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Paleo-exhumation histories of the Sakarya and the Istanbul Zones of the Western Pontides, the Almacık Block and its surroundings, NW Turkey

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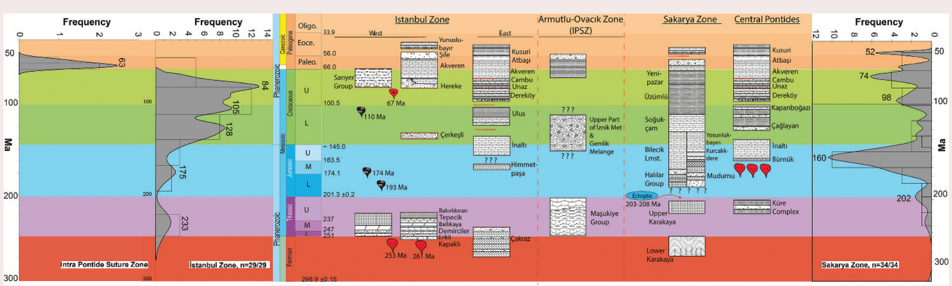
ABSTRACT

The Almacık Block is a tectonic sliver formed during the activity of the North Anatolian Fault Zone (NAFZ). It includes two important tectonic zones of the Western Pontides (NW Anatolia): the İstanbul and the Sakarya Zones meet along a suture zone called the Intra-Pontide Suture Zone (IPSZ). The units within the İstanbul Zone are exposed in the eastern part of the Almacık Block, whereas the rocks of the Sakarya Zone are exposed in the west. In the presented study, some of the magmatic rocks have been analysed using the zircon U-Pb method: these rocks have previously been either incorrectly or not dated. The U-Pb results have shown that some of the granitic rocks in the İstanbul Zone, which intruded into the amphibolites of the Intra-Pontide Suture Zone, have a crystallization age of 559–556 Ma. A granitoid block in the Upper Cretaceous wild flysch formed over the units of the İstanbul Zone had an age of ~566 Ma. Two distinct granitoid bodies in the Sakarya Zone were dated at 404.5 ± 3.9 Ma (Early Devonian) and 161.8 ± 0.82 Ma (Late Jurassic) ages. The palaeo-exhumation evolutions of the zones were obtained using the zircon (U-Th)/He technique (ZrHe) to understand the differences in the geological evolution of the individual zones. ZrHe ages of the samples obtained from the İstanbul Zone indicate a pronounced Early Cretaceous palaeo-exhumation period. The Middle-Upper Jurassic Mudurnu Formation in the Sakarya Zone gave ZrHe ages close to its sedimentation age, which indicates that the major part of the unit was not buried too deep to open the ZrHe closure system. Unlike those the İstanbul Zone, the main ZrHe age peaks of the Sakarya Zone are ~202, 160, 98, 74, and 52 Ma. Finally, a sample of the metamorphic rocks that were assigned to the IPSZ yielded a peak age of ~63 Ma, which indicates that the final closure of the Intra-Pontide Ocean (IPO) took place during the Early Tertiary.



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Western Pontides; Almacık Block; Sakarya Zone; Istanbul Zone; zircon U-Pb; (U-Th)/He ages

1. Introduction

The zircon U-Pb method is widely used for determining the emplacement ages of plutonic rocks or formation ages of volcanic rocks. Its reliability comes from the chemical and physical durability of zircon crystals which withstand most geological events such as weathering and metamorphism. The high isotopic closure temperature of zircon (~900°C, Cherniak and Watson 2001) allows researchers to date the formation ages of magmatic rocks even after they are subjected to high-grade metamorphism. Those powers of zircon also lead to provenance studies using detrital or inherited ages (e.g. Nance and Murphy 1996; Linnemann *et al*. 2004).

In addition to the aforementioned usages of zircon, the zircon (U-Th)/He (ZrHe) method has been utilized extensively to date the evolution of rock samples at lower temperatures. The ZrHe thermochronometer has a closure temperature between ca. 140°C and 190°C in zircon grains having a low or medium density of alpha damage (Reiners *et al*. 2004; Guenthner *et al*. 2013). This

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relatively low closure temperature of zircon can be used as follows: i) to date the cooling ages of metamorphic and magmatic rocks, ii) combined with other geochronometers (e.g. apatite (U-Th)/He, AFT, and ZFT) to obtain the timing and rate of exhumation processes, and iii) to date the formation ages of fast cooling rock bodies such as volcanic rocks.

In this study, we focused on the Almacık Block and its southern section, where two main tectonic units of the Pontides (NW Anatolia) amalgamated along the IPSZ (see Figure 1a). In the Mudurnu valley, the İstanbul and the Sakarya Zones are separated by the middle strand of the NAFZ (see Figure 1b). The middle part of the Almacık Block is occupied by serpentinites, amphibolites, and pyroxenites (former gabbros?) that were assigned to the IPSZ (Yılmaz *et al.* 1995). In the western part of the Almacık Block, there are low-grade metapelitic rocks including marble layers. These rocks are regarded as lying within the long Armutlu-Almacık Zone (Göncüoğlu *et al.* 1987) or Armutlu-Ovacık Zones (Elmas and Yiğitbaş 2001). A recent study (Akbayram *et al.* 2017) assigned these rocks as a part of the accretionary prism deposits of the IPSZ. The geological studies on the Sakarya and the İstanbul Zones indicate different pre-Palaeocene geological histories (Okay and Göncüoğlu 2004; Yiğitbaş *et al.* 2004; Okay *et al.* 2006; Bozkurt *et al.* 2008; Ustaömer *et al.* 2012; Lom *et al.* 2016), which is also evidenced by the detrital zircon studies (Ustaömer *et al.* 2010, 2012; Okay *et al.* 2011; Ülgen *et al.* 2018).

This study has been designed to answer the following questions about the geology of the NW Anatolia: 1 – What is the last pre-Tertiary exhumation period (Late Carboniferous or Mesozoic) in the İstanbul Zone? 2 – Are the previously defined earliest Late Cretaceous exhumation ages (Sunal 2012) also relevant to this part

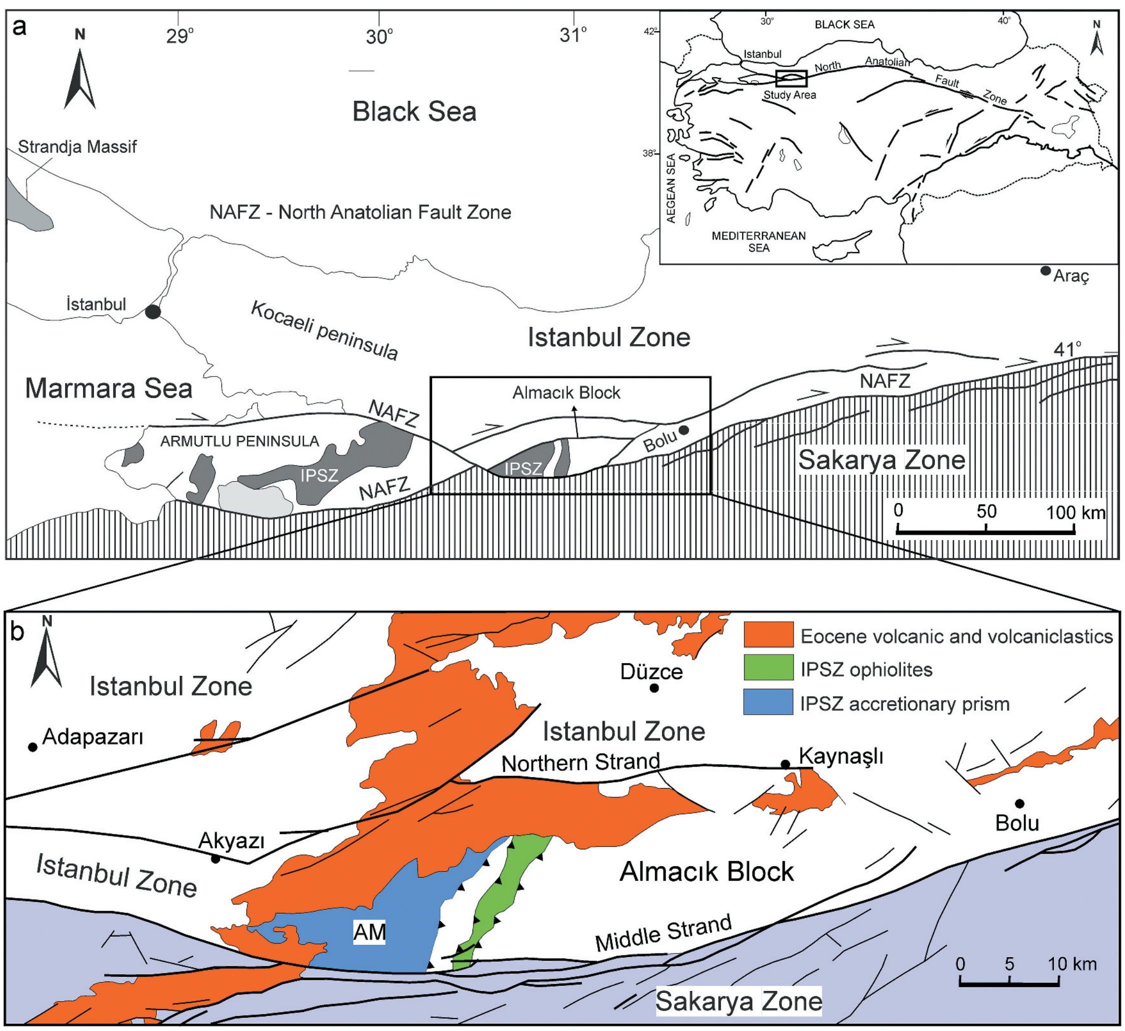

Figure 1. A; location and tectonic setting of the study area (modified after Yiğitbaş *et al.* 2004 and Bozkurt et al., 2013), b; geological map of the study area with the active faults from Emre *et al.* (2011). note that the Eocene deposits are the first common sedimentary cover on both zones. NAFZ: North Anatolian Fault Zone, AM: Almacik metamorphics, IPSZ: Intra-Pontide Suture Zone.

of the Sakarya Zone? 3 – What is the closure age of the IPSZ (Early Carboniferous, Triassic, Early Cretaceous, or Early Eocene)? and could we add any data to enlighten researchers examining this phenomenon? and 4 – to test the ages of the magmatic rocks using the zr U-Pb method, which was previously ill-dated (Delaloye and Bingöl 2000).

2. Geological setting

2.1. The İstanbul Zone (İZ)

The İstanbul and the Sakarya Zones of the Western Pontides are amalgamated along the IPSZ. A segment of the suture is located within the Almacık Block. However, the southern portion of the Almacık Block is bounded by the active middle strand of the NAFZ.

The İZ is located mostly to the north of the IPSZ (Şengör and Yılmaz 1981; Okay and Tüysüz 1999; Akbayram *et al*. 2017) (Figure 1, 2). It has a high-grade Precambrian metamorphic basement (Akbayram *et al.* 2013; Chen *et al*. 2002; Ustaömer *et al*. 2005). This basement is nonconformably overlain by an almost continuous succession of Palaeozoic rocks extending from Lower Ordovician to Upper Carboniferous, which were later intruded by Late Permian granitoids (Figure 3) (Bürküt 1966; Yılmaz 1977; Görür *et al*. 1997; Özgül *et al*. 2005, 2009; Şengör and Özgül 2010; Yılmaz-Şahin *et al*. 2010; Özgül 2011, 2012; Şengör 2011; Lom *et al.* 2016). All older rocks are unconformably overlain by the Upper Permian to Lower Triassic red sandstones, conglomerates with basaltic interlayers and overlying dolomitic limestones and dolomites (Altınlı 1968; Tüysüz *et al*. 2004; Lom *et al*. 2016). The Jurassic sequence is absent in the western part of the İZ. The Early Cretaceous period is represented by a conglomerate that crops out in a relatively small area in the Kocaeli Peninsula (Kaya *et al*. 1986; Figure 1a, 3), but it is absent in the western part of the İZ. The presence of Jurassic pebbles in the Lower Cretaceous conglomerate indicates erosion of the Jurassic section (Kaya *et al*. 1986). The Upper Cretaceous is represented by widespread occurrence of volcanogenic sedimentary rocks and intermediate intrusions (Çavuşbaşı Granodiorite, Zr U-Pb ages of 67.9 ± 0.6 Ma and 67.5 ± 0.5 Ma, Yılmaz-Şahin *et al*. 2010) and dikes (Zr U-Pb ages 72.4 ± 0.7 to 65.4 ± 0.9 Ma, Aysal *et al*. 2018) (Figure 3). Recently, Şen (2020) has reported that some shallow-level intrusions which intruded into the Palaeozoic rocks of the İZ during the middle Eosen.

The Palaeozoic succession of the eastern part of the İstanbul Zone (Zonguldak tTerrane of Bozkaya *et al.* 2012) is rather different (Figure 3) as there is an unconformity between the Silurian and Devonian units, and the Carboniferous interval is represented by terrestrial clastics with extensive coal seams (Bozkaya *et al*. 2012). This Palaeozoic succession is unconformably overlain by Permian–Triassic red beds and lacustrine marls (Alişan and Derman 1995). Unlike the western part of the İstanbul Zone in the Zonguldak region, there is a transgressive Middle Jurassic-Lower Cretaceous succession (Görür 1988).

The Palaeocene–Early Eocene interval in the western part of the zone is represented by continental clastics and the deposits with ophirags (Akbayram *et al*. 2017), which is interpreted as the closure of the IPSZ and subsequent uplift and erosion (Şengör and Yılmaz 1981; Genç and Tüysüz 2010; Sunal and Erturaç 2012; Okay *et al*. 2020a). Eocene turbidites with volcanic layers and volcanogenic sandstones conformably cover all of the units deposited early in the İZ (Lom *et al*. 2016). These formations were related to post-collisional magmatism, which is also widespread in the Sakarya Zone (Keskin *et al*. 2008). The Eocene unit represents the first common cover for both zones, which were developed after the closure of the IPO (Şengör and Yılmaz 1981; Altunkaynak *et al*. 2012; Gülmez *et al*. 2013; Akbayram *et al*. 2017). Eocene is also the last marine deposit in the studied section of both zones (Figure 1b). In this study, we are not going to discuss post-Eocene deposits of the zones because they lie beyond the focus of this study.

2.2. The Sakarya Zone (SZ)

In western Turkey, the SZ is bounded by the IPSZ in the north and the İzmir-Ankara-Erzincan suture in the south (İAEZ, Şengör and Yılmaz 1981; Okay and Tüysüz 1999; Figure 1). The SZ has different types of Palaeozoic and Triassic crystalline basements (Figure 3) nonconformably overlain by Jurassic and younger sedimentary units (Okay and Tüysüz 1999; Okay and Göncüoğlu 2004; Okay *et al*. 2006). The age of the oldest basement rocks is not known, but they are clearly older than Devonian, as Devonian granitoid intrusions cut them (Okay *et al.* 1994, 2006; Sunal 2012; Aysal *et al*. 2012a, 2012b). Karslı *et al*. (2020) reported that magmatism started at least during the Silurian in the Bozüyük and Borçak area in the Western Pontides. However, the Karakaya Complex forms a younger basement in the Sakarya Zone (Şengör and Yılmaz 1981; Yılmaz 1981; Okay and Göncüoğlu 2004; Okay *et al*. 2006). In addition to that, the metabasites include a tectonic lens of Triassic eclogites dated back to 205 ± 3 Ma (Okay and Monié 1997), revealing the termination of the ocean as a result of subduction. In the western part of the SZ, those basement units are nonconformably overlain by Lower Jurassic siliciclastic sandstones and Middle Jurassic-

Lower Cretaceous carbonates (Şengör and Yılmaz 1981; Altıner 1991; Altıner *et al*. 1991; Okay and Tüysüz 1999; Nicosia *et al*. 1991; Yılmaz and Kandemir 2006; Kandemir and Yılmaz 2009). In contrast, the Middle Jurassic in the studied area is represented by thick volcanics, volcaniclastics, and turbidites (the Mudurnu formation Saner 1977, 1980; Altıner *et al*. 1991, Figure 2, 3) and interpreted as either fore-arc or back-arc deposits (Genç and Tüysüz 2010). The Mudurnu Formation is overlain by Callovian- Pliensbachian deep-marine limestones (Altıner *et al*. 1991). All parts of the Sakarya Zone are covered by thinly bedded, Lower Cretaceous pelagic limestones. These Lower Cretaceous pelagic limestones are capped by an Upper Cretaceous–Palaeocene (?) succession including volcanics, limestones, and flysch deposits (Altıner 1991; Altıner *et al*. 1991). These Upper Cretaceous–Paleocene flysch deposits include blocks of limestones and granitoids, some of which are dated in this study using the Zr U-Pb method.

2.2. The Armutlu-Almacık Zone (and the IPSZ)

The IPSZ (Sengör & Yılmaz 1981; Yılmaz *et al*. 1982, 1995; Yiğitbaş *et al*. 1999, 2004; Elmas & Yiğitbaş 2005), also known as the Armutlu-Almacık-Ovacık (Elmas and Yiğitbaş 2001) Zone is a long belt extending from the Biga Peninsula in the west to the Kastamonu area in the east (Göncüoğlu *et al*. 2014; Marroni *et al*. 2020) (Figure 1a). The rocks that were previously assigned to the IPSZ in the Almacık Block are serpentinites, amphibolites, pyroxenites, and some metabasites cropping out mainly in the central part. Different ages have been proposed for the IPSZ; Precambrian (Yiğitbaş *et al*. 1999, 2004), Palaeozoic (Abdüsselamoğlu 1959), Early Carboniferous (Akdoğan *et al*. 2021), Permo-Triassic (plagiogranites, Bozkurt et al. 2013), Late Jurassic–Early Cretaceous (Akbayram *et al*. 2013), Late Cretaceous (Bozcu 1992; Yılmaz *et al*. 1995), pre-Cenozoic (Cavazza *et al*. 2012), and eEarly Eocene (Okay *et al*. 1994; Görür and Okay 1996; Akbayram *et al*. 2017). Tekin et al. (2012) reported Middle–Late Triassic radiolarian cherts in the eastern part of the IPSZ, indicating that they were already in existence during the Middle Triassic. In the same region, Göncüoğlu *et al*. (2014) recognized Santonian nanofossil taxa from different blocks. Recently, Di Rosa *et al*. (2019) dated a quartz-monzonite block in the Taraklı flysch that is located in the eastern part of the IPSZ (Zonguldak region), which yielded ~260 Ma and thus proved that the source area of this unit was the İstanbul Zone. Here in this study, we obtained Precambrian ages from the metagranitoids that cut banded amphibolites, and we therefore do not include such amphibolites and metagratoids within the IPSZ.

The main problem of tracing of the IPSZ in the east is the presence of the younger North Anatolian Fault Zone (the NAFZ) that mostly follows the IPSZ and considerably disrupted it (Yiğitbaş *et al*. 2004; Şengör *et al*. 2005; Marroni *et al*. 2020). The basement rocks of the both zones and the rocks of the IPSZ are intermingled because of strike-slip stacking.

Similar basement rocks are also present in the Armutlu Peninsula. Metagabbro and metagranites located to the north of the IPSZ yielded Precambrian ages (564–561 Ma, Özbey *et al*. 2021) similar to the ones presented here. In the Armutlu Peninsula and the Geyve region, different ages ranging from Ordovician to Precambrian were also reported by Okay *et al*. (2008). It indicates that the mafic-ultramafic rocks found in this region are not Cretaceous in age, although other rocks may be so.

In the western part of the Almacık Block, there are greenschist facies metamorphic rocks (schists, phyllites, and marbles). These rocks are bounded by amphibolites, which are most probably of Precambrian age. These metamorphic rocks are considered the extension of the larger Armutlu Peninsula metamorphics (Figure 1a) (Akbayram *et al*. 2017) and are interpreted as accretionary prism deposits formed during the subduction of the Intra-Pontide Ocean (IPO). In this study, we also follow such inference and assign these rocks to the IPSZ rather than the Sakarya Zone.

3. Analytical techniques

3.1. Sampling

All the information about the samples dated here is given in supplementary Table 1, and their locations are illustrated in Figure 2. Two samples from the Sakarya Zone and three from the İstanbul Zone are dated using the zircon U-Pb LA-ICP-MS method (MK56, MK66, MK73, MG05, and MG1001, supplementary Table 2, and 3). Seven samples from the İstanbul Zone, one sample from the IPSZ, and 14 samples from the Sakarya Zone are dated using the zircon (U-Th)/He method (Supplementary Table 4).

3.2. Zircon U-Pb LA-ICPMS dating

Zircons were extracted from rock samples using standard mineral separation techniques including crushing, sieving, Frantz isodynamic separator, and heavy liquids; they were then handpicked under a binocular microscope. Then, a number of them, of grain sizes 63–200 µm, were classified according to crystal properties

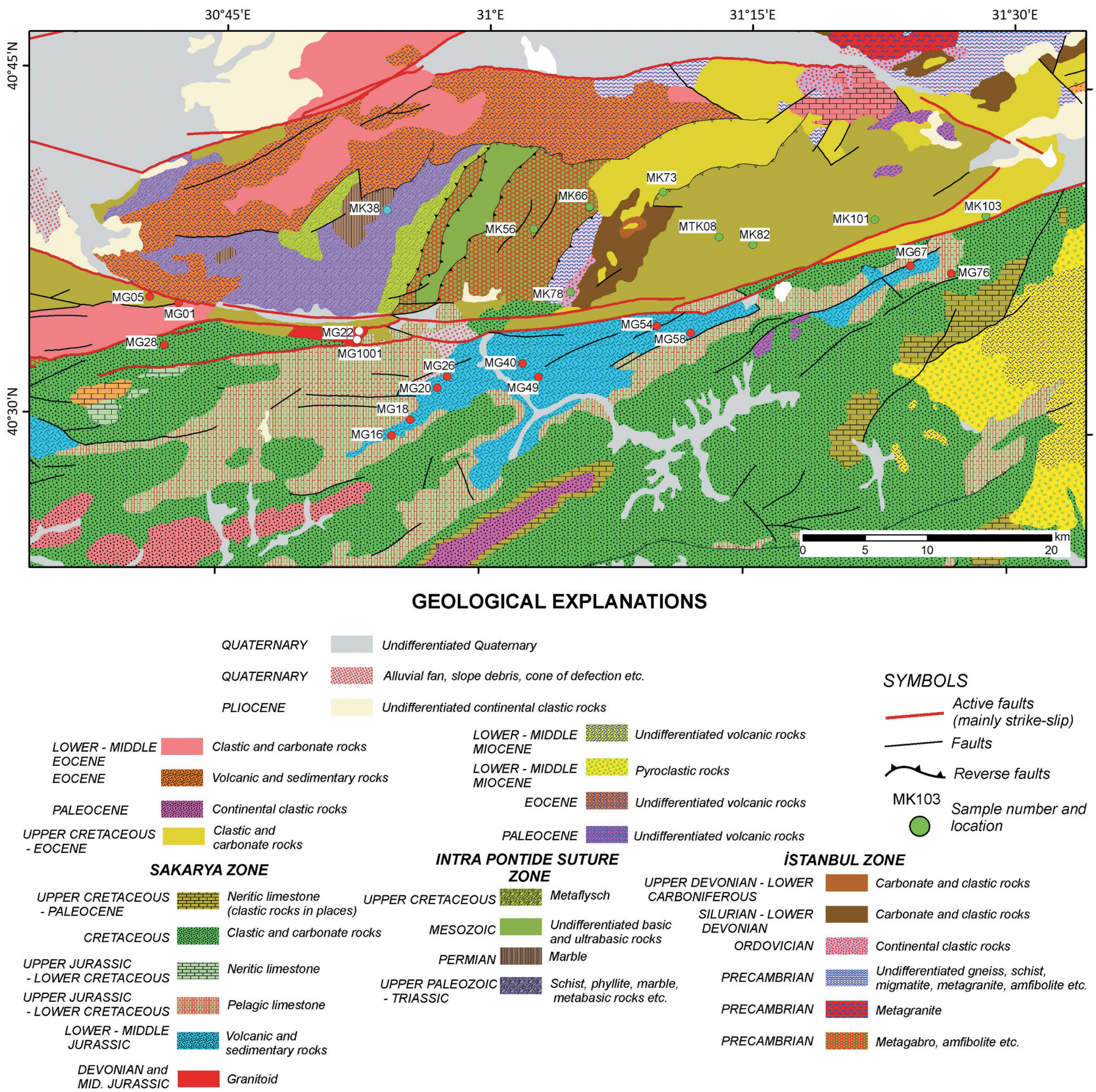

Figure 2. Geological map of the region with sample locations (after the MTA map, Gedik and Aksay 2002). relevant information about the samples is listed in the supplementary Table 1.

(i.e. euhedral morphology, lack of overgrowth, and visible inclusions). The grains were mounted in epoxy and polished.

Cathodoluminescence (CL) images were collected before zircon analyses to identify inherited cores, cracks, and inclusions. U–Pb isotope analyses of particular zircon zones were carried out using a New Wave Research (NWR) 193 nm Excimer laser-ablation system attached to a Perkin-Elmer ELAN DRC-e inductively coupled plasma mass spectrometry (LA–ICP–MS) at the Geological Institute, Bulgarian Academy of Science. The zircon crystals were preferentially analysed in the rims to obtain the magmatic crystallization age of the rock. Spatial resolution was 35 μm, and the frequency used was 8 Hz. Measurement procedure involved calibration against an external zircon standard (GEMOC GJ-1) at the beginning, middle, and the end of the analytical block. This technique allows for a suitable correction for instrumental drift along with the minimization of elemental fractionation effects. Raw data were processed using Iolite, a data reduction software (Paton *et al.* 2010). $^{207}Pb/^{206}Pb$,

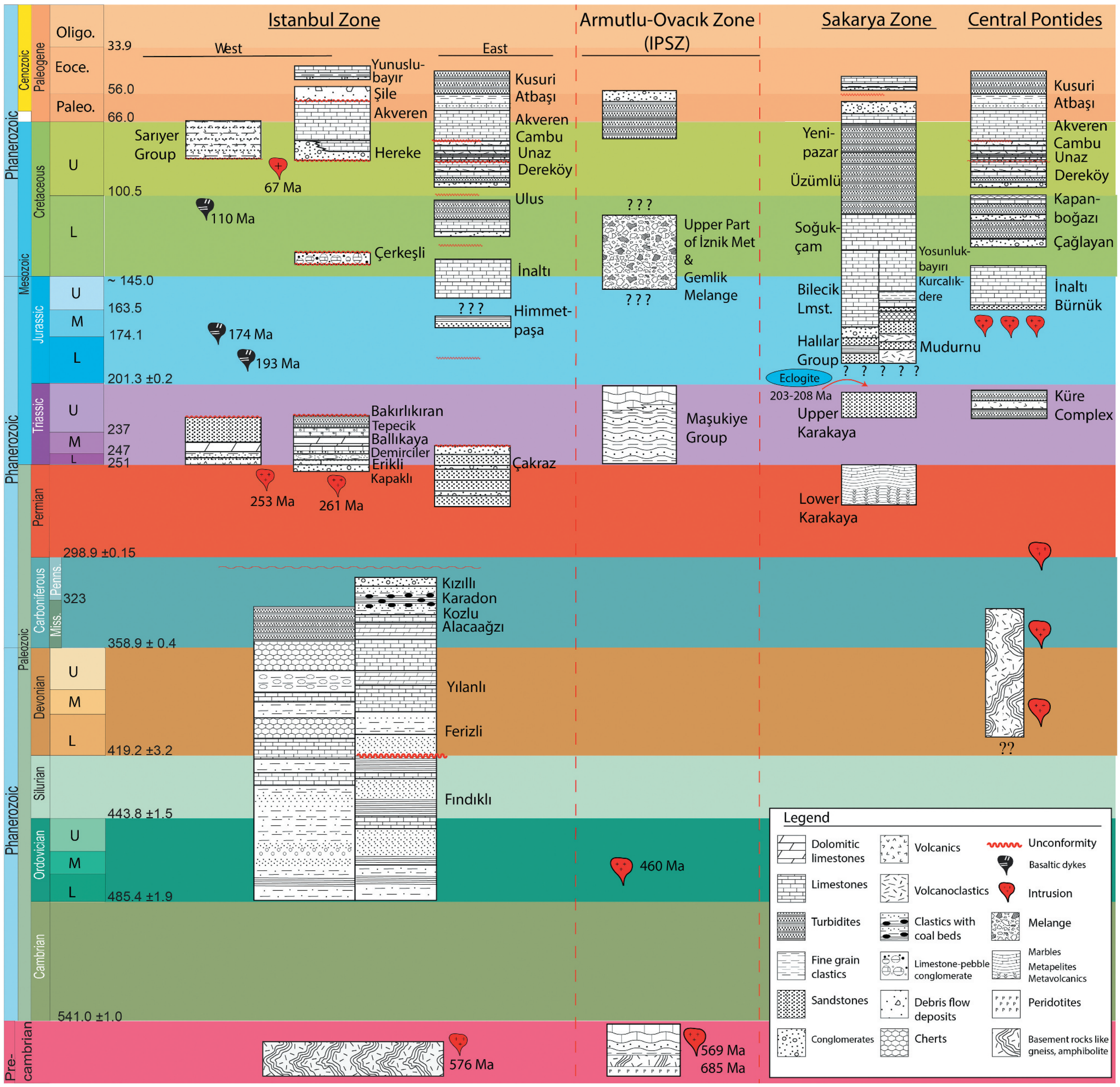

Figure 3. Comparative geological stratigraphic sections of the İstanbul, Armutlu-Ovacık, and the Sakarya Zones (compiled from: Akbayram *et al.* 2013; Altıner *et al.* 1991; Bozkaya et al. 2011; Chen *et al.* 2002; Genç and Tüysüz 2010; Görür *et al.* 1997; Lom *et al.* 2016; Okay & Göncüoğlu 2004; Okay & Monie 1997; Okay *et al.* 2013, 2014, 2018; Özcan et al. 2012; Özgül 2012; Şen 2017; Tüysüz *et al.* 2004, 2016; Zapcı 2007).

$^{208}Pb/^{232}Th$, $^{206}Pb/^{238}U$, and $^{207}Pb/^{235}U$ ratios were calculated, and the time-resolved ratios for each analysis were then carefully examined. Optimal signal intervals for the background and ablation data were selected for each sample and automatically matched with the standard zircon analyses. U–Pb Concordia ages are calculated and plotted using ISOPLOT (Ludwig 2003).

3.3. Zircon (U-Th)/He (ZrHe) dating

Single-crystal aliquots were dated, usually three aliquots per sample. Only fissure-free specimens were used, with well-defined completely convex external morphology, and preference was given to euhedral crystals. The shape parameters were determined and archived using multiple digital microphotographs. For individual crystals, besides length and widths, the proportion of the length of the prismatic and pyramidal zones was also considered.

The crystals were wrapped in platinum capsules of ca. 1 × 1 mm size. The Pt capsules were heated with an infrared laser for 5 minutes. The extracted gas was purified using a SAES Ti-Zr getter at 450°C. Chemically inert noble gases and a minor amount of other rest gases were then expanded into a Hiden triple-filter quadrupole mass spectrometer equipped with a positive ion counting detector. Beyond the detection of helium, the partial pressures of some rest gases were continuously monitored (H_2, CH_4, H_2O, N_2, Ar, CO_2). Helium blanks were estimated using the same procedure on empty Pt tubes (max. 0.0003 and 0.0008 ncc 4He; cold and hot blanks, respectively). Crystals were checked for degassing of He with sequential reheating and He measurement. The residual gas was usually around 1% to 2% after the first extraction in the case of zircon. The analysis procedure was operated using HeLID automation software through a K8000/Poirot interface board (developed by I. Dunkl, Göttingen).

Following the degassing, samples were retrieved from the gas extraction line, spiked with calibrated ^{230}Th and ^{233}U solutions. Zircon crystals were dissolved in teflon bombs using a mixture of double-distilled 48% HF and 65% HNO_3 at 220°C for 5 days. Each sample batch was prepared with a series of procedural blanks and spiked normals to check the purity and calibration of the reagents and spikes. Spiked solutions were analysed as 1.4 or 2 ml of ~0.5 ppb U-Th solutions by isotope dilution on a Perkin Elmer Elan DRC II ICP-MS with an APEX micro-flow nebulizer. Procedural U and Th blanks using this method are normally very stable in a measurement session and below 1.5 pg. Sm, Pt, and Ca were determined by external calibration. The oxide formation rate and the PtAr–U interference were always monitored, but the effects of these isobaric argides were negligible relative to the signal of actinides.

The He signal was processed and evaluated with the factory-made software of the mass spectrometer (MASsoft, HIDEN). The ejection correction factors (Ft) were determined for the single crystals by a modified algorithm of Farley *et al*. (1996) using an in-house spreadsheet.

4. Results

4.1. Zircon U-Pb ages

Samples MK56 and MK66 were collected from granitoids cutting amphibolites (Figure 2). The cross-cutting relationship and the origin of the granitoids will be discussed below in the text. Both samples were found to have plagioclase, quartz, K-feldspar, amphibole, biotite, and clinozoisite with minor zircon, sphene, and opaque minerals. They have a weak foliation and reflect deformation lamella and undulose extinction in quartz and plagioclases. MK73 is a block in the Upper Cretaceous flysch thrust above the rocks of the İstanbul Zone. This sample also has a similar mineralogy to that of the other two samples, with one exception: it is highly weathered and cataclasticly deformed in some parts. Biotites are partly replaced by chlorite.

Twenty-eight zircon crystals were analysed from sample MK56. All grains were idiomorphic and had oscillatory and sector-zoned internal structures (supplementary Figure 1). Their aspect ratio was mostly ≤1:1.5. All spots dated were found to have similar Ediacaran ages to the calculated 559.8 ±1.4 Ma Concordia age (Figure 4a).

Both internal structures and the outer morphologies of the zircons of the sample MK66 are different from the MK56. Obtained ages are also different, showing a large scatter. Some of the zircons have dark internal structures (supplementary Figure 2) indicating a high amount of uranium (see supplementary Table 2). Concordant (semi-concordant) ages are concentrated in three age groups (supplementary Table 2): ~700 Ma, ~600 Ma, and 550 Ma. The Concordia age from the younger coherent age group has been calculated as 556.7 ±1.4 Ma (Figure 4).

The sample MK73 is dated to understand the provenance of the granitic blocks in the younger wild flysch (Yılmaz *et al*. 1995). Three zircons out of 30 dated ones yielded analytically bad signals and were discarded. Zircons are idiomorphic and show good oscillatory and sector zoning indicating their magmatic origin. Unlike the other granitoid samples, their aspect ratio is higher than 1:2 (supplementary Figure 3). All concordant spots displayed ages of ^{206}Pb/^{238}U between 551 and 571 Ma except one which was 600 Ma. The Concordia age calculated from a coherent group is 565.5 ±1.9 Ma (Figure 4).

The sample MG1001 is a cataclastic and highly weathered granite with quartz, plagioclase, k-feldspar, chlorite, relict biotite, and minor apatite, zircon, and opaque minerals. Biotites are mostly replaced by chlorite. The association of undulose extinction in quartz grains but poorly developed foliation indicates that the rock was affected only by a low-temperature deformational event. Thirty-two zircon crystals were analysed, and most of them are idiomorphic and oscillatory zoned, indicating their magmatic origin (supplementary Figure 4).

Archaean ages were obtained from the cores of the grains (e.g. Grain 26, spot d19). Grain 25 (supplementary Figure 4) is a xenocrystic zircon that yielded Mesoproterozoic rim and Archaean core ages (supplementary Table 3). Almost all spots yielded Early

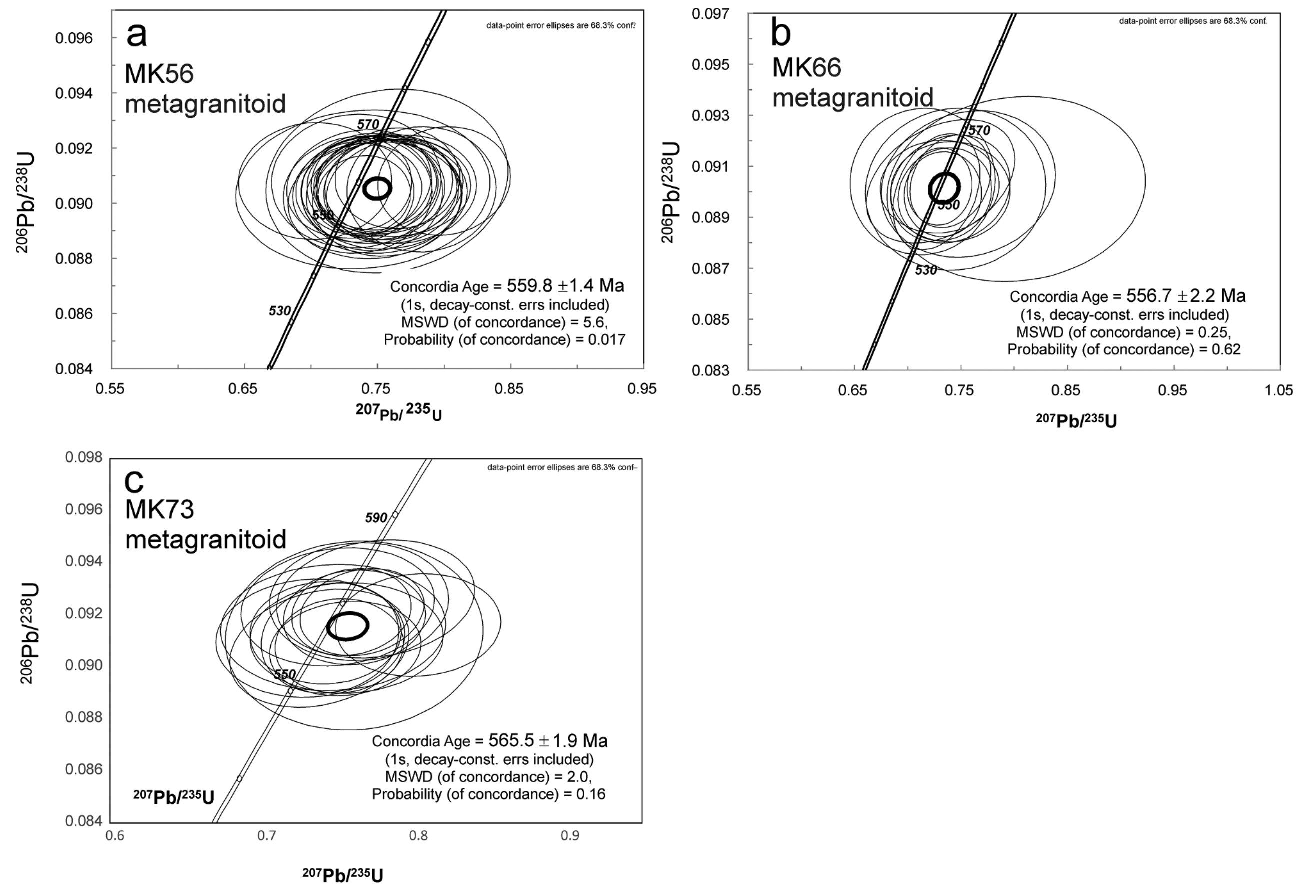

Figure 4. Concordia age diagrams of the metagranitoid samples MK56, MK66, and MK73. For single grain spot ages and relevant isotopic information see supplementary Table 2 and for the CL images see supplementary (Figure 1, 2) and 3.

Devonian $^{238}U/^{206}Pb$ ages except for one highly discordant late Carboniferous age (supplementary Table 3 and Figure 5). Unfortunately, only three Devonian ages are concordant. Apart from those Devonian ages, there are four Neoproterozoic, one Palaeoproterozoic, and one Neoarchean age. Both Discordia lower intercept and Concordia age calculations yielded identical results: the Discordia age was found to be 403.2 ± 4.2 Ma, whereas the Concordia age was 404.5 ± 3.9 Ma (Figure 5).

The sample MG05 is a typical monzonitic granite with quartz, pink K-feldspar, plagioclase, biotite, and minor amphibole and apatite. Unlike the sample MG1001, the rock is fresh and free of deformation. Thirty-two spots have been analysed from this sample (supplementary Table 3) but only 13 grains yielded semi-concordant ages (between 90% and 110%). Almost every grain has oscillatory zoning (supplementary Figure 5). All of the grains displayed Jurassic $^{238}U/^{206}Pb$ ages except two grains, which yielded the latest Permian (82% concordant) and latest Triassic (100% concordant) ages, respectively (supplementary Table 3, supplementary Figure 5; grains 20 and 24). Ten spot analyses revealed concordant Jurassic ages (between 90% and 110%). The Discordia and the Concordia ages are similar: the Discordia age is 158.3 ± 4.7 Ma and the Concordia age is 161.8 ± 0.82 Ma (Figure 5).

4.2. *Zircon (U-Th)/He thermochronology*

The basement rocks and their sedimentary cover were analysed. The amalgamation of the İstanbul and the Sakarya Zones took place during early Eocene (Okay *et al*. 1994; Görür and Okay 1996; Akbayram *et al*. 2017; Figure 1). The rocks that are formed before this interval have been interpreted to record their distinctive geological histories. The ages younger than Cuisian were not taken into account because post-Eocene ages were formed due to Eocene burial and subsequent exhumation events. Sunal *et al*. (2019) published AHe ages obtained from the same region and showed that

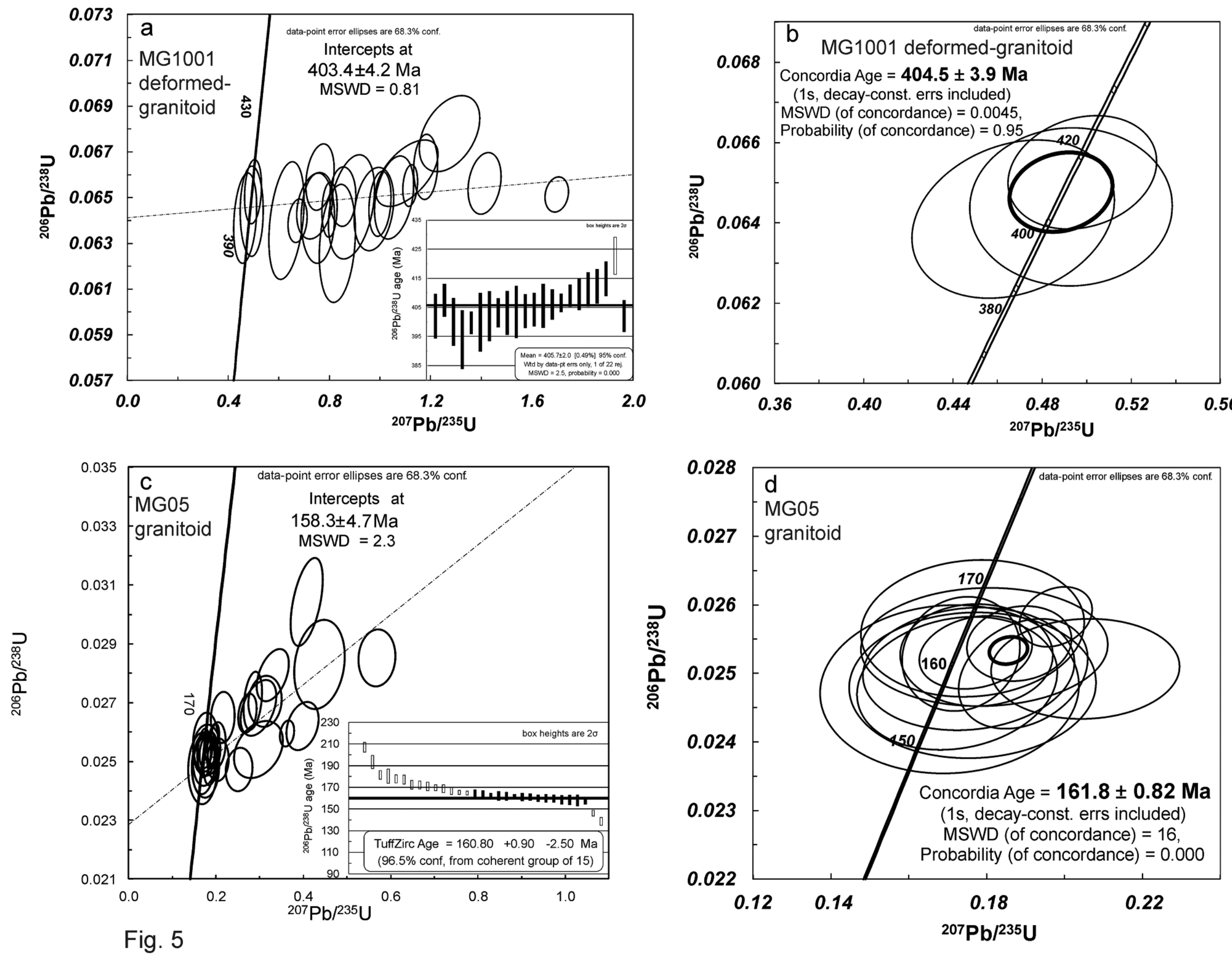

Fig. 5

Figure 5. Discordant (a) and concordant (b) age calculations of the dated deformed-granitoid sample MG1001 and discordant (c), and concordant (d) age calculations of the dated granitoid sample MG05. All calculations including tuffZirc age (inset of a and c) are performed using the isoplot 3.0 programme (Ludwig 2003). For single grain spot ages and relevant isotopic information see supplementary table 3.

Eocene burial could barely ever lead to the opening of the AHe system in the region and mostly did not cause higher temperatures that would reach the ZrHe closure temperature. In the following sections, we will introduce the ZrHe ages of the zones separately.

Figure 6 shows the formation ages of the units (Figure 2) *versus* relevant ZrHe ages obtained (supplementary Table 4). In this figure, ages are illustrated according to the zones from which they were obtained, and further divided by their rock types (magmatic, sedimentary, and metamorphic).

4.2.1 The İstanbul Zone (İZ)

The samples MK56, MK73, MK78, MK82, MK101, MK103, and MTK08 were collected from the rocks developed over the Palaeozoic basement succession of the İZ (Figure 2). Properties of the samples can be found in the supplementary Table 1, and isotopic characteristics and the ZrHe ages obtained from those samples are listed in supplementary Table 4. A probability distribution diagram of the ages obtained from the zones studied is illustrated in Figure 7.

Sample MK56 (similar to the MK66, ~559 and 556 Ma) is a foliated granitic rock that intruded into amphibolites and deformed together with them some time during the Mesozoic. Other rocks representing the basement of the İZ are the samples MK73, MK82, and MTK08, which are granite blocks in the Upper Cretaceous wild flysch (Yılmaz *et al.* 1995). One of the granite blocks (MK73) has been dated here and revealed ~566 Ma (Figure 4). Another sample from the basement of the İZ is MK78, which was collected from Ordovician quartz arenite. The samples from the Precambrian granites yielded ZrHe ages ranging from 146 to 93 Ma. Ages obtained from the Ordovician quartz arenite sample were similar to those from the granite samples and yielded a narrow age range of 136–106 Ma. The remaining two sandstone samples belong to the Upper Cretaceous flysch that thrusted over the rocks of the İstanbul Zone (Figure 2). The sample MK103 had a tight age range between 102 and 82 Ma, which is also similar to the introduced basement rocks. However, the sample MK101 displayed ages ranging from 248 to 73 Ma (Early Triassic to Latest Cretaceous, supplementary Table 4 and Figure 6, 7), which are interpreted by us as detrital ZrHe ages.

4.2.1 The Intra-Pontide Suture Zone (IPSZ)

Although only one sample yielded enough zircon to date, the results of the individual zircon grains gave a very tight range (Figure 6, 7). A schist sample (MK38) from the accretionary prism of the IPSZ that is located in the western part of the Almacık Block provided zircon crystals to date. The unweighted average age calculated from four grains is 62.0 ± 1.7 Ma (Supplementary Table 4).

4.2.1 The Sakarya Zone (SZ)

In general, the ages range between 311 and 51 Ma (supplementary Table 1 and 3). Two samples from Devonian granitoids were dated (MG22 and 1001).

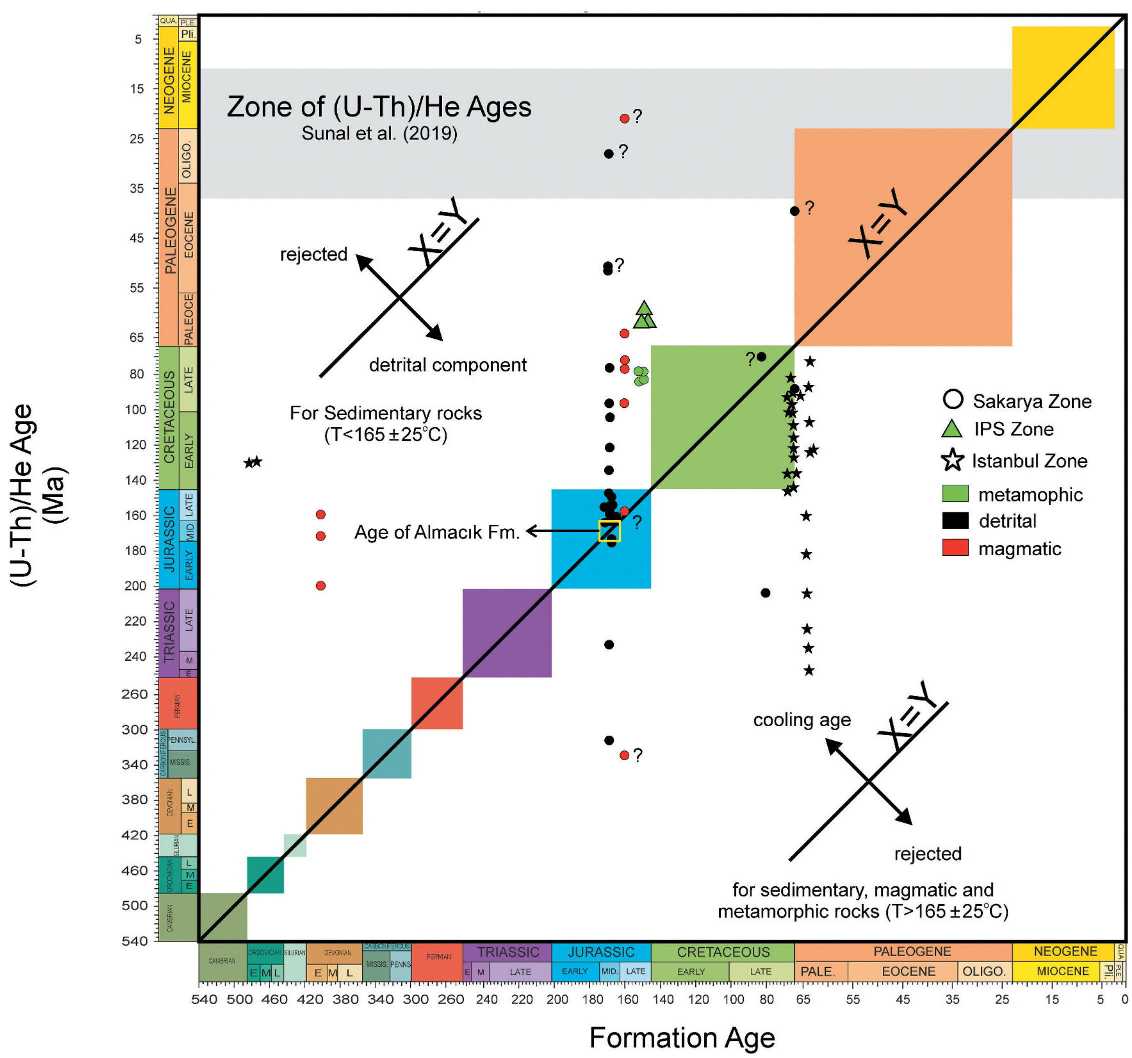

Figure 6. Formation age vs. ZrHe age distribution of the samples dated in this study (see supplementary Table 1 for the units dated and supplementary Table 4 for the ZrHe ages illustrated in the figure). The question marks are the ages that do not fulfill the requirements discussed in the text. Note that when the ZrHe ages obtained from sedimentary rocks are younger than the sedimentation age they should be rejected. Furthermore, when the ZrHe ages are older than the age of magmatic and metamorphic rocks they should be rejected too.

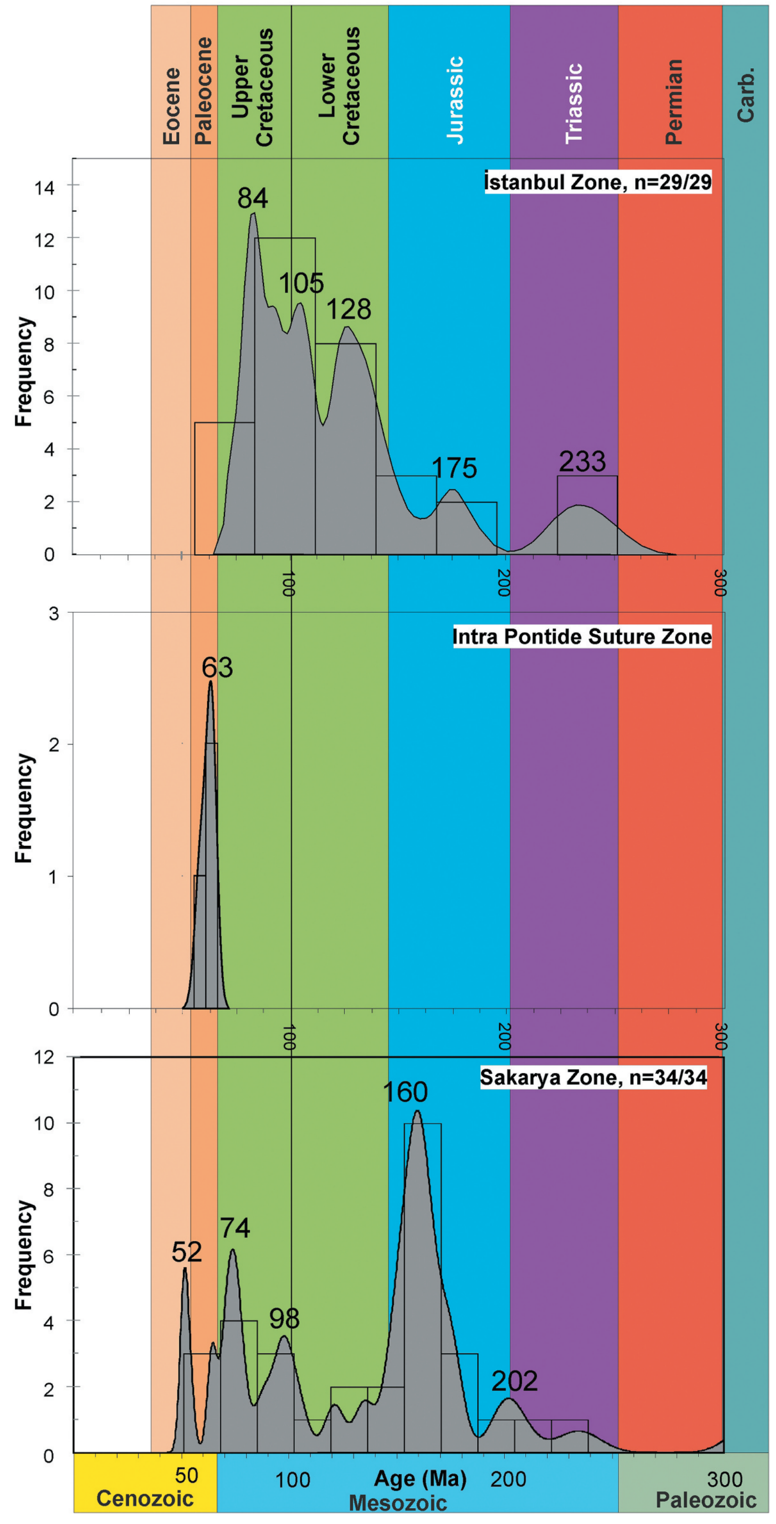

Figure 7. Binned histograms and probability density plots compiled from the single-grain zircon (U-Th)/he ages from the İstanbul zZone (a), IPS Zone (b), and the Sakarya Zone (c). Age components are calculated using the isoplot 3.0 program (Ludwig 2003).

Nine sandstone samples were dated from the Mudurnu Formation (Middle to Upper Jurassic, Altıner *et al*. 1991). The remaining four samples are from the Upper Cretaceous flysch in which one sample from a Jurassic granitoid block was dated (MG05, see Figure 5 for U-Pb age and supplementary Table 3). The ages obtained were concentrated in the five prominent peaks (see main peaks in Figure 7): Late Triassic (~202 Ma), Late Jurassic (~160 Ma), earliest Late Cretaceous (~98 Ma), Late Cretaceous (~74 Ma), and Ypresian (~52 Ma).

5. Discussion

5.1. Implication of the dated magmatic rocks in the Pontides

The epidote amphibolite facies rocks were previously assigned to the Pamukova Group (Göncüoğlu *et al*. 1987), and Precambrian to Ordovician ages are reported from such rocks (Akbayram *et al*. 2013; Okay *et al*. 2008). These metamorphic rocks are interpreted as the metamorphosed Neo-Proterozoic basement of the İstanbul Zone (Akbayram *et al*. 2013; Kaya 1977; Yiğitbaş *et al*. 1999, 2004; Okay *et al*. 2008). However, Bozkurt *et al*. (2013b) interpreted these rocks as a part of the sub-active continental margin of the Sakarya Zone. Based on zircon ages obtained from the plagiogranites cutting serpentinites in the Almacık Block, Bozkurt *et al*. (2013b) interpreted the closure of the IPO as Triassic. Because there is no direct dating of the serpentinites, it is not possible to say anything about the age of the oceanic crust forming the IPO. We are uncertain of the syn-origin of the serpentinites and amphibolites that were dated in this study. Thus, in order to ascertain this missing information, we dated two granitic stocks cutting the amphibolites. Both granitoids and amphibolites metamorphosed later and deformed together. The zircon U-Pb age data clearly show that the amphibolites (metagabbros?) developed before the Ediacaran (559–556 Ma, MK56, and MK66, Figure 4). Such older ages indicate that amphibolites (metagabbros?) are not a part of the IPSZ and are instead a member of the basement of either the İstanbul or the Sakarya Zones (Akbayram *et al*. 2013; Okay *et al*. 2008; Bozkurt *et al*. 2013b), which were later intruded by granitoids. Published data indicate that such Ediacaran ages are widespread in the İstanbul Zone (590–560 Ma, Chen *et al*. 2002, 576–565 Ma, Ustaömer *et al*. 2005; ~570 Ma, Okay *et al*. 2008, ~590 Ma, Akbayram *et al*. 2013, 564–561 Ma, Özbey *et al*. 2021). Similarly, the granitic block in the Late Cretaceous flysch dated in this study was found to be of the similar Ediacaran age (~565 Ma, MK73, Figure 8). Recently Şen (2021) published different dike samples cutting the basement of the İstanbul Zone and reported zircon U-Pb ages between 549 and 556 Ma. All the rocks mentioned above crop out in the W, N, and NE parts of the Almacık Block. In contrast, no granitoid of the Precambrian age is reported from the Sakarya Zone. Thus, we agree that the amphibolites cut by the dated meta-granitoids belong to basement rocks of the İstanbul Zone and represent widespread Cadomian arc magmatics in Anatolia (Ustaömer 1999; Gürsu and Göncüoğlu 2005; Ustaömer *et al*. 2005; Gürsu and Göncüoğlu 2006; Gürsu *et al*. 2015; Özbey *et al*. 2021).

In this region, there is only one age determination (the K-Ar method) reported by Delaloye and Bingöl (2002) giving the Jurassic age. Because the map presented by them is too small-scaled, which rock has been dated is not clear. In this study, one deformed

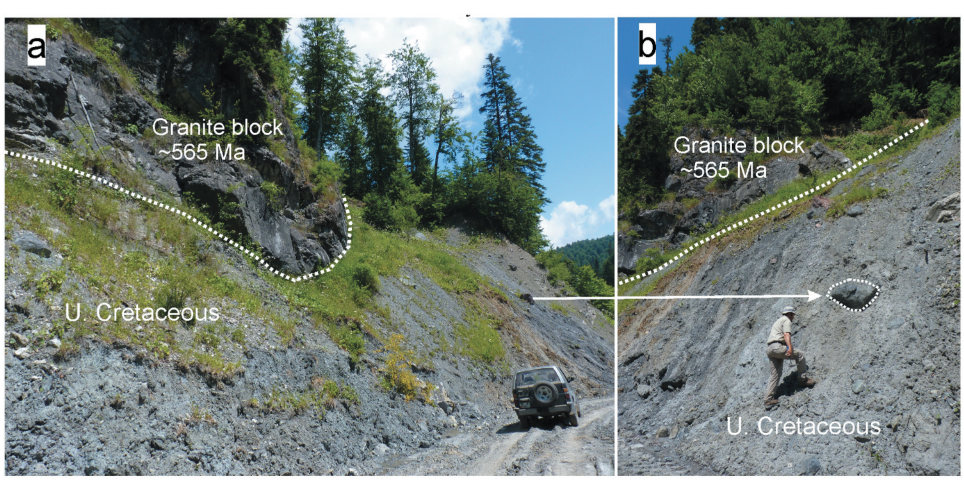

Figure 8. A deformed granitic block (the sample MK73) in Upper Cretaceous wild flysch. Different-sized blocks are embedded in a shaly matrix.

and altered, and one fresh monzonitic granite have been dated from the Sakarya Zone (Figure 5). However, the stratigraphic framework of the rocks analysed is not clear because of dense vegetation and the recent strike-slip deformation. They are either sedimentary blocks or tectonic lenses embedded in the surrounding Late Cretaceous flysch.

The deformed granitoid body displayed 404.5 ±3.9 Ma and the fresh one 161.8 ± 0.82 Ma zircon U-Pb age (Figure 5). The Devonian fits in the widespread magmatism reported in the western part of the Sakarya Zone (Okay *et al*. 2006; Sunal 2012; Aysal *et al*. 2012a, 2012b). The Jurassic age we obtained in this study is the only example reported so far in the western part of the Sakarya Zone.

5.2. Tectonic meaning of the ZrHe ages obtained from the studied zones

Samples MK56 and MK66 are interpreted as the Cadomian basement of the İstanbul Zone (see section *5.1*). Sample MK78 is an Ordovician quartz-arenite mostly fed by the Precambrian plutono-metamorphic basement of the İZ (see also Ustaömer *et al*. 2011). Such Precambrian and overlaying Early Palaeozoic rocks gave ZrHe ages ranging from 146 to 79 Ma with three peaks at 128, 105, and 84 Ma (Early Cretaceous–middle Late Cretaceous, supplementary Table 4 and Figure 7). The first two peaks match with the sedimentary hiatus defined in the western part of the İstanbul Zone (Kaya *et al*. 1986), see (Figure 10).

On the other hand, the Upper Cretaceous–Palaeocene sandstone sample MK101 gave Triassic–Jurassic cooling ages (248–160 Ma, supplementary Table 4 and Figure 7, 10).

The known youngest Palaeozoic rock of the İstanbul Zone are the Permian granitoids in its western part (Yılmaz-Şahin *et al*. 2010; Okay *et al*. 2013). These Triassic ZrHe ages (supplementary Table 4 and Figure 7, 10) may be an expression of the exhumation and related cooling of the Permian granitoids (262–253 Ma, Yılmaz-Şahin *et al*. 2010; Okay *et al*. 2014) or the cooling age of metamorphism reported from the Sünnice Massif in the east (Bozkurt *et al*. 2013b). Recently, some Jurassic sub-volcanic rocks have been described from the İstanbul Zone (Şen *et al*. 2015). The source of the obtained Jurassic ZrHe ages in the sample MK101 could be the cooling age of these rocks. In the Zonguldak part of the İZ, Akdoğan et al. (2022) obtained Late Triassic–Early Jurassic apatite fission-track ages and interpreted them as a compressional event, probably caused by the accretion of oceanic plateaus or seamounts to the southern margin of the Pontides.

The formation of the IPSZ and the age of the IPO are a matter of debate (Akbayram *et al*. 2013; Akbayram *et al*. 2017; Bozkurt *et al*. 2013a, 2013b). The protolith age of the amphibolites dated in this study, which were regarded as a part of the IPSZ must be older than Cambrian. In previous dating studies, there is only an age (Permo-Triassic) reported from a plagiogranite cutting ultramafic rocks (serpentinites) (Bozkurt *et al*. 2013a). If these serpentines and plagiogranites have the same Permo-Triassic age, then the amphibolites dated here cannot be syngenetic with these rocks.

Recently, Akbayram *et al*. (2017) proposed that low-grade metamorphic rocks of the Armutlu-Almacık Zone (AAZ) (Late Jurassic–Early Cretaceous) represent older accretionary prism rocks of the IPSZ, not a part of the SZ. Another reason why such rocks do not belong to the Sakarya Zone is that the Mesozoic interval in the central SZ is a nonmetamorphic time span but many of the rocks of the AAZ metamorphosed during the Mesozoic era (Akbayram *et al*. 2013; Akbayram *et al*. 2017; Bozkurt *et al*. 2013a, 2013b) (Figure 9). If such low-grade metamorphic rocks are really not a part of the SZ to the contrary a part of the IPSZ's accretionary material, then the only sample we have a ZrHe age from the IPSZ is sample MK38 (Figure 2). This sample is a schist derived from the alternation of schist-phyllite, and marble. Three zircon grains from this sample gave almost identical ZrHe ages with an average of 62.0 ± 1.7 Ma (see supplementary Table 4). This ZrHe age is compatible with the revised formation age of the IPSZ (Cuisian) given by Akbayram *et al*. (2017). These rocks should be cooled below (exhumed) the closure temperature of ZrHe during the early Paleocene before the termination of the IPO and the formation of the IPSZ.

In the Central Pontides, Frassi *et al*. (2018) has dated burial (~157 Ma) and exhumation stages of the high-pressure metasedimentary rocks of the Daday Unit that is regarded by them as a part of the IPSZ. They obtained ~58 Ma (latest Palaeocene) apatite fission track age and interpreted it as the last episodes of uplift of the Daday Unit. This age is about 4 Ma younger than what we found using the ZrHe method in this study, but it should be noted that there is a roughly 75°C difference between the closure temperatures of both methods.

5.1.3. The Sakarya Zone

Disregarding the dominant Jurassic ages in the Sakarya Zone (supplementary Table 4 and Figure 7, 10), which are obtained from the Mudurnu Formation and reflect the formation age of the succession, the rest of the ages can be separated into two parts: a Carboniferous age plus scarce and diffused Late Triassic ages, and the

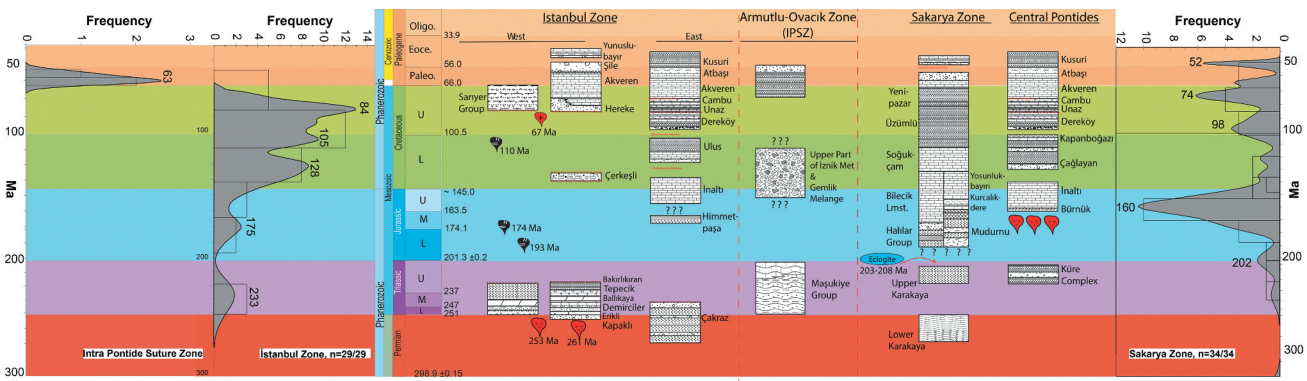

Figure 9. Correlation between stratigraphy of the individual zones and the probability density distribution plots of the ZrHe ages (see Figure 7) obtained from the zones.

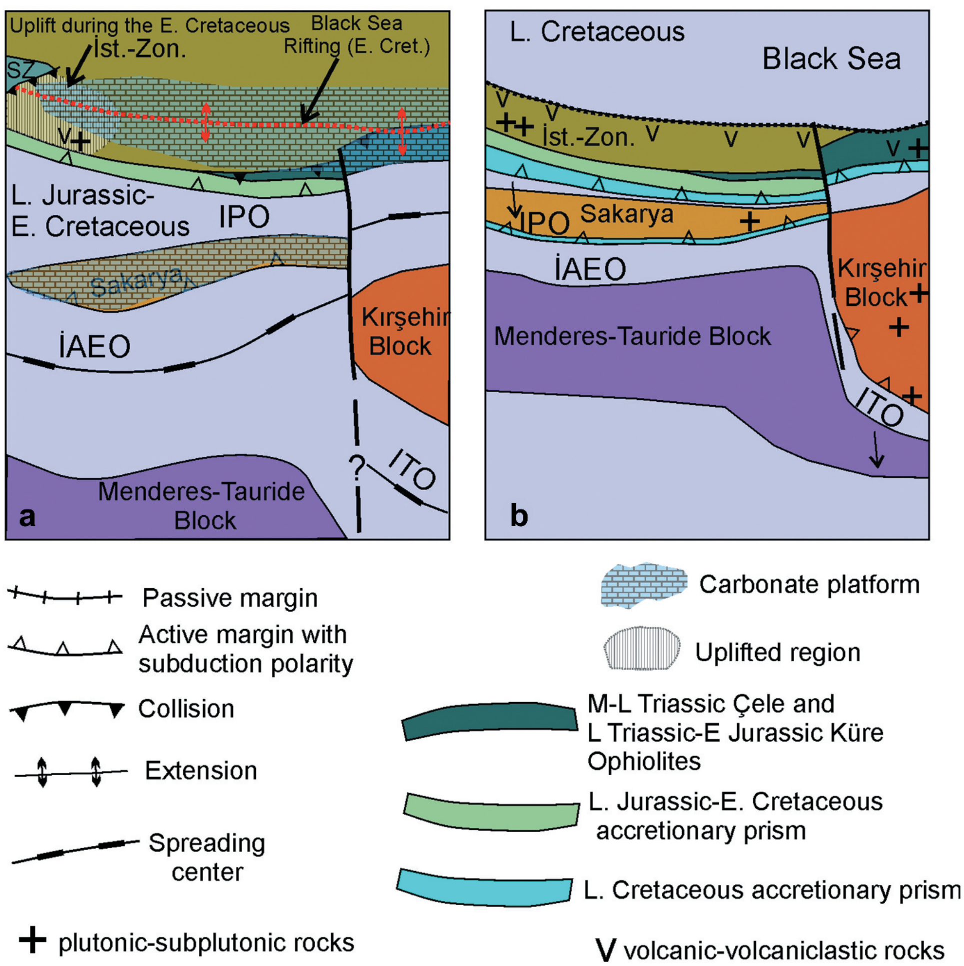

Figure 10. Late Jurassic-Late Cretaceous geodynamic evolution of the Pontides; A- Late Jurassic–Early Cretaceous, and B- Late Cretaceous. IPO: Intra-Pontide Ocean, İAEO: İzmir-Ankara-Erzincan Ocean, ITO: Inner-Tauride Ocean. Supplementary Fig. S1. Cathodoluminescence and backscattered electron images of the zircon crystals dated from the Devonian sample MG1001.

ages ranging from the very beginning of Early Cretaceous to Early Eocene (see supplementary Table 4). It is not easy to evaluate the first group. The average Early Jurassic age (176.5 ±11.9 Ma) is obtained from the Early Devonian (see Figure 5) cataclastic granite sample (MG22, supplementary Table 4 and Figure 7, 10). Similar Early Devonian rock has been dated in the western part of the Sakarya Zone using the ZrHe method. Unlike the sample in the studied area, an unweighted average of 93.0 ± 6.9 Ma is obtained from the western part of the zone (Sunal 2012). Different cooling (exhumation) timings of the Early Devonian granitoids indicate that the geological evolution of the Western and the Eastern Sakarya Zones is diachronous. A Jurassic (see Figure 5) granitoid sample (MG05) revealed Late Cretaceous cooling ages with an average of 77.6 ±7.6 Ma (supplementary Table 4 and Figure 9). This can be interpreted as exhumation and accompanying cooling of the Jurassic magmatic rock during the Late Cretaceous. Even though it is a block in the Upper Cretaceous rocks, there is enough time for emplacement of it as a block into the Upper Cretaceous unit because the exact age of the Upper Cretaceous unit is not clear (see Gedik and Aksay 2002). Similarly, evaluation of the Late Cretaceous ZrHe ages (detrital?) obtained from the Upper Cretaceous rocks is difficult because of the inexact lower age of the Upper Cretaceous units. If such granitoid rocks are blocks in the Upper Cretaceous rocks, the lower age of the Upper Cretaceous units must be younger than ~77 Ma.

The Middle Jurassic Mudurnu Formation (supplementary Table 4 and Figure 7, 10) yielded ZrHe ages clustered in the Middle to Late Jurassic with a mean peak at approximately 160 Ma (Figure 9). Although the palaeontological age range given for this unit is Callovian-Pliensbachian by Altıner *et al*. (1991), it is also stated in the same study that the volcanism was still active later than the Callovian interval. The deposition of the unit in this EW-trending basin is most probably diachronous. However, even if some of the ages fall into this palaeontological age range, there is a considerable number of ages that are younger than that. They may represent the cooling ages of the medial Jurassic volcanic zircons or an intense and long-lasting magmatic activity in the region. Another possibility is that some parts of the Mudurnu Formation have reached over the temperatures of the partial retention zone (PRZ) of zircon.

Genç and Tüysüz (2010) are interpreted the Mudurnu Formation as a deposit of either a back- or a fore-arc environment according to geochemical data obtained. We also agree with that because of the abundance of dated zircon minerals with almost identical ZrHe ages that should represent a long-lasting subduction-related Jurassic–Early Cretaceous magmatic activity in the region. If this is the case, we can assert that an extensive part of the Mudurnu Formation was not buried too deep and was not affected by high heat that can exceed and reset the closure temperature of the ZrHe system.

Two samples from the Mudurnu Formation gave younger ages than the usual Jurassic ones (supplementary Table 4). The sample MG58 has three different ages and is not easy to evaluate. Furthermore, the sample MG54 has two almost identical Early Eocene ages (~52 Ma). Because the unconformably overlying unit is the Middle Eocene in age (Gülmez *et al*. 2013), these Early Eocene ZrHe ages can be regarded as geologically meaningful.

5.1. A provenance perspective

The region presented here is pretty well known in terms of geological past of the units. So that we can make some statements about our ZrHe data as provenance indicators;

- The main difference between the İstanbul and the Sakarya Zones is the presence of the Early Cretaceous ZrHe ages in the İstanbul Zone (Figure 7, 10).
- Even though there are some Triassic ZrHe ages in the Sakarya Zone, they are too scattered and rare. However, the Triassic ages in the İstanbul Zone are much more condensed and pronounced (Figure 7, 10).
- Early Tertiary ages are well pronounced in the Sakarya Zone but absent in the İstanbul Zone.
- Both zones have Late Cretaceous ZrHe ages but to evaluate these ages accurately for provenance studies more detailed studies are needed.

5.2. Late Jurassic and Late Cretaceous geodynamic evolution of the Western-Central Pontides

Here, we propose a modified version of the geodynamic models illustrated previously taking our new data presented in this study into account (Figure 10). In the light of the data, we have obtained here, we prefer to modify the original model given by Şengör and Yılmaz (1981), using the ensuing studies and their findings. Figure 10 shows the non-palinspastic geodynamic evolution of the Pontides in the Late Jurassic and the Late Cretaceous intervals.

During the Late Triassic–Early Jurassic, the IPO was most probably connected with İAEO to the East and to allow diachronous closure along with it, both the Sakarya Zone and IPO possibly have been dissected by roughly NS-trending transform faults (future Sakarya Shear Zone? Okay *et al*. 2020b) that could lead to different travel times to the north. Şengör and Yılmaz (1981) and Dokuz *et al*. (2010) proposed that to form Early Jurassic back-arc magmatism and following carbonate deposition in the region, the Palaeo-Tethys Ocean should subduct southward under the Sakarya Zone. In addition, in the Early Jurassic some intra-oceanic materials such as oceanic plateaus and island arcs formed in the IPO attached to the northern part of the Sakarya Zone (not shown in Figure 10) (Çimen *et al*. 2016, 2017; Marroni *et al*. 2020). At the same time, the northern margin of the IPO was a passive continental margin because, in the western part of the İstanbul Zone (IZ), the Triassic period is represented by terrestrial and shallow marine rocks with some mafic lava layers (see Lom *et al*. 2016 and the references therein), which can be interpreted as the extensional and quiet geological environment.

The southern side of the Western Sakarya Zone was an active margin revealed by the ~200 Ma old eclogite dated in the northern part of the Karakaya Unit (Okay *et al*. 2002).

The Late Jurassic through the Early Cretaceous interval (Figure 11 a) is mostly a quiet interval in terms of magmatism for most of the Pontide region. Large areas were covered by platform carbonates (e.g. Saner 1980; Görür *et al*. 1983; Okay *et al*. 1990; Altıner *et al*. 1991; Koçyiğit and Altıner 2002; Atasoy *et al*. 2018 and the references therein). There are some sparse earliest Late Jurassic magmatic rocks in some parts of the Pontides (Okay *et al*. 2014, 2015; Çimen *et al*. 2017) and also Early Cretaceous in the İstanbul Zone (Şen *et al*. 2015). Even if magmatic activity was interrupted in the Central Pontides, subduction was still going on in the south of the carbonate platform (Okay *et al*. 2006, 2013; Aygül *et al*. 2015a; Frassi *et al*. 2018). This carbonate depositional environment most probably formed over the arc due to the southward retreating of the slab. Subsequently, during the Early Cretaceous such carbonates were disrupted by normal faults and created horst-graben morphology (Görür 1988; Okay *et al*. 1994, 2018; Tüysüz 1999; Tüysüz *et al*. 2012). In the grabens, turbidites with numerous giant basement blocks were deposited. This deformation has been assigned to the beginning of the opening of the Black sSea bBasin. However, our data show that the Early Cretaceous interval is one of the major exhumation periods for the basement rocks of the İstanbul Zone (see Figures 6, 8). As explained earlier in the text, the Late Jurassic carbonates were also deposited over the İstanbul Zone but eroded during the Early Cretaceous (Kaya *et al*. 1986) due to the regional uplift of the zone. This uplift event corresponds to the Late Jurassic–Early Cretaceous metamorphism and related deformation that happened in the adjacent Strandja Massif (Okay *et al*. 2001; Elmas *et al*. 2011; Sunal *et al*. 2011). It should also be noted that similar Late Jurassic cooling ages are reported from the Sünnice Mountains by Bozkurt *et al*. (2013b). Recently, Ülgen *et al*. (2018) claimed that the boundary between the İstanbul Zone and the Strandja Massif is a thrust where the Carboniferous rocks of the İstanbul zone thrust over the Triassic rocks of the Strandja Massif. The timing of this event is regarded as Early Cretaceous. Furthermore, Ülgen (2021) has reported a K-Ar age (90.2 ± 2 Ma) from the fault gouge of the thrust fault that was already interpreted as Early Cretaceous in Ülgen *et al*. (2018). Similar but older ages are also obtained from different faults (110 ± 3 and 98.2 ± 2.4 Ma). These ages, together with their errors, are very similar to our last two ZrHe age peaks obtained. This thrust is roughly EW trending, but if such boundary is not a strike-slip fault, then thrust should turn into NW–SE direction to bound the Strandja Massif in the west and the İstanbul Zone in the east. This would be the main reason for the early Late Cretaceous uplift that happened in the western part of the İZ not in the east. The thrust fault dated by Ülgen (2021) is a well-known Eocene thrust. Ülgen (2021) also reported a small number of ages distributed in the Palaeocene and an early Miocene one. The wide distribution of these ages indicates that the thrust fault was reworked at different times. There are two other exhumation data obtained mainly by the apatite fission track dating revealing the latest Early Cretaceous ages, one in the İstanbul part of the İstanbul Zone and another in the eastern continuation, in the Zonguldak part of the zone (Cavazza *et al*. 2012; Akdoğan *et al*. 2020). The major unconformity between Albian and Turonian in the eastern part of the İstanbul Zone has been interpreted as the result of shoulder uplift during back-arc rifting of the Black Sea (e.g. Görür 1988). If this inference is correct, when the Black Sea Basin started to open all along the Pontides (mainly central part), at the same time, the İstanbul Zone was exhuming because of the collision with the Strandja Massif.

The subduction of the İAEO under the Sakarya Zone created extensive Late Jurassic volcaniclastics with volcanics (the Mudurnu Formation radiometrically dated in this study) deposited in the fore-arc (back-arc?) environment (Genç and Tüysüz 2010). The Mudurnu Formation is exposed throughout almost the entire Sakarya Zone (Genç and Tüysüz 2010).

The least debated time frame in the evolution of the Pontides is the Late Cretaceous when the Black Sea was already opened as a back-arc basin (Şengör and Yılmaz 1981; Finetti *et al*. 1988; Görür 1988; Manetti *et al*. 1988; Tüysüz 1999; Tüysüz *et al*. 2016; Şengör et al. 2019) and intense arc-related magmatic activity covered all extend of the Pontide range (Rhodope-Pontide Arc, e.g. Boccaletti *et al*. 1974, 1978; Peccerillo and Taylor 1976; Manetti *et al*. 1979; Karacık and Tüysüz 2010; Aygül *et al*. 2015b; Keskin and Tüysüz 2017). This extensive magmatic belt can be traced mostly along the Black Sea coast of Turkey and Bulgaria (for the Bulgarian site, e.g. von Quadt *et al.* 2005; Kamenov *et al*. 2007; Georgiev *et al*. 2012) in the west. Because the Black Sea has already reached an extent during the Late Cretaceous, the Late Cretaceous arc-related magmatics situated only in the southern part of the Black Sea unlike Jurassic and Triassic arc magmatics (Meijers *et al*. 2010; Okay *et al*. 2015; Okay and Nikishin 2015). Late Cretaceous in our ZrHe data set is represented by ages related to the exhumation of the rocks of the IPO and also Jurassic and Upper Cretaceous rocks of the Sakarya Zone (Figure 7 and supplementary Table 4). However, only a few middle Late Cretaceous ages are obtained from the İstanbul Zone (Figure 7, 10, and supplementary Table 4), which can indicate that the last stages of the Early Cretaceous exhumation in the zone or can be related to the fore-arc development on the İstanbul Zone (Akbayram *et al*. 2017).

The closure of the İAEO has commonly regarded as Paleocene (Şengör and Yılmaz 1981; Okay and Tüysüz 1999). Unlike the İAEO, closure of the IPO is younger deduced from the Late Cretaceous–Paleocene fore-arc basin formed in the Kocaeli Basin and an upper Cuisian molasses cover, which indicates that the closure of the IPO is probably medial Cusian (Akbayram *et al*. 2017). The early Paleocene (~62 Ma) ZrHe age obtained from this unit favours Cuisian closure of the IPO (Okay *et al.* 1994; Görür and Okay 1996; Akbayram *et al*. 2017) rather than Early Cretaceous (Akbayram *et al*. 2013) provided that these rocks are a part of the accretionary prism formed during the long-lasting subduction of the IPO (Akbayram *et al*. 2017).

6. Concluding remarks

The age of the amphibolites, which were regarded as a member of the IPSZ turned out to be older than the Cambrian. This datum confirms the previously proposed idea that these rocks represent the basement of the İstanbul Zone (Akbayram *et al*. 2013).

The ZrHe ages obtained from the İstanbul Zone have clearly shown that the exhumation of the basement rocks of the zone occurred during the Early Cretaceous–middle Late Cretaceous interval. This result confirms the previously claimed idea that the Jurassic-Early Cretaceous stratigraphic hiatus in the İstanbul Zone is erosional.

The Middle Jurassic Mudurnu Formation (Altıner *et al.* 1991) gave a good age spectrum of the ZrHe ages ranging from 175 to 147 Ma (Middle to Late Jurassic). Keeping out the Late Jurassic ZrHe ages, which may have been formed in the PRZ, the remaining ages can be asserted as the long-lasting magmatism and penecontemporaneous deposition of the Mudurnu formation.

A fresh monzonitic granite in the Sakarya Zone yielded 161.8 ± 0.82 Ma zircon U-Pb age and the Late Cretaceous (~77 Ma) ZrHe ages. This Jurassic magmatism so far is the westernmost occurrence in NW Anatolia. A deformed granitoid body gave 404.5 ±3.9 zircon U-Pb age and the Lower Jurassic (~177 Ma) ZrHe age. This age confirms that the Lower Devonian magmatism is more common in the Sakarya Zone but their cooling timing is different from one side to another (see Sunal 2012).

The rocks of the Maşukiye Group (Akbayram *et al.* 2017) as a part of the Armutlu-Almacık Zone cropping out in the western part of the Almacık Block yielded Paleocene ZrHe ages (~62 Ma). If this unit is a part of the accretionary prism formed during the subduction of the IPO, then closure of it and formation of the IPSZ occurred during the Early Eocene (Akbayram *et al.* 2017), not in the Early Cretaceous interval (Akbayram *et al*. 2013). Upper Cretaceous and Tertiary ZrHe ages obtained from the İZ and the SZ also support this idea. However, more studies are needed to clarify this debate.

Highlights

- The main exhumation of the basement rocks of the İstanbul Zone occurred during the interval between the early Cretaceous and the middle late Cretaceous period.
- Precambrian (559–556 Ma) basement rocks of the İstanbul Zone crop out in the Almacık Block
- A monzonitic granite in the Sakarya zone yielded 161.8 ± 0.82 Ma and a deformed granite 404.5 ±3.9 Ma zircon U-Pb ages.
- Campanian ZrHe ages (~62 Ma) derived from the Intra-Pontide Suture Zone support the Early Eocene closure of the zone, not Early Cretaceous.

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