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Late Paleocene – Middle Eocene magmatic flare-up in western Anatolia

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Highlights

- Late Paleocene-Middle Eocene (58 Ma and 45 Ma) magmatic flare-up
- A 3000-km long Eocene magmatic belt from western Anatolia to Iran
- Magmatism started in the late stages of continental collision and continued into Eocene extension
- Geochemical features suggesting formation in subduction-related environments
- Geochemistry suggests thick crust at 58 to 54 Ma, and a relatively thin crust at 54 to 45 Ma

Abstract

A 3000-km long magmatic belt of predominantly Eocene age extends from Anatolia into Iran representing a major magmatic flare-up. We present new zircon U-Pb, Ar/Ar mica and apatite fission-track ages for this magmatism from northwestern Turkey, and review its geochemistry and geodynamic setting. The new age data show that magmatism started at the Late Paleocene (58 Ma) during the final stages of continental collision and continued into the early Middle Eocene (45 Ma) with most of the magmatism taking place in the Early-Middle Eocene (54 to 45 Ma). The Late Paleocene-Middle Eocene magmatism is separated from Late Cretaceous and Oligo-Miocene magmatic flare-ups by periods of magmatic quiescence. The Late Paleocene-Middle Eocene magmatism consists of plutonic and volcanic belts. The plutonic belt cuts across and post-dates the İzmir-Ankara suture. The plutonic rocks are mainly middle- to high-K calc-alkaline I-type granodiorite and granite, and the volcanic rocks are middle- to high-K calc-alkaline basalt, basaltic andesite and andesite. Geochemically, all the rocks are similar to those found in subduction-related environments. Crustal thicknesses calculated based on geochemistry suggest a thickened crust (60-70 km) at 58 to 54 Ma, and a relatively thin crust (ca. 40 km) at 54 to 45 Ma, which match with uplift and erosion during the Late Paleocene, and marine sedimentation during the Early-Middle Eocene in northwest

Anatolia, respectively. The Late Paleocene-Middle Eocene magmatism is tentatively assigned to subduction of the southern branch of the Neo-Tethys.

Key-Words: Paleocene-Eocene magmatism, magmatic flare-up, geochronology, Western Anatolia, slab break-off, post-collision, subduction

1. Introduction

Geochronological data on magmatic rocks in concert with their areal distribution in Western Anatolia indicate three temporally and spatially distinct magmatic flare-ups separated by magmatic lulls (Figs 1 and 2). These are Late Cretaceous (90-75 Ma), Late Paleocene–Middle Eocene (58-45 Ma) and Late Oligocene-Early Miocene (28-20 Ma) magmatic episodes (e.g., Türkecan, 2015; Schleiffarth et al., 2018; Okay et al., 2020a). The Late Cretaceous magmatic belt is part of a major magmatic arc extending from Georgia in the east to Serbia in the west (e.g., Gallhofer et al., 2015; Kandemir et al., 2019; Moritz et al., 2020). It formed as a result of northward subduction of the Tethyan ocean under the Pontides. The Izmir-Ankara-Erzincan suture represents the trace of this İzmir-Ankara ocean, which is also known as the northern branch of the Neo-Tethys (Fig. 1). The İzmir-Ankara ocean separated the Pontides and the Anatolide-Tauride Block during the Mesozoic and closed during the Paleocene (e.g., Okay and Tüysüz, 1999). There was another Mesozoic-Cenozoic ocean farther south between the Anatolide-Tauride Block and the Arabian Plate known as the southern branch of Neo-Tethys (e.g., Robertson et al., 2013; van Hinsgergen et al., 2020). The partial closure of this ocean during the Miocene created the Bitlis-Zagros suture (Fig. 1b, Okay et al., 2010), the Eastern Mediterranean represents a relict of the southern branch of Neo-Tethys.

The Late Paleocene-Middle Eocene magmatism, abbreviated as LP-ME magmatism, is observed in the Pontides, as well as in the Anatolide-Tauride Block, and extends ~30-50 km to the south of the Izmir-Ankara-Erzincan suture (Fig. 1). The Late Oligocene-Early Miocene magmatic rocks generally crop out farther south and show a substantially wider aerial distribution in western Anatolia than the LP-ME ones (Fig. 1). The origin of the LP-ME magmatism is controversial and has been attributed to slab breakoff (Altunkaynak, 2007; Keskin et al., 2008; Karacık et al., 2008; Altunkaynak et al., 2012; Altunkaynak and Dilek, 2013; Ersoy and Palmer, 2013; Gülmez et al., 2013; Kasapoğlu et al., 2016; Ersoy et al., 2017a, b; Gürarslan and Altunkaynak, 2019), delamination of the lower part of the thickened lithosphere (Köprübaşı and Aldanmaz, 2004) and subduction (Okay and Satır, 2006; Ustaömer et al., 2009; Rabayrol et al., 2021).

This paper deals with the LP-ME magmatic flare-up in northwestern Anatolia. We present new U-Pb zircon, Ar/Ar mica and apatite fission-track ages from a large number of LP-ME plutons (Table 1), and discuss these data in conjunction with the literature data on the distribution, duration, geochemistry and possible causes of the LP-ME magmatism in northwestern Turkey. Our reassessment demonstrates that the LP-ME magmatism was active between 58 Ma and 45 Ma with most of the magmatism occurring in the Early-Middle Eocene (54 to 45 Ma, Fig. 2). Magmatism started when the continental crust was thick, continued during the Early-Middle Eocene extension, and ended with the whole scale uplift of Anatolia at the end of the Middle Eocene. Although a Late Paleocene - Middle Eocene magmatic flareup is evident from the age and spatial distribution of the Eocene magmatic rocks (Figs. 1, 2), calculation of a meaningful magmatic flux is not possible because: a) Large part of western Turkey are covered by Neogene deposits (cf. Fig. 3), which disguises the true extend of Eocene magmatism, b) There has been extensive exhumation during the Cenozoic, as shown by the apatite fission track ages (cf. Fig. 7 of Okay et al., 2020), which eroded a significant part of Eocene volcanic rocks, c) The thickness of the Eocene volcanic rocks varies over short distances, because of post-Eocene tectonism, and is poorly constrained.

2. Tectonic setting of the Late Paleocene – Middle Eocene magmatism

The LP-ME magmatism in central and northwestern Anatolia is found both in the Pontides and in the northern part of the Anatolide-Tauride Block, straddling the İzmir-Ankara-Erzincan Tethyan suture (Figs. 1 and 3). The Cenozoic magmatic belt extends eastwards into the Eastern Pontides and into the Lesser Caucasus, where it is also found on both sides of the suture (e.g., Topuz et al., 2011; Moritz et al., 2020). It continues into Iran as the Urumieh-Dokhtar magmatic arc north of the main Zagros suture, where the magmatic flare-up is dated between 53 Ma and 37 Ma (e.g., Agard et al., 2011; Kazemi et al., 2019; Stern et al., 2021; Mokthari et al., 2022). The Cenozoic magmatic belt has a length of about 3000 km (Fig. 1b). The bulk of the magmatic rocks in this long belt have subduction-related geochemical signatures, however, there are lateral temporal changes in magmatism. The Late Paleocene magmatic rocks appear to be restricted to northwest Turkey and Iran (e.g., Nouri et al., 2021). The prominent late Middle Eocene – Early Oligocene magmatic lull (45-28 Ma) of the Pontides is not observed in the Lesser Caucasus and in the Urumieh-Dokthar belt in Iran (e.g., Grosjean et al., 2022).

The İzmir-Ankara-Erzincan suture in northern Turkey marks the trace of a middle Paleozoic – Mesozoic Tethyan ocean, which closed by northward subduction under the Pontides followed by a collision between the Anatolide-Tauride Block and the Pontides in the Paleocene (e.g., Okay and Tüysüz, 1999; Mueller et al., 2019). The LP-ME magmatism is post-tectonic with respect to the closure of the İzmir-Ankara ocean.

The LP-ME magmatism in northwest Turkey is represented by plutonic and volcanic rocks. The plutons form a 410-km-long and 40 km wide belt extending from the central Anatolia to the Marmara region, roughly parallel to the Eskisehir Fault, which is a major Late

Eocene - Oligocene dextral strike-slip fault (Fig. 1, Okay et al., 2008). After a gap represented by the Upper Eocene-Miocene sedimentary rocks of the Thrace basin, Eocene granites crop out in the Rhodopes in eastern Greece and Bulgaria (Fig. 1, e.g., Marchev et al., 2013; Rohrmeier et al., 2013). The magmatism in the Rhodopes is different from the main LP-ME magmatic belt in that there is no spatial or temporal separation of the LP-ME and Oligo-Miocene magmatic rocks, and the magmatism appears to be continuous from earliest Eocene into Miocene (Fig. 1).

In northwest Turkey, there are at least twenty LP-ME plutons of varying sizes. The real extent of the LP-ME plutonism is greater since large parts of this region are covered by Neogene deposits (Fig. 3). The Early to Middle Eocene volcanic rocks crop out north of the plutonic belt in a roughly E-W direction and the magmatism extends eastwards to the Eastern Pontides, Lesser Caucasus and Iran (e.g., Keskin et al., 2008; Topuz et al., 2005, 2011; Arslan et al., 2013; Göçmengil et al., 2019; Kaygusuz et al., 2020; Moritz et al., 2020; Stern et al., 2021). In the west the LP-ME plutonic belt and the Early to Middle Eocene volcanic belt merge in the Armutlu Peninsula. The width of the LP-ME magmatic belt ranges between 120 and 180 km in northwestern Turkey (Fig. 1).

The LP-ME plutons intrude the blueschists and ophiolites of the Tavşanlı Zone of the Anatolide-Tauride Block and the pre-Jurassic basement of the Pontides. The Tavşanlı Zone represents the northern margin of the Anatolide-Tauride Block, which was subducted during the Late Cretaceous (Okay and Whitney, 2010; Plunder et al., 2015). The blueschist metamorphism is dated to ca. 80 Ma and affects both continental and oceanic lithologies (Sherlock et al., 1999; Pourteau et al., 2019). The Tavşanlı blueschists are tectonically overlain by ophiolitic mélanges and by ophiolites, which are locally unconformably overlain by Lower and Middle Eocene continental and marine sedimentary rocks (Baş, 1986; Özgen-Erdem, 2007).

3. Analytical methods

Methods employed during this study include U-Pb and Ar/Ar geochronology and apatite fission-track (AFT) thermochronology. Mineral separation was done in the Istanbul Technical University using classical techniques including crushing, sieving, and magnetic separation. For zircon and apatite separation we used sodium polytungstate as a heavy liquid. The zircons were picked under a stereographic microscope and mounted in epoxy and were polished in the Istanbul Technical University. Cathodoluminescence imaging of the zircon internal structures was carried out at the Geological Department of the Hacettepe University (Ankara). The zircons were analyzed using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of California, Santa Barbara. For the details of the method employed, see Kylander-Clark et al. (2013) and Okay et al. (2020b). Long-term reproducibility in secondary reference materials is <2% and, as such, should be used when comparing ages obtained within this analytical session to ages elsewhere. Mica samples were dated using the Ar/Ar single-grain fusion method at the Open University in the United Kingdom. For the details of the method see Okay et al. (2020b). The U-Pb and Ar/Ar analytical data are given in supporting information Tables S1 and S2, respectively. The AFT analyses were carried out at the Department of Biological, Geological and Environmental Sciences of the University of Bologna, Italy. AFT analysis and the final selection of the apatite grains were done by hand-picking under a binocular stereographic microscope. Apatite grains were mounted in epoxy resin, ground, and polished to expose planar surfaces within the grains and then etched with 5NHNO3 at 20 °C for 20 s to reveal the spontaneous tracks. Apatite fission-track age data are reported as central ages, a weighted modal age calculated through an iterative algorithm.

4. Late Paleocene-Middle Eocene plutonic rocks and their geochemical features

In central and northwest Turkey, the LP-ME plutons occur in three clusters: Sivrihisar – Günyüzü, Western Tavşanlı Zone and Southern Marmara (Figs. 1 and 3). Geochemical and isotopic characteristics from literature as well as field relations and our new geochronological data are summarized below.

4.1. The Sivrihisar – Günyüzü Plutons

There are about six plutons in this region all intruding the metamorphic rocks of the Tavşanlı Zone (Fig. 4, Kibici et al., 2008; Shin et al., 2013; Demirbilek et al., 2018; Bağcı et al., 2019). The closely spaced plutonic bodies between Günyüzü and Sivrihisar are probably connected at depth. All the plutons form prominent features in the landscape and intrude the micaschists and marbles of the Tavşanlı Zone (Fig. 5a, b); intrusive veins and dykes are common in the metamorphic rocks (Fig. 5c). Around the Sivrihisar-Günyüzü Plutons, blueschist-facies metamorphic rocks of the Tavşanlı Zone were overprinted by an Eocene high-temperature/low-pressure metamorphism (Fig. 3, Whitney et al., 2011; Seaton et al., 2013).

The Sivrihisar-Günyüzü Plutons are mainly medium-grained biotite-hornblende-bearing granodiorites and granites with subordinate monzonite, quartz-monzonite and syenite (Fig. 6a, Kibici et al., 2008; Shin et al., 2013; Demirbilek et al., 2018; Bağcı et al., 2019). The Sivrihisar Pluton consists of monzonite and the Dinek intrusion is largely quartz-monzonite. Some of the intrusive bodies contain several centimeter large K-feldspar crystals (e.g., Dinek, Karacaören, Fig. 5d). Geochemical data from the literature (Table S3; e.g., Kibici et al., 2008; Shin et al., 2013; Demirbilek et al., 2018; Bağcı et al., 2019) indicate that the granodiorites and granites belong to middle- to high-K calc-alkaline series, and monzonites and quartz-monzonites mainly to shoshonitic series on the SiO_2 vs. K_2O diagram of Peccerillo and Taylor (1976) (Fig. S1a). Rocks of the Sivrihisar-Günyüzü Plutons fall into the calcic, calc-alkalic, alkali-calcic and minor alkalic fields based on the modified alkali-lime index [(Na_2O+K_2O)-CaO] defined by Frost et al. (2001) (Fig. S2a). Even the rocks from a single intrusive body, e.g., the Karacaören Pluton, show a large scatter on the SiO_2 vs. [(Na_2O+K_2O)-CaO] diagram, which can be explained by the composite nature of the pluton and/or by the difficulty of obtaining representative compositions from granites with several centimeter-large feldspar crystals (Fig. 5d). On the multi-element variation diagrams normalized to the primitive mantle after Sun and McDonough (1989), the rocks from the Sivrihisar-Günyüzü plutons display enriched large ion lithophile elements and negative anomalies of Nb-Ta, Sr and Ti, similar to the rocks formed in subduction-related environments (Kibici et al., 2008; Demirbilek et al., 2018; Bağcı et al., 2019). Chondrite-normalized rare earth element patterns of the samples from the Sivrihisar-Günyüzü Plutons are variably steep, and display variably negative Eu anomalies (Fig. S3). The samples from the plutons with igneous crystallization ages younger than 54 Ma tend to have less steep REE patterns ($(La/Yb)_{cn} < 15$) than those older than 54 Ma ($(La/Yb)_{cn} > 15$, Fig. S3). Samples from the Karacaören Pluton have variable $(La/Yb)_{cn}$ and Eu/Eu* ratios ((La/Yb)cn = 2.84-13.77; Eu/Eu*= 0.30-1.56). Initial $^{87}Sr/^{86}Sr$ and εNd values of the plutons are 0.7053-0.7068 and 0.23 to -2.92, respectively (Fig. 7a, Table S4, Demirbilek et al., 2018). Only samples of the Kaymaz granite display significantly different initial $^{87}Sr/^{86}Sr$ and εNd values (initial $^{87}Sr/^{86}Sr$ = 0.7097-0.7100; initial εNd = -6.17 - -6.49). There is no apparent relationship between the isotopic composition, age and lithology of the plutons.

We have dated zircons from six intrusions and a dyke from the Sivrihisar – Günyüzü Plutons; the U-Pb zircon crystallization ages of the plutons range from Late Paleocene (58 Ma) to Middle Eocene (45 Ma, Fig. 8, Tables 1 and S3) and they include the oldest intrusions of the Paleocene-Eocene plutonic belt. The dates are based on concordant zircon U-Pb ages from 271 grains from six intrusions and a granitic dyke; remarkably, inherited zircons are limited only to four grains in two samples (Tables 1 and S1). The closely spaced plutons between Sivrihisar and Günyüzü have ages between 58 and 53 Ma (Fig. 8). Zircons from a one-meter-thick granitic dyke vein cutting the marbles (sample 10372) also produced a Late Paleocene age of 56.6 ± 0.6 Ma (Fig. 9). The Sivrihisar Monzonite gave a zircon U-Pb age of 55.3 ± 0.2 Ma based on 57 zircon grains, which is compatible with its 55.2 ± 0.6 Ma zircon U-Pb age reported by Rabayrol et al. (2021) but older than the 50.6 ± 0.3 Ma U-Pb zircon age reported by Özdamar et al. (2018). The very scattered U-Pb zircon ages reported by Shin et al. (2013) from the Sivrihisar Monzonite are most likely an artifact of the in situ dating in thin section, especially considering that all of the 109 concordant zircon ages from the Sivrihisar granite from our data, from Rabayrol et al. (2021) and from Özdamar et al. (2018) fall in the range of 49 Ma to 56 Ma.

The Kaymaz Granite is a small body intruding metamorphic rocks and serpentinite; gold and silver are mined in the silicified serpentinite at the contact with the granite (Rabayrol et al., 2021, Yavuz et al., 2022). The Kaymaz Granite has yielded an Early Eocene U-Pb zircon age of 55.3 ± 1.2 Ma (Fig. 8); all the dated zircons are Early Eocene with no inherited zircon grains. The Topkaya Granodiorite is a poorly exposed intrusion south of Alpu (Fig. 3), and has yielded an early Middle Eocene (Lutetian) age of 45.3 ± 0.2 Ma (Fig. 8).

We also determined biotite Ar/Ar ages from the Kadıncık and Karacaören granitoids in the Günyüzü area, to constrain the cooling of the plutons (Table 1 and S2). The biotite Ar/Ar ages are within five million years of the respective zircon U-Pb ages (56.5 Ma → 51.0 Ma and 52.7 Ma → 49.3 Ma, respectively). For the Sivrihisar Monzonite the zircon U-Pb and Ar/Ar hornblende ages are 55.2 and 53-51 Ma, respectively (Sherlock et al., 1999; Demirbilek et al., 2018). Demirbilek et al. (2018) also reported K-Ar hornblende, biotite and feldspar ages from the Sivrihisar – Günyüzü plutons, which are close to their crystallization ages. The Ar/Ar and K-Ar ages indicate fast cooling below ca. 300 °C after the crystallization of the Sivrihisar-Günyüzü plutons.

Sedimentary Eocene sequences crop out north and southwest of the Sivrihisar – Günyüzü plutons and lie unconformably over the metamorphic rocks and peridotite of the Tavşanlı Zone (Fig. 4). The Eocene sequence southwest of the plutons near Çifteler consists of several hundred meters thick shallow marine limestone of Early Eocene age (Fig. 2, Shallow Benthic Zones 5 to 11, 56-50 Ma, Özgen-Erdem et al., 2007). The Eocene sequence north of Sivrihisar consists predominantly of fluviatile sandstone and conglomerate with rare marine sandy limestone intercalations. Large benthic foraminifera in different sandy limestone beds indicate Early (SBZ10, 53-51 Ma) and Middle Eocene (Lutetian, 48-41 Ma) ages (Fig. 2, Akkiraz et al., 2022). The conglomerate beds in the Eocene series contain well-rounded clasts of limestone, marble, schist, dacite and andesite. We dated a 40-cm-large porphyritic dacite clast (sample 10048) from a conglomerate bed to constrain the age of the continental sedimentation. Forty-three zircon grains gave a Middle Eocene (Lutetian) U-Pb age of 45.7 ± 0.4 Ma (Fig. 9), compatible with the paleontological data.

4.2. The Western Tavşanlı Zone Plutons

Four large plutons (Orhaneli, Topuk, Gürgenyayla and Tepeldağ) crop out in the western part of the Tavşanlı Zone south of Bursa (Figs. 1 and 3). Similar to the Sivrihisar-Günyüzü plutons, the Western Tavşanlı Zone plutons intrude the blueschist and ophiolite.

The Western Tavşanlı Zone Plutons are petrologically and geochemically similar to the Sivrihisar – Günyüzü plutons and are represented mainly by hornblende-biotite granodiorite and granite with subordinate syenite, quartz-monzonite and monzonite (Fig. 6b, Harris et al., 1994; Altunkaynak et al., 2012; Gürarslan and Altunkaynak, 2019; Özyurt and Altunkaynak, 2020). With the exception of the Orhaneli pluton, all the plutons display a narrow compositional variation ranging from granodiorite to granite of middle to high-K calc-alkaline affinity (Fig. 6b). The Orhaneli pluton, however, comprises diorite, granodiorite, granite, syenite, monzonite and quartz-monzonite, whereby quartz-monzonite occurs as dikes (e.g., Altunkaynak et al., 2012; Çelebi and Köprübaşı, 2014; Özyurt and Altunkaynak, 2020). Thus, rocks of the Orhaneli Pluton range from middle-K to high-K calc-alkaline to shoshonitic compositions, indicative of its composite nature (Fig. S1). According to the modified alkali-lime index [(Na_2O+K_2O)-CaO], the Topuk, Gürgenyayla and Tepeldağ plutons are mainly calcic to locally calc-alkalic, while samples from the Orhaneli Pluton plot in the whole spectrum (Fig. S2). Overall, samples from the relatively younger plutons (51 to 45 Ma) such as Topuk, Gürgenyayla and Tepeldağ are characterized by relatively low chondrite-normalized La/Yb ratios (3-8), and variable negative Eu anomalies (Eu/Eu* = 0.45-1.00) (Fig S3b, Harris et al., 1994; Altunkaynak et al., 2012; Gürarslan and Altunkaynak, 2019). However, rocks of the Orhaneli Pluton display a wide-ranging chondrite-normalized La/Yb ratios (5-84) and Eu anomalies (Eu/Eu* = 0.45-1.12, Fig. S3, Altunkaynak et al., 2012; Çelebi and Köprübaşı, 2014; Özyurt and Altunkaynak, 2020). On the multi-element variation diagrams normalized to primitive mantle, the rocks from the Western Tavşanlı Zone plutons are enriched in large ion lithophile elements and show negative anomalies of Nb-Ta, Sr and Ti, similar to the rocks formed in subduction-related environments. Despite highly variable rock types, the rocks of the Western Tavşanlı Zone are characterized by narrow initial $^{87}Sr/^{86}Sr$ and εNd values of 0.70524-0.70676 and 0.55-3.89, respectively (Fig. 7b; Table S4, Altunkaynak et al., 2012; Çelebi and Köprübaşı, 2014; Gürarslan and Altunkaynak, 2019; Özyurt and Altunkaynak, 2020).

The U-Pb zircon crystallization ages of the Western Tavşanlı Zone Plutons range from 53 Ma to 45 Ma (Early to early Middle Eocene, Table 1), and their Ar/Ar cooling ages are within a few million years of their crystallization ages (Harris et al., 1994; Altunkaynak et al., 2012; Kuşcu et al., 2019).

4.3. The South Marmara Plutons

Several large Eocene plutons crop out on the southern margin of the Marmara Sea and on the Marmara islands (Fig. 3, Köprübaşı and Aldanmaz, 2004; Karacık et al., 2008; Ustaömer et al., 2009; Altunkaynak et al., 2012; Sunal et al., 2019). The South Marmara plutons comprise mainly middle- to high-K calc-alkaline I-type granodiorite and granite, and minor diorite (Fig. 6, Köprübaşı and Aldanmaz, 2004; Karacık et al., 2008; Altunkaynak et al., 2012; Ustaömer et al., 2009; Sunal et al., 2019). In contrast to the Western Tavşanlı Zone and Sivrihisar-Günyüzü plutons, the South Marmara plutons do not contain any monzonite, syenite and quartz-monzonite. According to alkali lime index of Frost et al. (2001), the South Marmara plutons are calcic to calc-alkalic (Fig. S2c). Overall, rocks of the South Marmara Plutons display variable chondrite-normalized La/Yb (3-14) and Eu/Eu* (0.35-1.05) values (Fig. S3c, Köprübaşı and Aldanmaz, 2004; Altunkaynak et al., 2012; Sunal et al., 2019).

There are no published zircon U-Pb ages from the Fıstıklı Granite, which crops out on the Armutlu Peninsula, and the two published disparate K-Ar biotite ages are 48 and 35 Ma (Delaloye and Bingöl, 2000). We dated two samples from different parts of the Fıstıklı Granite (Fig. 1); they produced similar U-Pb zircon ages of 48.0 ± 0.4 and 48.0 ± 0.5 Ma (Fig. 9; Table 1 and S3), respectively, indicating crystallization during latest Early Eocene. There were no inherited zircons among the 66 grains dated. To constrain the temporal relation between plutonism and volcanism on the Armutlu Peninsula, we dated zircons from a 40-m-thick tuff bed in the northern part of the Armutlu Peninsula (sample 14396, Fig. 9). The tuff occurs within an Eocene sequence of turbiditic marine sandstone and shale (Fig. 10b, Özcan et al., 2012). An Early Eocene age 48.0 ± 0.7 Ma was obtained from the tuff bed based on 33 concordant zircon ages (Fig. 9), the same age as that of the Fıstıklı Granite. The age of the tuff also indicates that magmatism occurred during a time of marine sedimentation.

The North Kapıdağ Granite intrudes the Triassic metamorphic rocks of the Sakarya Zone. The northern margin of the pluton is deformed by a shear zone and the granite in this region shows a strong planar fabric (Fig. 10a, Türkoğlu et al., 2016). Sample 7569 was collected from the shear zone; it yielded a U-Pb zircon age of 47.8 ± 1.1 Ma (Fig. 9), which falls on the Early-Middle Eocene boundary. This age also provides a lower age limit for the shear zone activity. Again, there were no inherited zircon grains among the dated zircon grains. The K-Ar biotite and hornblende ages from the North Kapıdağ Granite are in the range of 42-38 Ma (Delaloye and Bingöl, 2000).

The LP-ME magmatic flare-up ended at 45 Ma, and was followed by a magmatically quiet period until the Late Oligocene (ca. 28 Ma). In this respect, the South Kapıdağ intrusion, which has a Late Eocene U-Pb zircon age of 36.8 ± 0.7 Ma (Altunkaynak et al., 2012) is an exception. This age value is consistent with the Ar/Ar hornblende age of 36.0 ± 0.1 Ma (Altunkaynak et al., 2012) and K-Ar biotite age of 36-38 Ma (Delaloye and Bingöl, 2000) from the same intrusion. The South Kapıdağ Pluton is also geochemically different from the Middle Eocene South Marmara plutons, characterized by high chondrite normalized La/Yb ratios of 12-19 and a near absence of Eu anomaly (Fig. S3c, Eu/Eu* = 0.85-0.99, Altunkaynak et al., 2012). It probably constitutes an extension of the Late Eocene-Oligocene magmatic activity observed in the Biga Peninsula and western Thrace (e.g., Ersoy et al., 2017a), possibly related to the exhumation of the Rhodope Complex.

5. The Eocene volcanic rocks

The Eocene volcanic and volcanoclastic rocks crop out north of the plutonic belt in two east-west trending belts and are coeval with plutonism farther south (Figs. 1 and 3). The Kızderbent volcanic rocks crop out on the Armutlu Peninsula and in the Almacık region;

these two regions were contiguous before the activity of the North Anatolian Fault (Akbayram et al., 2016). The Kızderbent volcanic and volcaniclastic rocks are intercalated with Lower and early Middle Eocene (Lutetian) marine sandstone, shale and marl (Özcan et al., 2012, Gülmez et al., 2013, Fig. 10b). The thickness of the Eocene sequence reaches 1500 meters. Eocene andesite dykes are common and crosscut the metamorphic rocks and the Eocene volcanic rocks (Kürkçüoğlu et al., 2008; Gülmez et al., 2013). A particularly dense dyke swarm with a width of 4 km cuts the marbles on the Armutlu Peninsula west of the İznik Lake (Fig. 10c, d). The dykes strike N42W and their width ranges from a few meters to tens of meters and they have lengths up to 8 km. The age of the Kızderbent volcanic rocks based on whole rock and mineral K-Ar and Ar/Ar dating ranges between 52 Ma and 42 Ma (Kürkçüoğlu et al., 2008; Gülmez et al., 2013; Büyükkahraman, 2016); a single zircon U-Pb age obtained in this study from a tuff bed is 48.0 ± 0.7 Ma (Figs. 9 and 10b).

In contrast to the Kızderbent volcanic rocks, which occur in an extensional marine setting, the Nallıhan volcanic rocks in the south are found in the Sarıcakaya foreland basin south of a major Eocene thrust fault (Fig. 3, Şahin et al., 2019; Mueller et al., 2019). The Nallıhan volcanic rocks are intercalated within a continental sequence of red sandstone and conglomerate (Şahin et al., 2019; Mueller et al., 2019) with rare shallow marine limestone beds of Middle Eocene age (SBZ13, ca. 44 Ma, Okay et al., 2020b). There are also small shallow-level intrusions. Zircon U-Pb ages from the Nallıhan volcanic rocks range between 52 Ma and 48 Ma (Kasapoğlu et al., 2016; Mueller et al., 2019).

A compilation of the literature data suggests that the Kızderbent and Nallıhan volcanic rocks consist predominantly of basaltic andesite and andesite and subordinate basalt, trachy-andesite, trachyte, dacite and rhyolite and their pyroclastic equivalents (Fig. 11a, Kürkçüoğlu et al., 2008; Gülmez et al., 2013; Yıldız et al., 2015; Büyükkahraman, 2016; Kasapoğlu et al., 2016; Ersoy et al., 2017a). They are variably altered as reflected in variable loss on ignition values (0.6-8.7 wt%, Table S3). The Eocene volcanic rocks display mainly a middle- to high-K calc-alkaline affinity, and a subordinate alkaline affinity (Figs. 10b and S1). The alkaline volcanic rocks appear to be confined to the Nallıhan area. All the volcanic rocks are characterized by narrow initial $^{87}Sr/^{86}Sr$ and εNd isotopic ratios (Fig. 7d, Kürkçüoğlu et al., 2008; Gülmez et al., 2013; Altunkaynak and Dilek, 2013; Kasapoğlu et al., 2016). The initial εNd values range from 5.40 to 0.50, and the initial $^{87}Sr/^{86}Sr$ values from 0.70390 to 0.70515. The alkaline volcanic rocks display nearly identical Sr and Nd isotopic compositions as the middle- to high-K calc-alkaline ones. The model ages calculated according to a depleted mantle range from 0.41 to 0.98 Ga; the majority is characterized by lower values of 0.44-0.75 Ga, which are significantly younger than those from the older granitoids (Kürkçüoğlu et al., 2008; Gülmez et al., 2013; Kasapoğlu et al., 2016; Büyükkahraman, 2016). All the volcanic rocks display geochemical features suggesting formation in subduction-related environments. However, the Nallıhan volcanic rocks tend to have much steeper REE patterns than the Kızderbent volcanic rocks with $(La/Yb)_{cn}$ values of 5-15 and 2-5, respectively (Fig. S3).

Cenozoic volcanic rocks crop out over large areas in the Biga Peninsula (Fig. 1). Volcanism on the Biga peninsula is different than the rest of northwest Anatolia in that it is continuous from late Middle Eocene to the Early Miocene (43-18 Ma, e.g., Ersoy et al., 2017a, b; Kuşcu et al., 2019). In this respect, it is similar to the magmatism in the Rhodopes (Fig. 1). The Biga Peninsula forms part of the Thrace Basin, where there is a thick Upper Eocene – Lower Oligocene marine clastic sequence with tuff horizons (Özcan et al., 2018).

6. Eocene thermal metamorphism

The Eocene thermal event, which was responsible for magmatism, also produced regional metamorphism, which is observed in two regions in the Tavşanlı Zone (Figs. 3 and 4). In both regions Late Cretaceous high pressure – low temperature metamorphic rocks of the Tavşanlı Zone were overprinted by an Eocene low to medium pressure - high temperature metamorphism. Southeast of Uludağ, blueschist metapelite has been transformed into andalusite micaschist with the paragenesis andalusite + cordierite + biotite + muscovite + quartz + K-feldspar + plagioclase over an area of ~ 10 km long and ~ 8 km across around the Tepeldağ pluton (Okay and Satır 2006). Eocene metamorphism was associated with folding and development of new foliation. Pressure-temperature conditions of the Eocene metamorphism were determined as 2 ± 1 kbar and 575 ± 50° C. Rubidium-strontium muscovite and biotite ages of a micaschist sample are 46 ± 3 Ma and 39 ± 1 Ma, respectively, similar to the 45.0 ± 0.2 Ma U-Pb zircon age from the neighboring Tepeldağ plutons (Okay and Satır, 2006).

Southeast of Sivrihisar, blueschist-facies micaschist and marble have been overprinted by a lower pressure and higher temperature regional metamorphic event of Eocene age characterized by andalusite and sillimanite (Fig. 4, Whitney et al., 2011; Seaton et al., 2013). Ar/Ar muscovite ages in the Günyüzü metamorphic rocks in the vicinity of Sivrihisar are mostly 63-59 Ma (Seaton et al., 2013), which is close to the ages of the intrusive granites (58-55 Ma). During this study, mica Ar/Ar ages were obtained from the micaschist from west of Günyüzü to constrain the extent of the Eocene metamorphism (Fig. 4). A sample (8877) close to the Karacaören granite yielded muscovite and biotite ages of ca. 50 Ma, and ca. 26 Ma, respectively (Table 1 and S2), whereas samples farther away from the granites (10131 and 10139) yielded Late Cretaceous ages of 84 Ma and 109 Ma (Table 1 and S2, Fig. 4). Whitney et al. (2011) regard the blueschist facies and lower pressure metamorphism as part of a progressive geological event. However, the 20 my time gap between these two events, and the close spatial and temporal association of Eocene metamorphic and granitic rocks in the Günyüzü area indicate that the Eocene event is unrelated to the high-pressure metamorphism. These high-temperature/low-pressure metamorphic areas are comparable to the low-pressure metamorphic belts associated with the Mesozoic plutonism in the Sierra Nevada and Great Basin (Western U.S.A) (e.g., Barton and Hanson, 1989; Spear, 1995, p. 5).

7. Exhumation of the Late Paleocene – Middle Eocene plutons

The LP-ME plutons form a belt spatially distinct from the partly coeval Eocene volcanic rocks (Figs. 1 and 3). This geometry indicates post-Middle Eocene uplift and erosion to exhume the plutons, which were emplaced at depths of about 10 km (Harris et al., 1994; Köprübaşı and Aldanmaz, 1994). To constrain the exhumation of the LP-ME plutonic belt, apatite fission-track ages (AFT) were obtained from five granite samples from the Sivrihisar-Günyüzü plutons. The AFT ages range from 42 Ma to 29 Ma and indicate Middle Eocene to Early Oligocene exhumation (Table 2, Figs. 2 and 4). A single published apatite U-Th/He age of 38 Ma from the Sivrihisar Monzonite also points to a Late Eocene exhumation (Özdamar et al., 2018). The Sivrihisar-Günyüzü and Western Tavşanlı plutons are aligned around the Eskişehir Fault, a major dextral strike-slip fault (Figs. 1 and 3), which was active during the Late Eocene and Early Oligocene (35-28 Ma, Okay et al., 2008; Topuz and Okay, 2017). The exhumation of these plutons is most likely linked to transpressive activity along the Eskişehir Fault.

8. Quantifying the crustal thickness from Late Paleocene to Late Eocene

Whole-rock Sr/Y and La/Yb ratios of basic and intermediate igneous rocks from modern magmatic arcs and young collisional belts display positive correlation with crustal thickness (e.g., Mantle and Collins, 2008; Chapman et al., 2015; Profeta et al., 2015; Hu et al., 2017). Garnet is stabilized at higher crustal pressures at the expense of plagioclase during the high-pressure fractionation of basic to felsic melts. Therefore, melts which are products of high-pressure fractionation will be depleted in garnet-compatible elements (heavy rare earth elements, Y, Sc) and enriched in plagioclase-compatible elements (e.g., Sr). Thus, melts will tend to have higher La/Yb and Sr/Y ratios when the crust is thick.

We calculated the crustal thicknesses using the empirically derived formulation for Sr/Y ratio of Hu et al. (2017). The results are given in Table S3. During the calculations, we used the bulk rock compositions with SiO_2 = 55-72 wt%, MgO = 0.5-6.0 wt%, Rb/Sr < 0.35, Sr/Y <60 and La < 60 ppm, as suggested by Hu et al. (2017). The Rb/Sr filter is used to discard samples that were strongly influenced by fractionation within the crust. In addition, analyses with high loss on ignition values (LOI > 3 wt%) are discarded. High values of loss on ignition values pose serious problems in the Early to Middle Eocene volcanic rocks (1.53 to 9.50 wt%) (Table S3).

Sr/Y and chondrite-normalized La/Yb ratios of the Late Paleocene igneous rocks (58-54 Ma) are high, and decrease in the Early to Middle Eocene igneous rocks (54-45 Ma) and increase again in the Late Eocene igneous rocks (ca. 38 Ma), although the latter is based only on data from the South Kapıdağ pluton (Fig. 12a, b, Table S3). These values display large scatter only in composite plutons such as Orhaneli. Calculation of the crustal thickness based on the Sr/Y ratios yielded crustal thicknesses of 63-66 km for the Late Paleocene, and 35-46 km for the Early to Middle Eocene and 60-65 km during Late Eocene (38 Ma) (Fig. 12c). The calculated crustal thicknesses show a close agreement with the time periods when the Pontides subsided below sea level, and emerged above sea level, as discussed below.

9. Depositional environment during the Late Paleocene – Middle Eocene magmatic flare-up

The depositional and tectonic environments before and during the LP-ME magmatism can be deduced from the geological record of the Pontides and the Anatolide-Tauride Block. The complete subduction of the İzmir-Ankara-Erzincan oceanic lithosphere was followed by the continental subduction of the northern margin of the Anatolide-Tauride Block during the Late Cretaceous at ca. 80 Ma (Sherlock et al., 1999). This is reflected in the blueschist facies metamorphism observed in the Tavşanlı Zone. The blueschists and the overlying ophiolites are unconformably overlain by shallow marine Lower Eocene limestone and sandstone (Fig. 1, Baş, 1986; Özgen-Erdem et al., 2007). The period between the latest Cretaceous and Early Eocene (80-56 Ma) was a time of uplift and erosion for the Tavşanlı Zone.

The Mesozoic-Cenozoic sedimentary record is more complete in the Pontides, which constituted the active margin during the Late Cretaceous. It is best preserved in the Central Sakarya Basin (Fig. 3, Saner, 1980; Ocakoğlu et al., 2018; Mueller et al., 2019). Here, Upper Cretaceous (Campanian) deep marine turbidites pass upwards into shallow marine sandstone, limestone and eventually to continental red beds of Paleocene age (Fig. 2). The transition from turbidites to continental red beds (flysch to molasse transition) is diachronic and youngs from Early Paleocene (ca. 63 Ma) in the south in the Nallıhan region (Saner, 1980; Ocakoğlu et al., 2018) to the Late Paleocene (ca. 58 Ma) in the north in the Göynük region (Açıkalın et al., 2015). The diachronic uplift reflects the northward migration of deformation front following the Early Paleocene collision between the Pontides and the Anatolide-Tauride Block. Convergence between Africa and Eurasia shows a major decrease during the latest Cretaceous and Paleocene (Fig. 2, Rosenbaum et al., 2002; Smith, 2006) possibly reflecting the continental collision. By the Late Paleocene (56 Ma) the whole collision zone has become subareal. Early Paleocene (ca. 63 Ma) can be taken as the beginning of the continental collision, defined as the first contact of the opposing continental plates.

The Late Paleocene uplift and erosion were soon followed by a major phase of marine and continental sedimentation starting in the Early Eocene (ca. 56 Ma) and continuing into the early Middle Eocene (ca. 45 Ma, Fig. 2, Özcan et al., 2012). Volcanism accompanied the Eocene sedimentation, and Kızderbent volcanic and volcanoclastic rocks are commonly intercalated with shallow marine and continental sedimentary rocks. The thickness of the volcano-sedimentary Eocene sequence in northwest Turkey ranges up to 1500 meters (Özcan et al., 2012). Northeast-southwest (N48E) extension during the Eocene is indicated by the regional dyke swarm on the Armutlu Peninsula (Fig. 10c, d). The strike of the regional dyke swarms is parallel to the σ1-σ2 plane, and the normal to the dykes represent the minimum compressive principal stress σ3 (e.g., Ramsay and Lisley, 2000). Marine sedimentation ceased at the end of the Middle Eocene (41 Ma) with the uplift of western and central Anatolia and the whole of the Pontides, with the exception of the Thrace Basin, became a land area (Özcan et al., 2018; Okay et al., 2020a). Close to the İzmir-Ankara suture, however, the shortening started already in the Early Eocene as documented in the Sarıcakaya foreland basin (Mueller et al., 2019)

The geochemistry of the LP-ME plutonic rocks indicates crustal thinning at the beginning of the Early Eocene (ca. 55 Ma, Fig. 11). The Early Eocene also corresponds to an increase in the convergence between Africa and Eurasia (Fig. 2, Rosenbaum et al., 2002; Smith, 2006). The increase in convergence can be related to the northward subduction of the southern Tethys. Although the İzmir-Ankara ocean closed in the Paleocene, the southern branch of the Neo-Tethys between the Anatolide-Tauride Block and Africa-Arabia stayed open until the Miocene (Okay et al., 2010; Cavazza et al., 2018). The present Eastern Mediterranean represents a relict of this ocean.

The sedimentary record indicates that the LP-ME magmatism started during the final stages of the Paleocene collision along the Izmir-Ankara-Erzincan suture and continued during the Early-Middle Eocene extension and ended with the uplift of western and central Anatolia.

10. Discussion on the origin of the Late Paleocene – Middle Eocene magmatism

Any mechanism for the origin of the LP-ME magmatism must be compatible with the following major constraints. 1) The LP-ME magmatic rocks in northwestern Turkey occur in a ca. 150-200 km wide, roughly E-W trending belt, and extend eastwards without any spatial or temporal break into the Eastern Pontides, Lesser Caucasus and Urumieh-Dokthar belt in Iran (Fig. 1b). In this 3000 km long belt, Eocene magmatism shows similar geochemical and tectonic features. 2) The magmatism started at the Late Paleocene (58 Ma) during the late stages of the continental collision and was most voluminous during Early to early Middle Eocene extension (53 to 45 Ma) and declined substiantially after 45 Ma with the uplift of Anatolia above sea level. In the Urumieh-Dokthar belt in Iran high-flux magmatism also took place between 53 and 37 Ma (Mokthari et al., 2022). 3) The geochemistry of the LP-ME magmatic rocks show typical subduction zone signatures with little or no evidence for crustal and asthenospheric melting, e.g., consistent negative Nb-Ta, Ti anomalies on the multi-element variation diagrams. Rocks that represent the products of pure crustal and asthenospheric melting have not been documented to date. 4) The magmatism was post-tectonic with respect to the formation of the İzmir-Ankara suture but was coeval with the northward subduction of the southern branch of the Neo-Tethys.

Slab-breakoff, lithospheric delamination and subduction were suggested as the cause of the LP-ME magmatism in northwest and central Anatolia. Most studies relate the LP-ME magmatism in northwest Anatolia to slab breakoff following the Paleocene continental collision (Altunkaynak, 2007; Keskin et al., 2008; Karacık et al., 2008; Altunkaynak et al., 2012; Altunkaynak and Dilek, 2013; Ersoy and Palmer, 2013; Gülmez et al., 2013; Kasapoğlu et al., 2016; Ersoy et al., 2017a, b; Gürarslan and Altunkaynak, 2019; Dokuz et al., 2019). Slab breakoff is frequently used as a model to explain post-collisional magmatism (e.g., Davis and von Blanckenburg, 1995; Atherton and Ghani, 2002; Yuan et al., 2010). It is a natural consequence of continental subduction; the down-going dense oceanic lithosphere will eventually separate from the attached buoyant continental lithosphere (Davis and von Blanckenburg, 1995). The hot asthenosphere rises and fills the space between the subducting continental and oceanic slabs, and generates magmatism and uplift. The main predictions of the slab breakoff model can be summarized as follows: 1) The slab breakoff occurs after the continental subduction, and is largely coeval with the continental collision (e.g., von Blanckenburg and Davies, 1995). 2) It results in the uplift of the collision zone. Modelling studies show a sharp breakoff signal in the topography over the collision zone with the uplift rate inversely related to the depth of breakoff (e.g., Duretz et al., 2011). However, in practice it is difficult to separate uplift due to continental collision from that due to slab breakoff. 3) Magmatism and uplift associated with slab breakoff occurs in a relatively narrow zone along the suture.

In slab breakoff models the LP-ME magmatism in northern Turkey is linked to the slab breakoff of the İzmir-Ankara oceanic lithosphere. The İzmir-Ankara ocean closed in the Paleocene with the collision of the Pontides and the Anatolide-Tauride Block, however, the southern branch of the Neo-Tethys, which extended into Iran, existed until the Miocene. The Eocene magmatism in the Urumieh-Dokthar belt in Iran is generally attributed to the northeastward subduction of this southern branch of Neo-Tethys (e.g., Stern et al., 2021). It is highly unlikely that the 3000-km-long LP-ME belt magmatic belt was formed by slab breakoff in the west and by subduction in the east, especially since magmatism along the belt shows similar temporal and geochemical features. It is highly probable that there is a single cause for the LP-ME magmatic belt in Anatolia and Iran. Furthermore, recent numeric models show that the slab break cannot produce much magmatism as commonly postulated (e.g., Freeburn et al., 2017; Niu, 2017; Garzanti et al., 2018). Thus, we regard the slab breakoff model an improbable cause for the LP-ME magmatic flare-up.

Köprübaşı and Aldanmaz (2004) suggested lithospheric delamination as the cause of the Eocene magmatism. Lithospheric delamination involves the detachment of the lithospheric mantle and lowermost part of crust following crustal and lithospheric thickening. The asthenospheric mantle flows into the space created by the detached lithospheric mantle and creates uplift, extension and magmatism (e.g., Bird, 1979). A prerequsite of lithospheric delamination is major crustal thickening, which allows the dense lower lithospheric mantle to detach and sink into the asthenosphere (e.g., Ducea, 2011). In northwest Anatolia crustal thickening following the Paleocene collision is confined to the Tavşanlı Zone. Paleocene sedimentary sequences are preserved in the Pontides within a few ten kilometres of the İzmir-Ankara suture (Fig. 3). In the Menderes Massif the pre-metamorphic sedimentary sequence extends up to the Paleocene and locally into Early Eocene (Özer et al., 2001). The continental collision between the Pontides and the Anatolide-Tauride Block did not lead to large scale crustal thickening because part of the convergence was taken up by the subduction of the southern branch of the Neo-Tethys. Furthermore, delamination occurs in a broad semi-circular area, such as the southern Sierra Nevada in California (e.g., Saleeby et al., 2003); it is difficult to attribute the 3000 km Eocene magmatic belt to this process, especially considering that the collision along the Zagros suture was Oligo-Miocene in age (e.g., Okay et al., 2010; Stern et al., 2021). Hence, delamination is an unlikely cause of the Eocene magmatism

The third model for the LP-ME magmatism is subduction. Episodic magmatic flare-ups in arcs are a widely observed phenomenon (e.g., Ducea et al., 2015), and might be related to tapping of previously stored magma in the mantle lithosphere (e.g., Chapman et al., 2021). Tomographic studies indicate the presence of a major subducted slab under the Aegean reaching a depth of ~1,400 km (e.g., Bijwaard et al., 1998; Piromallo and Morelli, 2003; Wortel and Spakman, 2000). This shows that the subduction of the southern Neo-Tethys goes back at least to the Eocene and possibly earlier (e.g., Spakman et al., 1988). An argument against the magmatic arc origin for the LP-ME magmatism is the 450 km distance between the present Hellenic trench and the LP-ME magmatic rocks. In subduction zones the mean distance between the trench and volcanic arc is 230 ± 84 km, although it can be as large as 570 km (e.g., Heurat et al., 2011). However, the Aegean region and the Western Anatolia have undergone major north-south extension in the Neogene, and the distance was smaller during the Eocene (e.g., Jolivet and Brun, 2010). Most subduction zones are characterized by the presence of a magmatic arc, fore-arc basin and subduction-accretion complex. During the LP-ME (58-45 Ma) magmatism, the region between the arc and the trench in western Anatolia was, on the other hand, mostly an erosional area. Arguments in favor of the subduction model include: a) The Paleocene-Eocene magmatic belt extends for over 3000 km from northwest Turkey to Iran (Fig. 1b); such a long magmatic belt is difficult to generate except above a subduction zone. b) The geochemistry of the LP-ME Paleocene-Eocene magmatic rocks are similar to those formed above subduction zones. c) The southern branch of the Neo-Tethys was subducting northward during the Eocene.

Episodic magmatic flare-ups in arcs are a widely observed but poorly understood phenomenon (e.g., Ducea et al., 2015); they might be related to tapping of previously stored magma in the mantle lithosphere (e.g., Chapman et al., 2021).

11. Conclusions

The main conclusions of this study are as follows:

1. Late Paleocene –Middle Eocene represents a period of intense magmatism in the Pontides extending into the Lesser Caucasus and Iran forming a belt of over 3000 km in length (Fig. 1b).

2. New U-Pb zircon data indicate that the magmatism in northwest Anatolia started at the Late Paleocene (58 Ma) during the final stages of continental collision. It was particularly intense during the Early to early Middle Eocene (53-45 Ma) extension and decreased abruptly at 45 Ma with the uplift of Anatolia (Fig. 2).

3. The LP-ME plutonic belt, ca. 410 km long and ca. 40 km wide, cuts across the Izmir-Ankara-Erzincan suture (Fig. 3). New apatite fission tract ages indicate that the plutonic belt

was exhumed during Late Eocene-Early Oligocene (44-28 Ma, Fig. 2), possibly by transpression along the dextral strike-slip Eskişehir Fault.

4. Crustal thickness variations based on whole rock Sr/Y ratios of the intermediate igneous rocks point to the presence of a thickened crust during Late Paleocene to earliest Ypresian (58-54 Ma), and of a relatively thinned crust during middle Ypresian to middle Lutetian (52-45 Ma), and relatively thickened crust during Late Eocene-Early Oligocene (38-28 Ma, Fig. 12). These periods are compatible with the depositional environments in the Pontides. The most voluminous magmatism occurred during the period of relatively thinned crust at 53-47 Ma when the NW Anatolia was below sea level (ca. 53-45 Ma).

6. All of the LP-ME magmatic rocks show subduction-related geochemical signatures. The volcanic rocks were derived mainly from juvenile melts, and the intrusions from the juvenile melts that assimilated variable amounts of crustal material. So far, there are no documented rock types that could be interpreted as products of pure crustal or asthenospheric melts.

7. The LP-ME magmatic flare-up probably occurred in a magmatic arc above the northward subducting southern Neo-Tethys ocean.

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Figure captions

Fig. 1. a) Tectonic map of northern Aegean and northwest Anatolia showing the distribution of Late Cretaceous, Eocene and Oligo-Miocene magmatism. b) Tectonic map of the Middle East showing the the distribution of the Eocene magmatism. For the Cenozoic isotopic ages in the Rhodopes see the compilations in Marchev et al. (2005) and Perkins et al. (2018).

Fig. 2. Late Cretaceous to late Cenozoic magmatism, sedimentation and tectonic events in northwest Turkey. Also shown is the convergence rate between Africa and Eurasia after Rosenbaum et al. (2002) and Smith (2006). Kz, Kızderbent volcanics; Na, Nallıhan volcanics; SBZ, shallow benthic zones.

Fig. 3. Geological map of northwestern Turkey and northern Aegean showing the distribution and ages of the Late Paleocene - Eocene magmatic rocks. *Al* Almacık; *Bz* Bozaniç; *Fs* Fıstıklı; *Gy* Gürgenyayla; *Kb* Karabiga; *Ky* Kaymaz; *Kz* Kızderbent; *Mr* Marmara; *Na* Nallıhan; *Nkp* North Kapıdağ; *Pi* Princes Island: *Skp* South Kapıdağ; *Tep* Tepeldağ; *Tp* Topuk. The sources for the ages are: 1. This study, 2. Ersoy et al., 2017, 3. Altunkaynak et al., 2012, 4. Ustaömer et al., 2009, 5. Sunal et al., 2019, 6. Şen 2020, 7. Kürkçüoğlu *et al* 2008, 8. Kasapoğlu et al., 2016, 9. Gülmez et al., 2013, 10. Akgündüz et al., 2012, 11. Topuz and Okay 2017, 12. Şahin et al., 2019, 13. Mueller et al., 2019, 14. Büyükkahraman 2016.

Fig. 4. Geological map of the Sivrihisar – Günyüzü area in central Anatolia showing the distribution of the Cenozoic granites and the new isotopic ages (based on Demirbilek et al. (2018) and our mapping). For location see Fig. 3.

Fig. 5. Field photographs of the Late Paleocene – Middle Eocene magmatic rocks from the Sivrihisar-Günyüzü plutons. a. Tekören Granodiorite intruding the marbles and schists of the Tavşanlı Zone in the Sivrihisar-Günyüzü area. b. Sivrihisar Monzonite. c. Granitic veins cutting the schists in the Günyüzü area. d. Kadıncık granite with several centimeter large feldspar crystals.

Fig. 6. Compositional variations of the Late Paleocene – Middle Eocene igneous rocks from the Western Anatolia in the diagram SiO_2 vs $Na_2O + K_2O$ diagram (after Middlemost 1994). The division line (broken) for alkaline and subalkaline series is taken from Irvine and Barager (1971). Data sources are given in the text.

Fig. 7. Initial $^{87}Sr/^{86}Sr$ versus initial εNd values of Late Paleocene-Middle Eocene igneous rocks. Data are from Karacık et al. (2008), Kürkçüoğlu et al. (2008), Altunkaynak et al. (2012), Gülmez et al. (2013), Kasapoğlu et al. (2016), Büyükkahraman (2016), Demirbilek et al. (2018), Bağcı et al. (2019), Çelebi and Köprübaşı (2014), Gürarslan and Altunkaynak (2019) and Özyurt and Altunkaynak (2020).

Fig. 8. Zircon U-Pb concordia diagrams from the Late Paleocene – Early Eocene granites. For data see Table S1.

Fig. 9. Zircon U-Pb concordia diagrams from the Late Paleocene – Middle Eocene granites and volcanic rocks. For data see Table S1.

Fig. 10. Field photographs of the Eocene magmatic rocks. a. Sheared Northern Kapıdağ Granite. b. Lower Eocene tuff (sample 14396, 48.0 Ma) overlying siliciclastic marine turbidites. c. Google Earth image of the Eocene dyke swarm west of the İznik Lake on the Armutlu Peninsula. For location see Fig. 3. d. Field photo of the dyke swarm. Andesite dykes are less resistant to weathering than marble and form the green ribbons in c and d.

Fig. 11. a. Nb/Y vs. Zr/Ti classification diagram (Pearce 1996) showing compositional variation of the Early to Middle Eocene volcanic rocks from NW Turkey. b. Co vs Th classification diagram (Hastie *et al* 2007) showing mainly middle- to high-K nature of the Eocene volcanic rocks. c. Data plotted in the Nb/Yb vs. Th/Yb diagram (Pearce 2008) showing their orogenic nature. Data are from Gülmez et al. (2003), Yıldız et al. (2015), Kasapoğlu et al. (2016), and Büyükkahraman (2016).

Fig. 12. a-b. Yb_{cn} vs. (La/Yb)cn, and Y vs Sr/Y diagrams for Late Paleocene –Eocene plutonic rocks from NW Anatolia. **c**. Temporal variation of crustal thickness calculated from Sr/Y ratios of the intermediate plutonic rocks after Hu et al. (2017). Compositional data are from Harris et al. (1994), Köprübaşı and Aldanmaz (2004), Kibici et al. (2008), Ustaömer et al. (2009), Altunkaynak et al. (2012) Çelebi and Köprübaşı (2014), Demirbilek et al. (2018), Sunal et al. (2019), Bağcı et al. (2019), Gürarslan and Altunkaynak, (2019) and Özyurt and Altunkaynak (2020).

Tables

Table 1. Zircon U-Pb and Ar/Ar mica age data from northwest Anatolia.

Table 2. Apatite fission track age data from the Late Paleocene – Middle Eocene granites from northwest Anatolia.

Supplementary Figures

Fig. S1. SiO_2 vs. K_2O variation of the Late Paleocene - Middle Eocene igneous rocks from the Western Anatolia. The dividing lines for low-K tholeiitic, middle-K calc-alkaline, high-K calc-alkaline and shoshonitic series are after Peccerillo and Taylor (1976). For dataset see Table S3.

Fig. S2. Compositional variation of the Late Paleocene – Middle Eocene intrusive rock types from the Western Anatolia in SiO_2 vs. (Na_2O+K_2O)-CaO after Frost et al. (2001). For dataset see Table S3.

Fig. S3. Variation of Eu/Eu* vs chondrite normalized La/Yb ratios of the Late Paleocene – Middle Eocene igneous rocks from the Western Anatolia. Data sources are given in the text. For dataset see Table S3.

Supplementary Tables

Table S1. New U-Pb zircon data from magmatic zircons from twelve Late Paleocene – Middle Eocene magmatic rock samples from central and northwest Turkey. For location of samples see Fig. 3.

Table S2. Ar/Ar muscovite and biotite age data from the metamorphic rocks of the Tavşanlı Zone and intrusive plutons. For sample locations see Fig. 3.

Table S3. Whole rock major and trace element compositions of the Late Paleocene – Middle Eocene igneous rocks from the NW Anatolia.

Table S4. The Sr-Nd isotopic compositions of the Late Paleocene – Middle Eocene igneous rocks in the Western Anatolia.