Tectono-stratigraphy, formation and emplacement ages of the Beyşehir-Hoyran Nappes in the south of the Sultan Dağları (Isparta, SW Türkiye)

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ABSTRACT

The Beyşehir-Hoyran Nappes (BHN), in the south of Sultan Dağları, consist of ophiolite, mélange and nappe slices of different lithologies and ages belonging to the oceanic crust and related rocks, which originated from the northern Neotethys and were thrusted southwards over the Taurus Platform. These nappes, namely the Marmaris ophiolite nappe, the Gülbahar nappe and the Domuzdağ nappe, are represented by three tectonically related nappe-slices that extend as a narrow NW-SE trending belt to the south of the Sultan Dağları. The Marmaris ophiolite nappe (Upper Cretaceous) is formed by three subunits namely the Marmaris ophiolite, the Kızılcadağ mélange and the Yenicekale metamorphics. Hornblende minerals from amphibolites of the Yenicekale metamorphic rock unit yielded a ^{40}Ar-^{39}Ar age of 93.9±0.34 Ma (Cenomanian-Turonian boundary). Besides, late Triassic to early Jurassic ages were obtained from the deep marine sedimentary rocks of the Gülbahar nappe based on the radiolarian assemblages.

Paleontological and radiometric ages obtained from this study show that the formation of the BHN should began in the Turonian and ended in the Late Maastrichtian. The nappes, on the other hand, were emplaced over southern Sultan Dağları in the early-middle Paleocene and reached their present position as a result of late Eocene movements.

Key words: Beyşehir-Hoyran nappes, Sultan Dağları, Gülbahar nappe, Metamorphic sole.

1. Introduction

Türkiye, which is situated on the Alpine-Himalayan orogenic belt, has been significantly shaped by the closure of the Neotethys Ocean during the Late Cretaceous-Early Cenozoic and the subsequent collision between the Anatolian and Arabian plates by the end of the Middle Miocene (Şengör and Yılmaz, 1981). During this process, several suture zones developed in Türkiye. The İzmir-Ankara-Erzincan suture zone (Şengör and Yılmaz, 1981; Görür et al., 1983; Okay and Tüysüz, 1999) and the Inner-Tauride suture zone (Görür et al., 1984; Robertson and Dixon, 1984; Okay and Tüysüz, 1999), formed by the closure of the northern branch of the Neotethys Ocean, constitutes the northern boundary of the Anatolide-Tauride Block (Okay and Tüysüz, 1999), while the Bitlis-Zagros suture zone (Şengör and Yılmaz, 1981; Yılmaz, 1993; Parlak et al., 2009), formed by the closure of the southern branch, defines the southern boundary.

The Anatolides (*sensu* Ketin, 1966), located in the Anatolide-Tauride Block, represent those parts of the Taurides that underwent regional metamorphism during the Late Cretaceous-Early Cenozoic due to the Alpine orogeny (e.g., Pourteau et al., 2013). The Taurides consist mainly of parautochthonous and allochthonous, imbricated, folded, non-metamorphic or low-grade metamorphic units (Geyikdağ, Aladağ, Bolkardağ, Bozkır, Antalya and Alanya units) (Özgül, 1976). The Sultan Dağları and its surroundings is one of the regions where the relationships between Geyikdağ, Aladağ and Bozkır units can be best observed.

The Sultan Dağları is a mountain range consisting of Paleozoic to Mesozoic low-grade metamorphic rocks and a Cenozoic cover that extends between the Afyon Zone (Okay, 1984; Okay and Tüysüz, 1999; Candan et al., 2005) and the Anamas-Akseki Autochthon (Şenel et al., 1992) with a NW-SE direction and forms the NE flank of the Isparta Angle (*sensu* Poisson et al., 1984). The NW-SE trending allocthonous units extending south of the Sultan Dağları are referred to as the BHN (Gutnic et al., 1968; Monod, 1977) (Figure 1). The BHN is composed of ophiolites, mélanges and rocks of different ages and lithologies, derived from the northern branch of the Neotethys Ocean (İzmir-Ankara-Erzincan and/or Inner Tauride Oceans) and emplaced on the Taurus platform (Andrew and Robertson 2002; Çelik and Delaloye, 2006; Elitok and Drüppel, 2008). The BHN can be regarded as the eastern continuation of the Lycian Nappes (*sensu* Şenel et al., 1989), which lies west of the Isparta Angle.

Units of the BHN are genetically represented in the northern branch of the Neotethys by rift-related rocks in the Triassic, by carbonate and clastic sediments of the passive continental margin in the Jurassic-Cretaceous, and by supra-subduction ophiolites and mélanges associated with northward subduction in the Late Cretaceous (Andrew and Robertson, 2002; Çelik and Delaloye, 2006; Elitok and Drüppel, 2006; Mackintosh and Robertson, 2009; Parlak et al., 2019). The formation and emplacement processes of the BHN are key to understanding the geodynamic evolution of the region. The general assumption about these nappes is that they were formed in the Late Cretaceous due to the closure of the northern branch of the Neotethys and emplaced on the Taurus platform during the Late Cretaceous-Eocene interval (Andrew and Robertson, 2002; Çelik and Delaloye, 2006; Elitok and Drüppel, 2008; Güngör, 2013). Constraining these too-long intervals by paleontological and radiometric dating provides more accurate data on the formation and emplacement processes of the BHN. In addition, the majority of present studies of the BHN are concerned with the age and geochemical properties of the ophiolites and metamorphic sole rocks (e.g. Elitok and Drüppel, 2002; Çelik and Delaloye, 2006; Parlak et al., 2019). Thus, the tectono-stratigraphy of the nappes and their relationship to the cover rocks has not been sufficiently investigated.

This study aims to provide a detailed tectono-stratigraphy of the BHN and to constrain the formation and emplacement ages of these nappes by integrating the biostratigraphic, radiometric and structural data.

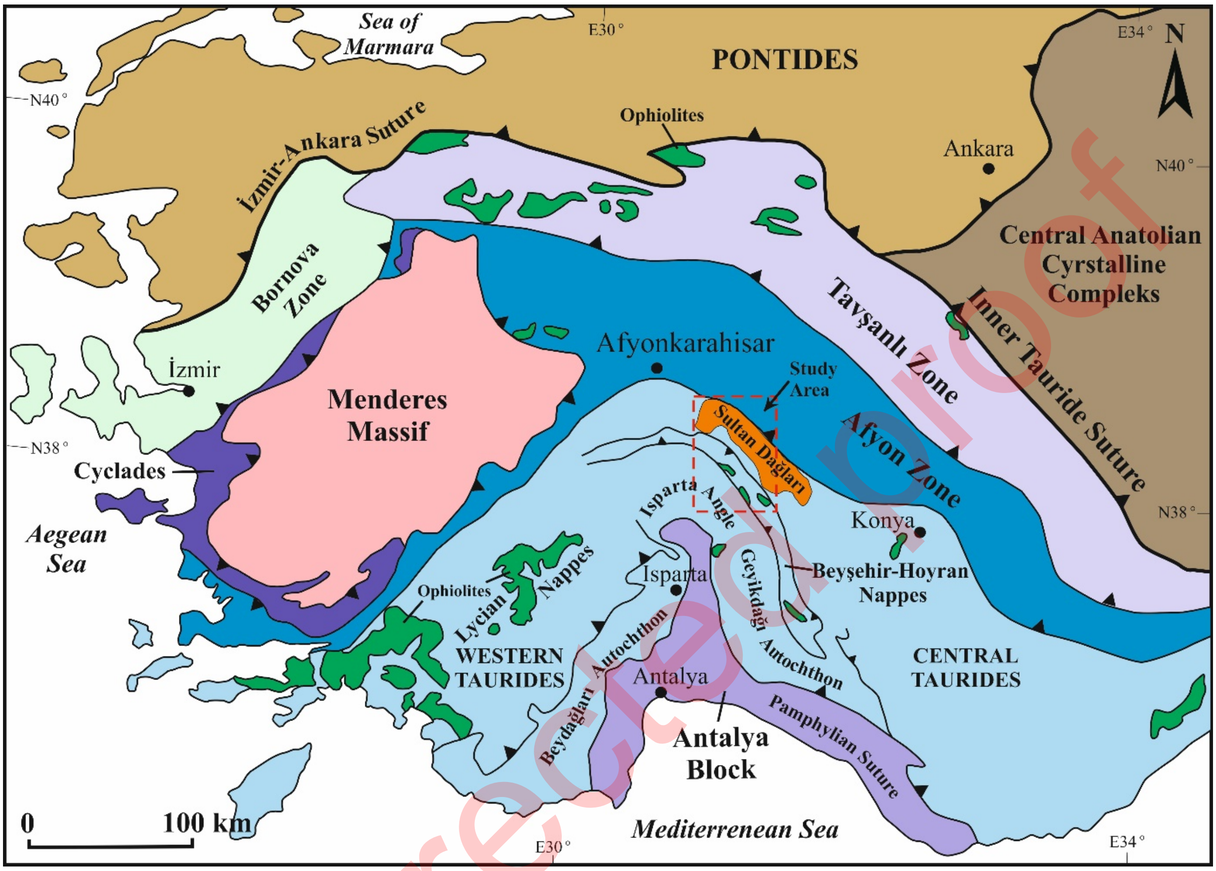

Figure 1- Tectonic map of the western Anatolia (modified after Pourteau et al., 2010, 2013).

1.1. Material and Method

Basic studies to identify tectono-stratigraphic features and solve geological problems are based on the production of geological maps at a scale of 1:25,000 in the field. The paleontological and petrographic samples studied in the MTA laboratories were collected in the field from appropriate levels of the formations. Radiometric dating studies were carried out at the Nevada Isotope Geochronology Laboratory (USA) using the ^{40}Ar-^{39}Ar method on hornblende minerals from amphibolites of the Yenicekale metamorphics.

2. Tectono-stratigraphy

Early Cambrian to Quaternary rock units of different origins and lithologies outcrop in the study area (Figure 2). Formations of the Geyikdağı, Bolkardağı/Aladağ and Bozkır units form the basement of the region (Özgül, 1976).

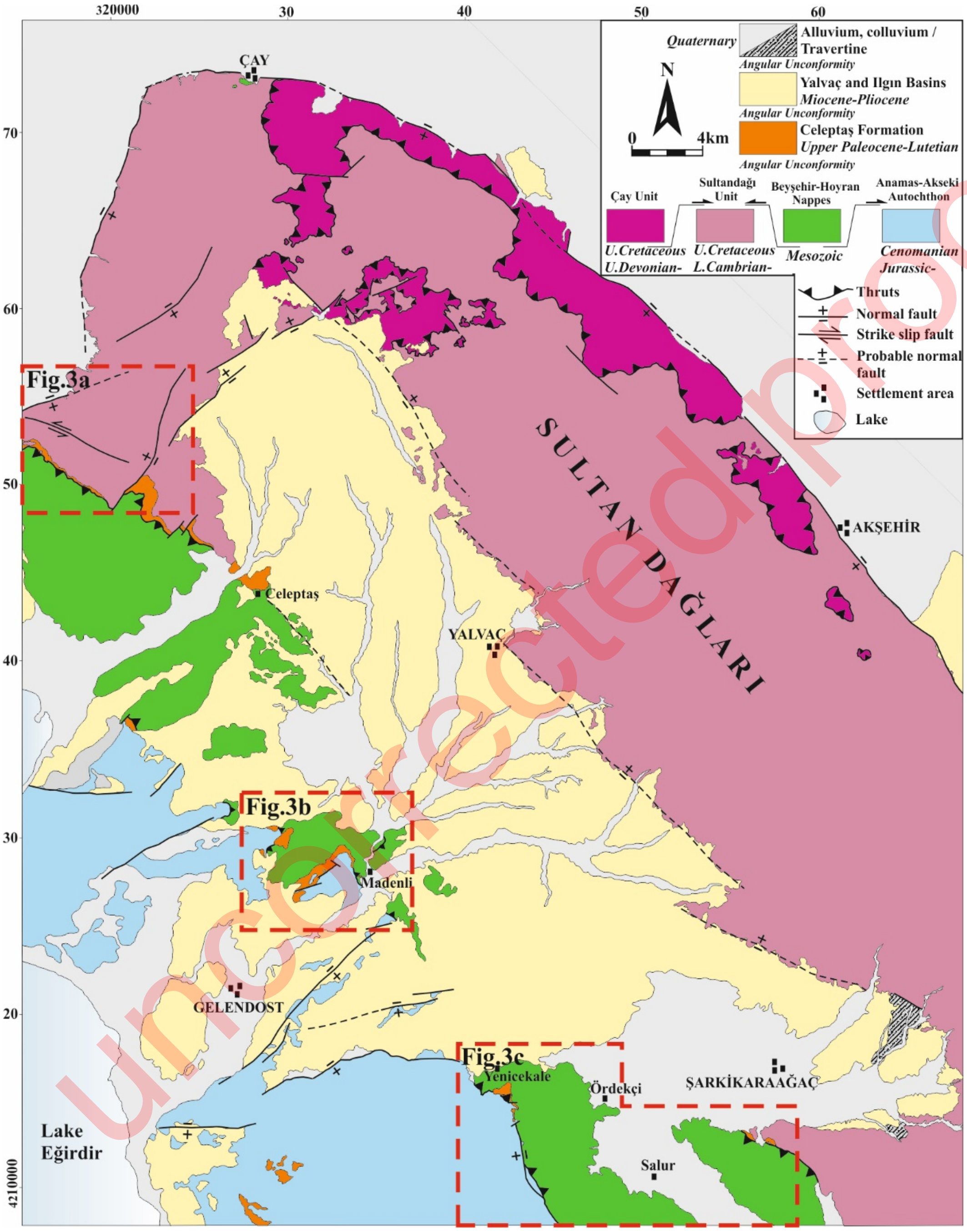

Figure 2- Simplified geological map of the Sultan Dağları and its surroundings (simplified after Ergen et al., 2021).

The widespread parautochthonous rocks of the Geyikdağı Unit (Özgül, 1976) are studied under the names of Sultandağı Unit (*sensu* Özgül et al., 1991) and Anamas-Akseki Autochthon (*sensu* Şenel et al., 1992) in the study area, while the allocthonous rock assemblages of the Bolkardağı/Aladağ Unit and the Bozkır Unit are studied under the names of Çay Unit (*sensu* Özgül et al., 1991) and the BHN (*sensu* Monod, 1977) respectively (Figures 2 and 3).

The late Paleocene-Lutetian Celeptaş Formation and deposits of the Miocene-Pliocene Yalvaç and Ilgın basins form the Cenozoic cover. Quaternary deposits are the youngest cover in the region. As the units of the BHN observed in the study area are a continuation of the Lycian Nappes and show strong stratigraphic similarities, the nomenclature of the Lycian Nappes is followed to ensure regional correlation.

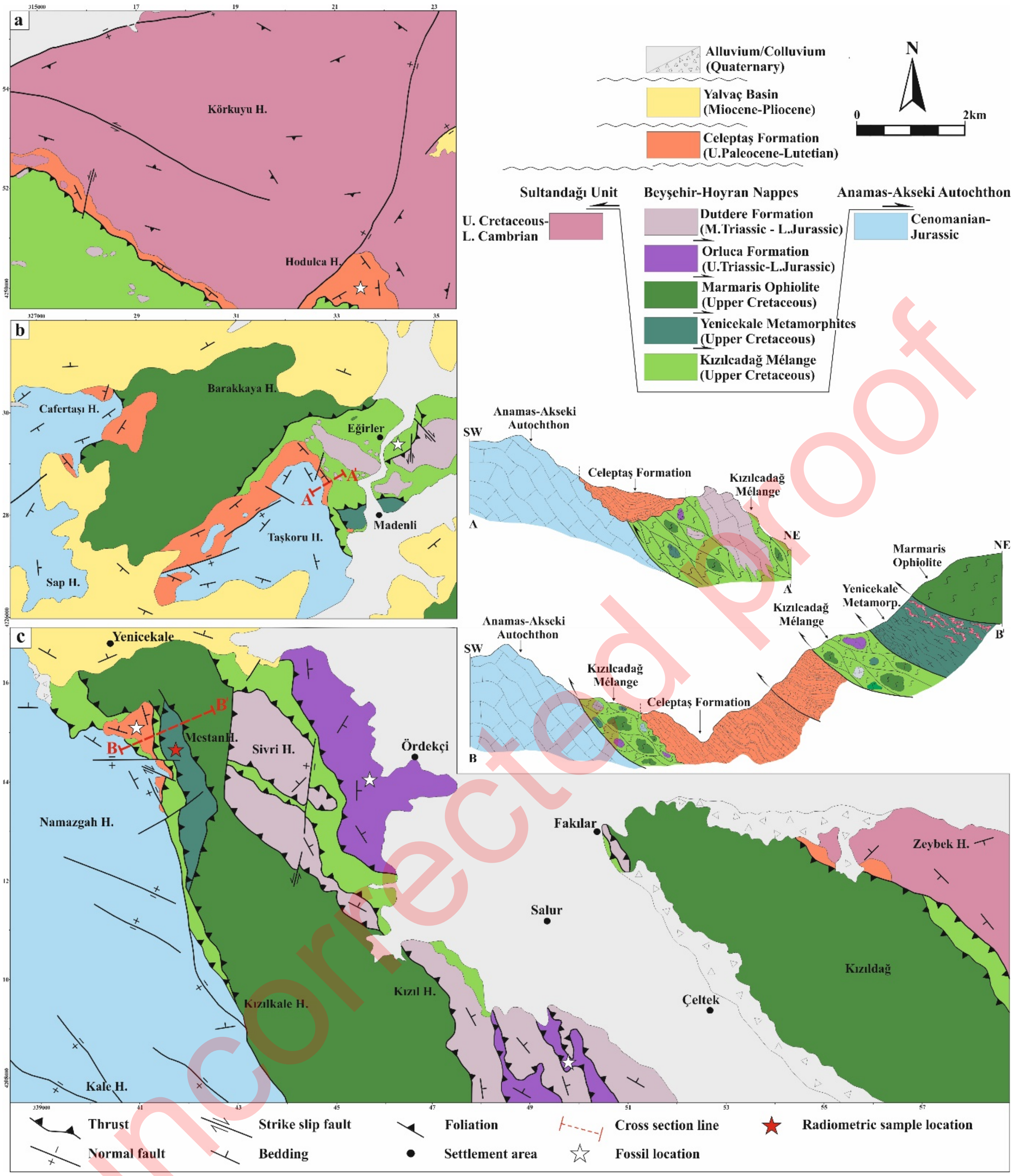

Figure 3- Geological map and cross-sections showing the relationship of the units of the BHN to the parautochthonous basement and cover rocks (modified after Ergen et al., 2021).

2.1. Sultandağı Unit

The Sultandağı Unit forms the dominant rock mass of the Sultan Dağları. The unit consists of lower Cambrian to Upper Cretaceous metasedimentary and metavolcanic rocks (Özgül et al., 1991; Ergen et al., 2021).

The Sultandağı Unit, which represents a transgressive sequence associated with back-arc basin development in the early Paleozoic (Linneman et al., 2008; Nance et al., 2010; Dedeoğlu et al., 2021), is composed of quartzite, marble and turbiditic clastic rocks. An upper Paleozoic succession of quartzite, phyllite, recrystallized limestone and dolomite overlies the early Paleozoic units after the Late Devonian unconformity. The Mesozoic succession begins in the Middle Triassic with terrestrial metaconglomerates and metasandstones, overlain by Jurassic-Cretaceous metacarbonate rocks. The Sultandağı Unit underwent lower greenschist metamorphism (Güngör, 2013) in the early-middle Paleocene based on the emplacement of the Çay Unit and the BHN (Ergen et al., 2021; Ergen, 2023). The late Paleocene-Lutetian Celeptaş Formation and the Neogene deposits of the Yalvaç and Ilgın basins unconformably overlie the Sultandağı Unit.

2.2. Anamas-Akseki Autochthon

The unit consists of non-metamorphic Jurassic-Cretaceous aged (Şenel et al., 1992) neritic carbonates belonging to the Geyikdağı Unit in the south of the Sultan Dağları. The Anamas-Akseki Autochthon (*sensu* Şenel et al., 1992), observed in the SW parts of the study area, is represented by Jurassic-Cenomanian grey-colored, medium to thick-bedded limestones and dolomites. The lower contact of the unit is not seen in the study area, being unconformably overlain by the Celeptaş Formation and tectonically overlain in places by ophiolites of the BHN.

2.3. Çay Unit

The Late Devonian to Cretaceous lower greenschist-facies rocks of the Bolkardağı/Aladağ Unit, outcropping in a NW-SE trending narrow strip along the northeastern edge of the Sultan Dağları, are called the Çay Unit (Özgül et al., 1991; Ergen et al., 2021). The Çay Unit, which consists of metasedimentary rocks intercalated with metavolcanics, tectonically overlies the Sultandağı Unit and is also tectonically overlain by the BHN (Figure 2).

2.4. Beyşehir-Hoyran Nappes

The BHN are the allocthonous masses composed of ophiolite, mélange and associated blocks and slices of different lithologies and ages, formed as a result of the closure of the northern branch of the Neotethys Ocean and were emplaced on the Taurus Platform during the Late Cretaceous-early Cenozoic (Monod, 1977; Andrew and Robertson, 2002; Çelik and Delaloye, 2006; Ergen et al., 2021). These nappes, which are exposed in a NW-SE trending narrow belt and are tectonically interrelated with each other, are the Marmaris Ophiolite nappe (the Kızılcadağ mélange, the Yenicekale metamorphics and the Marmaris ophiolite), the Gülbahar nappe and the Domuzdağ nappe from bottom to top (Ergen et al., 2021; Ergen, 2023) (Figure 4).

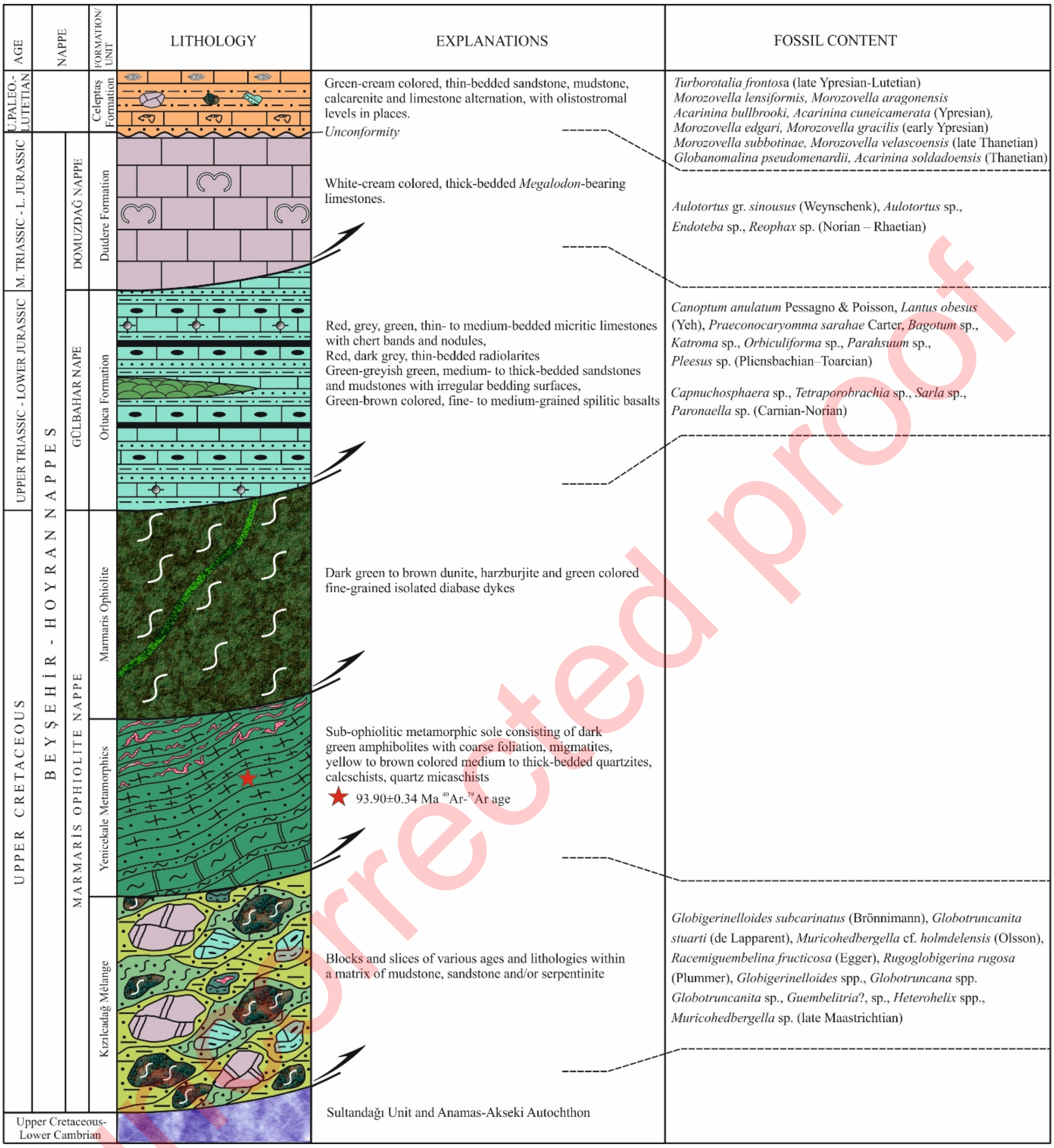

Figure 4- Tectono-stratigraphic column of the BHN in the study area (not to scale).

The Marmaris ophiolite nappe (Upper Cretaceous) is formed by three subunits as the Marmaris ophiolite, the Kızılcadağ mélange and the Yenicekale metamorphics. The Marmaris ophiolite is composed of dunite, harzburgite, serpentinite and diabase dykes, while the Kızılcadağ mélange is composed by blocks of different ages and lithologies contained in an ophiolitic/sedimentary matrix. The Yenicekale metamorphics consist mainly of amphibolites that characterize a sub-ophiolitic metamorphic sole (Elitok and Drüppel, 2008). The Orluca Formation (Şenel et al., 1989), which is composed of micritic limestone, radiolarite, chert, mudstone and basalt intercalations, represents the Gülbahar nappe. The Domuzdağ nappe at the top is represented by the Dutdere Formation (Ersoy, 1989), which consists of *Megalodon*-bearing limestones.

The Celeptaş Formation unconformably overlies the BHN, which tectonically rest on the parautochthonous Sultandağı Unit and the Anamas-Akseki Autochthon.

2.4.1. Marmaris Ophiolite Nappe

Kızılcadağ mélange (Kkm): It is composed of blocks and slices of different lithologies contained in an ophiolitic and sedimentary matrix (Poison, 1977; Şenel et al., 1989; Ergen et al., 2021). The majority of the matrix consists of green, intensely sheared serpentinites and, to a lesser extent, mudstones. Blocks and slices belonging to the Domuzdağ and Gülbahar nappes and the Marmaris Ophiolite are observed in the matrix. Blocks and slices of the Domuzdağ and Gülbahar nappes and the Marmaris Ophiolite, ranging from a few centimetres to tens of metres, are observed in the matrix, and they are composed of such rocks as marble, micritic limestone, chert, radiolarite, dunite, harzburgite, gabbro, diabase and amphibolite (Figures 5a and 5b). Radiolarian assemblages obtained from micritic limestone, chert and radiolarite blocks of the formation yielded ages from Aalenian to early Tithonian.

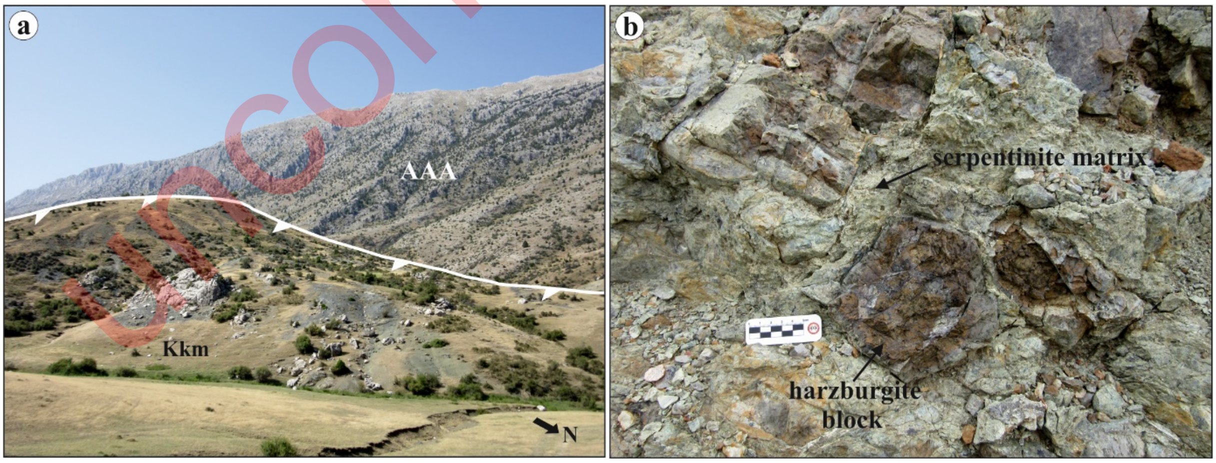

Figure 5- a) General view of the Kızılcadağ mélange (Kkm) and its tectonic contact with the Anamas-Akseki Autochthon (AAA), b) harzburgite blocks in the serpentinite matrix of the mélange, south of Yenicekale village, Şarkikarağaç.

The lower contact of the Kızılcadağ mélange is tectonic. It tectonically overlies the Jurassic-Cretaceous carbonates of the Sultandağı Unit to the south of Şarkikaraağaç, while tectonically overlying the Jurassic-Cenomanian limestones of the Anamas-Akseki Autochthon to the south of Yenicekale (Figures 5a and 6a-d). The Celeptaş Formation covers the Kızılcadağ mélange with an unconformable contact. In addition, the Marmaris ophiolite, Yenicekale metamorphics, Domuzdağ and Gülbahar nappes tectonically overlie the Kızılcadağ mélange. It is also unconformably overlain by deposits of the Miocene-Pliocene Yalvaç Basin to the south of Yenicekale village (Figure 3c).

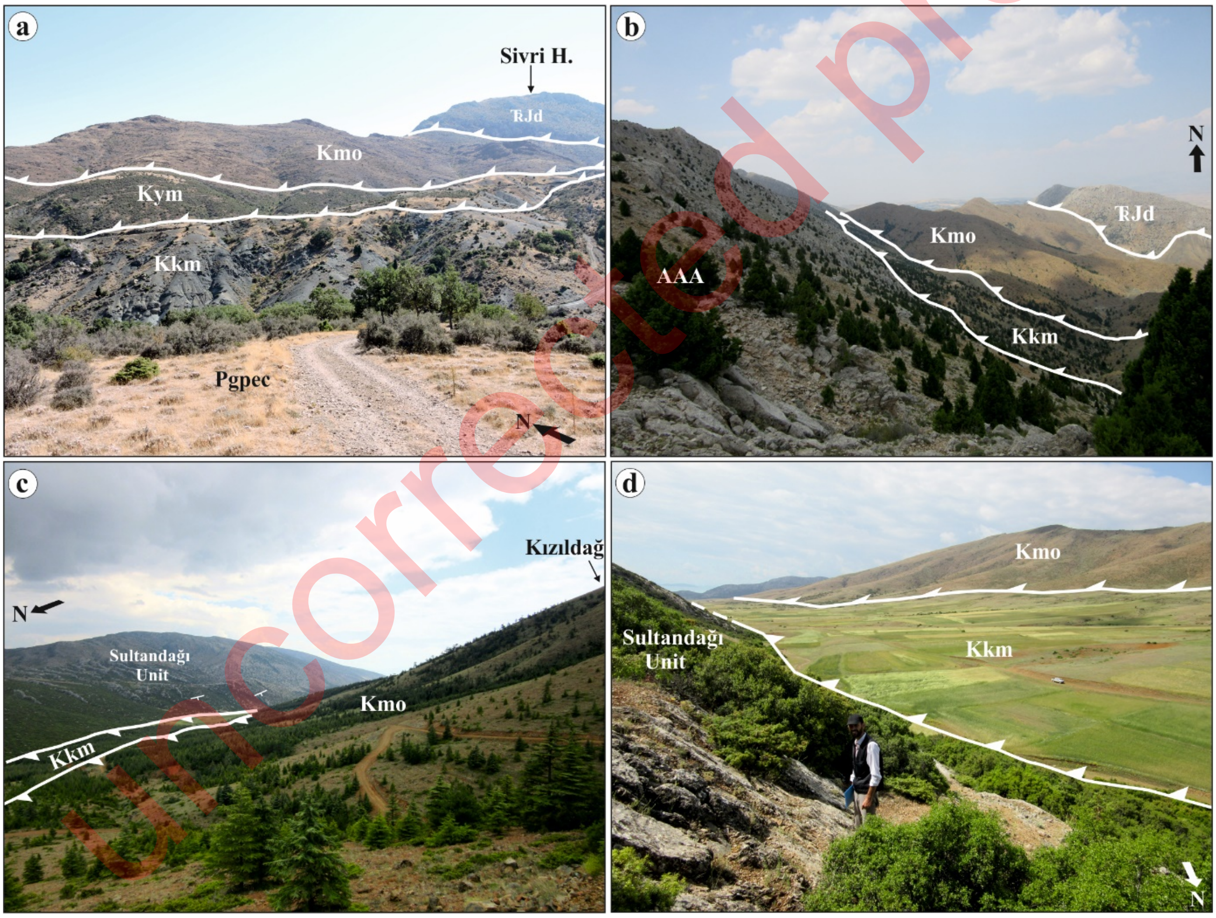

Figure 6- Tectonic relationships of units of the BHN. a, b) SW-vergent thrust contacts, SE of Yenicekale village, Şarkikaraağaç, c, d) NE-vergent back-thrusts, S of Şarkikaraağaç. Kmo: Marmaris ophiolite, Kkm: Kızılcadağ mélange, Kym: Yenicekale metamorphics, T_RJd: Dutdere Formation, AAA: Anamas-Akseki Autochthon.

The age of the mélange in the Lycian Nappes is accepted as Late Cretaceous based on the planktonic foraminiferal assemblages (Poisson, 1977; Şenel et al., 1989). Besides, it is claimed that the age of the mélange near Bozkır town (Konya) is late Maastrichtian. It was also reported that the age of the mélange near Bozkır district (Konya) is late Maastrichtian (Özgül, 1997; Andrew and Robertson, 2002).

In this current study, planktonic foraminiferal assemblage including *Globigerinelloides subcarinatus* (Brönnimann), *Globotruncanita stuarti* (de Lapparent), *Muricohedbergella* cf. *holmdelensis* (Olsson), Racemiguembelina fructicosa (Egger), *Rugoglobigerina rugosa* (Plummer), *Globigerinelloides* spp., *Globotruncana* spp. *Globotruncanita* sp., *Guembelitria*?, sp., *Heterohelix* spp., *Muricohedbergella* sp. species, indicating a late Maastrichtian age, has been identified from the mudstones that forms the sedimentary matrix of the Kızılcadağ mélange around the Eğirler village.

In addition, assemblages containing radiolarian species such as *Transhsuum brevicostatum* gr. (Ozvoldova), *Zhamoidellum* sp., *Tritrabs casmaliaensis* (Pessagno), *Homoeoparonaella* sp. cf. H. *argolidensis* Baumgartner, *Emiluvia* sp., *Mirifusus* sp., *Pantanellium* sp., *Mirifusus guadalupensis* Pessagno, *Archaeospongoprunum* sp., *Podobursa* sp., *Transhsuum* sp., *Praewilliriedellum convexum* (Yao), *Saitoum* sp., *Hsuum* sp., *Eucyrtidiellum unumaense* s.l. (Yao), *Praewilliriedellum convexum* (Yao), *Transhsuum maxwelli* gr. (Pessagno), *Homoeoparonaella* (?) *pseudoewingi* (Baumgartner), *Tetraditryma* sp. cf. T. *pseudoplena* Baumgartner, *Saitoum* sp., *Hsuum* sp., *Parahsuum* sp. are obtained in different samples of micritic limestones and radiolarites of the mélange, yielding an Aalenian-early Tithonian age. The Kızılcadağ mélange was formed by the emplacement of blocks and slices of different lithologies and ages in an ophiolitic/sedimentary matrix during the Late Cretaceous northward subduction of the northern branch of the Neotethys Ocean, and thus gained a chaotic structure depending on intense tectonics.

Yenicekale Metamorphics (Kym): The rock assemblage containing amphibolite, amphibole-biotite schist, calcschist and quartz schist, which are observed as sub-ophiolitic metamorphic sole in the BHN (Elitok and Drüpbel, 2008), are referred to as the Yenicekale metamorphics (Ergen et al., 2020, 2021).

The Yenicekale metamorphics are composed of dark green, medium to coarsely foliated amphibolites, with ptygmatic folds in places (Figures 7a and 7b), and grey-blue, thin to medium-bedded calcschists and yellow-brown, thin to medium foliated quartzites (Figure 7d) and quartz schists. Amphibolites, which are the dominant lithologies of the unit, are composed of plagioclase, hornblende, chlorite and titanite minerals, with a granonematoblastic to nematoblastic texture (Figure 7f). Sericitization and argillization are common in plagioclase minerals. Quartzites are composed of quartz, feldspar, mica and apatite minerals, with a granoblastic texture. These rocks show a metamorphic grade from amphibolite to greenschist facies (Elitok and Drüpbel, 2008). Inverted metamorphic grade, one of the characteristic features of the sub-ophiolitic metamorphic rocks, can be observed within the Yenicekale metamorphics. The amphibolites are at the top of the sequence, while the greenschist facies rocks such as quartzite, quartz schist and calcschist are at the bottom of the sequence. These metamorphic rocks are intruded by non-metamorphic isolated diabase dykes, as is in the Marmaris ophiolite (Figure 7e). These dykes, which yield U-Pb zircon ages ranging from 90.8 ± 1.6 Ma to 87.6 ± 2.1 Ma (Parlak et al., 2019), are geochemically tholeiitic and, to a lesser extent, alkaline in composition (Elitok and Drüppel, 2008; Parlak et al., 2019).

The Yenicekale metamorphics are generally observed between the ophiolites and the ophiolitic mélange, representing various thicknesses (Figure 6a-b and 7c). It has a thickness of up to 140 metres around Yenicekale village (Elitok and Drüppel, 2008) and has a lenticular geometry.

Hornblende minerals from amphibolites of this unit in the south of Yenicekale village (coordinates: 36342124N/4214144E) yielded a ^{40}Ar-^{39}Ar age of 93.90±0.34 Ma (Figure 8). Parlak et al. (2019) obtained ages of 90-94 Ma and 91-93 Ma from amphibolites in the same area using U-Pb and ^{40}Ar-^{39}Ar methods, respectively. These are in agreement with the 91-93 Ma age of Çelik et al. (2006) determined from amphibole and mica minerals of the Lycian Nappes, Antalya Nappes and metamorphic basement rocks of the BHN.

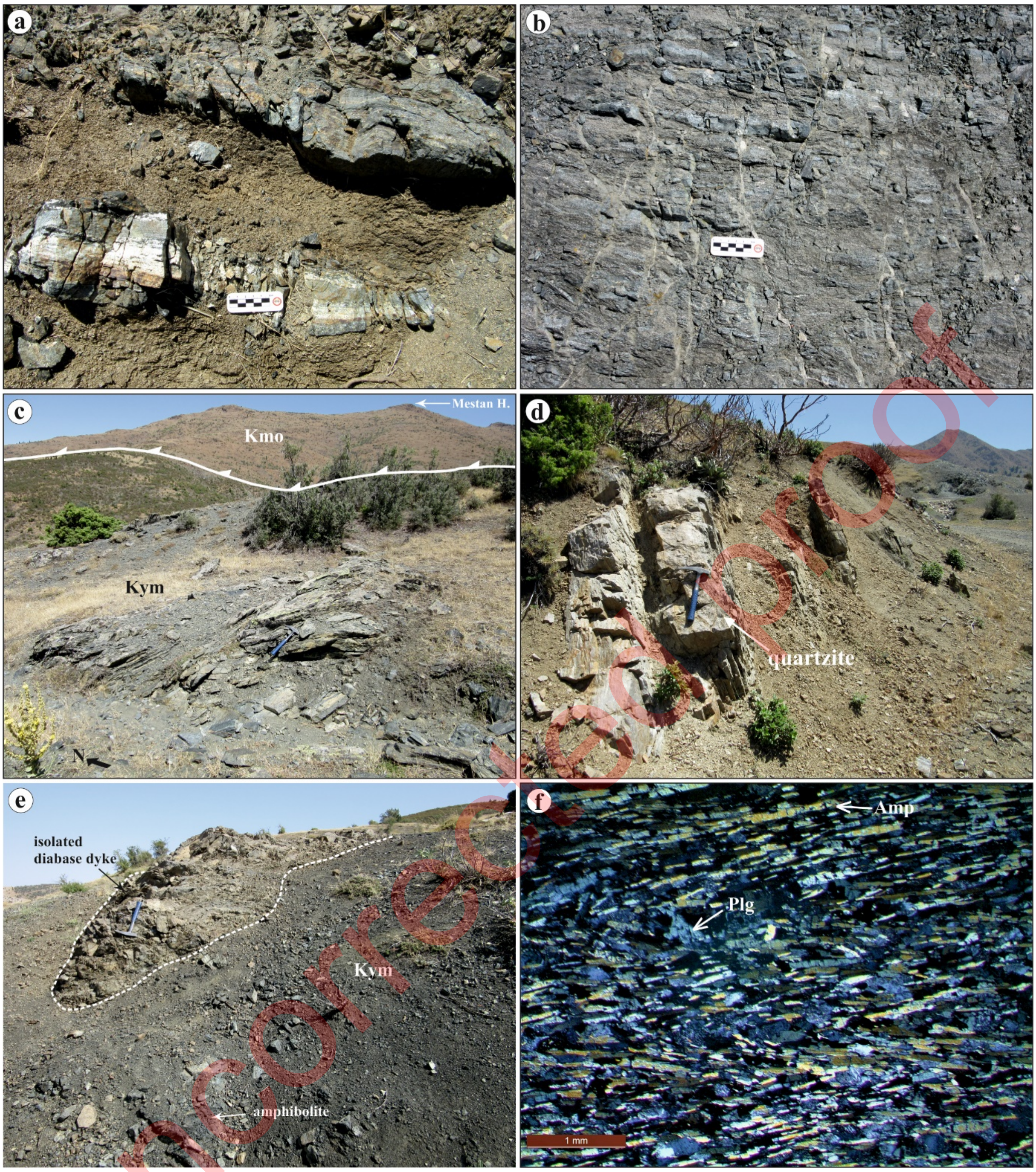

Figure 7- a, b) General view of the amphiolites of the Yenicekale metamorphics, c) tectonic relationships between the Yenicekale metamorphics (Kym) and the Marmaris ophiolite (Kmo) W of Mestan Hill, d) general view of the quartzite, quartz schist and calcschist, SE of Yenicekale village, e) an isolated diabase dyke intruding the amphibolites of the Yenicekale metamorphics (Kym), SE of Yenicekale village, f) thin section view of an amphibolite sample with a nematoblastic texture, under cross polarized light (Amp: amphibole, Plg: plagioclase).

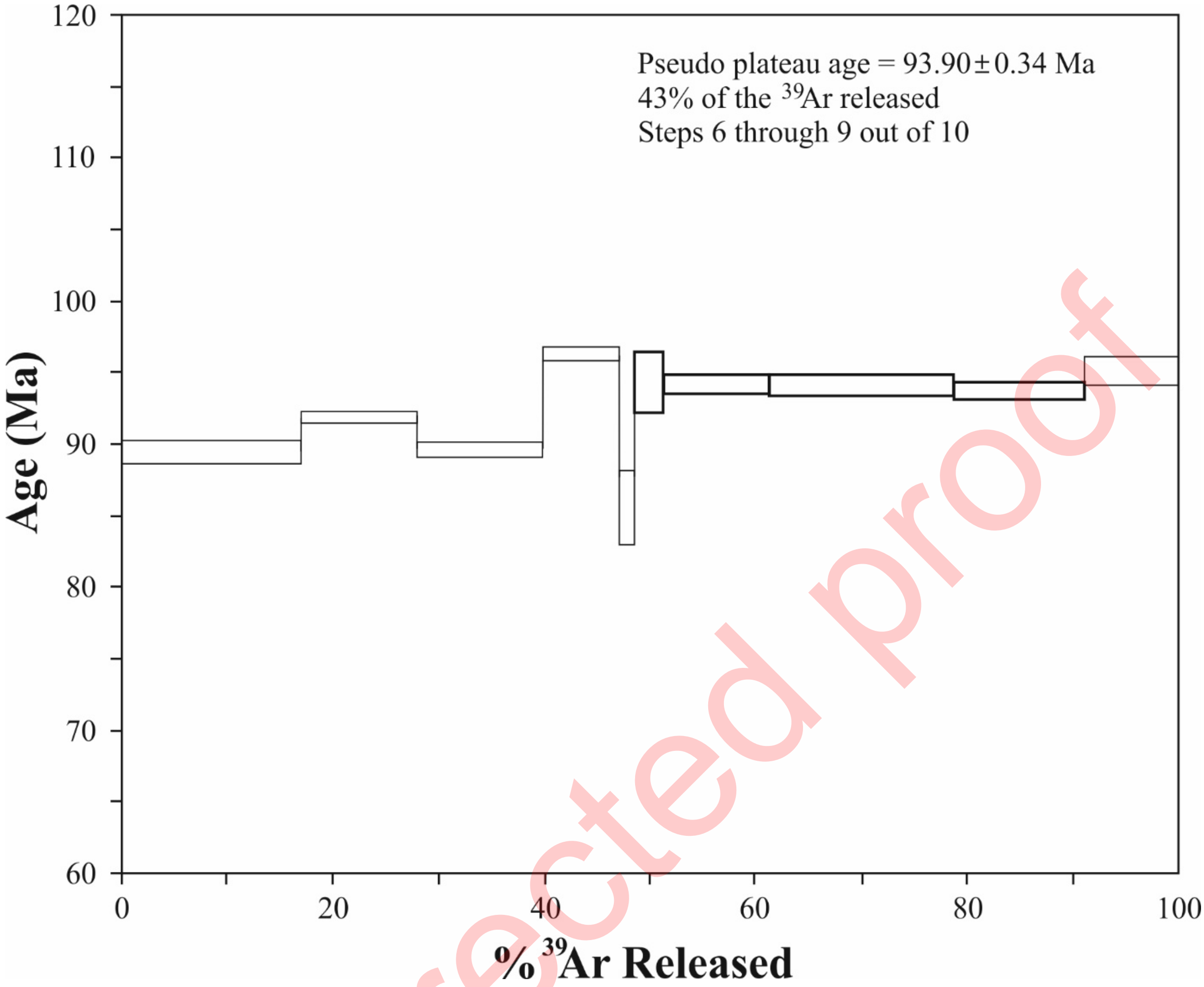

Figure 8- Age spectrum for the amphibolite of the Yenicekale metamorphics.

Based on the analysis of the amphibolites, P-T conditions of 630-770°C and 6±1.5 kbar, corresponding to a burial depth of 18-20 km, are calculated for the metamorphism of these sub-ophiolitic metamorphic sole rocks (Elitok and Drüppel, 2008). The amphibolites show two different geochemical characters, alkaline and tholeiitic. According to this, the protoliths for alkaline amphibolites are within-plate type alkalin basalts, while the tholeiitic amphibolites are ocean island basalts (Elitok and Drippel, 2008; Parlak et al., 2019).

Marmaris Ophiolite (Kmo): The ophiolitic rocks outcropping in the Lycian Nappes and the BHN, which are continuations of each other in southwestern Anatolia, have been defined under different names by various researchers. Various names have been given to the rock association, which consists mainly of dunite, harzburgite and serpentinized peridotite were referred to various names such as Beyşehir ophiolite (Ricou et al., 1975; Çelik and Delaloye, 2006) and Hoyran ophiolite (Demirkol and Yetiş (1983-1984) within the BHN; ophiolites (Andrew and Robertson, 2002) and peridotites (Elitok and Drüppel, 2008) within the Hoyran Nappes; peridotite nappe (Graciansky, 1972), Yeşilova-Tefenni ophiolites (Sarıkaya and Seyrek, 1976), Yeşilova ophiolites (Sarp, 1976), Marmaris peridotite (Çapan, 1981) and Marmaris ophiolite (Ergen et al., 2021) within the Lycian Nappes.

The Marmaris ophiolite, whose lower and upper contacts are tectonic, is up to 1000 m thick. (Şenel, 1997). In the study area, it tectonically overlies the Sultandağı Unit to the south of Şarkikaraağaç and the Anamas-Akseki Autochthon, the Kızılcadağ mélange and the Yenicekale metamorphics to the south of Yenicekale (Figure 9c). On the other hand, the units belonging to the Gülbahar and Domuzdağ nappes rest on the ophiolites with a tectonic contact.

The Marmaris ophiolite consists of serpentinized dunite and harzburgite and isolated diabase dykes (Figure 9a). The most common rocks observed in this ophiolitic units are harzburgites, which are medium to coarse grained, with green olivine and grey to black pyroxene minerals, brown on altered surfaces and blackish green to green on fresh surfaces. Dunites, apart from olivine, also include orthopyroxene and chromite minerals, with a mesh texture, light green to greenish grey in color, are less common than harzburgites. Serpentinization is common, especially along fractures. Dunites and harzburgites are intruded by 0.5-2 m thick isolated diabase dykes composed of plagioclase, clinopyroxene and opaque minerals with an ophitic texture. Zircon and titanite minerals from these dykes, which characterize geochemically subduction-related island arc tholeiites, yielded U-Pb ages of 87.5-102 Ma, while hornblende minerals yielded a ^{40}Ar-^{39}Ar age of 91-93 Ma (Çelik et al., 2006). Stockwork magnesite veins are widely observed in the ophiolites outcropping around Madenli village (Figure 9b).

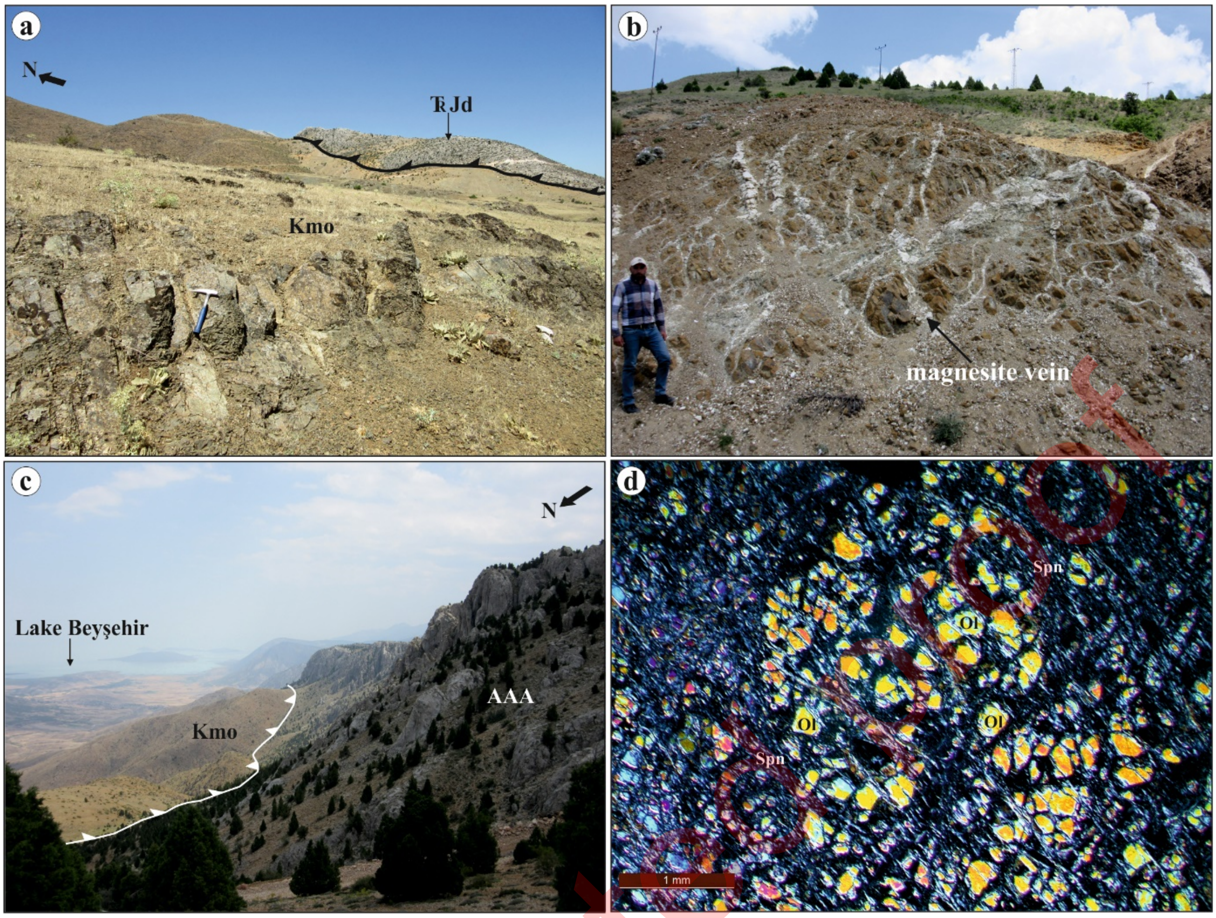

Figure 9- a) Tectonic relationship between the Marmaris ophiolite (Kmo) and the Dutdere Formation (T_RJd) of the Domuzdağ Nappe, NW of Sivri Hill, Yenicekale, b) stockwork magnesite veins in the ophiolites, NW of Eğirler, c) tectonic contact between the Marmaris ophiolite (Kmo) and the Anamas-Akseki Autochthon (AAA), NW of Lake Beyşehir, d) thin section view of a serpentinized dunite sample under cross polarized light (Ol: Olivine, Spn: Serpentine).

The unit, which characterizes supra-subduction ophiolites, is accepted as Late Cretaceous in age based on radiometric data and geochemical analysis obtained from its isolated diabase dykes and metamorphic sole (Andrew and Robertson, 2002; Çelik et al., 2006; Elitok and Drüppel, 2008; Parlak et al., 2019; Ergen et al., 2021, Ergen, 2023).

2.4.2. Gülbahar Nappe

The Mesosoic allochthonous sequence of deep marine limestone, chert, radiolarite and mudstone and spilitic basalt is called the Gülbahar Nappe (Graciansky, 1972; Şenel et al., 1994). The Gülbahar Nappe and the Orluca

Formation from this nappe have been identified and mapped in this study for the first time in the south of Sultan Dağları.

The Gülbahar Nappe is generally observed as blocks and slices of different sizes in the Kızılcadağ mélange. Outcropping west of Ördekçi village and south of Salur (Şarkikaraağaç), the Gülbahar Nappe is represented in the study area by the Orluca Formation. The aforementioned locations where the Orluca Formation is exposed have been misinterpreted by previous researchers (e.g. Elitok and Drüppel, 2008; Parlak et al., 2019) as Upper Cretaceous slope and basin deposits.

Orluca Formation (T_RJo): The formation, which consists of volcanics, radiolarites, cherty micritic limestones, mudstones and sandstones (Şenel, 1989), is exposed west of Ördekçi and south of Salur (Şarkikaraağaç).

The formation is composed of thin to medium-bedded, red, grey, green, intensely folded, deformed micritic limestones with chert bands and nodules, and red, dark grey thin-bedded radiolarites, and green-greyish green, medium- to thick-bedded sandstones and mudstones (Figures 10a-c). They are occasionally accompanied by green, brown, fine- to medium-grained spilitic basalts (Figure 10d), which consist of plagioclase, clinopyroxene, kaersutite, biotite, calcite and opaque minerals with an intersertal texture (Figure 10e). Sericitization and argillization are common in plagioclase minerals, while chloritization is common in pyroxene minerals. Radiolarites consist entirely of fossil radiolarian tests filled with very fine-grained siliceous minerals. The fact that the formation consists of sandstone, mudstone, radiolarite, cherty micritic limestone with basic volcanic intercalations indicates deposition in a slope and basin environment where both volcanism and turbidity currents are occasionally active.

Tectonically overlying the Kızılcadağ mélange (Figures 10 c and 10f), the Orluca Formation is also observed as blocks of various sizes in the mélange.

In this study, radiolarian assemblages that contains *Capnuchosphaera* sp., *Tetraporobrachia* sp., *Sarla* sp., *Paronaella* sp. in the west of Ördekçi (coordinates: 36346310N/4213840E) and *Canoptum anulatum* Pessagno & Poisson, *Lantus obesus* (Yeh), *Praeconocaryomma sarahae* Carter, *Bagotum* sp., *Katroma* sp., *Orbiculiforma* sp., *Parahsuum* sp., *Pleesus* sp. in the south of Salur (coordinates: 349530N/4208601E) have been identified, yielding the ages of Late Triassic and Pliensbachian-Toarcian (Early Jurassic), respectively.

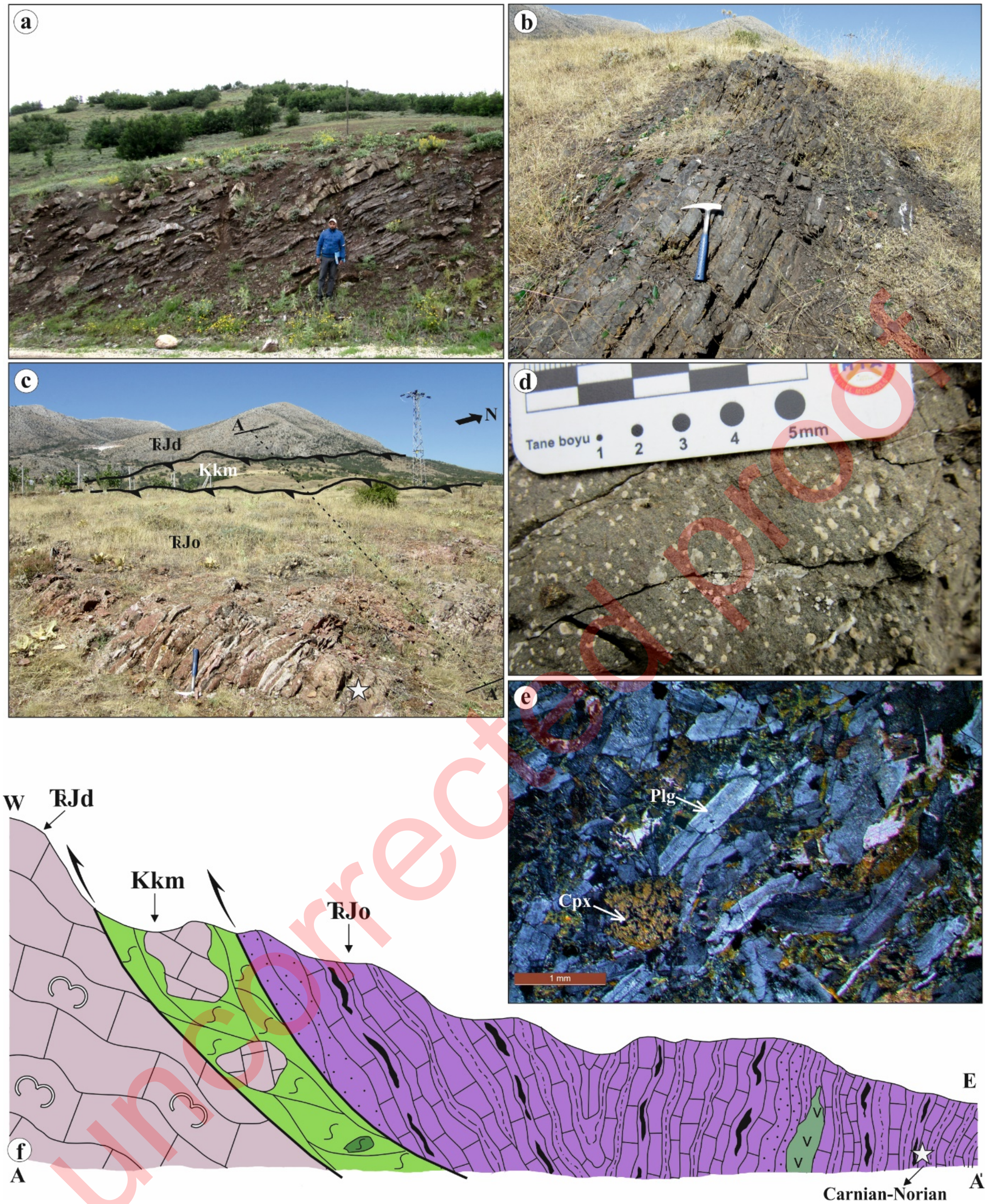

Figure 10- a) Alternation of micritic limestone and mudstone in the Orluca Formation, S of Salur, b) dark grey radiolatites, W of Ördekçi, c) tectonic relationships of the Orluca Formation with the Kızılcadağ mélange and the Dutdere Formation, NW of Ördekçi, d) a close-up view of the spilitic basalts, e) thin section view of a basalt sample under cross polarized light (Cpx: Clinopyroxene, Plg: Plagioclase), f) a geological cross-section showing relations between the Dutdere Formation (T_RJd), Kızılcadağ

mélange (Kkm) and Orluca Formation (T_{R}Jo) (Note that the star indicates the stratigraphic position of the dated paleontological sample).

2.4.3. Domuzdağ Nappe

The unit, which is observed as blocks and slices at various sizes within the Marmaris Ophiolite Nappe and characterized by *Megalodon*-bearing neritic limestones, is recognized as the Domuzdağ Nappe (Poisson, 1977; Ersoy, 1989; Şenel et al., 1994). The Middle Triassic-Early Jurassic Dutdere Formation represents the Domuzdağ Nappe in the study area.

Dutdere Formation (T_{R}Jd): The Dutdere Formation (*sensu* Ersoy, 1989) consists mainly of grey, light grey, beyaz and beige-colored, medium- to thick-bedded, *Megalodon* and algae-bearing and occasionally recrystallized limestones, which are very fine-grained biomicrite, microsparite and sparry micrite. The limestones, composed of calcite minerals and poorly preserved fossils in a micritic carbonate cement, are sometimes recrystallized due to the intense tectonics caused by nappe movements. It contains cracks and fractures developed in different directions and is observed as cataclastic and brecciated, especially at the nappe contacts. Şenel et al. (1994) reported that pink to red, thin- to medium-bedded, ammonite-bearing cherty limestones occur outside the study area above the *Megalodon*-bearing lower levels of the formation.

In the study area, the formation tectonically overlies the Marmaris ophiolite, Kızılcadağ mélange, and Orluca Formation. The Kızılcadağ mélange is also observed over the Dutdere formation, depending on the tectonic movements after its primary emplacement. One such contact relationship can be seen at the SE of Yenicekale.

Within the formation, which is easily recognized in the field by bearing *Megalodon* fossils, foraminifera such as *Aulotortus* gr. *sinousus* (Weynschenk), *Aulotortus* sp., *Endoteba* sp., *Reophax* sp. have been determined in this study at the south of Sultan Dağları, indicating a Late Triassic (Norian-Rhaetian) age. Şenel et al. (1989, 1994) assigned a Middle Triassic-Early Jurassic age to the formation, which is also accepted in this study, based on the foraminiferal fauna obtained from the same formation at different locations in the Western Taurides.Based on the lithological characteristics and fossil content, it can be inferred that the formation was deposited in a shallow carbonate shelf environment.

2.5. Cover rocks

2.5.1. Celeptaş Formation (Pgpec)

The Celeptaş Formation (sensu Demirkol, 1977) is mainly composed of thin-bedded limestones, calcarenites, siltstones, mudstones, sandstones and subordinate conglomerates that form different facies and facies associations (Figure 11). The thin-bedded, cream-coloured pelagic limestones and claret-coloured calcarenite and biomicrite with abundant planktonic foraminifera are exposed in the north of the basin (Figures 11a, b). The fine-grained calcarenites are well-sorted and show planar parallel stratification and wave-ripple cross-lamination (Figure 11b). They pass southwards into the interbedded mudstones, siltstones and sandstones, forming mudstone- and sandstone-dominated sequences (Figures 11c, d, e).

Greenish-grey mudstones are laterally extensive and generally massive in the mudstone-dominated sequences (Figure 11c). Very thin-bedded siltstones and very fine to fine sandstones interbedded with mudstones are generally 0.5-5 cm thick, and in lesser amounts up to 15 cm. Sedimentary structures include planar parallel stratification, normal grading and current ripple cross-lamination.

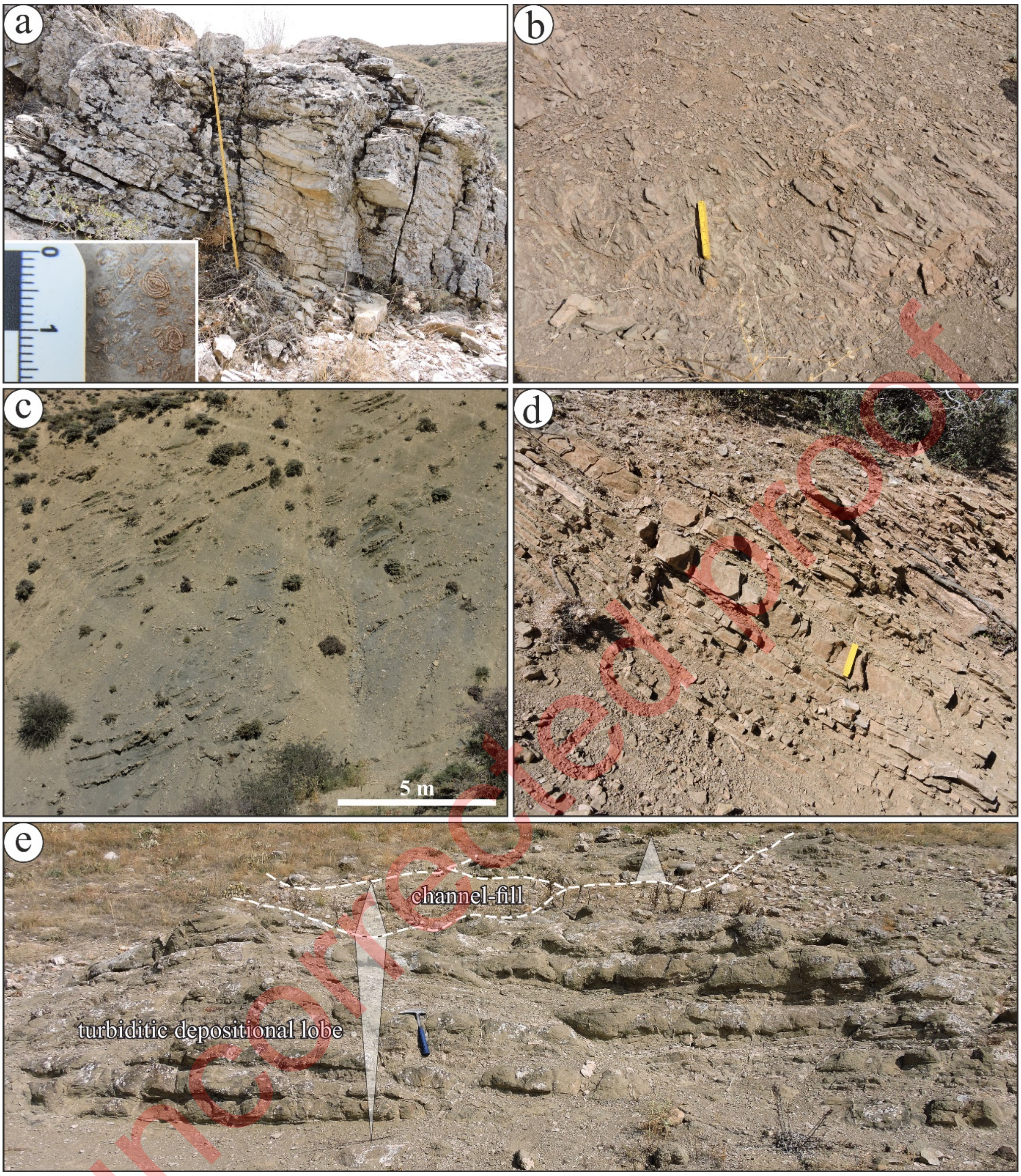

Figure 11- Facies details of Dursunlu Formation, a) Thin-bedded pelagic limestones with *Nummulites* fossils and b) claret-coloured calcarenite and biomicrite, c) Massive mudstones of the basin-plain hemipelagic deposits interbedded with siltstone and sandstone turbidites, d) The sandstone-dominated sequence consists mainly of Bouma-type Tbc and lesser amounts of Tabc turbidites, e) The coarsening- and thickening-upward bed packages of the turbiditic depositional lobes are erosionally overlain by the fining-upwards bedsets of the channel-fill deposits. The ruler is 1 m in figure a and 10 cm in figures b and d, the hammer is 33 cm.

The sandstone-dominated sequence consists mainly of grey to light brown sandstones and siltstones interbedded with grey mudstones (Figure 11d). The tabular sandstones, which are generally 10-30 cm thick, contain mainly Bouma-type Tbc and lesser amounts of Tabc turbidites. Other sedimentary structures include flute and groove marks, load casts, convolute laminations and some trace fossils. The interbedded sandstones, siltstones and mudstones, form coarsening- and thickening-upward bed packages a few metres thick (Figure 11e). These are erosionally overlain by lenticular channel-fill deposits in the axial part (Figure 11e). The fining upward bedset of the channel-fill deposits consist of coarse sandstones to granule conglomerates, rich in pebble gravels at the base.

The *Nummulites*-bearing pelagic limestones and biomicrites, rich in planktonic foraminifers, indicate a neritic carbonate platform formed on the basin-margin narrow shelf. The calcarenites are interpreted to represent wave-worked, lower shoreface to offshore transition deposits (cf. Clifton, 1981; Dott and Bourgeois, 1982). The mudstones are interpreted to be basin-plain hemipelagic deposits interlayered with thin silstone and sandstone turbidites in the mudstone-dominated bed packages. The graded sandstone beds with planar stratification are tractional deposits of low-density turbidity currents (Bouma, 1962; Lowe, 1982; Kneller, 1995). The sandstone-dominated coarsening-upwards bed packages are interpreted as turbiditic depositional lobes and the overlying fining-upwards bedsets as channel-fill deposits. The sedimentary facies of these deposits indicate high- and low-density turbidity currents. The composition of the sandstone and the pebbles indicates that the sand grains and clasts are of ophiolitic origin.

The Celeptaş Formation unconformably covers the Sultandağı Unit, the Anamas-Akseki Autochthon and the BHN (Figure 12), while it is tectonically overlain in places by the BHN (Figure 13).

The results of the planktonic foraminiferal analyses performed on the marine mudstone samples from Hodulca Hill northwest of Yalvaç (327382E/4244438N), north of Celeptaş village (327382E/4244438N) and south of Yenicekale (341350E/4214700N) (Figures 2, 3) are given below.

Among the abundant planktonic foraminiferal assemblages of the Celeptaş Formation, the species such as *Globanomalina pseudomenardii* and *Acarinina soldadoensis* in the Thanetian, *Morozovella subbotinae* and *Morozovella velascoensis* in the late Thanetian, *Morozovella edgari* and *Morozovella gracilis* in the early Ypresian, *Morozovella lensiformis* and *Morozovella aragonensis* in the Ypresian, *Acarinina bullbrooki*, *Acarinina cuneicamerata* and *Turborotalia frontosa* in the late Ypresian to Lutetian levels have been identified in a stratigraphical order as markers. The age of the Celeptaş Formation has been assigned as Late Paleocene-Lutetian based on this planktonic foraminiferal content.

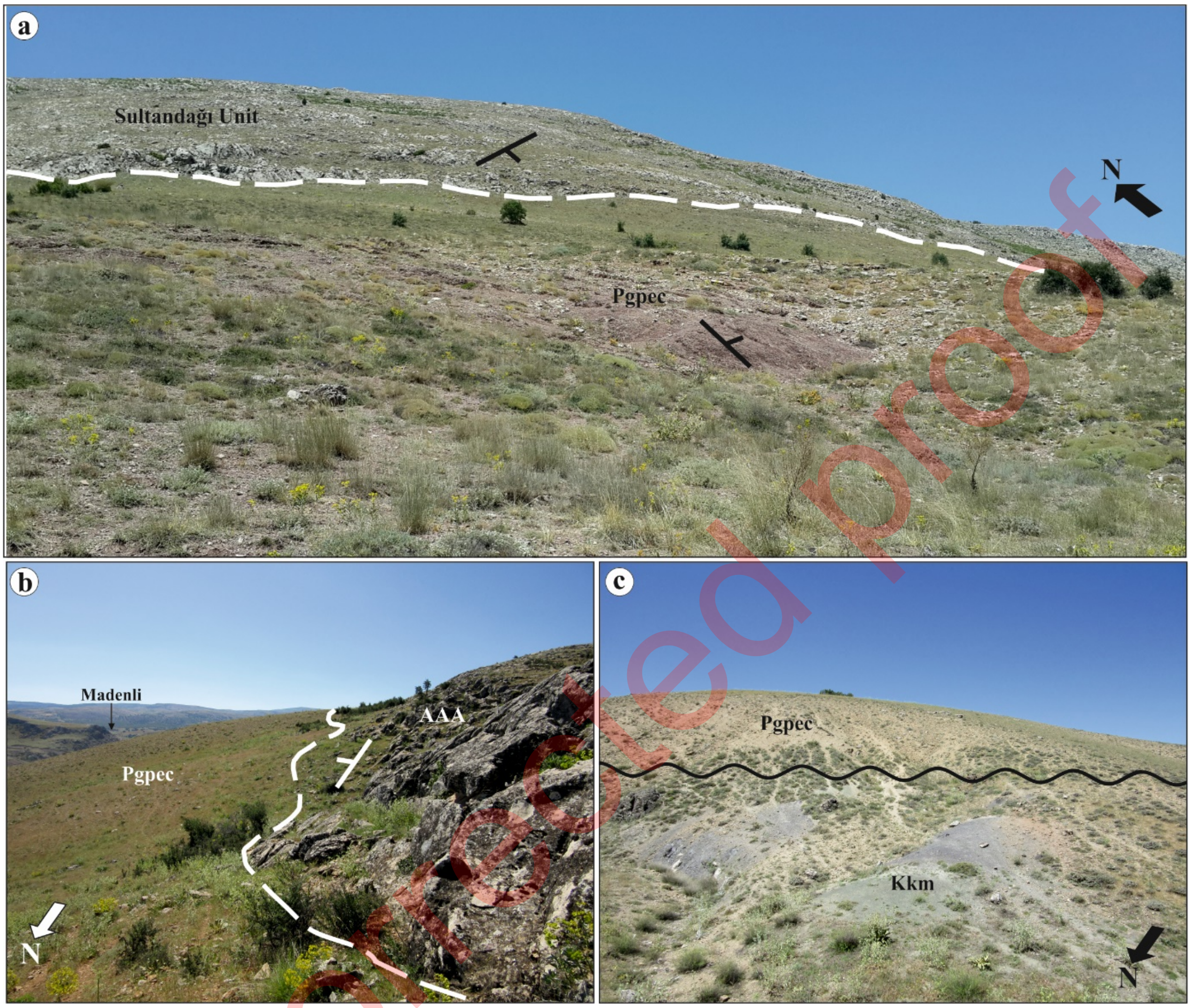

Figure 12- a) The unconformable contact between the Celeptaş Formation and the Middle Jurassic-Upper Cretaceous recrystallized limestones of the Sultandağı Unit, near Hodulca Hill, Yalvaç, b) unconformable contacts between the Celeptaş Formation and Jurassic-Cenomanian limestones of the Anamas-Akseki Autochthon (AAA) and c) Kızılcadağ mélange (Kkm) of the BHN, north of Madenli.

Figure 13- a) Thrust contact between the Kızılcadağ mélange of the BHN and the Celeptaş Formation, SE of Yenicekale, b) close-up of the first figure showing folds.

2.5.2. Yalvaç Basin

The Yalvaç Basin, which is formed of terrestrial and lacustrine deposits, is a triangular molasse basin that extends in a NW-SE direction between the Sultan Dağları and the Anamas Mountains (Yağmurlu, 1991; Ilgar et al., 2021). Deposits of the basin are alluvial fan, lacustrine clastic and carbonate sediments. The formation of the Yalvaç Basin, which began to open after nappe emplacement as a result of orogenic collapse, is known to have been influenced by the break-up or roll-back of the Southern Neotethys slab during the Early Miocene (Koçyiğit and Deveci, 2007; Koçyiğit et al., 2013; Koç et al., 2016; Ilgar et al., 2021). The sediments of the Yalvaç Basin unconformably overlie all pre-Miocene units in the region.

3. Discussions

The formation and emplacement processes of the BHN are important in revealing the geodynamic evolution of the region. The generally accepted aspect is that the BHN was formed as a result of horizontal movements due to the closure of the northern branch of the Neotethys Ocean (İzmir-Ankara-Erzincan and/or Inner Tauride Ocean) and settled in the region by thrusting over the Sultan Dağları from north to south during the Late Cretaceous-Eocene (Özgül, 1984; Andrew and Robertson, 2002; Çelik and Delaloye, 2006; Elitok and Drüppel, 2008).

There are several critical issues in dating nappes formed by oceanic subduction processes such as the BHN, the most important of which are the age of the sub-ophiolitic metamorphic rocks, the age of the matrix and blocks of the mélange and the age of the cover of the nappes. The formation of nappes begins with the development of the sub-ophiolitic metamorphic rocks, which represent the onset of subduction, while it ends with the youngest age obtained from the matrix in the mélange. The emplacement time, on the other hand, is constrained by the youngest unit the nappes thrust over and the overlying oldest unit.

The sub-ophiolitic metamorphic rocks, which formed during the onset of subduction, are widely accepted as definitive indicators of subduction initiation ages, with metamorphic ages derived from their amphibolites (Çelik and Delaloye, 2006). In this context, the 93.90±0.34 Ma (Cenomanian-Turonian boundary) age data obtained from the Yenicekale metamorphics is accepted as the onset of the formation of the BHN (Figure 14a).

The ages obtained from the blocks and matrix of the mélange are another significant parameter related to the formation of the mélange. Accordingly, the occurrence of Upper Triassic Domuzdağ Nappe, Upper Triassic-Lower Jurassic Gülbahar Nappe and Upper Cretaceous Marmaris Ophiolite Nappe blocks and slices within the Kızılcadağ mélange and the determination of late Maastrichtian planktonic foraminifera from the matrix of the mélange indicate that the formation of the BHN lasts possibly from the Turonian to the late Maastrichtian.

The basin type in which the Celeptaş Formation was deposited has been inferred from the sedimentary characteristics of the formation and its tectonostratigraphic relationship with the surrounding units. The rapid transition of the neritic carbonate and offshore transition deposits of the Celeptaş Formation into the deep marine facies indicates a narrow shelf and increased supply of terrigenous sediments to the basin. In addition, intense compressional tectonic deformation during and after deposition suggests that the sediments were deposited in a tectonically controlled basin. Therefore, taken together, we have interpreted the Celeptaş Formation as being deposited in a foreland basin that was fed by and developed in front of the BHN. The flexural subsidence of the basin floor, driven by the crustal load of the BHN, led to the development of sediment accommodation space. Tectonic loading from the north resulted in the development of a deep-marine environment. Thus, the turbidite deposits of the Celeptas Formation both transgressively overlie the BHN and, in the ongoing process, the BHN tectonically overlies the Celeptas Formation from north to south (Figure 14d).

The first emplacement age of the BHN must be younger than the tectonically underlying early Cambrian-Late Cretaceous Sultandağı Unit and the Jurassic-Cenomanian Anamas-Akseki Autochthon, while it must be older than the late Paleocene-Lutetian Celeptaş Formation, the common cover of the parautochtonous and allochthonous units in the region, thus pointing to an early-middle Paleocene emplacement age (Figure 14c). The ongoing movements of the BHN and its settlement in the basin caused the synsedimentary deformation of the Celeptaş Formation.

Şenel (1991) argued for the presence of a Paleocene-Lutetian common marine basin extending from the Lycian Nappes towards Seydişehir along the Isparta Angle. These data also support the idea that the BHN was not emplaced in the region during late Eocene, contrarily, but already existed there before the late Paleocene.

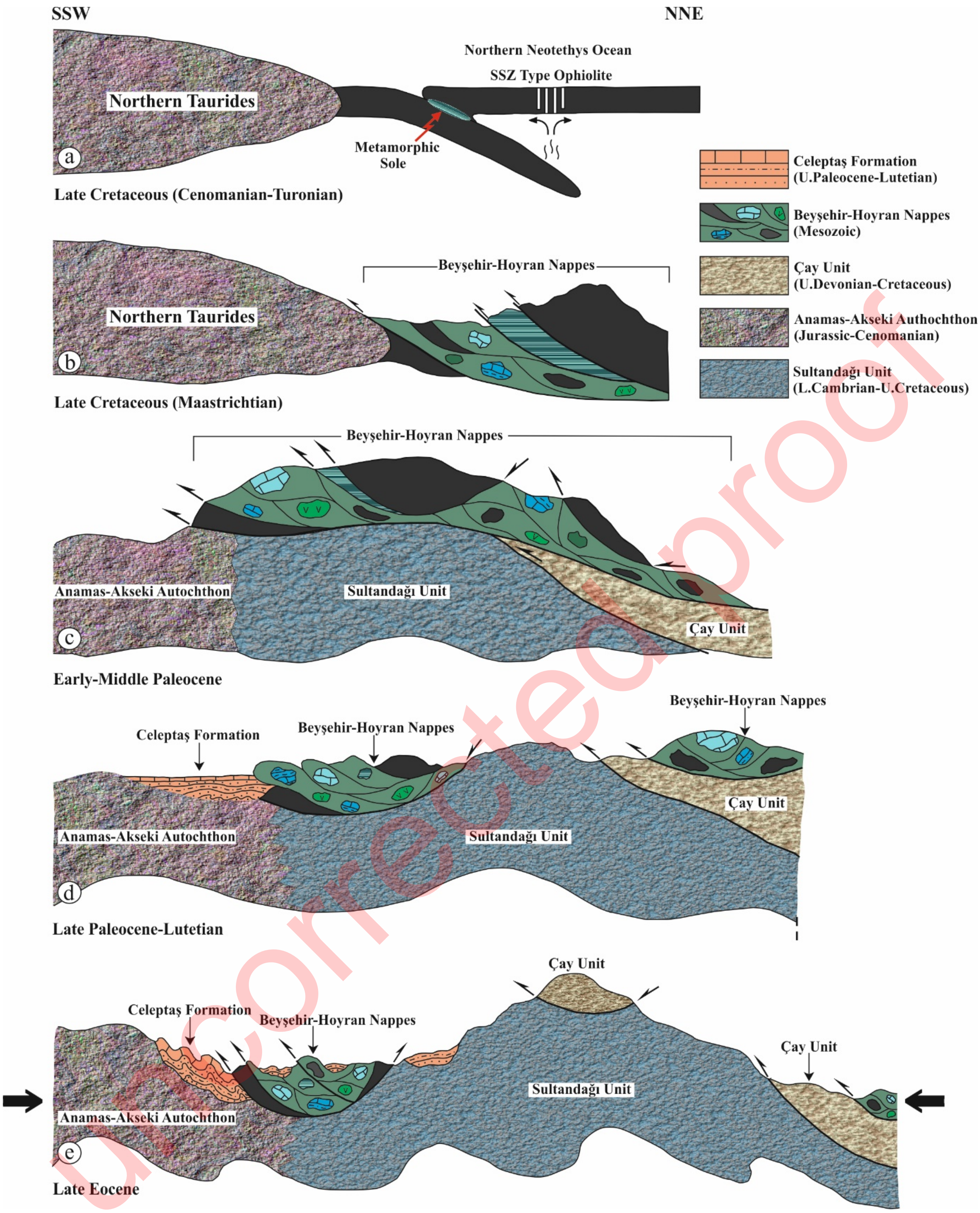

Figure 14- Geological sections illustrating the evolution of the BHN during the Late Cretaceous to late Eocene period.

The stratigraphic studies and geological mapping carried out in the region during this study, as well as the age data obtained from both the BHN and the Celeptaş Formation, helped to reinterpret the Late Cretaceous-

Eocene geological evolution of the region. The initiation of the northward subduction of the northern branch of the Neotethys Ocean led to the formation of SSZ-type ophiolites (Marmaris ophiolite) and consequently to the development of sub-ophiolitic metamorphic sole (Yenicekale metamorphics) at the Cenomanian-Turonian boundary (Figure 14a). During the Late Cretaceous-early Paleocene, from north to south, the BHN thrusted over the Çay Unit and the Çay Unit thrusted over the Sultandağı Unit (Figures 14b-c). In the early Paleocene, the BHN crossed the Sultan Dağları and reached the Anamas-Akseki Autochthon (Figure 14c). During this period, the rocks of the Sultandağı and Çay units underwent both deformation and low-grade metamorphism depending on the emplacement of the BHN (Figure 14c). Following this process, the Celeptaş Formation was deposited in the foreland basin, which developed in the south of Sultan Dağları, in the late Paleocene-Lutetian period. Following this process, the Celeptaş Formation was deposited in the foreland basin that developed in the south of Sultan Dağları in the late Paleocene-Lutetian period (Figure 14d).

The Celeptaş Formation was folded due to the tectonic movements, probably occurred in the late Eocene, and subsequently was overthrusted in places by units of the BHN. These can be considered as secondary thrusts after the primary emplacement (Figure 14e).

4. Conclusions

The BHN, which extends as a NW-SE belt to the south of Sultan Dağları, consists of allocthonous masses such as the Marmaris Ophiolite Nappe, Gülbahar Nappe and Domuzdağ Nappe. The Marmaris ophiolite nappe (Upper Cretaceous) is formed by three subunits as the Marmaris ophiolite, the Kızılcadağ mélange and the Yenicekale metamorphics. The Marmaris ophiolite is composed of dunite, harzburgite, serpentinite and isolated diabase dykes, while the Kızılcadağ mélange is composed by blocks of different ages and lithologies contained in an ophiolitic/sedimentary matrix. The Yenicekale metamorphics are characterized by sub-ophiolitic metamorphic sole rocks such as amphibolites, quartzites and calcschists.

The Gülbahar Nappe is represented by the Late Triassic-Early Jurassic Orluca Formation, which is composed of deep marine mudstones, cherts, radiolarites, micritic limestone and basic volcanics. The Orluca Formation, which has been identified for the first time at the south of Sultan Dağları, yielded paleontological ages of Carnian-Norian (Late Triassic) and Pliensbachian-Toarcian (Early Jurassic) from its micritic limestones and radiolarites.

In addition, we obtained a ^{40}Ar-^{39}Ar age of 93.90±0.34 Ma (Cenomanian-Turonian boundary) from the hornblende minerals of amphibolites from the Yenicekale metamorphics. Tectonic processes, which were triggered by and occurred immediately following the formation of the metamorphic sole during the aforementioned time started the formation of the nappes. We therefore accepted that the Turonian time should be the onset of the formation of the BHN.

On the other hand, the late Maastrichtian age, which is obtained from the mudstones in the matrix of the Kızılcadağ mélange, is considered to mark the end of the formation of the BHN.

The evaluation of the stratigraphic, palaeontological and radiometric data together reveals that the formation of the BHN began in the Turonian and ended in the Late Maastrichtian. The Late Paleocene-Lutetian Celeptaş Formation unconformably overlies the Sultandağı Unit, Anamas-Akseki Autochthon and BHN as common cover in the study area. This clearly indicates that the BHN was emplaced in the region during the early-middle Paleocene. The BHN reached its final position as a result of late Eocene movements.

5. Acknowledgements

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