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Research Paper

A Late Cretaceous ensimatic arc developed during closure of the northern branch of Neo-Tethys (central-northern Turkey)

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A R T I C L E I N F O

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A B S T R A C T

Studies on differentiation of ensimatic arc units from melange units in the Northern Anatolian Ophiolitic Belt (NAOB) are very rare. The study area represents the southern edge of the central part of the NAOB. The aim of the study is to distinguish the main units of NAOB and to define the geotectonic setting of the Darmik Ensimatic Arc Association (DEAA). To study the ensimatic arc units as an independent tectonic unit is important and facilitates understanding of the geological evolution of the NAOB. During field studies, the contact relationships within the Darmik Ensimatic Arc Association (DEAA) units and also with other tectonic units were reviewed. Then, paleontological, geochronological, petrological and also geochemical properties of the DEAA have been defined. In the present study, ensimatic arc units have been distinguished from ophiolitic association for the first time, in the region. As a result of the study, the DEAA is divided into two levels and lower level named as the Kartal unit and upper level named as the İzibüyük unit. In the Kartal unit, basaltic and andesitic lavas with their equivalent pyroclastic rock units are dominant. Radiolarite and mudstones interbedded within the Kartal unit of DEAA have Turonian and Santonian age. In addition, the age of basalt samples of DEAA are 98.7 ± 2.4 Ma, defined using the ^{40}Ar/^{39}Ar method. The İzibüyük unit of DEAA comprises conglomerate, sandstone, claystone, mudstone, clayey limestone, micritic limestone with volcanic interbeds and also calciturbidites. Santonian–Maastrichtian ages were obtained from this unit of the DEAA. In conclusion, the age of DEAA is widely accepted as Late Cretaceous. After the evaluation of the analysis, the volcanics of the DEAA originated from calcalkaline-basalts, which reflect ensimatic arc magmatism.

1. Introduction

The Northern Anatolian Ophiolitic Belt (NAOB) is one of the most important ophiolitic belts in Turkey (Fig. 1A). The study area represents the central part and southern edge of this belt (Fig. 1B).

In fact this region has been the focus of various studies over a long period of time. For example, Özcan et al. (1980) defined the main geological units of the region. On the basis of this study, the Darmik volcanics constituted the upper level of Eocene units, which are the main topic of the present study. Yılmaz and Özer (1984) correlated Akdağmadeni and Karaçayır regions and they suggested that the Darmik volcanics were Upper Eocene in age. However, during the same period it was also suggested that similar volcanics to the east outside of the study area, around Karaçayır (Sivas) region, could be Upper Cretaceous in age (Yılmaz, 1981).

In later years, during preparation of 1/100,000-scale geological maps of the region, it was proposed that the Darmik volcanics might be older than Eocene and might be Paleocene in age, without presenting new data (Yılmaz et al., 1995a). In addition, 1/100,000-scale geological mapping efforts continued around the Yozgat region (Akçay et al., 2008; Dalkılıç et al., 2008). New geological studies have gone on to solve different problems that arose as a result of the studies presented above and to specify the age, setting and structural evolution of the Darmik volcanics in the framework of MTA projects.

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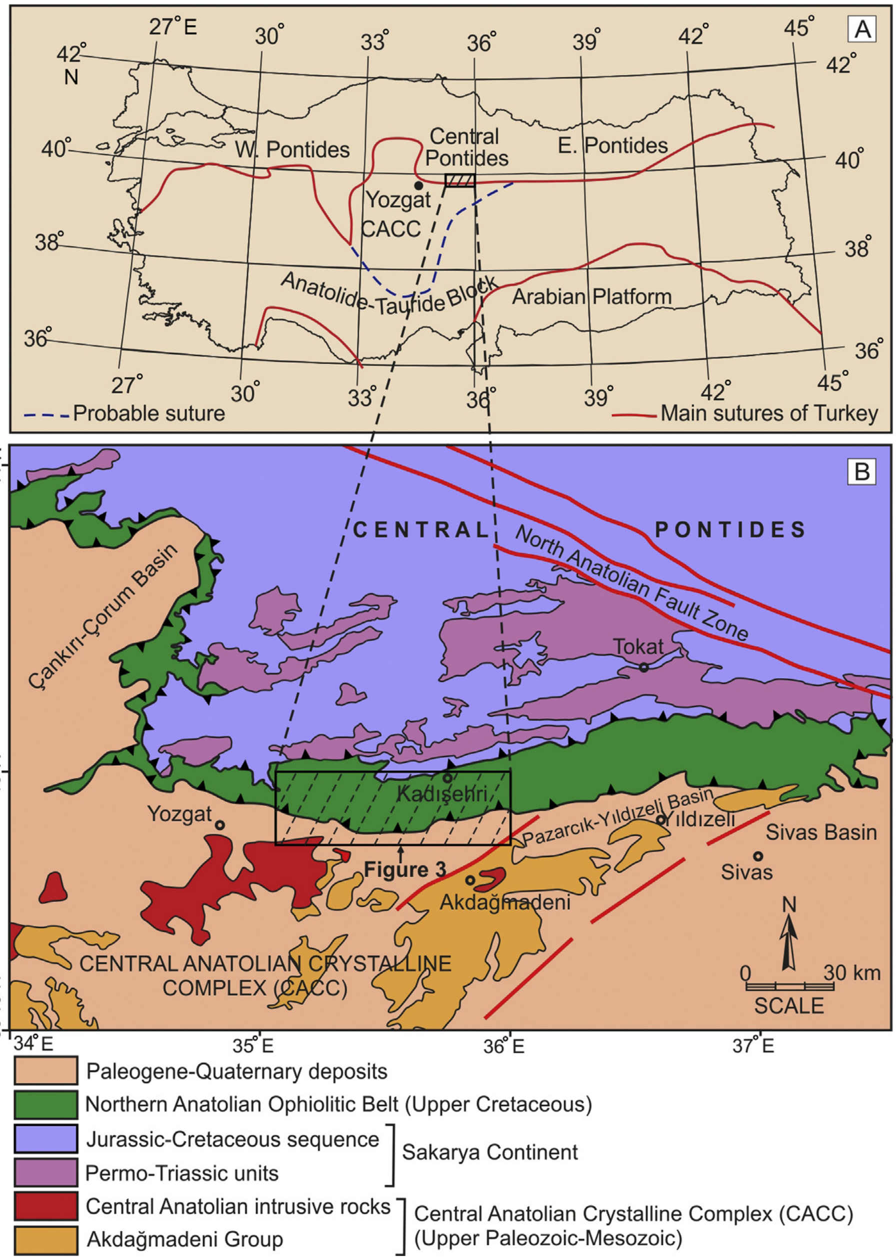

Figure 1. Simplified location map showing the distribution of the suture zones (A) and some of the major tectonic units (B) in Turkey (modified after MTA, 2001; Yılmaz and Yılmaz, 2013). CACC: Central Anatolian Crystalline Complex.

In the studied region, the ensimatic arc units and melanges form the NAOB together. Previously, the arc units and ophiolitic units were mapped as one mapping unit. They have not been distinguished from each other. In the present study, the arc units and melanges are defined as independent tectonic units. This definition of the arc units as a tectonic unit is a new contribution.

The purpose of the present study is primarily to define and reveal the location and geotectonic setting of the Darmik Ensimatic Arc Association (DEAA) within the regional structure. In this context, the inner contact relationships of the DEAA and those with other tectonic units are reviewed in the light of field studies. Then paleontological, geochronological, petrological and also geochemical properties of the DEAA are defined as a whole. Accordingly, to the south of the NAOB, which is E–W trending, the existence of an ensimatic arc has been defined, which developed in the Cenomanian–Maastrichtian interval.

2. Regional geology

The North Anatolian Ophiolitic Belt (NAOB), where the ophiolites were accreted to the melange prism in Late Cretaceous time, is one of the main and most important ophiolitic sutures in Turkey (Yılmaz and Yılmaz, 2013), which is also known as the İzmir-Ankara-Erzincan suture zone (Şengör and Yılmaz, 1981; Okay, 1989; Okay and Tüysüz, 1999), as well. This belt separates the Central Pontides (the Sakarya Zone and/or Sakarya Continent) to the north, from the Kırşehir Block and/or metamorphic equivalent of Anatolide-Tauride Block to the south (Fig. 1). In fact, NAOB starts in İzmir and continues eastwards in the direction of Ankara-Erzincan and joins with the Lesser Caucasus ophiolitic belt (Yılmaz and Yılmaz, 2013).

There are many different regional studies around the study area. For instance, on the basis of Rojay et al. (2004) the Cretaceous pillow basalts from NAOB in the Central Anatolia are within-plate ocean island alkali basalts and enriched MORB. To the northwest part of the study area, the Armutlu peninsula has been interpreted as a composite tectonic entity made up of sections of the Sakarya Continent, the Rhodope-Pontide fragment and an ophiolite (Yılmaz et al., 1995b) and Yılmaz et al. (1997) suggested that the northern branch of Neotethys eliminated due to its northward subduction under the Pontides in the late Cretaceous.

The study area is situated to the southern edge of the central segment of the NAOB. Regional tectonic units of the region, from north to south, are known as the Sakarya Zone, NAOB and Central Anatolian Crystalline Complex (CACC) (Figs. 1B and 2).

The NAOB consists of ophiolites and ophiolitic melange and of fore-arc sequences, which lie unconformably over the melange. The Late Cretaceous ophiolitic melange (Yılmaz, 1981) was thrust along the Northern Anatolian Ophiolite Belt northward and southward over other tectonic units (Yılmaz and Yılmaz, 2013). For instance, in the region between Tokat and Sivas, the present structures are characterised by north-dipping and also south dipping thrusts. This setting may be a result of continuing contraction following the emplacement of the ophiolitic melange (Yılmaz et al., 1997; Yılmaz and Yılmaz, 2004). In this study, Upper Albian–Lower Cenomanian ages were obtained from deep-sea sediments in ophiolites.

In the present study, an ensimatic arc association was differentiated within the NAOB and the arc association has been defined as a new unit in the following sections. This association indicates the existence of a southern subduction zone.

The Late Paleozoic–Mesozoic Akdağmadeni Massif, which represents the NW part of the CACC, constitutes the lowermost level of the tectonic units in the region. Tectonic contacts between the paleotectonic units were represented by overthrusts, dipping towards the north.

The Akdağmadeni Massif, which structurally forms the lowermost rock association, is also a part of the Kırşehir Massif (Seymen, 1985). According to Seymen (1985), the schist and marble envelope of the Kırşehir Continent is a sedimentary sequence of metamorphic, north-facing, Atlantic-type, passive continental margin. The Akdağmadeni Massif consists of gneiss, amphibolite, schist, quartzite and marble. These metamorphic rocks with intrusive bodies are named the Akdağmadeni Group (Özcan et al., 1980) and/or Akdağmadeni lithodem (Yılmaz et al., 1995a, b). The Akdağmadeni Group, which has continental crust origin, was regionally metamorphosed to amphibolite facies, and later affected by cataclastic metamorphism (Alpaslan, 1993). The age of the cataclastic metamorphism, determined using the K/Ar method, falls in the Santonian–Maastrichtian (Alpaslan et al., 1996). This age corresponds to the period when the ophiolitic melange prism was thrust bilaterally to the north and to the south. The metamorphic rocks of the Akdağmadeni Group which bear traces of the Alpide orogeny (Şengör, 1987) are regarded as the metamorphic equivalents of the Anatolide-Tauride Platform (Yılmaz and Yılmaz, 2013). It has been suggested that the upper parts of the Akdağmadeni Group represent north-facing Atlantic-type, passive continental-margin deposits (Seymen, 1985).

In this study, the Akdağmadeni group was studied in detail and includes from bottom to top, the Yahyasaray formation (Late Devonian), Akçakışla formation (Carboniferous–Early Permian), Topaktaş formation (Late Permian), Hisarbey formation (Mesozoic) and Davulbaz formation (Early Cretaceous) (Fig. 2). In this study, a 65.5–98.1 Ma (Cenomanian–Maastrichtian) was obtained from the Central Anatolian granitoids with the $^{40}Ar/^{39}Ar$ method (Table 1). In addition, metaflysch with different block types, representing the uppermost level of the Akdağmadeni Group and overlying the other sequences of the Group with tectoniccontact (Fig. 2), may be a product of the southern subduction zone. Because, the overthrusts, dipping to the north are dominant in the region and the Akdağmadeni Group is located to the south.

Paleocene–Quaternary volcano-sedimentary cover of the Pazarcık-Yıldızeli Basin, which was interpreted as a sub-basin of the Sivas Basin, overlies the tectonic units presented above with an unconformity (Yılmaz and Yılmaz, 2006). The basin fill is bounded by the NAOB to the north and the Akdağmadeni Group metamorphics to the south. Pazarcık-Yıldızeli Basin is located between the Sivas Basin and Çankırı-Çorum Basin and it may be a transitional Basin between them. Because, Pazarcık-Yıldızeli Basin is in contact with the Çankırı-Çorum Basin in the west and the Sivas Basin in the east (Fig. 1). The Çankırı-Çorum Basin was interpreted as a collisional basin (Erdoğan et al., 1996) and also as a post collisional basin (Tüysüz et al., 1995; Keskin et al., 2008).

The rock units of the Pazarcık-Yıldızeli Basin are made up of Upper Paleocene–Middle Eocene volcano-sedimentary sequence, which developed on the ensimatic arc association with an unconformity (Fig. 2) and unconformably overlies the Akdağmadeni Group, as well. The sequence includes Pazarcık volcanics, Boğazköy formation and Kılıçlı olistotrome (Özcan et al., 1980; Yılmaz et al., 1995a, b), as seen in Fig. 2. There are lateral and vertical transitions between the formations. The Eocene marine and clastic level, in general, overlies the volcanic rocks conformably and passes upward into an olistostromal level containing reworked material from ophiolitic units and limestones. Bayat volcanics, which were interpreted as having a collisional setting by Erdoğan et al. (1996), can be correlated with the Pazarcık volcanics in the studied region. In addition, the existence of a huge olistostromal level in the basin fill indicates a collisional stage, as defined by Erdoğan et al. (1996).

The Upper Miocene–Pliocene fluvial to lacustrine rock units were deposited unconformably on the older units. The paleo environment of the lower level is interpreted as fluvial for conglomerate and sandstone alternations and as lacustrine for mudstone and limestone alternations inthe upper level. The northern boundary of this deposition was affected by overthrusting and the North Anatolian Overthrust Zone, which originated from reactivation of nappe emplacement. These reactivated movements occurred during Late Miocene–Pliocene times. Plio-Quaternary clastic rocks and Quaternary basalts unconformably overlie the overthrusts and also the older units (Yılmaz and Özer, 1984).

3. Analytical techniques

Many samples were taken for paleontological and petrographical determinations. For geochronological evaluation, plagioclase minerals from only one sample were analysed with the $^{40}Ar/^{39}Ar$ method, by Dr. Yakov Kapusta at Actlabs, Canada. The summary results of $^{40}Ar/^{39}Ar$ can be seen in Table 1.

Six samples were analysed for geochemical evaluation. Two of them (Numbers: (C5)12A268K and (C6)12A269K) were analysed by AcmeLabs (Canada). Four of them (Numbers: (C1)14A49K, (C2) 14A50K, (C3)14A51K and (C4)14A52K) were analysed at General Directorate of Mineral Research and Exploration Labs in Ankara (MTA, Turkey). All samples were collected from the study area (see Fig. 3 for locations) on the basis of their freshness. Major, trace and REE analyses were performed using both directly coupled plasma (DCP) and inductively coupled plasma mass spectrometry (ICP-MS). The results of the whole-rock major (wt.%) and trace element (ppm) analyses of the DEAA can be seen in Table 2. The results of the whole-rock rare earth element analyses (ppm) of the DEAA can be seen in Table 3.

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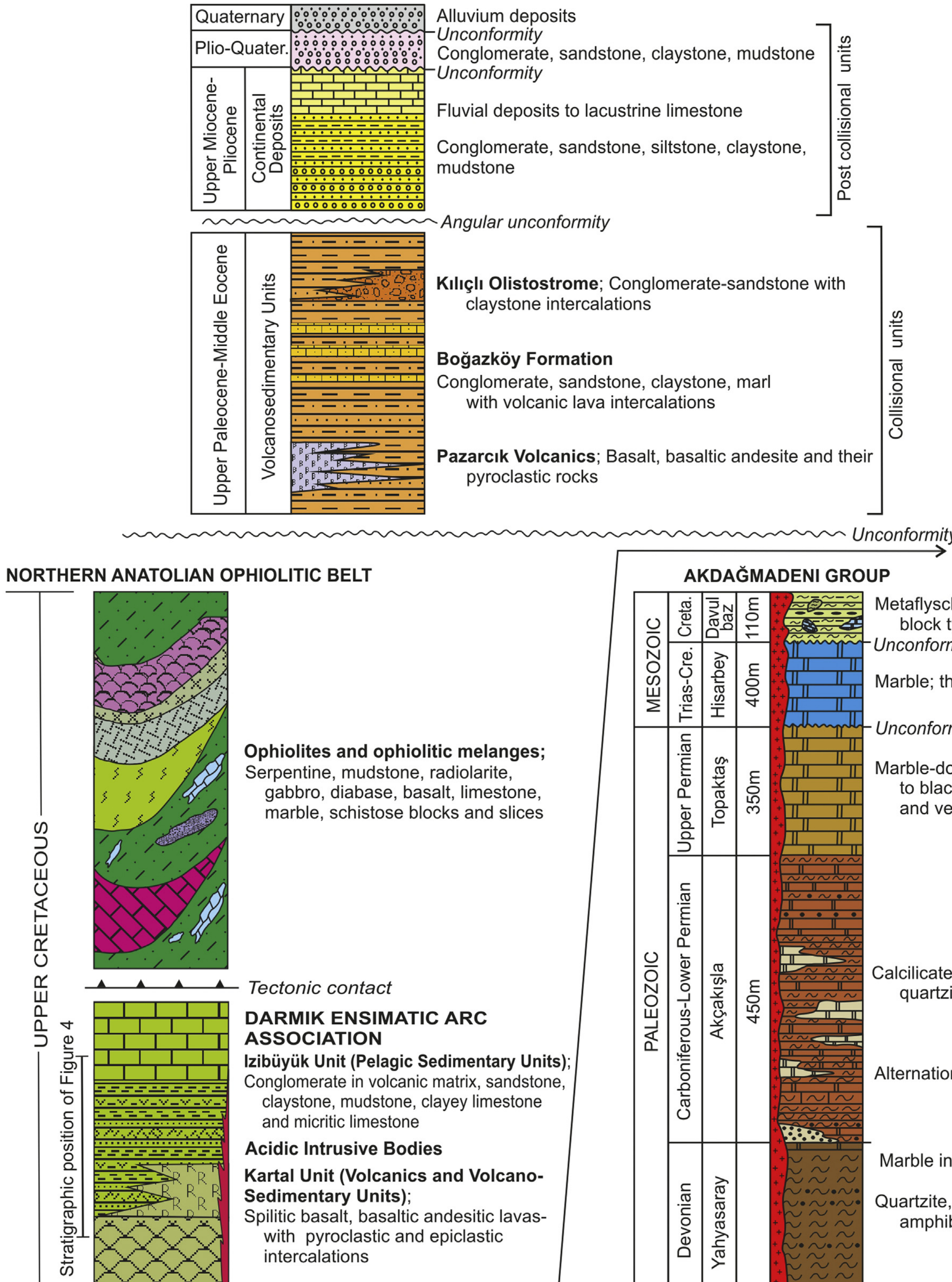

Figure 2. Generalized tectonostratigraphic sections of the study area and surrounding regions.

4. Geological setting of the ensimatic arc

The ensimatic arc in the region was named for the first time as the Darmik Ensimatic Arc Association (DEAA) and forms the scope of the present study. DEAA has been divided into two levels; the lower level and upper level. The lower level is named first time as the Kartal unit and it is mainly made up of the volcano-sedimentary units (basaltic and andesitic lavas with pyroclastic and epiclastic rocks) and intruded by acidic magmatic bodies. These bodies altered much and it is not possible to define them in detail. The upper level is named as the Kartal unit and it is mainly made up of the pelagical sedimentary units, which contain a sequence of

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Table 1
Summary data of $^{40}Ar/^{39}Ar$ results. See Fig. 3 for the location of geochronological rock sample.

T (°C)	^{40}Arcc (STP)	$^{40}Ar/^{39}Ar$	±1σ	$^{38}Ar/^{39}Ar$	±1σ	$^{37}Ar/^{39}Ar$	±1σ	$^{36}Ar/^{39}Ar$	±1σ	Ca/K	$\sum^{39}$Ar (%)	Age (Ma)	±1σ
500	$4.8 \times e^{-9}$	8.4142	0.0269	0.01559	0.00091	1.3201	0.0322	0.00495	0.00315	4.75	6.0	121.4	16.0
600	$17.6 \times e^{-9}$	6.2701	0.0058	0.01416	0.00058	3.6050	0.0063	0.00137	0.00085	12.98	36.0	103.0	5.0
750	$10.1 \times e^{-9}$	5.8840	0.0051	0.01429	0.00039	7.7879	0.0130	0.00029	0.00078	28.04	54.3	101.8	4.7
875	$9.8 \times e^{-9}$	6.1892	0.0021	0.01692	0.00101	6.8878	0.0144	0.00340	0.00011	24.80	71.3	91.3	2.4
1000	$8.4 \times e^{-9}$	6.3100	0.0085	0.01448	0.00055	2.6916	0.0136	0.00208	0.00131	9.69	85.4	100.1	7.1
1130	$9.9 \times e^{-9}$	7.2685	0.0040	0.01494	0.00077	1.4214	0.0038	0.00403	0.00020	5.12	100.0	106.6	2.9

Sample: YK-26 plagioclase.
±1σ = Estimated uncertainty (1 sigma).
IIA (Inverse isochrone age, ±1σ) = 100.2 ± 6.8 Ma.
TFA (Total fusion age) = 102.0 ± 3.3 Ma.
WMPA (Weighted mean plateau age, ±1σ) = 98.7 ± 2.4 Ma.
Ca/K (Apparent Ca/K ratios) = 4.75–28.04.
Comments: Five steps plateau.

conglomerate, sandstone, claystone, mudstone, clayey limestone, micritic limestone and calciturbidite alternations and in places, epiclastic volcanic interlayers (Figs. 3 and 4).

4.1. Kartal unit

Kartal unit comprises basalts, basaltic andesite, andesitic lavas and their pyroclastic and epiclastic equivalents, representing the lower levels of the ensimatic arc. Field views of typical relationships between subunits of the DEAA and other units (Fig. 5) and microscopic views of thin sections from various volcanic rocks within the DEAA, taken from the Incesu area (Fig. 6) are respectively presented, in the following. This unit is overlain by pelagic limestone units of İzibüyük unit.

4.2. Distribution

Kartal unit is situated to the south of the ophiolites and ophiolitic melanges and lie from east (Incesu village) to west (Selimiye village) throughout the study area, and also beyond the map (Fig. 3). This location represents the southern edge of NAOB. In places, the outcrops of the units are widespread as seen at Kartal area between Selimiye and Boğazköy villages.

4.3. Contact relationships

Fig. 5A shows basaltic volcanics and conformably overlying İzibüyük unit of DEAA to the north of Boğazköy village. In this area, volcanics represent the base of the sequence and the upper level represents pelagic sedimentary units of DEAA. Fig. 5B displays a pyroclastic intercalation between pelagic limestone layers of DEAA to the south of İzibüyük village. On the basis of relationships presented above, there are conformable and transitional contacts between the rock units of DEAA. The thickness of the lower unit of DEAA is approximately more than 500 m (Fig. 4).

In addition, the ensimatic arc association is tectonically situated between ophiolitic melanges of NAOB (to the north) and Tertiary basin fill of Pazarcık-Yıldızeli Basin (to the south). All the present-day tectonic contacts between the DEAA and ophiolitic units dip to the north, by approximately 45° in the study area. These tectonic relationships can be seen in Fig. 5C and D, respectively. It is the first time the DEAA has been distinguished from ophiolitic units, as seen in Fig. 5D and E illustrates basaltic volcanics and one of the acidic intrusive bodies at İzibüyük village. Fig. 5F shows the tectonic contact between the DEAA and Paleocene–Eocene basin fill of Pazarcık-Yıldızeli Basin (to the south).

4.4. Geological age

Many fossils were determined from mudstones in the Kartal unit of DEAA. For instance, in the mudstones and micrites of the volcano-sedimentary units, the following faunal associations were determined: *Marginotruncana renzi* (Gandolfi), *Marginotruncana pseudolinneiana* Pessagno, *Marginotruncana* cf. *Tarfayaensis* (Lehman) and *Dicarinella asymetrica* (Sigal). This fossil content shows Cenomanian–Santonian interval.

In addition, in this study, a 98.7 ± 2.4 Ma radiometric age (Cenomanian) was obtained from basalts of DEAA with the $^{40}Ar/^{39}Ar$ method (Fig. 7A and B). Fig. 7A presents the $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ diagram; Fig. 7B shows the age vs. cumulative ^{39}Ar diagram. This radiometric age indicates Cenomanian–Santonian interval, as well.

4.5. Depositional environment

Abundant radiolaria and pelagic fossils in the volcano-sedimentary units of DEAA indicate deep marine environment. This marine environment may be around paleo-ensimatic arc.

4.6. Correlation

The Kartal unit of DEAA can be partly correlated with the Kalecik unit of Tüysüz et al. (1995) and Söğütözü volcanics of Yılmaz (1981) in terms of lithological characteristics and geological age. All of these units represent ensimatic arc and/or arc setting in Late Cretaceous time.

4.7. İzibüyük unit

İzibüyük unit contains a sequence of conglomerate, sandstone, claystone, mudstone, clayey limestone, micritic limestone and calciturbidite alternations and in places, epiclastic volcanic interlayers, representing the upper level of the ensimatic arc. Pelagic limestone is the dominant lithology of the sequence. Therefore, it was named the Boyalık unit by Akçay et al. (2008). To define and show vertical and lateral facies changes in the sequence better, two combined (integrated) measured stratigraphic sections were prepared from the data collected at Kartal-İzibüyük profiles in detail (Fig. 4).

The Kartal profile is located to the south of Kartal village. On the basis of a measured stratigraphic section (Coordinates: 36725808, 4410318), the pelagic sedimentary unit overlies the volcanic rocks of DEAA conformably and includes, from bottom to top, intraformational monogenic (only volcanics) conglomerate, sandstone-

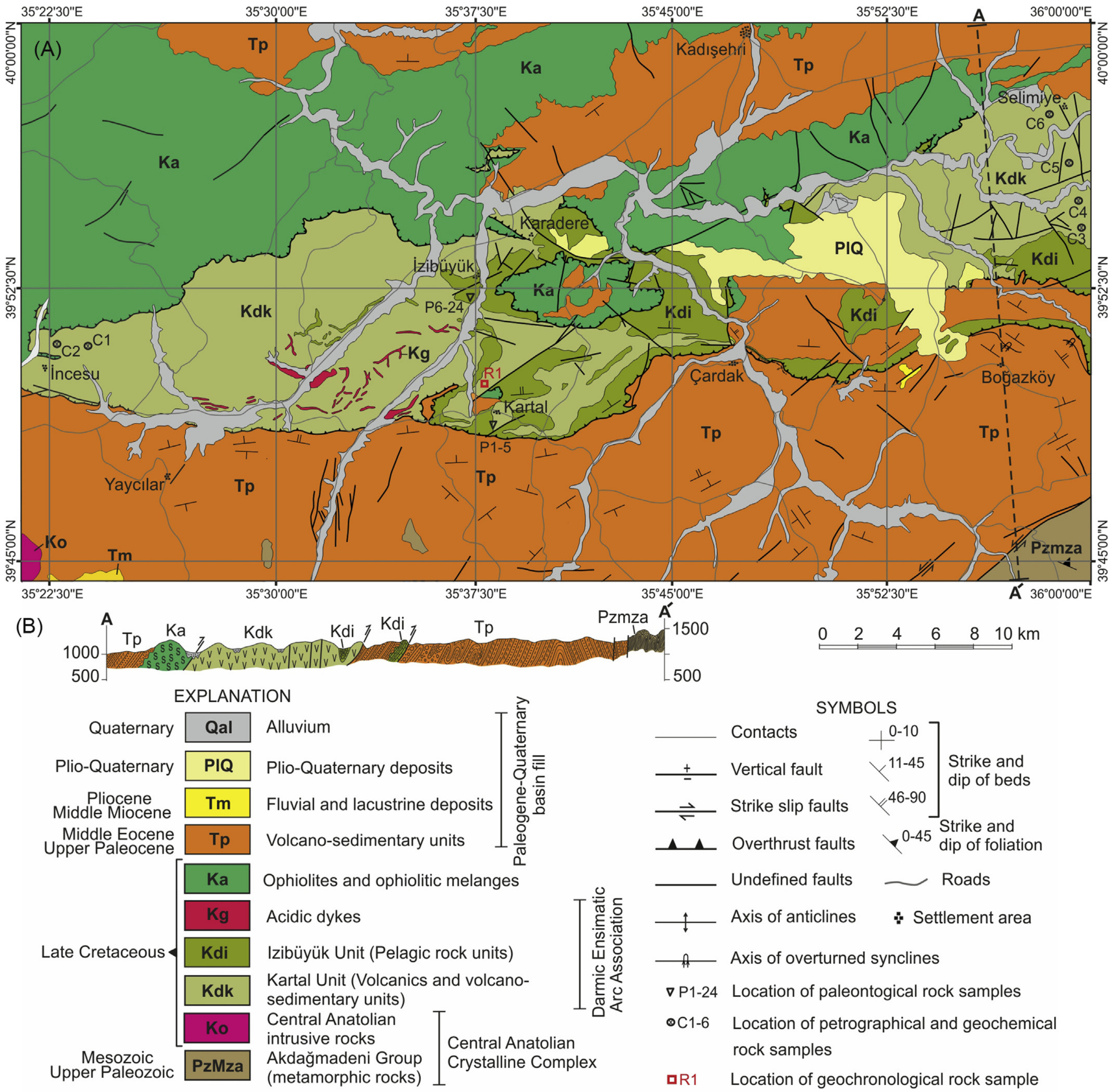

Figure 3. Geological map (A) and cross-section along A–A′ in the east part (B) of the study area (see Fig. 1 for location).

mudstone, and mudstone-clayey limestone alternations and red micritic limestone (Fig. 4).

The İzibüyük profile is located to the south of İzibüyük village. On the basis of a measured stratigraphic section (Coordinates: 3672486, 4416617), the pelagic sedimentary units overlie the volcanic rocks of DEAA conformably and from bottom to top, comprise micritic limestone, red micrite, claystone, clayey micrite and claystone-clayey micrite alternations. The total measured thickness of the Kartal unit of DEAA is approximately 200 m (Fig. 4).

As explained above, pelagic sedimentary units overlie the volcanic rocks of DEAA conformably and are underlain by ophiolitic melange with a thrust fault dipping to the north.

The pelagic sedimentary units show lateral and vertical facies changes. The sedimentation of the İzibüyük unit probably represents deep sea fans (lobes) which may have formed in a low energy, deep-sea depositional environment, where turbidity currents were predominant. The units have undergone intensive deformation. Red pelagic limestones of the İzibüyük unit are characterised by widespread fracturing and tight folds.

Faunal content of the different levels of the pelagic sedimentary units are presented in Fig. 4. The faunal content of the lower level of the pelagic sedimentary units is listed as follows: *Marginotruncana coronata* (Bolli), *Marginotruncana* cf. *tarfayaensis* (Lehmann), *Marginotruncana pseudolinneiana* Pessagno, *Dicarinella* cf. *asymetrica* (Sigal), *Dicarinella concovata* (Brotzen), *Globigerinelloides* sp., *Heterohelix* sp., and *Marginotruncana* sp., Radiolaria. The aforementioned fossil assemblages suggest Santonian age for the lower level volcanics of DEAA.

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Table 2
The results of the whole-rock major (wt.%) and trace element (ppm) analyses of the DEAA (Darmik Ensimatic Arc Association). See Fig. 3 for the locations of petrographical and geochemical rock samples.

Sample number/content	(C5)12A268K andesite	(C6)12A269K basalt	(C1)14A49K andesite	(C2)14A50K andesite	(C3)14A51K basalt	(C4)14A52K basalt
Major elements (wt.%)						
SiO_2	58.70	49.00	62.60	62.90	47.80	49.40
Al_2O_3	14.35	18.45	14.20	14.40	19.10	18.60
Fe_2O_3	6.43	10.75	8.20	8.60	11.20	11.00
CaO	5.57	7.81	3.50	2.50	8.90	8.60
MgO	1.70	3.51	2.40	2.40	4.50	4.10
Na_2O	2.16	4.46	5.00	5.20	4.00	3.50
K_2O	0.91	0.75	0.60	1.00	0.40	0.40
TiO_2	0.70	0.86	0.70	0.70	0.60	0.70
MnO	0.15	0.21	0.20	0.20	0.20	0.20
P_2O_5	0.12	0.15	0.20	0.20	0.10	0.10
SrO	0.09	0.02	0.05	0.04	0.06	0.06
BaO	0.05	0.04	0.02	0.06	0.02	0.03
LOI	8.36	3.52	2.20	1.80	2.90	3.15
Total	99.29	99.53	99.87	100.00	99.78	99.84
Trace elements (ppm)						
Ba	379.00	336.00	221.20	515.90	173.50	227.50
Nb	1.40	1.90	2.52	2.12	4.50	4.00
Zr	55.00	47.00	67.58	90.75	53.12	58.77
Cs	0.92	0.14	0.90	0.43	0.90	0.70
Ga	16.10	17.70	12.69	12.44	12.13	11.44
Hf	2.10	1.70	1.68	2.18	1.17	1.18
Rb	13.10	12.20	6.55	11.49	4.28	4.95
Sn	1.00	<1	0.93	1.22	2.19	0.75
Sr	778.00	290.00	435.90	308.50	490.00	528.70
Ta	<0.1	0.10	0.11	0.16	0.24	0.19
Th	1.10	0.98	2.42	2.64	1.61	1.63
Tl	<0.5	<0.5	0.66	0.66	0.66	0.64
U	0.35	0.28	4.53	0.75	3.56	0.89
V	116.00	298.00	134.90	138.20	526.90	467.30
W	<1	<1	2.01	1.81	0.84	2.29
Y	30.30	20.20	42.55	29.27	19.13	21.79
As	2.80	0.20	0.60	0.50	0.60	0.60
Be	2.80	0.20	0.60	0.50	0.60	0.60
Bi	0.45	0.36	0.44	0.22	0.11	0.17
Cd	0.04	0.01	0.62	1.05	0.77	0.64
Co	0.13	0.09	0.17	0.27	0.14	0.19
Cr	10.00	20.00	17.74	14.31	49.14	91.80
Cu	13.60	29.20	19.33	18.40	59.52	57.52
Ge	21.80	139.50	4.00	4.39	5.46	5.95
Mo	0.11	0.09	4.00	4.39	5.46	5.95
Ni	1.07	0.25	1.74	1.63	1.32	1.37
Pb	3.10	7.70	16.24	17.67	41.59	42.35
Sb	5.50	2.40	4.24	4.71	12.47	3.46
Sc	0.25	0.05	0.17	0.20	0.65	0.21
Zn	24.20	22.50	24.01	32.85	32.62	28.50

Table 3
The results of the whole-rock rare earth element analyses (ppm) of the DEAA (Darmik Ensimatic Arc Association). See Fig. 3 for the locations of petrographical and geochemical rock samples.

Samples number/content	(C5)12A268K andesite	(C6)12A269K basalt	(C1)14A49K andesite	(C2)14A50K andesite	(C3)14A51K basalt	(C4)14A52K basalt
La	6.00	6.10	8.69	5.76	5.77	5.99
Ce	13.00	13.20	11.61	7.77	7.44	7.32
Pr	2.00	1.95	1.77	1.24	1.03	1.09
Nd	9.30	8.80	11.45	7.92	6.23	6.72
Sm	2.82	2.48	3.45	2.43	1.66	1.99
Eu	0.99	0.94	0.78	0.62	0.41	0.49
Gd	3.96	3.11	3.85	2.72	1.83	2.09
Tb	0.72	0.53	0.49	0.36	0.21	0.25
Dy	5.00	3.61	6.24	4.61	2.56	2.94
Ho	1.19	0.80	0.70	0.53	0.27	0.33
Er	3.35	2.30	2.46	1.91	1.03	1.22
Tm	0.51	0.32	0.30	0.23	0.12	0.15
Yb	3.21	2.14	3.37	2.54	1.33	1.55
Lu	0.53	0.34	0.23	0.36	0.27	0.13
La	6.00	6.10	8.69	5.76	5.77	5.99
Ce	13.00	13.20	11.61	7.77	7.44	7.32

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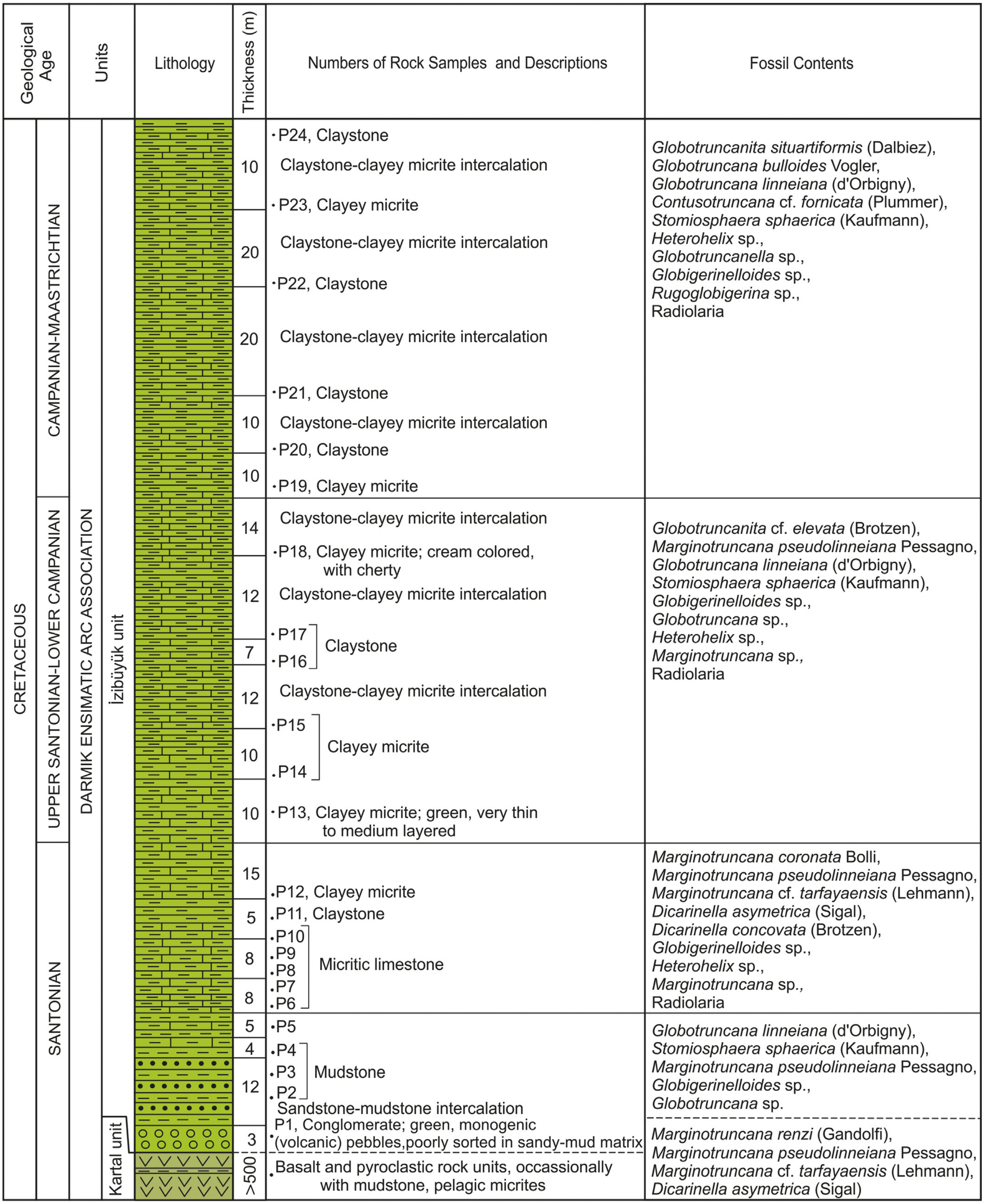

Figure 4. Measured integrated columnar section of the Darmik Ensimatic Arc Association (DEAA) at the Kartal-İzibüyük area (see Fig. 3 for location).

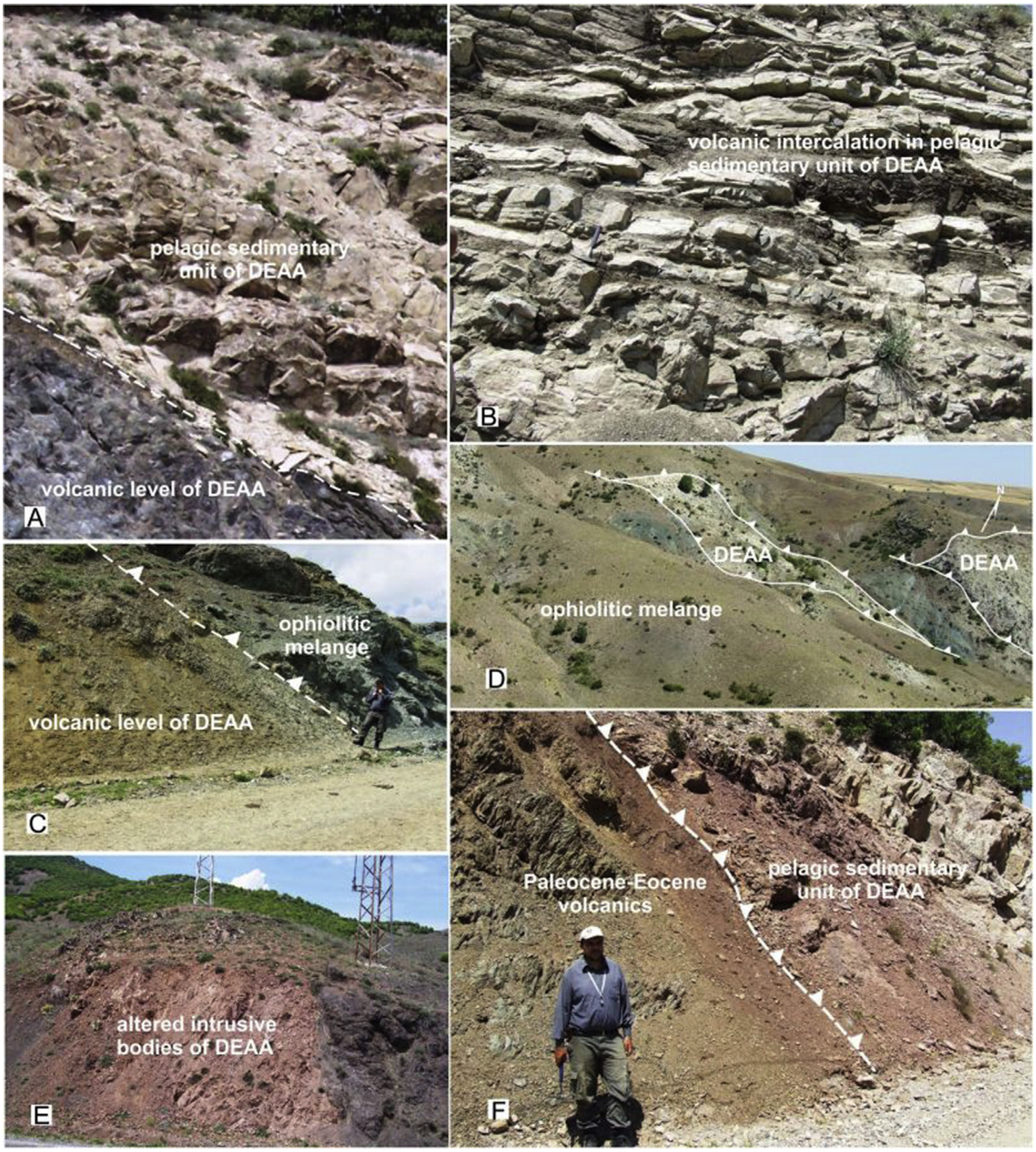

Figure 5. Field pictures of typical relationships between subunits of the Darmik Ensimatic Arc Association (DEAA) and other units. See Fig. 3 for locations. (A) A general view from DEAA; lower level represents volcanics and upper level represents pelagic sedimentary units of DEAA, to the north of Boğazköy village. (B) A pyroclastic intercalation between pelagic limestone of DEAA, south of İzibüyük village. (C) An overthrust between basaltic volcanic level of DEAA and ophiolitic melange, north of Çardak village. (D) Tectonic slices of DEAA in the ophiolitic melanges. (E) Basaltic volcanics and acidic intrusive bodies, at İzibüyük village. (F) An overthrust between Paleocene–Eocene volcanics and pelagical sedimentary unit of DEAA, north of Çardak village.

The upper level of the İzibüyük unit includes the following fossil content: *Reinhardtites levis* Prins and Sissingh, *Micula swastica* Stradner and Steinmetz, *Arkhangelskiella cymbiformis* Vekshina, *Lucianorhabus cayeuxii* Deflandre, *Quadrum gothicum* (Deflandre), *Prediscosphaera cretacea* (Arkhangelsky), *Tranolithus phacelosus* Stover, *Micula decussata* Vekshina, *Microrhabdulus decoratus* Deflandre, *Cretarhabdus crenulatus* Bramlette and Martini, *Watznaueria barnesae* (Black, Black and Barnes). On the basis of the fossil content presented above, the age of the upper level could be Campanian–Maastrichtian.

The following fossils were found in the wash samples from the pelitic levels of the pelagic sedimentary units: *Globotruncana bulloides* Vogler, *Globotruncana* cf. *arca* (Cushman), *Globotruncana* cf. *linneiana* (d'Orbigny), *Globotruncana* sp., *Globotruncanita* sp., and *Heterohelix* sp. On the basis of presented faunal content, the age of the unit could be Santonian–Early Maastrichtian.

In conclusion, it can be said that the age of the İzibüyük unit is Santonian–Maastrichtian. When the ages and contact relationships of the volcano-sedimentary units and pelagic sedimentary units are correlated, they have conformable and transitional facies changes and their ages can be accepted as late Cretaceous, on the whole.

5. Petrographical features

The main volcanics of the Kartal unit have been defined as basalt and basaltic andesite, according to detailed petrographic studies.

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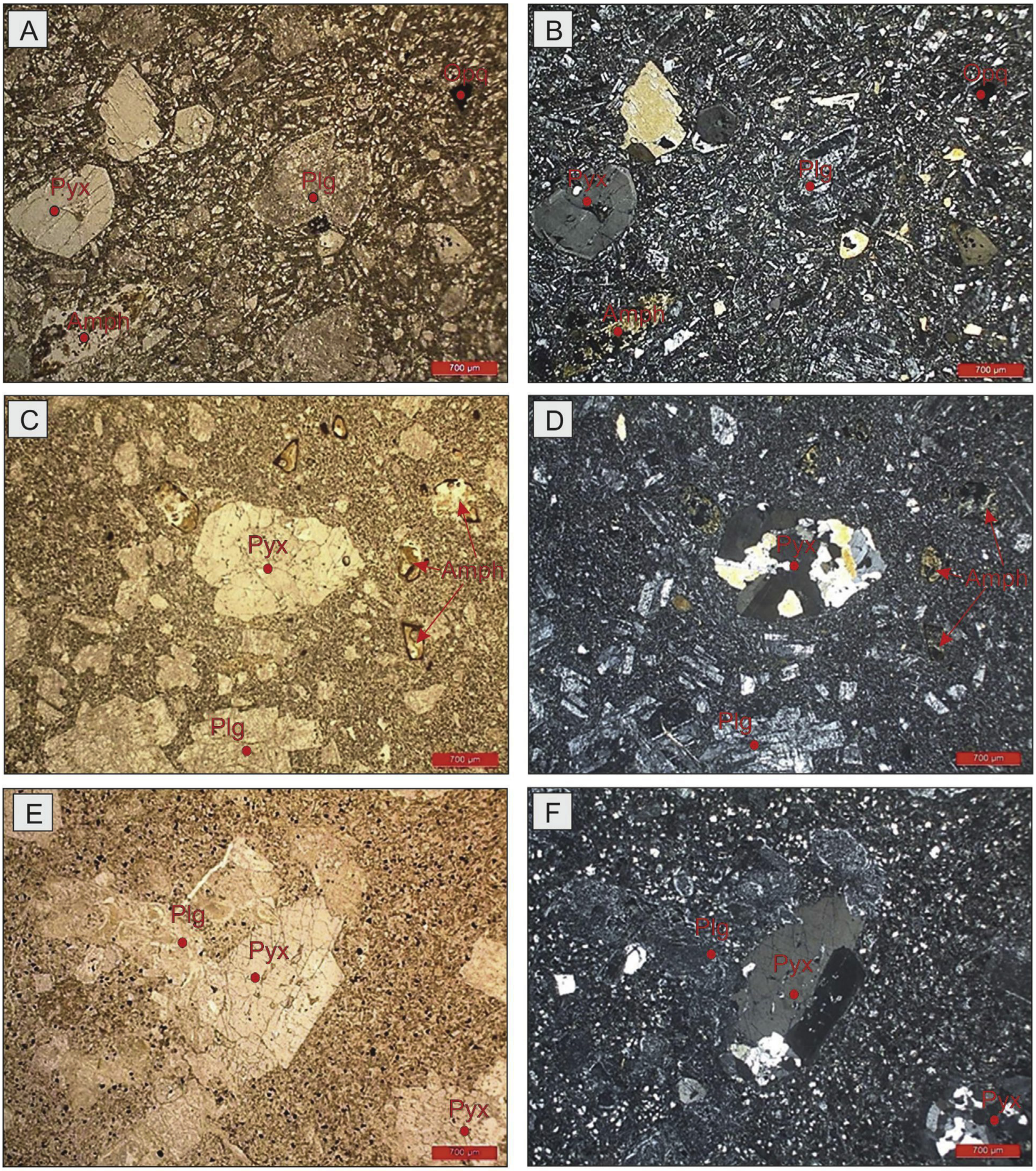

Figure 6. Microscopic pictures of thin sections from various volcanic rocks within the DEAA, taken from the Incesu area. See Fig. 3 for location, west part of the area. (A) and (B) basalts; (C–F) basaltic andesites. Plagioclase (Plg), Pyroxene (Pyx), Amphibole (Amph) and Opaque (Opq) mineral phenocryts have been embedded in the microlitic to glassy matrix. DEAA: Darmik Ensimatic Arc Association.

Samples identified as basalt display hypocrystalline porphyry and seriated texture and include plagioclase, clinopyroxene, olivine and plagioclase phenocrysts in microfibers, pyroxene minerals and small amounts of chloritized glassy matrix (Fig. 6A and B). Plagioclase phenocrystals were observed as sub-hedral prismatic crystals with intensive fractured and fragmented texture. Plagioclases have textures with polysynthetic twinning and zoning, with a lesser amount epidotized and carbonitised.

Pyroxene minerals can also be observed as sub-idiomorphic nanocrystals and fine-grained crystals also in the matrix. Some pyroxenes display simple twinning and exsolution lamellae are evident. Olivine minerals are half-euhedral, medium grained and have fractured-cracked structure, partially serpentinized along the cracked lines. They also contain plenty of large and small opaque minerals. There are alteration types such as chloritization, carbonation and epidotization in some rock samples.

In petrographic studies, basaltic andesite displays hypocrystalline porphyric and intergranular texture, including plagioclase, pyroxene (orthopyroxene + augite), olivine phenocrystals, plagioclase and pyroxene (augite) microlites, opaque mineral crystals and

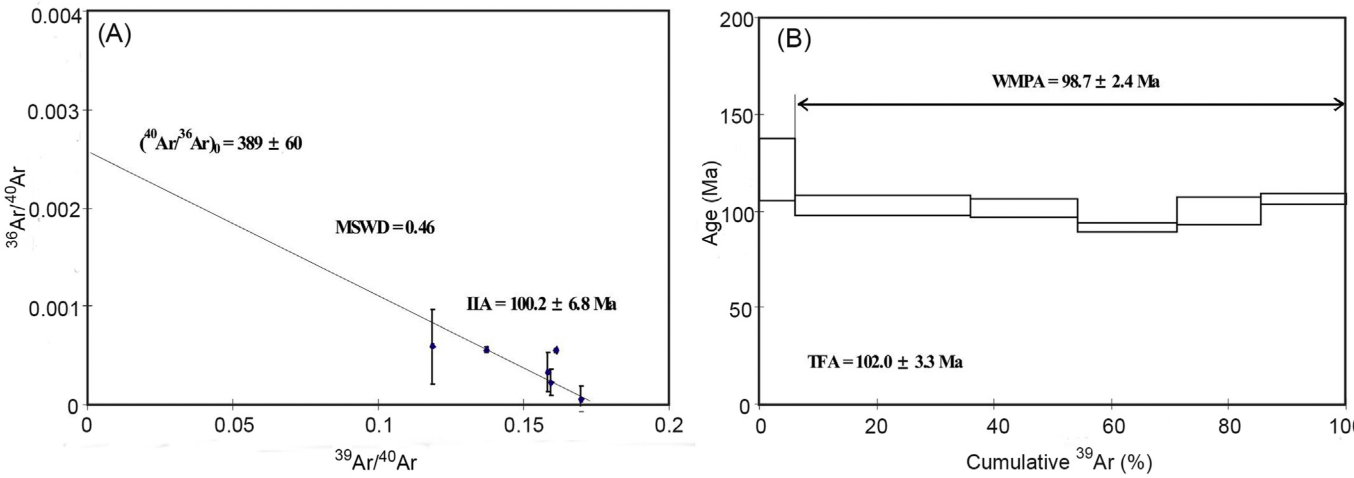

Figure 7. Isochronous and plateau age of DEAA. (A) $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ diagram; (B) Age vs. Cumulative ^{39}Ar diagram (see Fig. 3 for the location of geochronological rock sample, R).

glass (Fig. 6C–F). Polysynthetic twinning with zoned texture developed in semi euhedral plagioclase crystals. In general, in plagioclase phenocrystals with fractured texture, irregular epidotization in very fine grains and from centre to side transformation (saussuritization) in fine grained sericite-epidote minerals aretypical alterations.

Olivine phenocrystals are observed in thin section. Both subidiomorphic and rounded shapes can be seen in different samples. In general, the crystals are fine to medium grained, completely iddingsitized and have lost primary features. Pyroxene group minerals with seriate and half euhedral textures, where exsolution lamellae developed, are the most abundant mafic minerals in the thin section area. Amorphous opaque minerals are observed in the matrix, developed probably by small amounts from opacification of mafic phenocrysts and abundantly from fine-grained euhedral-euhedral cubic crystals. Alteration such as iddingsitization, serpentinization, saussuritization, opacification, epidotization and carbonation are present in the thin sections of samples.

In addition, there are many small scale acidic intrusive outcrops in the area between Izibüyük, Yaycılar and Kartal villages. Magmatic rocks occur as dikes and sills in the lower level of the DEAA. These volcanic rock units were cut by acidic bodies (Fig. 5E). Because of intensive alteration, it is not possible to clearly determine the rock-forming minerals in theacidic bodies. However, it can be said that rock samples of the bodies have a porphyritic texture and include quartz and sodic feldspar minerals in a microlithic matrix.

6. Geochemical features

In the study area, basaltic and andesitic lavas and pyroclastics of the Kartal unit of DEAA are highly altered. Therefore, it is quite difficult to find fresh rock samples for geochemical analysis. In spite of that whole-rock, rare earth and trace element analyses were performed on fresh samples collected from the rock units of DEAA. The results of the whole-rock major geochemical analyses are presented as % oxide (wt.%), with rare earth and trace elements as ppm, respectively, in Tables 2 and 3. On the basis of the results of chemical analysis, rock samples have SiO_2 content from 47.80 wt.% to 62.90 wt.% and loss on ignition values (LOI) vary between 1.80 wt.% and 8.36 wt.%.

Chemical analysis results are evaluated within the frame of different classifications established by various researchers (Winchester and Floyd, 1977; Pearce, 1996; Hastie et al., 2007). In the diagram of major oxides (SiO_2) vs. (Zr/TiO_2) (Winchester and Floyd, 1977) six rock samples are evaluated. Half of them plot in the basalt field and the other half plot in the andesite field (Fig. 8A). In the Pearce (1996) diagram, half of rock samples plot in the basalt

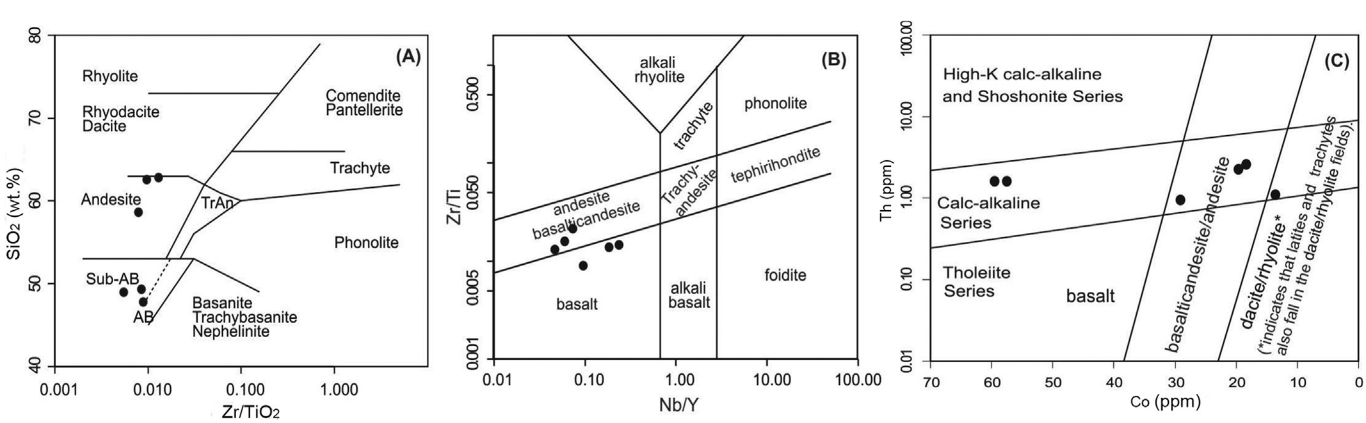

Figure 8. Geochemical characteristics of the Kartal unit of DEAA. (A) Zr/TiO_2 vs. SiO_2 diagram of Winchester and Floyd (1977); (B) Nb/Y vs. Zr/Ti diagram of Pearce (1996); (C) Th vs. Co diagram of Hastie et al. (2007).

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field also, the other half plot in andesite/andesite-basalt field (Fig. 8B). All rock samples show calc-alkaline series (Fig. 8C) in the diagram of Th versus Co (Hastie et al., 2007).

In conclusion, when geochemical and petrographic data are evaluated together, it can be said that volcanics of DEAA, in general, are made up of lavas and pyroclastics with basalt, basaltic andesite and andesite compositions and show calc-alkaline character.

Chemical analysis results are also evaluated within tectonic diagrams established by Wood (1980), Pearce (1982), Meschede (1986), Pearce (2008) and also in the framework of the normalized spider diagram according to MORB (Pearce, 1983). Considering the Hf/3-Th-Ta triangle diagrams of Wood (1980), rock samples of the DEAA plot in the calc-alkaline and volcanic arc basalt fields (Fig. 9A). When the results of chemical analyses are evaluated within the frame of Zr/4–2Nb–Y triangle discrimination diagrams of Meschede (1986), the rock samples of the DEAA plot in the field of volcanic arc basalts (Fig. 9B). On the basis of Ti vs. Zr discrimination diagram of Pearce (1982), the rock samples of the DEAA plot in the field of island arc lavas (Fig. 9C). Rock samples plot in the field of volcanic arc area in the diagram of Pearce (2008) as well (Fig. 9D). In the Th/Yb vs Ta/Yb diagram of Pearce (1983), all rock samples plot in the calc-alkaline area, which represents oceanic arc (Fig. 9E).

In the Zr/Y vs. Zr discrimination diagram only one sample plots in the transition field of continental and oceanic arcs, all others plot

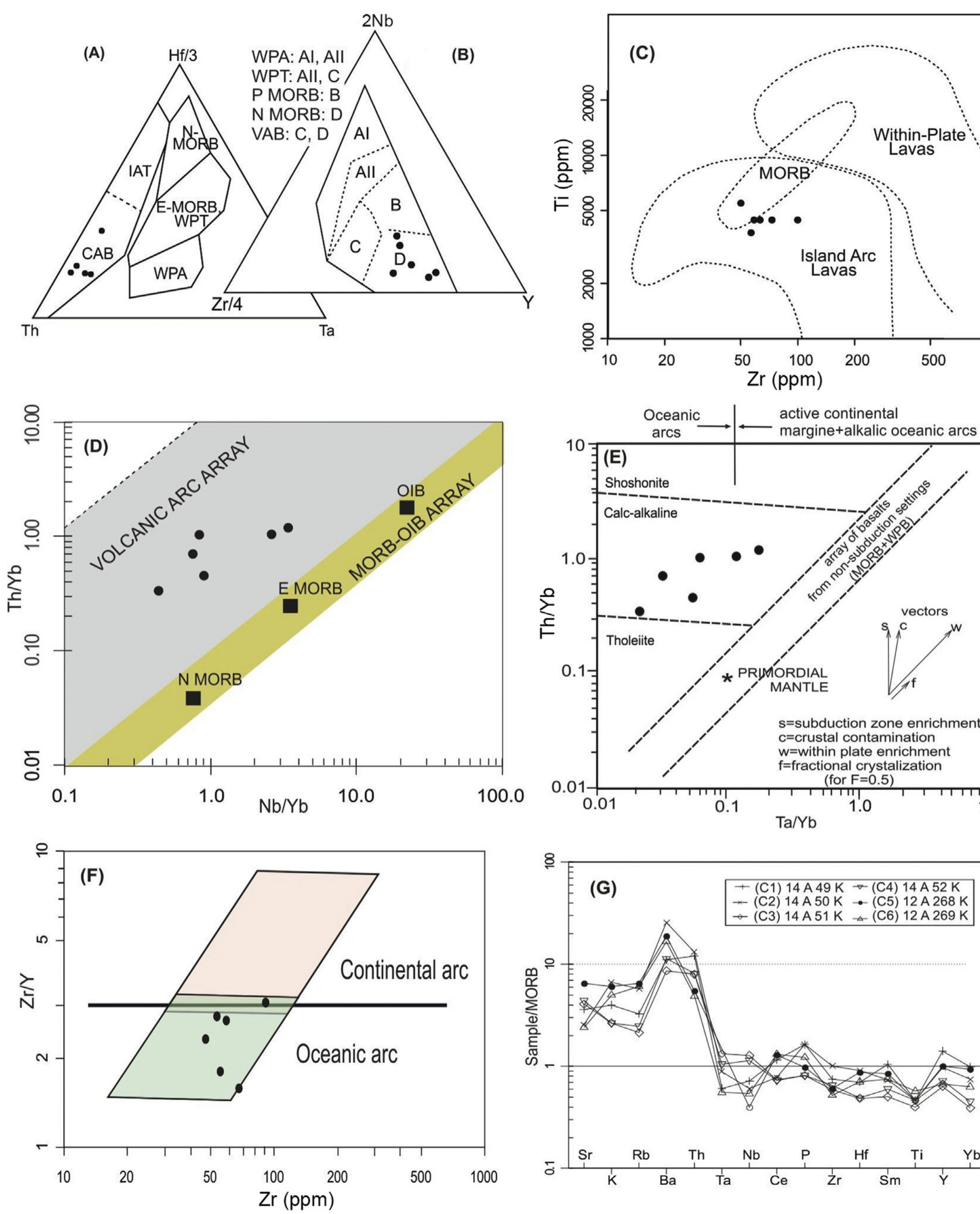

Figure 9. Tectonic discrimination diagrams for the Kartal unit of DEAA. (A) Hf/3–Th–Ta triangle diagram of Wood (1980); (B) 2Nb–Zr/4–Y triangle diagram of Meschede (1986); (C) Ti vs. Zr diagram of Pearce (1982); (D) Th/Yb vs. Nb/Yb diagram of Pearce (2008); (E) Th/Yb vs.Ta/Yb diagram of Pearce (1983); (F) Zr/Y vs. Zr diagram of Pearce (1983); (G) MORB normalised spider diagram of Pearce (1983). Abbreviations: IAT, island arc tholiites; CAB, calcalkaline-basalts; WPA, within plate alkali basalts; WPT, within plate WPA, within plate alkali basalts; WPT, within plate tholiites; VAB, volcanic arc basalts; VAB, volcanic arc basalts.

in the field of oceanic arc (Pearce, 1983) (Fig. 9F). To evaluate the trace element anomalies of volcanic rocks in the DEAA in the study area, in the framework of the normalized spider diagram according to MORB (Pearce, 1983), large cation LILE (Sr, K, Rb, Ba and Th) show enrichment and Zr, Hf, Ti and Yb partially show depletion (Fig. 9G).

On the basis of previous studies (Erdoğan et al., 1996; Tüysüz et al., 1995; Gökten and Floyd, 2007 and all data presented above, it can be concluded that oceanic crust started to subduct to the north beneath to the Sakarya Continent during the Cenomanian along the northern branch of Neo-Tethys and a second subduction occurred in the ocean to the south. Then, new ensimatic arc volcanics with pelagical units developed during the Santonian–Maastrichtian (Fig. 10A and B).

7. Discussions and conclusions

In the previous studies (Özcan et al., 1980; Yılmaz and Özer, 1984), it was proposed that the age of the Darmik Volcanics was Eocene. Then, the age was questioned by Yilmaz et al. (1995a, b) and a Maastrichtian–Paleocene age was suggested for the Darmik Volcanics. In the present study, the volcano-sedimentary units with conformably overlying pelagic sedimentary units are defined and named the DEAA. On the basis of paleontological findings obtained from mudstone intercalations in the volcanics, it is concluded that the age of the lower level of the DEAA is Cenomanian–Santonian (Fig. 4). In addition, on the basis of radiometric age obtained from lower level of the DEAA with the $^{40}Ar/^{39}Ar$ method, the formation of the volcanism was 98.7 $\pm$ 2.4 Ma; also indicating Cenomanian. Then, the age of the pelagic sedimentary rocks of the İzibüyük unit, which including rare volcano-sedimentary levels, representing the upper level of DEAA, was determined as Santonian–Maastrichtian. Therefore, it can be concluded that the age of the DEAA is Late Cretaceous, as a whole (Fig. 4). The age determination of the DEAA is the first contribution to the study area.

In addition, late Cretaceous, Söğütözü Volcanics of the Karaçayır-Sivas area were interpreted as an island arc by Yılmaz (1981). On the basis of Erdoğan et al. (1996), the arc developed in the Çankırı-Çorum area may be a primitive island arc in the Neo-Tethys Ocean. However, Tüysüz et al. (1995) suggested a system including two north-dipping subduction zones for the Çankırı-Çorum area. On the basis of this system, the northern zone was along the southern margin of the Sakarya Continent. As a result of this subduction zone, an ensialic magmatic arc, some fore-arc basins and a melange belt developed from north to south in the same region. The second subduction zone, located to the south, gave rise to a melange belt and an island arc developed on it.

The study area is located far from the areas between Çankırı-Çorum and also Karaçayır-Sivas. There are no geochemical determinations on the study area. In this framework, the whole-rock major, rare earth and trace element analysis of the rock samples collected from the DEAA were completed (Tables 2 and 3). The results of chemical analyses were evaluated in the framework of different classifications and tectonic diagrams, which were defined by different researchers (Figs. 8 and 9). In this study, it is concluded that the lower level volcanics of the DEAA are products of an ensimatic island arc. That is the second important contribution to the study area.

It is well known that the North Anatolian Ophiolitic Belt (Yılmaz and Yılmaz, 2013) includes Jurassic–Cretaceous MORB-type and SSZ-type ophiolites (Yılmaz, 1981; Buket, 1982; Tüysüz et al., 1995; Erdoğan et al., 1996; Sarıfakıoğlu, 2006; Gökten and Floyd, 2007; Sarıfakıoğlu et al., 2009; Çelik et al., 2013, 2016; Göçmengil et al., 2013; Parlak et al., 2013; Robertson et al., 2013; Topuz et al., 2013). Then Dilek and Thy (2006) suggested back arc basin for the Early Jurassic ophiolite of the Ankara area and Eyuboglu et al. (2016) suggested that the ultramafic rocks exposed in the south of Pontide belt belong to subcontinental mantle.

Rice et al. (2006) suggested that the İzmir-Ankara-Erzincan suture zone (IAESZ) in the Central and Eastern Pontides comprise a stack of thrust sheets. These are mainly the Late Cretaceous–Early Cenozoic age that were restored as a subduction-accretion complex, a continental-margin magmatic arc, an associated forearc basin, a back-arc basin and as a mainly sedimentary fill.

One of the important questions is the polarity of the subduction. The subduction polarity of the NAOB is a controversial topic. On one hand, North dipping subduction suggested by Şengör and Yılmaz (1981) and then accepted by Yılmaz et al. (1995b), Tüysüz et al. (1995), Yılmaz and Yılmaz (2013) and references there in. This model is widely accepted and proposes that the ultramafic-mafic rocks exposed between the Pontide arc and the Tauride belt, which are remnants of a Jurassic Penrose-type and/or supra-subduction zone ophiolite. In addition, double north-dipping

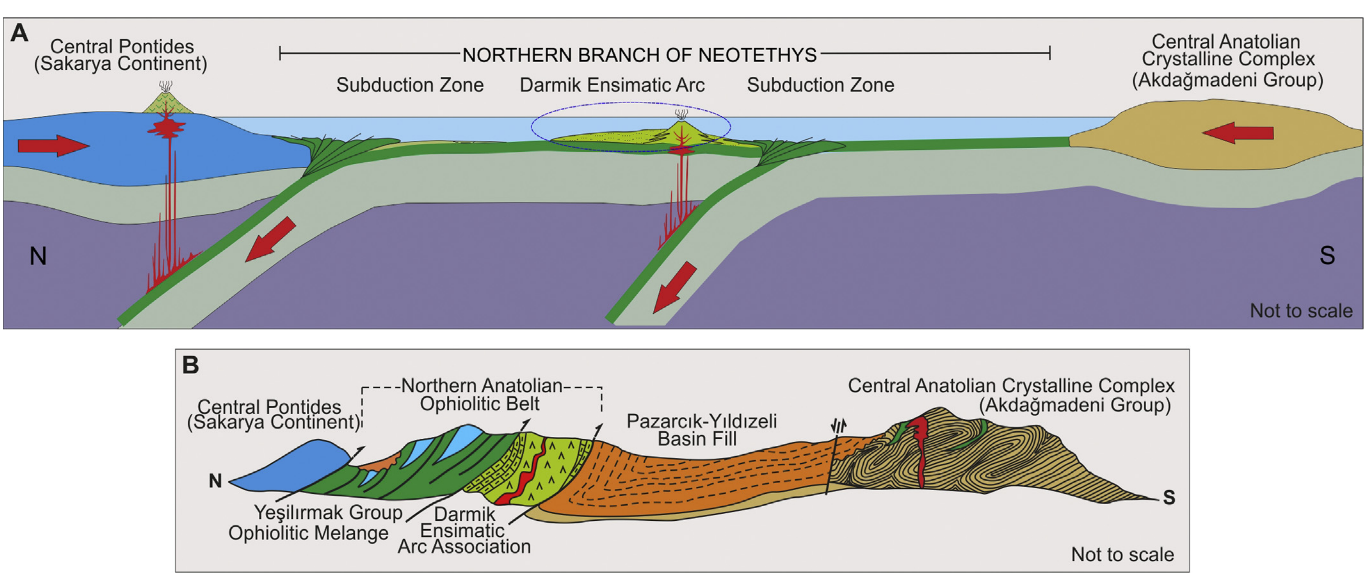

Figure 10. Proposed representative model for DEAA, in the begining of late Cretaceous (A) and recent tectonic setting of the region (B).

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subduction zones have been suggested to describe the tectonic evolution of the northern branch of Neo-tethys, in the Jurassic (Göçmengil et al., 2013), Jurassic–Cretaceous (Parlak et al., 2013; Robertson et al., 2013), Cretaceous (Sarıfakıoğlu et al., 2009) and Late Cretaceous (Erdoğan et al., 1996; Tüysüz et al., 1995; Yılmaz and Yılmaz, 2013).

On the other hand, concrete data about south dipping subduction was suggested by Eyüboglu et al. (2011a, b, c). In addition, new zircon U–Pb age data from mafic lithologies cutting the Kop ultramafic massif and clearly indicate that the ultramafic lithologies are Paleozoic or older in age and are not remnants of a Jurassic ocean that known as 'Northern Branch of Neotehtys' (Eyüboglu et al., 2016). As a result, it can be said that there are many uncertainties.

Surely, each of the models has pros and cons, as well. DEAA is located along the southern edge of NAOB in the study area, which represents a new subduction zone as well. The setting of dominant overthrusts of the studied region are north dipping and the Anatolide-Tauride Block represent the metamorphic equivalent of passive continental fragment. In this framework, the north dipping subduction model has been preferred in stead of south dipping model.

In the framework of geotectonic setting of DEAA, it can be concluded that oceanic crust started to subduct to the north beneath to the Sakarya Continent forming an ansialic arc during the Cenomanian along northern branch of Neo-Tethys and simultaneously a subduction occurred in the ocean. As a result, a new ensimatic arc with pelagic units (DEAA) developed during the Santonian–Maastrichtian time interval (Fig. 10A and B).

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