-called Cimmerian orogeny), and resulted in the initiation of a new subduction zone along the Izmir-Ankara Erzincan oceanic domain (Okay 2000; Topuz *et al*. 2014, 2018). There was a major marine transgression in the Sakarya Zone in the Early Jurassic, in clear distinction to the Istanbul Zone (Figure 2). Most of the Istanbul Zone remained above sea level from Permian to Late Jurassic, except for the Kocaeli Triassic sequence and local mid-Jurassic shallow marine sequences with swamp deposits in Bartın-Amasra (e.g., Tüysüz *et al*. 2004; Figure 2). Thus, Late Triassic-Early Jurassic apatite fission-track ages are related to a compressional event, probably caused by the accretion of oceanic plateaus or seamounts to the southern margin of the Pontides. The temporal evolution of the Intra-Pontide suture which separates the Istanbul and Sakarya zones is highly contentious (e.g., Şengör and Yılmaz 1981; Elmas and Yiğitbaş 2001, 2005; Robertson and Ustaömer 2004; Ustaömer and Robertson 2005; Akbayram *et al*. 2013). However, abundant Carboniferous detrital igneous zircons from Carboniferous and younger succession of the Istanbul Zone indicate Carboniferous amalgamation of the Sakarya and Istanbul zones, since, the Carboniferous igneous rocks are absent in the Istanbul zone, in contrast they are common in the Sakarya Zone (Okay *et al*. 2011; Okay and Topuz 2017; Akdoğan *et al*. under revision). However, Okay *et al*. (2011) argued that the Early Carboniferous detrital zircons of the Carboniferous flysch sequence might have originated from the Bohemian Massif, because the Late Devonian-Early Carboniferous magmatic events were not documented yet from the Sakarya Zone at that time.

The mid-Cretaceous uplift/exhumation phase

The only Albian apatite fission-track central age (101 ± 6 Ma) was obtained from a Permian continental sandstone (Figures 4a and Figure 5). The published apatite fission-track ages reveal only sporadic presence of Early Cretaceous ages in the Istanbul Zone (107 ± 12 Ma; Cavazza *et al*. 2012) and Sakarya Zone (107 ± 10 Ma; Ballato *et al*. 2018). The major unconformity between Albian and Turonian in both the Sakarya and Istanbul zones (e.g., Okay and Şahintürk 1997; Hippolyte *et al*. 2010, p. 2) has been interpreted as the result of (i) shoulder uplift during back-arc rifting of the Black Sea (Cavazza *et al*. 2012), (ii) exhumation of the HP-LT accretionary complexes of Central Pontides as a result of trench roll back, slab steepening, and wedge extension (Ballato *et al*. 2018), and (iii) accretion of an oceanic plateau or seamounts and subsequent flat subduction (Okay *et al*. 2013; Akdoğan *et al*. 2017). However, back-arc rifting related to opening of the Black Sea took place mostly during the Late Cretaceous, and post-dates the Albian-Cenomanian uplift (Okay *et al*. 2013; Akdoğan *et al*. 2017, 2019). To date, there are no reports of the Early Cretaceous arc magmatism in the Sakarya and Istanbul zones that can be linked to steep subduction

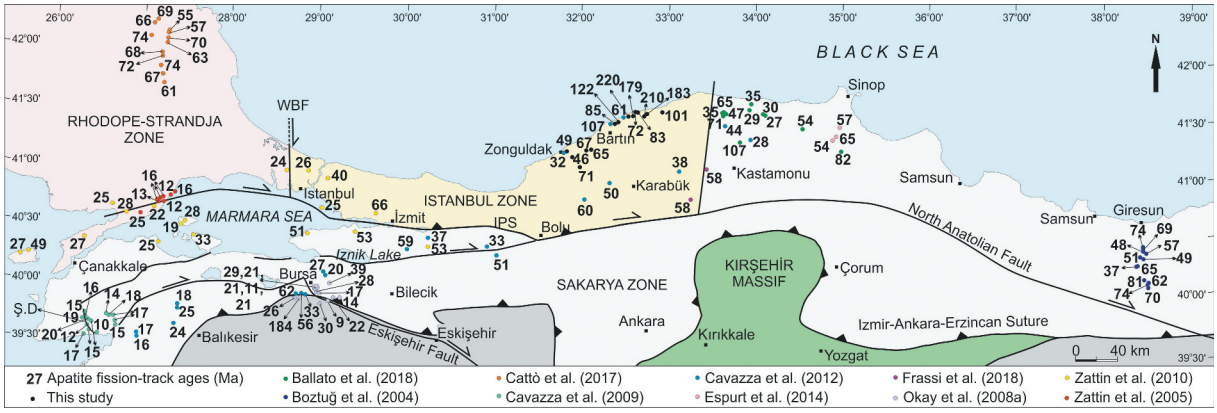

Figure 5. Compilation of apatite fission-track central ages determined from the Pontides. Ş.D.: Şelale Detachement (Boztuğ *et al*. 2004; Zattin *et al*. 2005, 2010; Okay *et al*. 2008; Cavazza *et al*. 2009, 2012; Espurt *et al*. 2014; Cattò *et al*. 2017; Frassi *et al*. 2018; Ballato *et al*. 2018; this study).

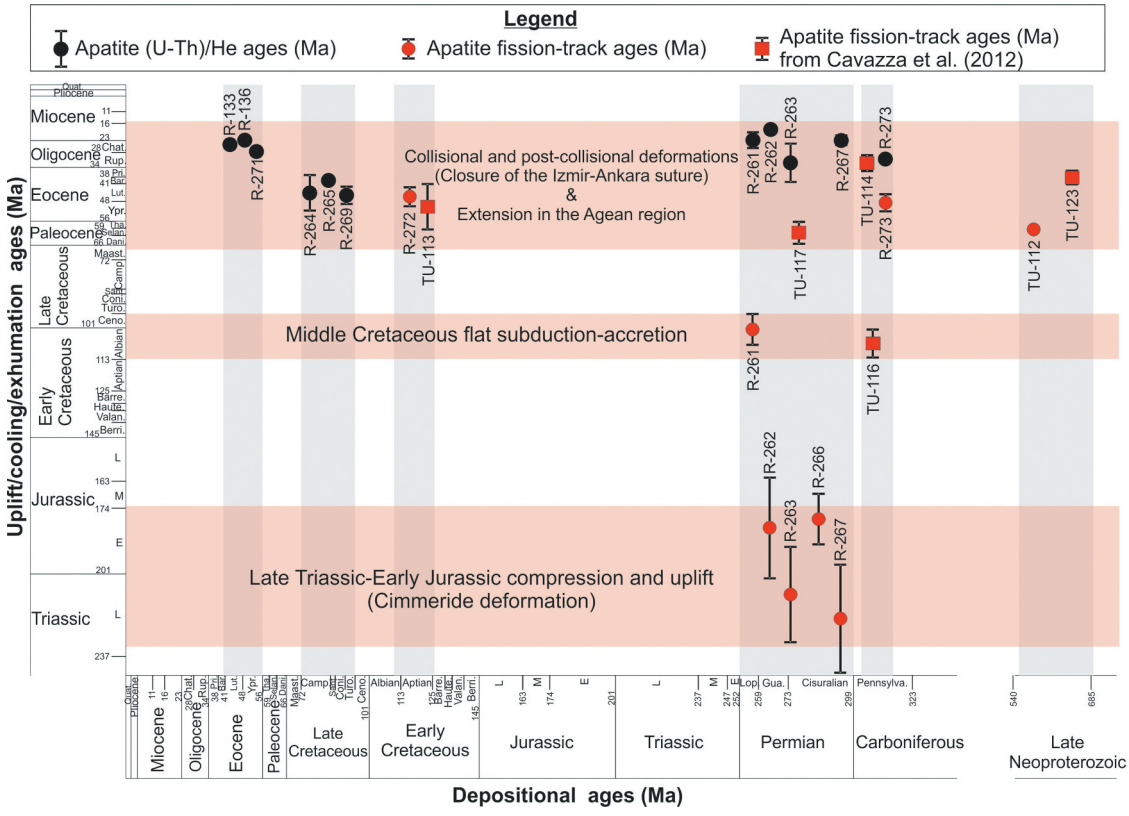

Figure 6. Depositional ages of the dated samples (grey boxes) versus apatite fission-track and (U-Th)/He ages with error bars (1σ). Note that only reset ages are shown. Pink horizontal boxes show the time of the major tectonic events effected the region. The time scale is from Cohen *et al*. (2020)

process. Moreover, there are only a few U-Pb detrital zircons ages of Early Cretaceous in the Lower and Upper Cretaceous sandstones of the Central Pontides indicating a general lack of magmatism during the Early Cretaceous (e.g., Okay *et al*. 2013; Akdoğan *et al*. 2017, 2019). This can be linked to flat subduction, which also resulted in intense normal faulting of the fore-arc block and local block uplifts in the hinterland (e.g., Dickinson and Snyder 1978; McGeary *et al*. 1985; Cloos 1993; van Hunen *et al*. 2002). Therefore, we favour flat subduction following accretion of oceanic plateau or seamount (Okay *et al*. 2013). Presence of systematic block-faulting, horst-graben system, was inferred between Akçakoca and Cide by Tüysüz *et al*. (2012), based on lateral facies and thickness variations (Figure 4c). The extensional tectonics is thought to

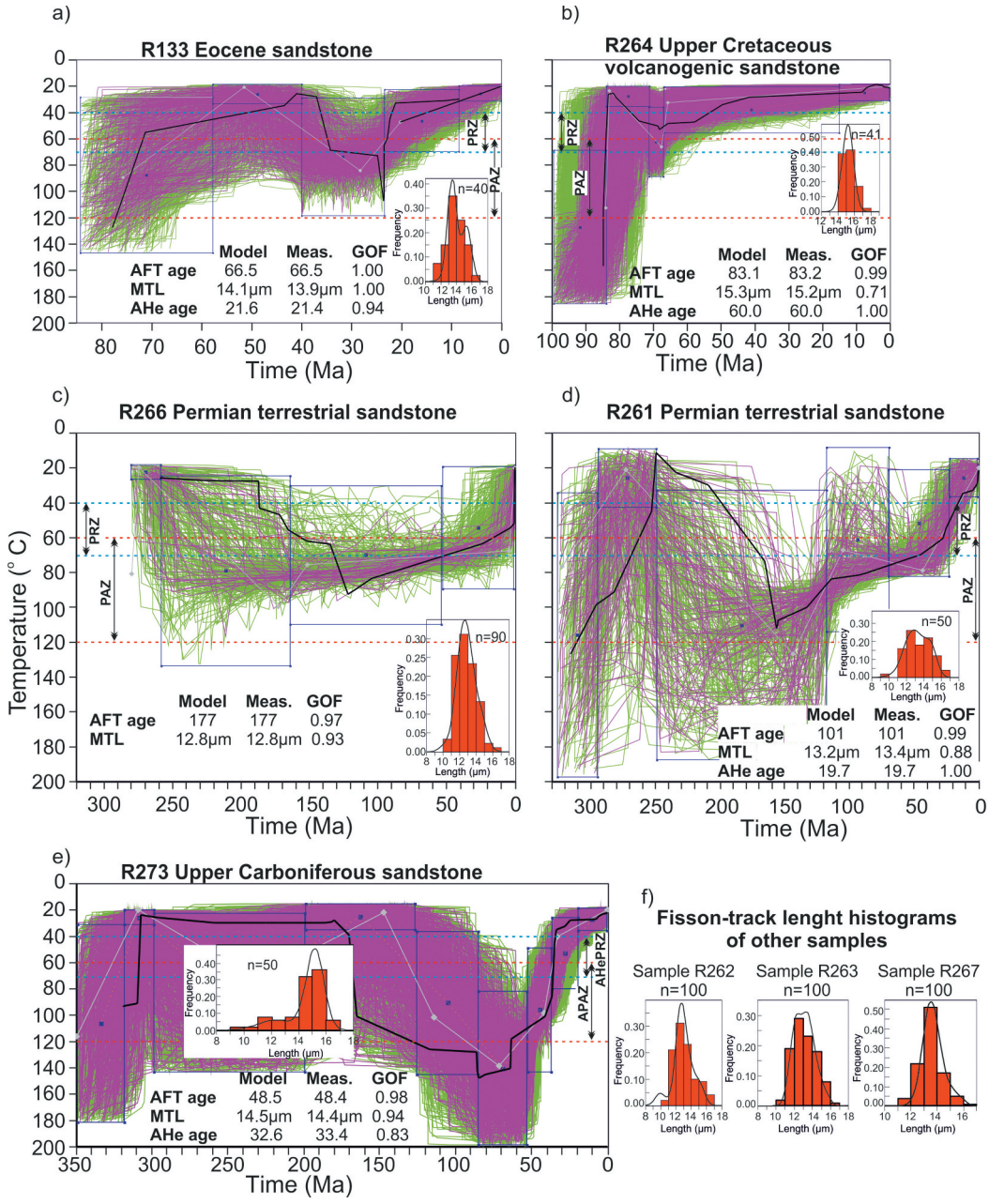

Figure 7. Thermal modelling results for representative samples a) R133 Eocene sandstone, b) R264 Upper Cretaceous volcanogenic sandstone, c) R266 continental sandstone, d) R261 continental sandstone, e) R273 Upper Carboniferous sandstone f) apatite fission-track length distribution of other samples from the study area. The data set used for each modelling and the goodness of fit (GOF) of the best run is indicated in the plots. The track-length distribution of the modelled and unmodelled samples for ≥ 40 measurements are given. AFT: apatite fission track, MTL: mean track length, AHe: apatite (U-Th)/He. Each good path is displayed as a magenta line, and each acceptable path is displayed as a green line. Thick black lines correspond to the most probable thermal histories (best-fit curves). Boxes represent T–t domains constrained by available data (radiometric ages, stratigraphic relationships, AFT analyses). PRZ: Apatite (U-Th)/He partial retention zone, PAZ: Apatite fission-track partial annealing zone.

have occurred during the Turonian-Santonian or slightly earlier.

The track-length distribution of the apatites from Permian continental sandstone (sample R261) show wide spread (Figure 7d inset), implying a complex burial-exhumation history. The thermal modelling demonstrates burial and reset between 250 and 130 Ma, and fast cooling/uplift during mid-Cretaceous (ca. 101 Ma; Figure 7d). This is followed by slow cooling in the partial retention zone (PRZ) up to early Miocene (20 Ma), when the rock was rapidly exhumed. This thermal model closely resembles that of the apatites from the Upper Carboniferous sandstone (sample TU-116; see Figure 3 for location; Figure 3 in Cavazza *et al*. 2012).

The Palaeocene to early Miocene uplift/exhumation phase

Apatite fission-track ages of 49 and 46 Ma (early to mid-Eocene) have been obtained from the Upper Carboniferous and Lower Cretaceous siliciclastic rocks (Figure 4a). The track lengths of apatites from the Upper Carboniferous sandstone (R273) are variable, but the majority of the track lengths is relatively long (mean track length 14.5 μm; inset in Figure 7e). The thermal modelling indicates long-term residence in the PAZ, and fast cooling/uplift during early Eocene. The last phase of exhumation occurred at early Oligocene (ca. 30 Ma).

The data from the literature indicate that the apatite fission-track and (U-Th)/He ages commonly range from Palaeocene to early Miocene (66 to 16 Ma) in the Istanbul and Sakarya zones (Boztuğ *et al*. 2004; Zattin *et al*. 2005, 2010; Okay *et al*. 2008; Cavazza *et al*. 2009, 2012; Espurt *et al*. 2014; Frassi *et al*. 2018; Ballato *et al*. 2018; Sunal *et al*. 2019; Figure 5). The late Oligocene-early Miocene ages are clustered in the western part of the Sakarya Zone mostly to the Kazdağ and Uludağ metamorphic core complexes (Figure 5). Sporadic younger ages such as 14 to 10 Ma are also confined to regions adjacent to strike-slip or detachment faults. The Palaeocene to early Eocene ages can be tentatively ascribed to the closure along the Izmir-Ankara-Erzincan oceanic domain (Okay and Şahintürk 1997; Figure 1). The Late Oligocene-Miocene ages can be related to the large-scale extension in the Aegean region and to the activity of major faults, such as the North Anatolian Fault and its branches (Cavazza *et al*. 2009; Figures 1 and Figure 5).

Conclusions

The main conclusions of this study can be summarized as follows:

(1) Upper Cretaceous and Eocene sedimentary formations in the Istanbul Zone were not deeply buried, and still contain unreset apatite fission-track ages, while the Lower Cretaceous successions contain either reset or unset ages.
(2) The apatites in the Upper Cretaceous volcaniclastic rocks and Eocene siliciclastic formations were derived from the Late Cretaceous magmatic arc of the Pontides.
(3) The reset apatite fission-track and (U-Th)/He fission-track thermochronometers indicate three main periods of cooling/exhumation in the Istanbul Zone: Late Triassic-Early Jurassic, mid-Cretaceous, and Palaeocene to early Miocene.
(4) The Late Triassic-Early Jurassic uplift/deformation stage is the oldest known low-temperature thermal event preserved in the Istanbul Zone, which can be attributed to the compressional event leading to the emergence of parts of the Istanbul Zone above sea level.
(5) The mid-Cretaceous uplift/deformation is probably related to a compressional event, which led to major unconformity in the stratigraphic record. This is probably triggered by the accretion of an oceanic plateau or a seamount to the southern margin of the Pontides which led to the flat subduction.
(6) Late Palaeocene-early Miocene uplift stage can be tentatively attributed to the closure of the Izmir-Ankara-Erzincan suture and large-scale extension in the Aegean region at Palaeocene-early Eocene and by Oligocene-early Miocene, respectively.
(7) The absence of cooling ages younger than early Miocene can be attributed to the fact that the convergence between the Arabian platform and the Eurasia is taken up by the major strike slip faults since the mid Miocene (ca. 15 Ma).
(8) Results of the thermal modelling on apatites from the same formations yield different thermal histories (e.g., Permian and Lower Cretaceous sandstones). This is probably caused by the extensional tectonics during mid- to earliest Late Cretaceous time, leading to the development of the horst-graben structures.

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Disclosure statement

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