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New Insıght ınto a Subductıon-Related Orogen: A Reappraısal of the Geotectonıc Framework and Evolutıon of the Middle and West Parts of the Southeast Anatolıan Orogenıc BELT (Türkiye)

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Authors' contributions

This work was carried out in collaboration between both authors. Authors AFB and MB completed the entire study together. Both authors read and approved the final manuscript.

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Review article

ABSTRACT

The geotectonic framework and the evolutionary history of the Southeast Anatolian Orogenic Belt are closely related to the assemblage of eastern and western Gondwana and the subsequent events from the opening of the southern branch of the Neo-Tethys to the final collision. The first geotectonic event is the subduction of the Proto-Tethys under the northern Gondwana during the Ediacaran and accordingly the formation of igneous rocks within the lower units of Bitlis-Pütürge Massifs. The first orogeny affecting the region was the Cadomian orogeny. The southern branch of the Neo-Tethys began to open between the Arabian Plate (North of Gondwana) and today's southeastern Anatolian metamorphic massifs in the Late Triassic, and oceanic spreading continued

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until the Late Cretaceous. The ophiolites and an intra-oceanic arc were formed during the Late Cretaceous (92 to 82Ma and 84–72 Ma respectively) in a SSZ tectonic environment formed by the northward subducting South Branch of Neo-Tethys ocean crust. The Arabian Platform entered the subduction zone and as a result ophiolites thrust on the Arabian Plate margin, the metamorphic massifs were fragmented and migrated to the South onto the ophiolites and arc magmatics in the Maastrichtian. Despite the collision, the continental subduction continued and a break-off of subducted slab was formed. A widespread marine transgression is realized onto the Arabian Platform and ophiolites from Latest Cretaceous to Early Miocene to the South of the Bitlis-Pütürge metamorphics. The remnant of the ocean continued untill Late Miocene to the North of the Bitlis-Pütürge massifs as marine basins with different depths and morphological characteristics. The magma formed by the partial melting of the mantle wedge, the rising deep asthenosphere mantle and the continental crust forms Maden arc over the ophiolites and the Bitlis-Pütürge Massifs in the Middle Eocene. Behind the Maden arc, shallow-deep marine carbonates and clastics were deposited in a back-arc basin (Kırkgeçit basin). The closure which started in the Late Eocene and ended in the Late Miocene enabled Southeast Anatolian Orogenic Belt to take its actual position.

Keywords: Southeast Anatolia; neo-tethys; tectonics; geological evolution; subduction.

1. INTRODUCTION

The Southeast Anatolian Orogenic Belt (SEAOB) forms a belt over 1000 km in length from Iskenderun Bay to triple joinction of Türkiye-Iran-Irak between the Arabian Platform and the Anatolian (Türkiye) microplate. There are 4 major units in the SEAOB: a) metamorphic massifs, b) ophiolites and arc related rocks, c) Maden Complex, d) Upper Cretaceous–Neogene cover units. The geological studies of these units prior to the 1990s were largely based on the studies in the field (relationships between different units) and limited number of chemical analyzes [1-31]. Therefore, in these studies before the 1990s, the geotectonic models of the region were created according to these insufficient data. Since it was generally accepted that like other ophiolites in the world, the Turkish ophiolites also were formed at the ocean floor spreading center and thrust onto the continental crust. Pearce al. [32] indicated that many of the world's best-known ophiolites have petrological and geochemical characteristics that suggest formation above a subduction zone (supra subduction-zone; SSZ). After this acceptance, the formations of ophiolites cropping out in the region have also been reinterpreted according to this new theory [33-54]. Various geochemical analyzes, isotope studies, and geochronological data on metamorphic massifs [39,41,53-55], ophiolites and arc-related magmatic rocks [34,38,40-42, 44-48,56-59] were also used in the development of these new models.

The purpose of this study is, by Our field studies for 40 years, our observations based on the relationships between different units, our geochemical-geochronological data and using the data of researchers working for different purposes in the region, to revise the geotectonic framework and the evolutionary history of Middle and west parts of the Southeast Anatolian Orogenic Belt.

2. MAJOR GEOTECTONIC UNITS

The Southeast Anatolian Orogenic Belt (SEAOB) is located between the Arabian Platform and the Anatolian microplate and is separated from Arabian Platform by the Southeast Anatolian Thrust Belt (Bitlis-Zagros Suture Zone). The Arabian Platform represents the northwestern part of the Arabian Plate. The Arabian foreland located at the South of the Bitlis-Zagros Suture Zone has a basement composed mainly of Precambrian rocks, overlain with a thick pile of shallow water sedimentary formations of Early Paleozoic to Miocene ages [60].

Except for the Arabian Platform, the SEAOB is mainly composed of the Neoproterozoic to Early Cenozoic orogenic elements, i.e. regional metamorphic rocks, ophiolites, arc-related magmatics, and volcanic and sedimentary rocks that align roughly parallel to the general trending of the SEAOB (Fig. 1).

2.1 Metamorphic Massifs

The metamorphic massifs named as Southeast Anatolian metamorphic complex by Ketin [58], include Bitlis-Pütürge- Engizek-Keban-Malatya and Binboga Massifs. Bitlis-Pütürge-Engizek massifs forming the southern belt form subparallel units to the Keban-Malatya-Binboğa massifs forming the northern belt.

2.1.1 Bitlis Pütürge-Engizek Massifs

The Bitlis-Pütürge-Engizek Massifs are an arcuate belt of allochthonous metamorphic massifs. This belt is approximately 30 km wide, dipping northwards at low to moderate angles, and and they extend approximately parallel to the Southeast Anatolian Thrust Belt (Fig.1). They are separated from Arabian Platform by a narrow tectonic belt consisting of ophiolitic and flysch units [13,20,34,40,61-64] The massifs consist of a Neoproterozoic-Cambrian high grade metamorphic lower unit and a Devonian-Triassic lower-grade metamorphic cover. The lower unit consist of granitoid gneiss, amphibolite, and mica-schists [39,53,65-70]. $^{207}Pb/^{206}Pb$ single-zircon age determinations on the metagranites from meta-granites in the Bitlis massif (53,54) and on the augen gneisses in the Pütürge Massif [39] reveal that they crystallize at an age range of 572-520 Ma (Ediacaran–Early Cambrian). Geochemical characteristics of the metagranites and augen gneisses suggest the existence of Andean type arc-related magmatism. The εHf(t) values of augen gneisses suggest the involvement of older continental crust in magma genesis [39].

Derik volcanics outcropping in the Arabian Platform south of the thrust zone and contemporaneous age with augen gneiss and meta granites were formed in a back arc basin [71].

The lower unit underwent high-grade metamorphism by the closure of the Proto-Tethys and final amalgamation of exotic terranes during the Cadomian Orogeny the northeastern part of Gondwana [58, this study). Paleozoic-Lower Mesozoic metamorphic platform sediments unconformably overlie the Lower Unit. There is no sedimentary or igneous rock yielding Cambrian-Ordovician aged units. The first marine clastic and carbonate rocks overlying the lower unit are of Middle Devonian age [68]. This cover unit consists of muscovite schist containing Mid-Devonian fossils with kyanite-bearing quartzite lenses, garnet staurolite mica schists, and Permian recrystallized limestones [67,68]. Late Triassic characterized by radiolarite meta-mudstone, meta-basalt meta-tuff and meta-shale indicates that the sea deepened suddenly and the region rifted. This rifting marks the opening of the southern branch of the Neo-Tethys. Rifting occurred between the Arabian Platform and the present metamorphic massifs. Present metamorphic belt thereafter remained as submerged continental margin up to the Late Campanian-Early Maastrichtian. The Lower-Unit and the Upper Unit both together rocks were metamorphosed under greenschist facies conditions during the Upper Cretaceous [67,73].

2.1.2 Keban-Malatya Metamorphics

The Malatya Metamorphics cropping out in the west of Malatya and the Keban Metamorphics cropping out around Keban-Baskil (Elazığ) and Pertek (Tunceli) areas display similar successions.

The Malatya Metamorphics crop out between Malatya and Kahramanmaraş, and consist of meta-carbonates, mica schist, phyllite, meta-clastic rocks, and meta-cherts [21]. Özgül et al. [74], based on the very limited number of fossils they have found, accept that the Malatya metamorphics were formed in the Late Permian to Early Triassic. The Malatya metamorphics cropping out around Gölbaşı overlie the Berit ophiolite in the north and the Karanlıkdere ophiolite which is an extension of the Koçali ophiolite in the south as an allochthonous unit. The tectonic contact between metamorphics and Karanlıkdere ophiolite dips to the north and the metamorphics thrust over the ophiolites [75, this study] and the tectonic contact between the metamorphics and Berit ophiolite is a southward dipping [76]. This situation shows that the Malatya metamorphics are found as an allochthonous unit over the ophiolites in the north and south and that the two ophiolites are the continuation of each other under the metamorphics (Fig. 2).

A tectonic relationship is observed between the Malatya metamorphics and the Pütürge metamorphics in the vicinity of Çelikhan (Adıyaman) [2]. This shows that the Malatya metamorphics and the Pütürge metamorphics are parts of the same large massif. They were metamorphosed in greenschist facies during the Late Cretaceous [5,77,78].

The Keban metamorphic rocks consist of meta-carbonates, meta-conglomerates meta-sandstone, and phyllite-chlorite-sericite schist with intrusions of meta-diabase dykes [5,79]. Keban metamorphics thrust over the Late Cretaceous Elazig magmatics in the South. The northward dipping of the thrust is cut by the granitoid of the Elazig magmatics. The granitoid also intrudes the Keban platform Permo-Carboniferous carbonate deposits in the NW of Birivan (Ulupınar) village. The contact between granitoid and metamorphosed Keban platform carbonates displays well-exposed hornfels and skarn rocks. Such a skarn contact is also found in the SE of Aşvan village, near the Keban Dam, between a diorite intrusion and the Keban marbles with a large magnetite mineralization. Keban metamorphics also crop out tectonically over the Late Cretaceous aged Elazig magmatics around Pertek. The tectonic contact between the two units is covered by the Eocene Kırkgeçit Formation to the east and west of Pertek [5]. Keban metamorphics are found as small allochthonous blocks over the Elazig magmatics in the vicinity of Elazig City center.

Kipman [80] suggested that the age of the Keban metamorphics is Permo-Carboniferous according to fossils Glomospira and Ammodiscus families identified in the crystallized limestones.

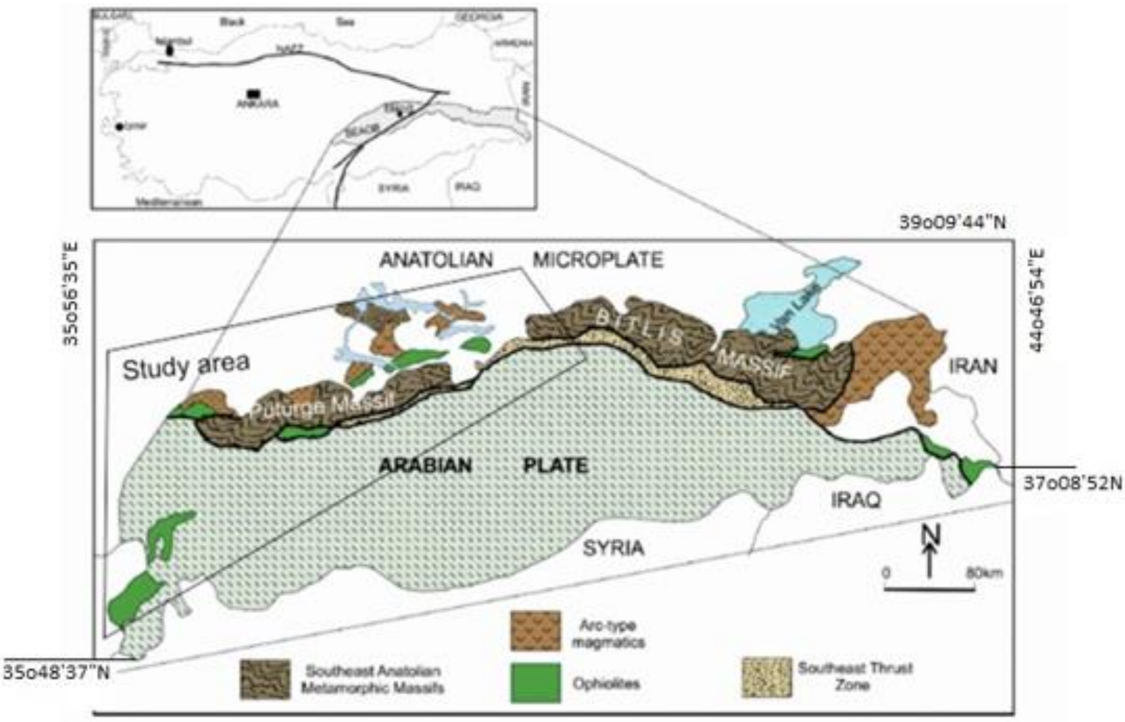


Fig. 1. Major geological units of Southeast Anatolian orogenic belt (simplified from 18)

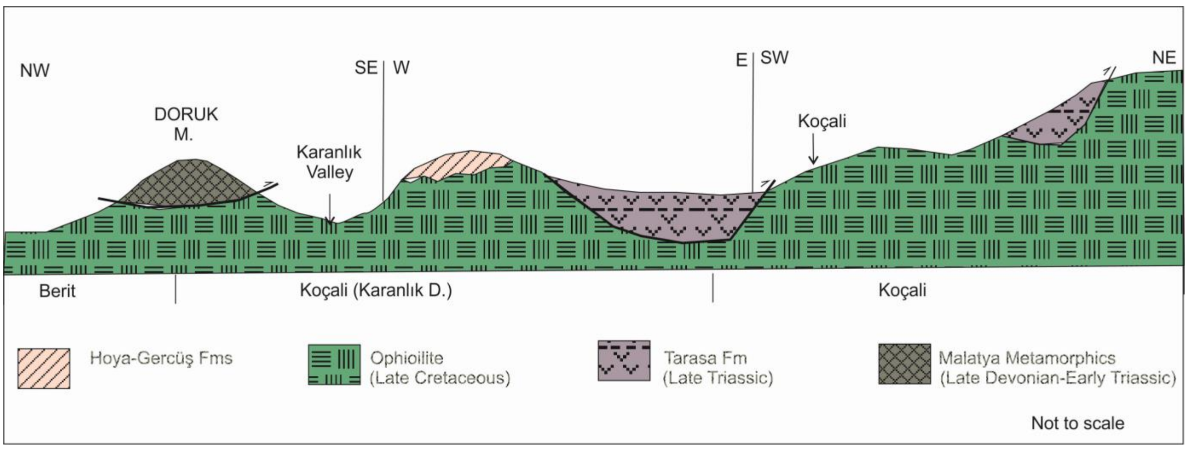


Fig. 2. Cross-section between Doruk M. and Koçali

All metamorphics of SEAOB were metamorphosed in greenschist facies due to northward subduction of the southern branch of the Neo-Tethys in the Late Cretaceous.

Field data indicate that all metamorphic massifs in the SEAOB are parts of an once-united giant tectonostratigraphic unit [40,81].

2.2 Ophiolites

SEAOB ophiolites are an important part of the 3000 km long Neotethys ophiolite belt extending from Italy to Oman. Neotethys is divided into two branches in the region where today's Turkey and Iran are located. These are 1) main branch, 2) south branch. While the Neotethys ophiolites are mostly MORB type in the west, they are around 170-140Ma aged (e.g., Ligurian in Italy, Mirdita in Albania, Pindos in Greece, Refahiye in Turkey, and Makran in Iran), those in the central and eastern parts show typical SSZ geochemical signatures and 125-86Ma aged (Troodos in Cyprus, Kızıldağ, Koçali, Ispendere, Kömürhan–Guleman in southeastern Turkey, Neyriz in Iran, and Oman) [40,81-84]. Many researchers have conducted studies on the SEAOB ophiolites locally or regionally [6,19,33-37,40,42-,45,47,48,57,58,85,86-99]. The SEAOB ophiolites extend for approximately 1000 km from the Iskenderun Bay in the West to the Turkey-Iran-Iraq triple intersection in the East and include the Kızıldağ, Koçali, İspendere, Kömürhan, Guleman, Gevaş, Cilo ophiolites, and numerous small unnamed ophiolite fragments (Fig. 3).

The Kızıldağ ophiolite, located in the westernmost part of SEAOB, was thrust over the thick Cambrian-Cretaceous autochthonous Arabian platform and is unconformably overlain by the Late Maastrichtian–Late Miocene autochthonous sediments [100]. The Kızıldağ ophiolite contains all of the lithological units seen in an ideal ophiolite succession: harzburgitic mantle peridotite, the dunitic mantle-crust transition zone (DTZ), ultramafic-mafic cumulats, sheeted dykes and volcanic rocks [40,42-45, 48,89-92,95-97].

The Koçali ophiolite is a part of the Koçali complex which consists of the Triassic Tarasa volcanic rocks, the Konak formation, and the Late Cretaceous Kale formation [20,101]. The Kale Formation extends towards the east to the vicinity of Çermik. Further east, the unit cropping out around Çermik (Diyarbakır), containing an ophiolite sequence and showing the same characteristics as the Kale Formation, was named Koçali ophiolite by Bingöl [88]. The unit corresponding to the Kale formation, which crops out to the West of Gerger and consists of mantle peridotites, cumuLates, diabase dyke complex and basalts, was named as Koçali ophiolite [34]. The Tarasa volcanics and the Konak formation were thrust onto the Koçali ophiolite. The Koçali ophiolite has been thrust onto the Upper Campanian Karadut Complex. The Tarasa volcanic rocks, the Konak formation and the Koçali ophiolite stratigraphically overlain by Upper Maastrichtian-Eocene sedimentary units of the Arabian Platform [34] and the Çüngüş Formation and Pütürge metamorphics overlie them tectonically in the West of Sincik (Adıyaman) [2] (Fig. 4).

Some ophiolite fragments were tectonically overlain by the Çüngüş Formation belonging to Arabian Platform and the Çüngüş Formation was thrusted by the Pütürge metamorphics. The Karanlık Dere ophiolite cropping out to the East of Gölbaşı (Adıyaman) is an extension of the Koçali ophiolite under the neo-autochthonous cover of the Arabian Platform [40,75]. The Malatya Metamorphics cropping out in the North of the Karanlık Dere tectonically overlain the Karanlık Dere ophiolite in the south and the Berit ophiolite in the north. Well, the Malatya Metamorphics overlie the ophiolites as allochthonous unit (Fig. 2). Therefore, the Berit ophiolite and the Koçali ophiolite are parts of the same ophiolite (Fig. 2). Between the Kızıldağ ophiolite and the Koçali ophiolite, a large number of unnamed ophiolite fragments crop out under young sediments and volcanics. The Koçali ophiolite consists of harzburgitic mantle peridotites, gabbros, plagiogranite, sheeted dikes, and basalts. In the Çermik anticline, arc-related volcano-clastics are observed on the ophiolite, while in the Karanlık Dere, the ophiolite is cut by granitoid dykes.

The Guleman ophiolite cropping out in the Southeast of Elazig shows a very different tectonic situation. The Guleman ophiolite thrust over the Late Miocene Lice formation, which is the youngest unit of the Arabian Platform. It is thrusted by the Pütürge metamorphics in the South of the Hazar Lake, and by the Bitlis metamorphics in the northeast. It is depositionally overlain by the Late Maashtrichtian–Early Eocene Hazar Group and Middle Eocene Maden Complex [20,40,102-105]. Guleman ophiolite presents an ideal ophiolitic sequence consisting of mantle peridotites, dunitic mantle-crust transition zone (DTZ), ultramafic-mafic crustal rocks [40,57]. The basalts called Caferi volcanics by Özkan and Öztunalı [19] are controversial. However, the Guleman ophiolite and arc magmatics developped on the ophiolite are examined in detail, it is seen that these basalts form the uppermost part of the ophiolite and also form the base of the arc magmatics (Fig. 5 and 6).

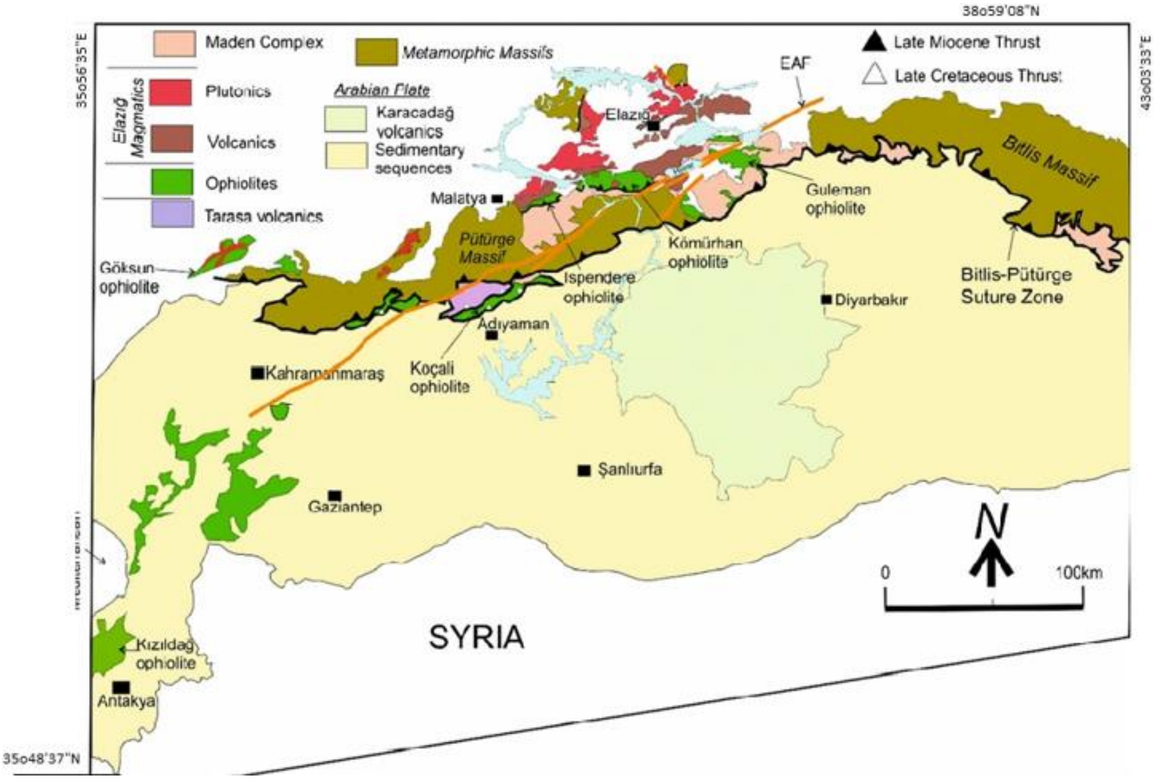


Fig. 3. Distribution of the ophiolites in the study area (From 38)

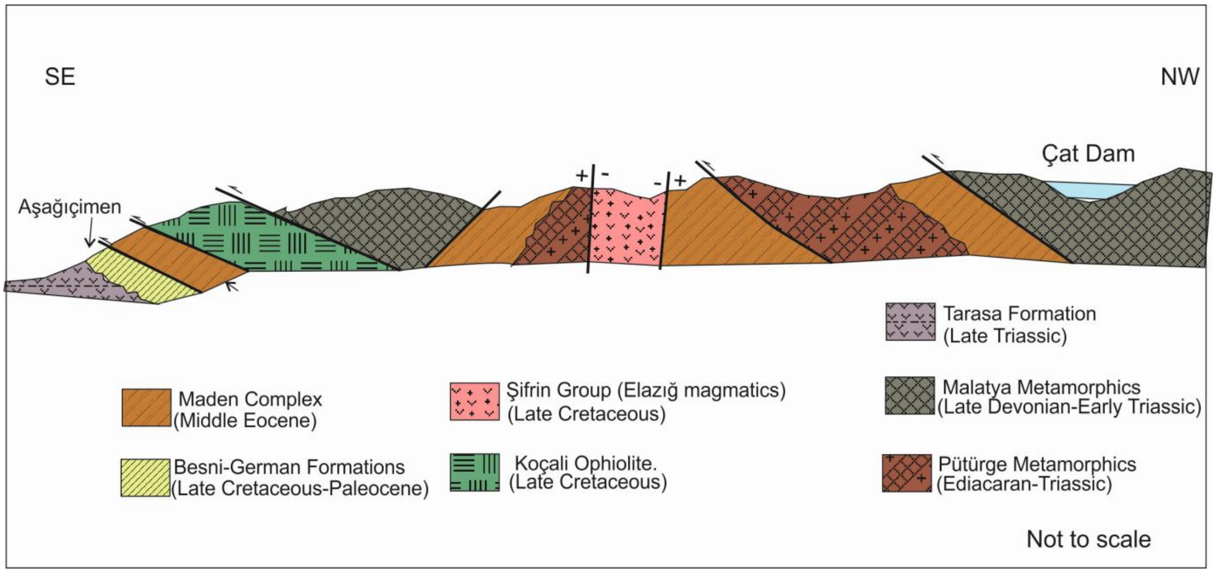


Fig. 4. Cross-section between Aşağıçimen (Sincik-Adıyaman) Çat Dam (Çelikhan-Adıyaman)

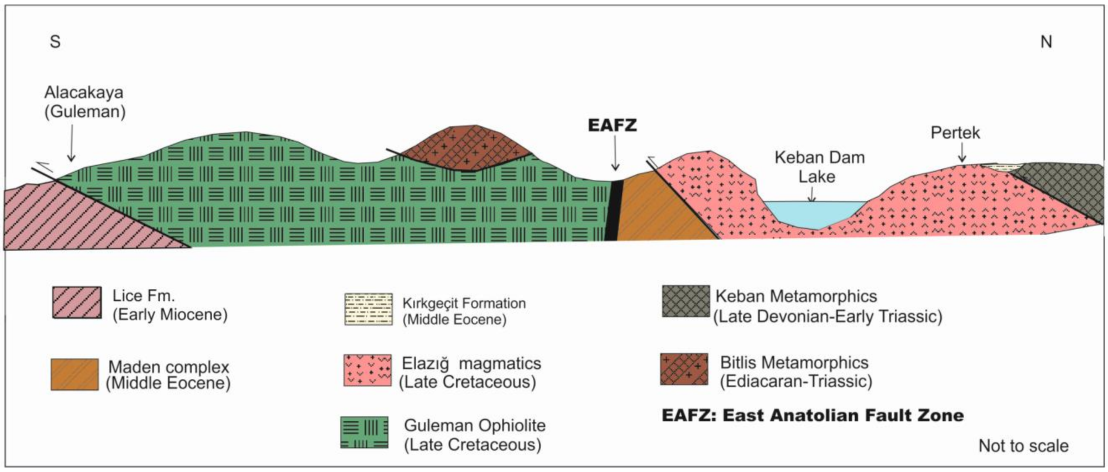


Fig. 5. Cross-section between Alacakaya (Elazığ)-Pertek (Tunceli)

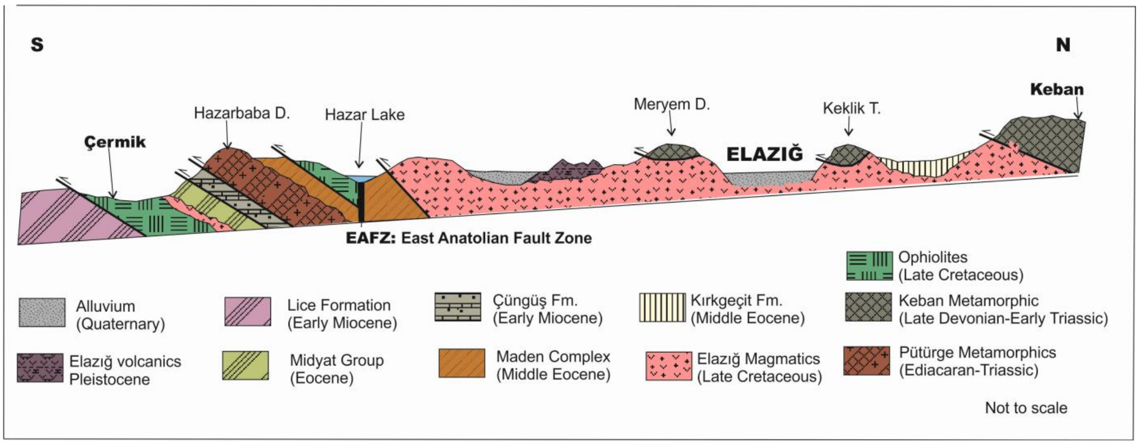


Fig. 6. Cross-section between Çermik (Diyarbakır)- Keban (Elazığ)

The Kömürhan and Ispendere ophiolites, which are the western extension of the Guleman ophiolite, thrust over the Middle Eocene Maden Complex developed over the Pütürge metamorphics, and are overlain by the arc-related magmatics (Fig. 7). Mantle peridotites are missing in both ophiolites. They consist of ultramafic cumulates, cumulate gabbros intruded by ultramafic–mafic dykes and stocks, sheeted dykes, basaltic pillow lavas, and lava flows. While the Kömürhan ophiolite is cut by granitic dikes, a tectonic relationship is observed between the Ispendere ophiolite and granitic rocks [33,35,40]. The lower part of the Kömürhan ophiolite containing amphibolite, pyroxenite, and garnet–peridotites is metamorphosed in greenschist and amphibolite facies [106]. The granitic dykes of the arc magmatites cut the Kömürhan ophiolite and form contact metamorphism around it. [33,35].

The U–Pb zircon datings provide the ages 92 to 82 Ma for the Southeastern Taurus ophiolites [40,43,44,93]. These ages indicate that ophiolites were formed in a maximum time period of ~ 10 Ma [40]. The whole-rock geochemical, geochronological, and isotropic data described by different researchers [34,40,42-45, 48,57,58,89-92, 94-97,106] strongly suggest that the Southeast Anatolian ophiolites were generated in SSZ tectonic settings during the Late Cretaceous.

2.3 Arc-Related Magmatic Rocks

Perinçek [104] suggests that a very complex unit consisting of Late Cretaceous basic-andesitic igneous rocks and sedimentary rocks has been named the Yüksekova complex at the easternmost end of SEAOB, and a group of rocks similar to this unit also crops out around Elazığ-Malatya. Hempton and Savcı [107] showed that this unit predominantly consits of igneous rocks and named the Elazığ complex in the Elazığ area. Hempton [15] also named this unit the Elazig volcanic complex. We carried out detailed studies and geological mapping for the first time on this unit in the North-Northeast of Elazig, and we published the results of these studies in two articles [4,5]. Although we used the name Yüksekova Complex in these articles, in later studies it was revealed that the unit was not a complex and therefore named it as Elazığ magmatics [108,109]. Some researchers, on the other hand, named the plutonic rocks in different regions of the unit with the name of that place; e.g: Baskil batholite [106], Baskil granitoid [56,98], Baskil magmatic[81], Pertek granitoid [46], Şifrin group [110]. Ural et al. [111] use the name Yüksekova complex.

Elazığmagmatics crop out most widely between the Elazig and Malatya provinces. The unit crops out in a very wide area around the city center of Elazig, between Kovancılar, Keban, Baskil districts, Pertek (Tunceli), Kale (Malatya) districts [4,5,7,33,35,37,38,40,46,56,59,64,72, 87,93,111-114] (Fig. 8). The most comprehensive study on the unit was given by Beyarslan and Bingöl [32].

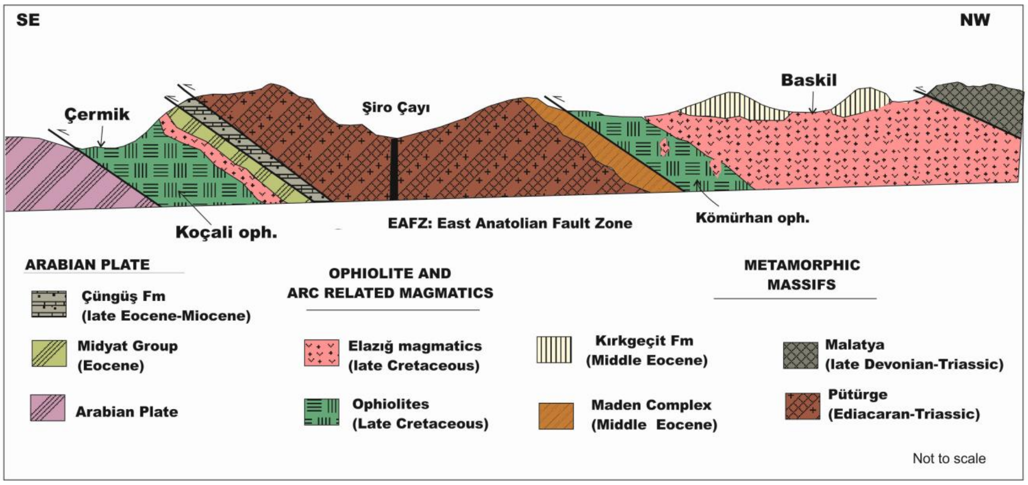


Fig. 7. Cross-section between Çermik (Diyarbakır)- Baskil (Elazığ)

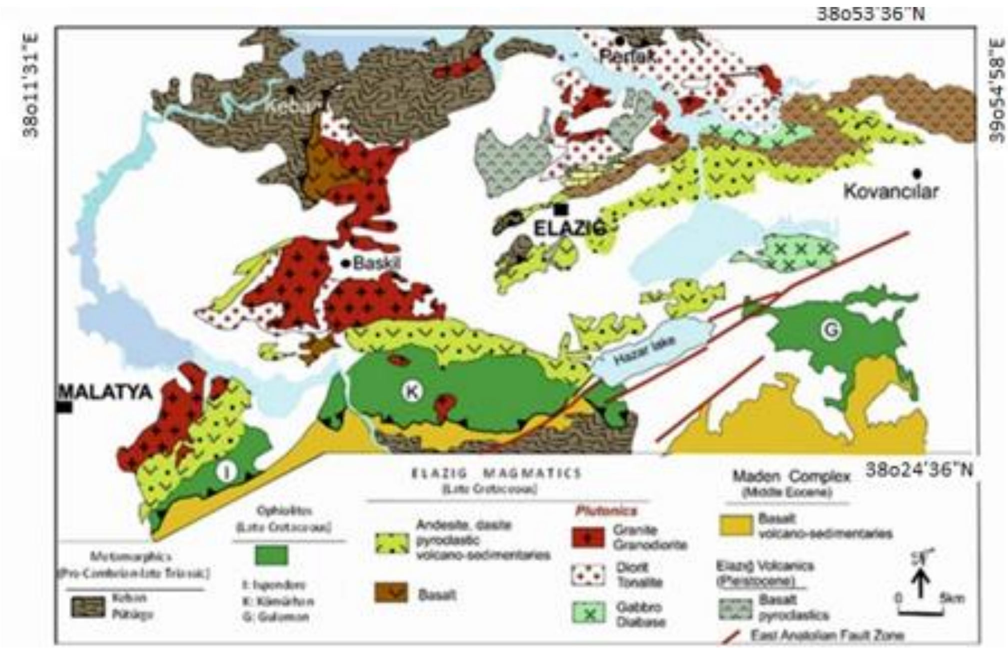


Fig. 8. Geological map of the late cretaceous magmatics in the Elazığ-Malatya regions (From 38)

The Elazig magmatics mainly overlie ophiolites. The relationships between Elazig magmatics and ophiolites are sometimes tectonic and sometimes transitive. The Elazığ magmatics thrust over the Middle Eocene Maden Complex to the South and North of Hazar Lake and to the South of the Elazig-Bingöl highway (Fig. 9).

The Keban metamorphics thrust onto the Elazığ magmatics in the Keban and Pertek regions and the granitic rocks of the Elazığ magmatics cut the thrusting contact. It can be observed some small skarn zones at this contact [5]. While the Late Cretaceous Harami formation transgressively overlies the Elazığ magmatics, the Early Paleocene Kuşcular, Late Paleocene-Early Eocene Seske [115], and Upper Bartonian-Priabonian Kırkgeçit Formations [116] unconformably overlies the Elazığ magmatics. The Kırkgeçit Formation also overlies the tectonic contact between the Keban metamorphics and the Elazığ magmatics in the vicinity of Pertek town [5].

The Elazığ magmatics consist of volcanic and volcano-sedimentary rocks and intrusive rocks. Volcanic rocks, outcropping in a wide area between Elazığ city center-Kovancılar and Pertek composed of basalt lavas and lava flow, basaltic andesite, andesite, andesite-pyroclastic alternation dacite and occasionally rhyolite [4,5,7,38,114]. Fine-grained andesite and dacite dykes transect the basalts. The andesitic lava flows overlie the basaltic rocks. Andesites starting with lava flows pass upwards andesite/pyroclastic alternation and then continue with pyroclastics. The pyroclastic rocks consist of agglomerate, pyroclastic breccia, lapillistone and tuff. The dacitic dykes cut vertically all the alternation of andesite/pyroclastic rocks. These dykes, 0,5 to 2 meters thick and 100 to 200 meters long, feed small dacite domes. The dacitic and rhyolitic rocks are relatively infrequent. The andesitic to rhyolitic rocks are characterized by the calk-alkaline series. Lin et al. [93], who made a detailed U-Pb age determination on Elazig magmatics, reported that the volcanic rocks were formed in the range of 84-81 Ma. According to Beyarslan and Bingöl [38], the age of andesite determined by the $^{206}Pb/^{238}U$ method is 82 Ma. Karaoğlan et al. [44] give an age of 74 Ma for a rhyolite sample on the Kömürhan ophiolite and 83 Ma for a sample of a rhyolite on the Göksun ophiolite.

Intrusive rocks crop out most commonly in the North-Northeast of Elazig city, in the vicinity of Pertek (Tunceli), in the Baskil district (Elazığ) and Ispendere (Malatya). In addition, these rocks crop out in the region between Çelikhan and Sincik (Adıyaman) [110]. Intrusive rocks consit of a wide lithological composition from gabbro to granite and at lesser rates monzonite-syenite. Different lithological units intersect each other and also other units such as basaltic volcanics and metamorphics, ophiolites. According to the lithological features in the regions they examined, Akgül [72] divided them into diorite and tonalite groups, Sar [59], on the other hand, divides them into granitic and dioritic groups. Lin et al. [93] divide the Elazig magmatics into three groups according to their crystallization ages and magmatic series. They are: (1) 84-81 Ma: tholeiitic suite that consists of extrusive (basalt and andesite) and intrusive (gabbro and diorite) rocks: (2) 80-79 Ma: calc-alkaline suite of monzonite, granodiorite, and granite; (3) 74-72 Ma: calc-alkaline suite of intrusions (gabbro, monzodiorite and monzonite). Beyarslan and Bingöl [38] group plutonic rocks of the Elazig magmatics as (1) first-stage intrusions—mostly gabbro-diorite-tonalite and a lesser granodiorite-granite, 2) second-stage intrusions—mostly granodiorite-granite and a lesser tonalite, 3) Late-stage intrusions—mostly monzodiorite-monzonite-syenite subgroup) subgroups. The granodiorite and granite of the second stage have intruded into ophiolites, volcanic rocks, and first group rocks. They also cut the tectonic contact between the Keban metamorphics and Elazığ magmatics [5,7,35,38,43,72,108]. The Late-stage subgroup crops out at the North of Elazığ city and between Çelikhan and Sincik (Adıyaman). These outcrops of Late-stage intrusive rocks named Şifrin group by Yıldırım [110] in the Çelikhan region are mostly composed of monzonite. However, in different proportions, gabbro, diorite, quartz diorite, tonalite, quartz monzonite, syenite, quartz syenite, granite, granodiorite, monzodiorite, quartz monzodiorite are also found. In the studies carried out by Pişkin [117], these rocks were named leucocratic quartz monzonites and according to K/Ar measurements, it is indicated that these rocks are 62 Ma or older. Esence granitoid cropping out between Göksun and Afşin (Kahramanmaraş) [118-120] was intruded into the Malatya Metamorphics and Late Cretaceous Göksun Ophiolite. The 85 to 77 Ma ages obtained by the K-Ar method [43,47] from Esence granitoid, display that this granitoid is the western extension of the intrusive rocks of the Elaziğ Magmatics.

Zircon U-Pb age determination made from Elazig magmatics with low K-tholeiitic, calc-alkaline, and shoshonitic series features that the arc-related magmatism took place between 84–72 Ma in an intra-oceanic arc-system that developed on a northwardly dipping oceanic crust in the Upper Cretaceous.

2.4 Maden Complex

The unit that is widely exposed in SEAOB has been different named by different researchers: i.e "Maden Unit" [121] "Maden Complex" [2,15,30,122,123], "Baykan Complex" [64], "Karadere Formation" [124], "Maden Formation" [17,65,103], and "Maden Group" [102].

The unit is located in different positions compared to other units. It is located under the Bitlis-Pütürge metamorphic massifs to the south, while it unconformably overlies the Pütürge massif on the Malatya-Pütürge road. In the district of Maden, from which the unit is named, the Maden Complex unconformably overlies the Guleman ophiolite and the Hazar group. In the same region, it is observed that the Guleman ophiolite and the Hazar group were thrust over the Maden Complex (Fig. 4 and 10).

The Maden Complex has a complex internal structure. The complex begins with transgressive sediments continues upwards with sandstone, silicified red chert, and red-colored mudstones. Lateral and vertical lithological discontinuities are very common in the complex. The red-colored marly and clayed limestone is interbedded by volcanic rocks. The Ypresian-Lutetian clastic sediments unconformably overlie the Pütürge metamorphic massif on the Malatya-Pütürge road [66,67,106]. There are many olistrostromal parts consisting of Upper Lutetian limestone, andesitic epiclastics, sandstone, volcanic, and diabase blocks. The uppermost of the unit is composed of basalt, andesite, pyroclastic, and hypabyssal rocks. The hypabyssal rocks composed of diabase and tonalite intruded through Bitlis-Pütürge metamorphic basement [65,110,117,125]. Large tectonic lenses of tourmaline-bearing micro-leucogranite occurs above the autochthonous sediments (Çakçak Tepe-Malatya), and in the Pütürge metamorphic rocks [2]. Moreover, tonalitic and andesitic vein rocks belonging to the Maden Complex are intruded into pütürge metamorphics at Sakız, Çakçak Tepe-Gazitahara Tepe and Baizge regions [2,104]. The enrichment of large-ion lithophile elements (LILE), depletion of high field strength elements (HFSE), and positive Pb and negative Nb-Ta anomalies [126] indicate that magma yielding the volcanic rocks and dykes of the Maden Complex derives from the a lithospheric mantle source affected by continental contamination.

2.5 Upper Cretaceous–Paleogene Cover Units

As we briefly summarized above, sedimentary units of the Arabian Platform crop out in the South of Pütürge and Engizek Massifs, while marine sediments from Late Cretaceous to Miocene crop out in the North. There are 6 group or formation sedimentary units crop out at the North of the Pütürge and Engizek Massifs. They are: 1-Hazar group (Maastrichtian-Early Eocene), 2) Harami Formation (Late Maastrichtian), 3) Kuşçular Formation (Early Paleocene), 4) Seske Formation (Late Paleocene to Early Eocene), 5) Kırkgeçit Formation (Middle Eocene-Oligocene) and 6) Plio-Quaternary sedimentary rocks [5,28,108,116,127-130].

2.5.1 Hazar group

The typical locality of the Hazar Group, which is named differently such as Hazar unit [121,131], Hazar complex [20], Hazar formation [132], Hazar Group [1], is in the East of Hazar Lake (Elazığ). The group unconformably overlays the Late Cretaceous Guleman ophiolite. Coarse-grained ophiolite-derived conglomerates form the base of the Group. Shale and limestone alternations dominate towards the upper levels. The unit continues with shallow-marine mudstones and sandstones and ends up with neritic limestones at the top.

According to the fossils determined within the group, the age of the group is Maastrichtian–Early Eocene [1,20,131]. The possible equivalents of the Hazar Group are reported to be Maastrichtian to Middle Eocene in the Malatya and Palu areas [20,123].

2.5.2 Harami formation

The unit, first described by Erdoğan [133] to the North of Gölbaşı (Adıyaman), crops out in limited areas around Gölbaşı and Elazığ. The Harami Formation crops out in the North (around Harput) and in the South of Elazig city center. The Harami Formation depositionally overlays the

Elazığ magmatics. While the contact is angular unconform in some places, it is vertical transitive in some places at least locally [134,135]. The ophiolites are depositionally overlain by the Harami Formation in the Gölbaşı area. The formation is overlain by the Paleocene Kuşçular Formation, Middle-Upper Eocene Kırkgeçit formation and the Quaternary Harput volcanics [5,116,134,136,137]. The Harami formation begins with Elazig magmatics-derived conglomerate level in some place, the base of the formation consists of sandstones and sandy limestones in some other places [5,134,135, 138]. The unit continues by shallow-marine limestone. The age of the unit is commonly accepted as (Late) Maastrichtian [5,30,112, 139]. The upper age range of the unit has been lately extended into the Late Paleocene by Herece and Acar [140]. Other areas where the Harami formation outcrops are the West of Elazig (Baskil) and the surroundings of Gölbaşı district of Adıyaman province. The Harami Formation which is represented by alternating pelagic limestone, shale, marl, radiolarite, manganiferous shale, and mudstone tectonically overlies the Esence Granitoid and Göksun ophiolite and is thrusted by Malatya Metamorphics, in the Gölbaşı (Adıyaman)-Kahramanmaraş areas [141]. Elsewhere, in another area, the ophiolites are depositionally overlain by the Harami Formation [2].

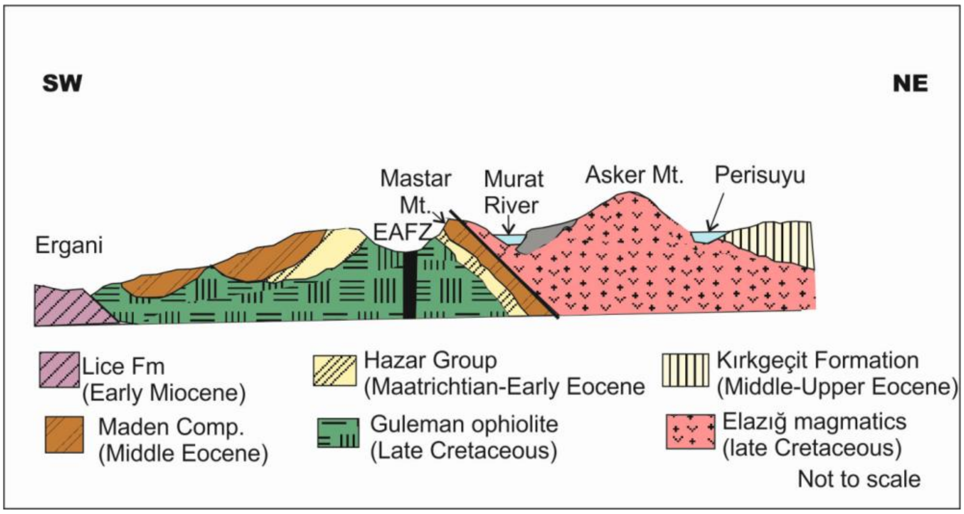


Fig. 9. Cross-section between Ergani (Diyarbakır)- Perisuyu (Tunceli)

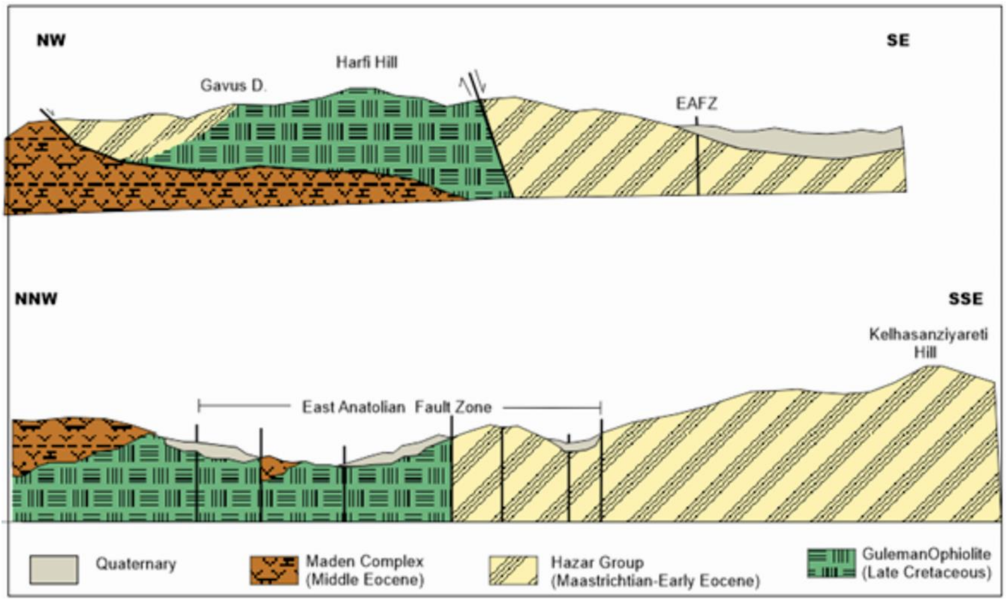


Fig. 10. Cross-section in the south and southeast of lake Hazar

2.5.3 Kuşçular formation

The Kuşçular Formation crops out in the West of Elazığ, Baskil area. It rests unconformably on the Keban metamorphics, the Elazığ magmatics and the Harami limestones, and is unconformably overlain by a prominent carbonate unit, the Seske Formation. The Formation consists of conglomerates, sandstones, red mudstones, and gypsum levels. Its Early Palaeocene age is inferred from the bio-sstratigraphic ages of the underlying and overlying formations [128,130, 142]. The Kusçular Formation was deposited in the Early Paleocene in a tectonically-controlled foreland basin [128].

2.5.4 Seske formation

The Seske formation crops out in narrow areas around Adıyaman and Elazığ [129,133,139, 140, 143]. The Seske Formation unconformably overlies the Elazığ magmatics and the Kuşçular Formation and is unconformably overlain by Kırkgeçit Formasyon. Although the Seske Formation is mostly represented by limestones around Elazig, it shows local lithological differences. The formation, which starts with massive limestones at the base in some areas, passes into bedded limestones and mudstones with red pelagic foraminifera towards the upper levels. In some places, it consists of massive limestones. The unit consists of shallow-marine limestone containing Late Paleocene-Early Eocene foraminiferal assemblages [139].

2.5.5 Kırkgeçit formation

Compared to other cover sedimentary units outcropping to the North of the Bitlis-Pütürge Massifs and ophiolites, the Kırkgeçit formation crops out in a wide area from Malatya to Van. The Kırkgeçit Formation rests unconformably on the Keban metamorphics, the Elazığ magmatics and the other (Late) Maastrichtian-Early Paleocene sedimentary units such as Harami, Kuşçular, Seske Formations. It is unconformably overlain by the Late Miocene–Early Pliocene Karabakır Formation and Quaternary volcanic (Harput volcanics) and sedimentary rocks. The Kırkgeçit Formation consists of a wide range of lithofacies and fossil assemblages [5,116,127,128,139,140,143,144-148]. The facies characteristics indicate a deposition environment highly irregular basin floor topography and various depositional environments, from very shallow-marine to pelagic. The fossils it contains indicate that the age of the formation ranges from the Middle Eocene to the Oligocene.

3. DISCUSSION

SEAOB was under the influence of intense tectonic events from Neoproterozoic to the Late Miocene. Therefore, primary relationships between units are not seen everywhere. There are many allochthonous units in the belt. The oldest unit in the belt is the Lower-Unit of the Bitlis-Pütürge metamorphics, and the crystallization ages of the augen gneisses and metagranites in the Lower Unit vary between 570-520 Ma. The oldest orogeny affecting the region is the Cadomian orogeny. U–Pb magmatic zircon ages indicate that Cadomian magmatism took place between 600 and 500 Ma and was especially intense during a 45-Myr timespan ca 570–525 Ma in Iran and Anatolia [39,53,55]. Researchers working in Turkey and Iran agree that the Late Proterozoic units cropping out in Iran and Turkey, including the Lower Unit of the Bitlis-Pütürge Massifs, are the remnants of an orogenic (Cadomian) belt along the Northern Margin of Gondwana. The geochemical, isotopic and geochronological features of augen gneiss and metagranites in the Lower Unit reveal the existence of Andean-type magmatic arcs and back-arc basins forming the Northern Margin of Gondwana, with southward subduction of Proto-Tethys oceanic lithosphere [39,54,55,71,149-156] (Fig.11a). Avigad et al [157], who studies on the origin of the Mediterranean, suggest that the base of the Taurus Mountains chiefly consists of the graywacke succession formed in the Mid- to Late Ediacaran back-arc basin over the southward subduction Proto-Tethys Ocean. The arc and back-arc units were metamorphosed to various degrees and intruded by Ediacaran granites during Cadomian orogeny. The Ediacaran magmatism in the North of Gondwana is quite intense and there is a very prolonged flare-up [55,84]. Most of the Cambrian-Ordovician-Silurian Lower Devonian rocks are absent. The first sedimentary unit overlying the metamorphic Lower Unit is the Mid-Devonian aged transgressive sedimentary rocks. The deposition starting from the Mid- Devonian continues under shelf environment conditions until the Late Triassic and abruptly change into deep-sea environment in the Late Triassic. These sudden change conditions indicate a Late Triassic rifting between metamorphic Massifs and Northern Gondwana There is general acceptance that this rifting is onset of the opening of southern branch of Neo-Tethys. The

Tarasa volcanics and Konak Formation of the Koçali complex which are the remains of an upper part of the oceanic crust, contain Late Triassic radiolarian fauna [99]. These radiolarian fauna indicating that the opening of the Southern Neotethys Ocean began in the Triassic time. After rifting, spreading continued for about 140 million years (from Carnian? to Cenomanian?) between Gondwanaland and future Southeast Anatolian metamorphic massifs resulting in the creation of the southern branch of the Neotethys Fig.11c). Karaoğlan et al. [157] and Robertson et al. [78] suggest that there were two different active oceanic realms within the southern branch of the Neotethys Ocean during the Late Cretaceous. One realm, called the Berit Ocean, was located between the Tauride platform to the North and the Bitlis– Pütürge microcontinent to the South; the other oceanic realm was situated between the Bitlis–Pütürge microcontinent to the North and the Arabian Platform to the South. Therefore, as we explained in the section ophiolites (section 2.2), the Malatya metamorphics are allochthonous on the Berit ophiolite and the Koçali ophiolite. In that case, these two ophiolites are products of the same oceanic crust.

The whole-rock geochemical, geochronological, and isotropic data described by different researchers strongly suggest that the Southeast Anatolian Ophiolites were formed during the Late Cretaceous (92 to 82My) in a SSZ tectonic environment formed by the northward subducting of south branch of Neo-Tethys ocean crust [38,40,42,43,44,48,57,89,90,91,94,96,98,106].
The recent geochronological data of ophiolites obtained from crustal rocks (92-82Ma) [40,45,94] have revealed that the northwards subduction of Southern Neo-Tethyan oceanic lithosphere started prior to 92 Ma. The continued northward subduction characterized by a moderate and constant dip of the subducted rock resulted in the formation of an intra-oceanic arc (Elazığ magmatics—volcanics, volcanoclastics, and granitoid) during the Late Cretaceous (84–72 Ma) (Fig. 11d and e).

The units on the subduction zone which are ophiolites, arc magmatics and Southeastern Anatolian metamorphics migrated towards the South depending on the South-North compression at the end of the Cretaceous. The ophiolites thrust over the Arabian Platform together with the Karadut Complex. The massif forming the metamorphics was fragmented and migrates southward over ophiolites and arc magmatics and metamorphosed under greenschist facies conditions Fig. 11f). During all these tectonic events, the intrusive rocks of Elazig magmatics continue to form and cut the thrust zone between metamorphics and arc magmatics, metamorphics and ophiolites. After the southward thrust of the ophiolite and other units, the subsiding ocean is closed and the continental Arabian Plate enters the subduction zone. Despite the emplacement of the first ophiolitic nappes onto the Arabian Continent during the Campanian– Early Maastrichtian period, the oceanic environment survived in the North of the Arabian Platform [112,157].

There is still much debate on when the northward subduction of Arabian Plate beneath Anatolia ceased and when the closure of the southern Neotethys and subsequent continental collision actually took place [1,13,35,38,40,41,158, 159].

There are three main alternative theories related to the time of the collision: 1) in the Late Cretaceous [35,160,161], 2) in the Late Eocene [141,162], or 3) during the Oligocene to Early Miocene [1,76,159,163,164]. In order to fully explain this issue, the units formed in the region after the Late Cretaceous thrust need to be examined in detail. The metamorphic massifs were fragmented and were thrust over the ophiolites by the Late Cretaceous thrust. The marine environment continues to the north and south of these massifs. Rising eustatic sea-level [165] possibly combined with isostatic regional subsidence following ophiolite emplacement resulted in a widespread marine transgression onto the Arabian Platform and the Koçali and the Kızıldağ ophiolites from Latest Cretaceous to Early Miocene times. The South of the Bitlis-Pütürge-Engizek massifs and Hatay areas, was dominated by shallow marine conditions in these periodes [189]. Maastrichtian–Early Eocene Hazar Group and Maastrichtian-Late Paleocene Harami Formation indicate the presence of the remnant of southern Neo-Tethys Ocean realm over subduction zone to the North of the Bitlis-Pütürge metamorphics. The Hazar Group was deposited on the Guleman ophiolites in a shallow marine environment. The Harami Formation, on the other hand, was deposited in an east-west oriented basin over the Elazig magmatics. Both basins are not very large. Perinçek and Kozlu [21] suggest that the Harami Formation was deposited during periods when the island arc volcanism forming the Elazığ magmatics (Yüksekova Complex) was inactive. İnceöz [137] accepts that the formation was deposited after the Elazig magmatites completed their formation. Aksoy et al. [134] hypothesize that the Harami formation started in the shallow parts of the inner Tauride ocean during the late arc phases forming the Elazig magmatics. According to Herece et Acar [140], the Late Maastrichtian-Late Paleocene (Selandian) Harami Formation was deposited in shallow shelf environment. All field data show that the formation of the Harami Formation started in the last phase of the intra-oceanic arc, and the basin floor is of very different depth and shape.

Until today, the most discussed issue in the region is the formation of the Middle Eocene aged Maden Complex. The seven different models have been proposed for the formation of the this Complex. According to these models, the geotectonic environments in which the Maden complex is formed are:

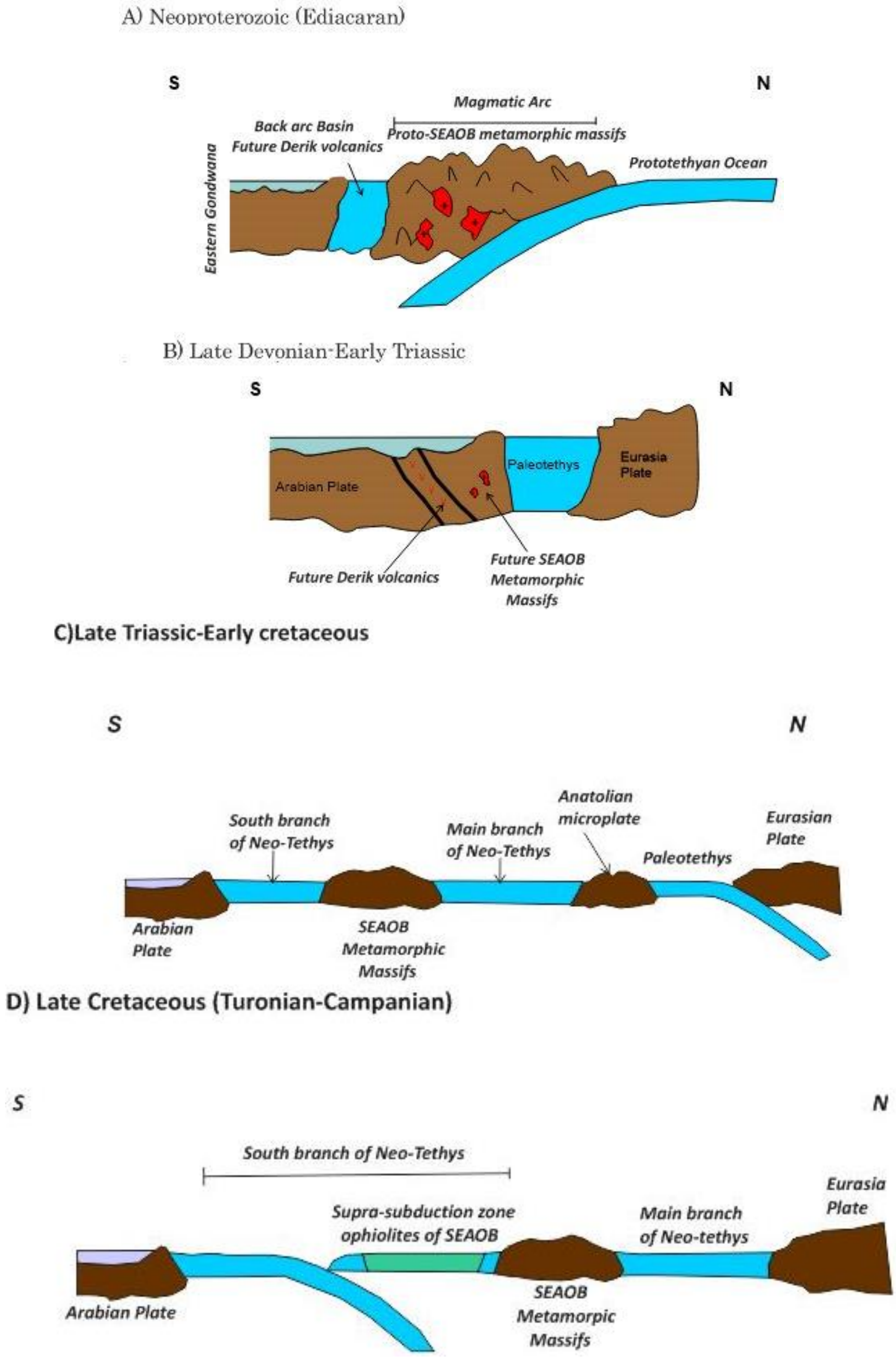
(1) a synorogenic “back-deep” type basin [121],
(2) an immature island arc [10,102],
(3) an Eocene rifting zone [166],
(4) a marginal basin formed behind the arc above a south-dipping subduction zone [122],
(5) a back-arc basin [167],
(6) a collisional belt [30,123],
(7) a lithospheric removal and asthenospheric upwelling associated with the extensional collapse of Southeastern Anatolian [126]

However, none of these models can fully explain the formation of the Maden Complex.

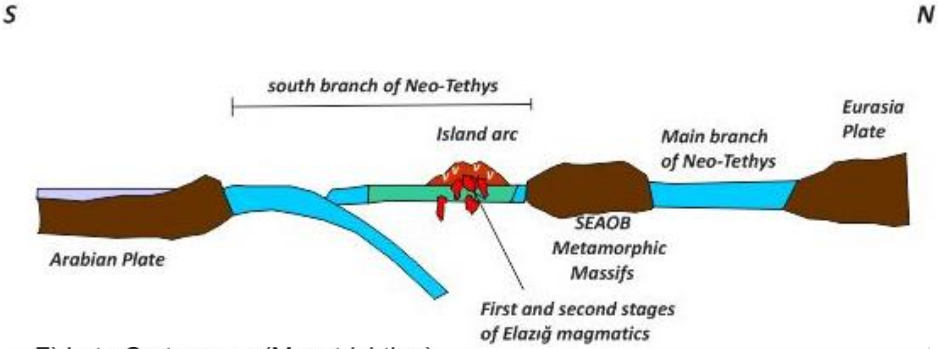
After the thrusting of the ophiolites on the the Arabian Platform, even though the subsiding ocean is closed, the subduction continued and due to the continental lithosphere and oceanic lithosphere exhibit different buoyancy, their contrasting buoyancy will finally lead in the breakoff of subducted slab. The subsiding ocean closure in Latest Maastrichtian and breakoff probably weakening the lithospheric mantle. This would have provided suitable conditions for subduction of the Arabian Plate because the breakoff of the subducted oceanic crust would have provided the pulling force for the subduction of the Arabian Plate Fig. 11g). The geochemical data suggest that the volcanic rocks of the Maden Complex are derived from a lithospheric mantle source. However, the positive and negative εNd(t) values indicate the involvement of continental material [126]. The presence of the tourmaline-bearing leucogranites above the autochthonous Maden sediments has been interpreted by a large-scale intracrustal subduction [106]. Slab breakoff would open a slab window that allows the hot asthenosphere beneath the slab to rise into the mantle wedge, resulting in the intensification of magmatism. Magmatic rocks generated by such a process display compositional diversity with varying sources, such as the mantle wedge, the deep asthenosphere mantle, and the continental crust [168,169]. The magma formed by the partial melting of the mantle wedge, the rising deep asthenosphere mantle and the continental crust forms Maden arc over the ophiolites, Bitlis-Pütürge Massifs and the Hazar Group in the Middle Eocene (Fig.11h). Above subduction zones, while Maden arc develops, behind it, shallow-deep marine carbonates and clastics (Kırkgeçit Formation) were deposited in a back-arc basin [148]. During the Middle –Early Eocene and Early Oligocene, marine sediments were deposited in a large basin (Kırkgeçit Basin) to the North of the Bitlis– Pütürge Massifs [134,170] (Fig.11i).

The last marine sedimentary rocks cropping out in the region belong to the Early Miocene Alibonca Formation and are not very common. Closure of the sea in the Early Miocene was related to regional uplift following the closure of Neotethys and regional continent–continent collision in the Middle Miocene, marking the beginning of the Neotectonic Period [167,171-174].

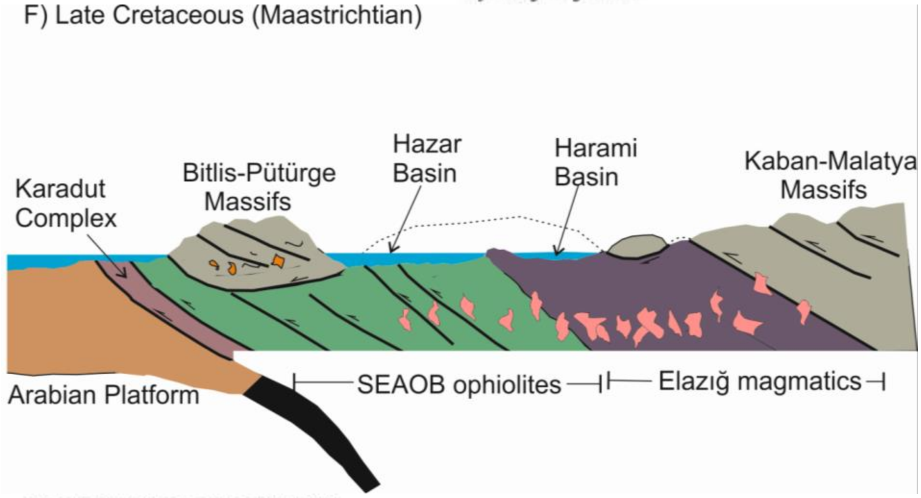
The continuous northward migration of the Arabian Plate led to the disruption of the Tethys seaway and the final closure related to continental collision of Arabia and Eurasia. Figures (11 a-j) show the actual situation of the SEAOB. According to some researchers [141,175], in its central segment of the SEAOB, the collision between Arabia and Eurasia started possibly from the Latest Eocene. After the Middle Eocene the large Kırkgeçit basin was closed. In early Miocene only a very shallow and narrowly distributed marine basin continues. Alibonca formation was deposited in this narrow basin. All these data indicate that the closure of the Southern Branch of the Neo-Tethys began in the Late Eocene and was completed in the Late Miocene. The continental collision of the Arabian Plate with the Eurasian Plate gave rise to the East Anatolian Accretionary Complex and the Caucasus-Iran-Anatolia (CIA) volcanic province [60,61,159,163,167,176,177]. This collision zone is associated with widespread "post-orogenic" [178] or "post-collisional" [32,179,180] volcanic eruptions. From this moment onward, the ongoing northward movement of the Arabian Plate (still continuing today) [181,182,183], and the retreat of the Hellenic subduction zone to the west [184,185,186] led to westward tectonic escape of Anatolia along the North and East Anatolian Faults [174,187,188].



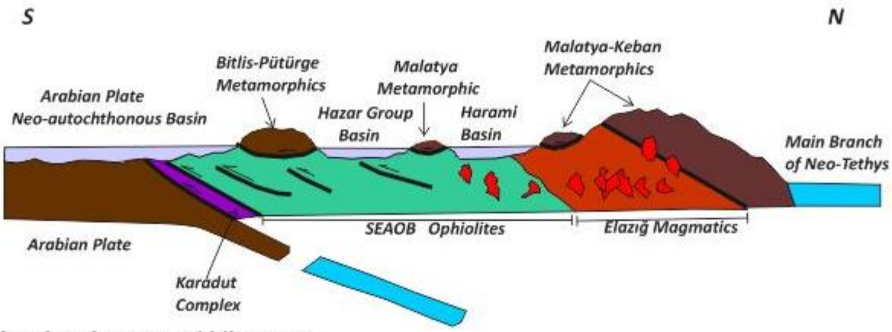
E) Late Cretaceous (Campanian)



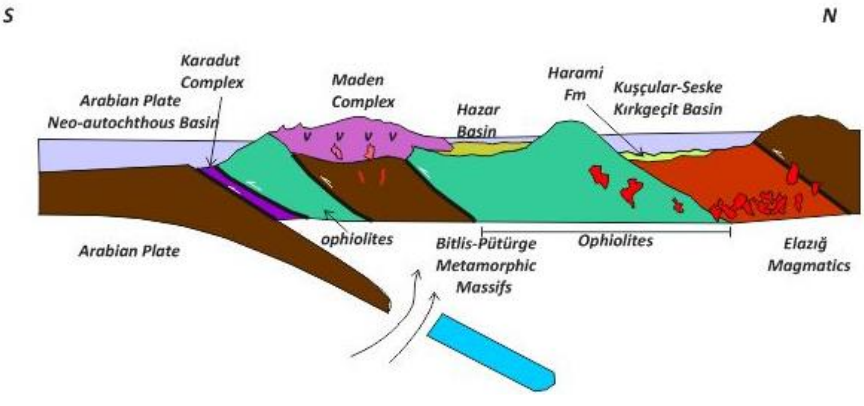
F) Late Cretaceous (Maastrichtian)



G) Late Cretaceous (Maastrictian)



H) Early Paleocene-Middle Eocene



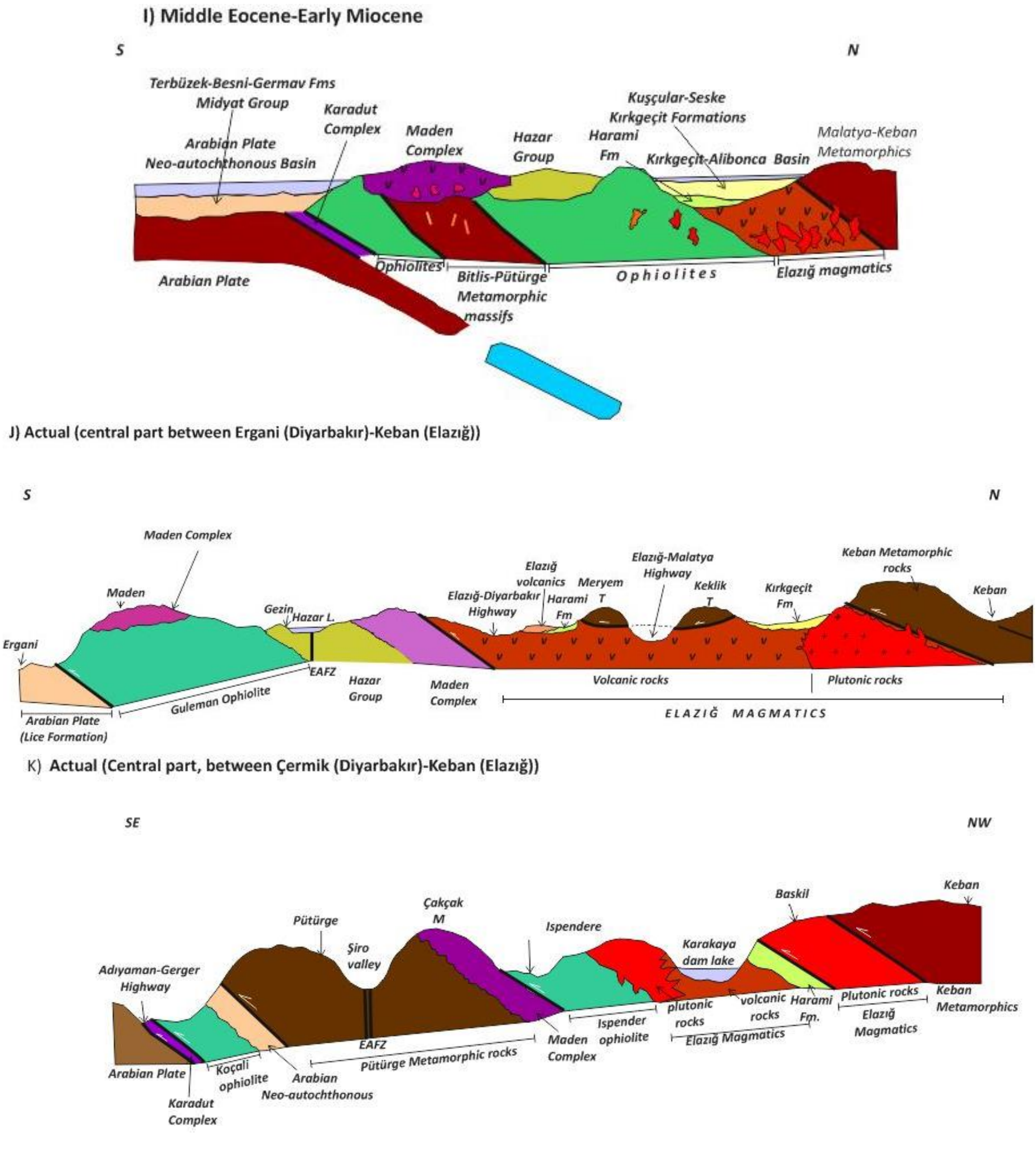


Fig. 11A-K. Tectonic evolution of the Souteast Anadolian orogenic belt

4. CONCLUSIONS

Major advances are taking place in the study of geotectonics of the SEAOB from various aspects that include: 1) Detailed field studies of the internal structures of different units and their relations with each other, 2) the various geochemical, geochronological and isotopic evidences gathered by new methodology. A synthesis of these results lead to the following major conclusions:

- The oldest rocks of SEAOB is the Ediacaran Early Cambrian Lower Unit rocks of the Bitlis-Pütürge metamorphics. The geological, geochemical and geochronological data of augen gneiss, metagranites demonstrate the presence of a Cadomian active margin setting along the Northern Gondwana margin. Terranes within the Cadomian active margin were involved in the Cadomian orogeny from ~570 to ~520 Ma.

- The absence of Cambrian-Ordovician rocks onto the metamorphic basement indicates that the basement was exhumed and transgressed by sedimentary rocks during Mid-Devonian.
- In the Late Triassic, the southern branch of the Neo-Tethys began to open with the rifting that started between the Arabian Platform and the proto-Bitlis Pütürge massifs, and the oceanic expansion continued until the beginning of the Late Cretaceous.
- A northwards subduction of southern Neo-Tethyan oceanic lithosphere started prior to 92 Ma and as a result SE Anatolian ophiolites and arc magmatics were formed. At the end of the Late Cretaceous, the ophiolites were thrust over the Arabian platform and the metamorphic massifs were fragmented and drifted southward over the ophiolites and arc magmatics.
- After the thrusting of the ophiolites on the the Arabian Platform the subsiding ocean is closed and the continental Arabian Plate enters the subduction zone. Even though the subsiding ocean is closed, the subduction continued and the breakoff of subducted slab has occurred.
- Following ophiolite emplacement resulted in a widespread marine transgression at the South of Bitlis-Pütürge Massifs onto the Arabian platform and the Koçali and the Kızıldağ ophiolites from Latest Cretaceous to Early Miocene times. In the same period, remnant basins of neotethys develop in the North of Bitlis-Pütürge Massifs.
- The magma formed by the partial melting of the mantle wedge, the rising deep asthenosphere mantle and the continental crust forms Maden arc over the ophiolites, Bitlis-Pütürge Massifs and the Hazar Group in the Middle Eocene. In the same periode, back-arc basin deposits in the north of the Maden arc are formed.
- The final closure, which started in the Late Eocene, ended in the Late Miocene. After the final closure, all units forming the SEAOB were thrust towards the south.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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