TECTONICS OF THE SOUTHEAST ANATOLIAN OROGENIC BELT

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Abstract. The tectonic development of the Southeast Anatolian Orogenic Belt (SAOB) is closely related to the demise of the NeoTethys Ocean, which was located between the Arabian and Eurasian plates from the late Cretaceous to Late Miocene. The ocean contained several continental slivers and intra-oceanic magmatic arcs. The continental slivers represent narrow tectonic belts rifted off and drifted away from the Arabian Plate while the NeoTethyan Ocean and the back-arc basins were opened. Later they collided with one another during the branches of the oceans were eliminated. In these periods, the continental slivers were involved in the subduction zone and turned into metamorphic massifs.

During the Late Cretaceous, the first collision occurred when an accretionary complex was thrust over the Arabian Plate's leading edge. Despite the collision, the ocean survived in the North and Its northward subduction generated a new intra oceanic arc, which collided later with the northerly located continental slivers. In this period, the metamorphic massifs and the intra-oceanic arc front migrated to the South. The new magmatic arc collided with the southerly transported nappe package during the Late Eocene. The amalgamated nappe pile eventually obducted onto the Arabian Plate during the Late Miocene. The collision produced escape structures during the Neotectonic period.

1-Introduction

The Anatolian Orogen is a tectonic mosaic formed during the collisions of the continental slivers rifted off from the African-Arabian Plate and accreted to Eurasian Plate. During the collisions, two oceans were closed: 1) the PaleoTethys during the late Paleozoic-early Mesozoic and 2) the NeoTethys during the Mesozoic-Cenozoic (Şengör and Yılmaz 1981). The tectonic events in association with the closure of the Paleo-Tethyan ocean are recorded mainly in the Pontide Range (see the accompanying paper by Yılmaz et al. in this volume).

The Southeast Anatolian Orogenic Belt (SAOB) is the southernmost component of the Anatolian orogen extending eastward along with the Zagros Mountains of Iran to the Oman-Makran subduction system (Fig 1). Despite the collision of the surrounding continents in Anatolia and Iran, on both ends, the Indian Ocean and the Eastern Mediterranean are still open as remaining parts of this ocean

(Fig 1 inset). Therefore, the geology of the SAOB provides data to decipher the tectonic development of the Tethyan system. There is a rich literature about the eastern Mediterranean ophiolites, significantly increased after the pioneering papers of Gass (1968) and Moores and Vine (1971) on the Troodos Ophiolite of Cyprus.

Within the NeoTethys ophiolites, the northern and southern branches were differentiated in the Anatolian Orogen (Şengör and Yılmaz 1981). They were developed because of the consecutive separation of the continental slivers from the Afro-Arabian Plate during the early Mesozoic. The Southern NeoTethys, generating the SAOB, evolved between the Afro-Arabian Plate and the Bitlis Massif-Tauride Platform- (Şengör and Yılmaz 1981). The latter belt was possibly connected with the narrow strip of the Pelagonian continent and Adria in the west, separating the Southern NeoTethys from the Alpine Tethys (Dilek 2019). To the east, the Southern NeoTethys widened toward the present Indian Ocean.

The SAOB represents the northwestern part of the Bitlis-Zagros Orogen (Inset in Fig1). It is a composite tectonic entity that consists of nappes of the metamorphic massifs and ophiolites. The SAOB is subdivided into three east-west trending zones. They are from South to North, the Arabian Platform, the Imbricated zone, and the Nappes. The zones are separated by major thrusts (Yılmaz 1993) (Fig1).

Since the late 1970 numerous researchers have worked in this region and published many papers concerning different aspects of the SAOB, providing valuable information on the local and regional scales. Among the papers may be mentioned Şengör et al. 1979; Şengör and Yılmaz 1981; 1990; Dilek and Moores 1990, Yılmaz and Yiğitbaş 1991; Aktaş and 1991; Beyarslan and Bingöl 2000; Parlak et al. 2004, 2009; 2012; Dilek and Sandvol 2009; Silja et al. 2009; Oberhänsli et al. 2010., Rolland et al. 2012., Karaoğlan et al. 2016; Robertson 2002; Robertson et al. 2006.,2007, 2012, 2016 A, 2016 B; Pourteau et al. 2013; Akıncı et al. 2016; Seyitoğlu et al 2017; Dilek 2019, Van Hinsbergen et al 2020 Yılmaz 2017, 2019, 2021). Most of the post 2005 works are related to petrological problems of the metamorphic and ophiolitic associations based mainly on the isotope and geochemical data (Rızaoğlu et al. 2006; Bağcı et al. 2008; Parlak et al. 2010; Karaoğlan et al. 2013 A, 2013 B, 2013 C; 2013D; Oberhänsli et al. 2010, 2012, 2014; Candan et al. 2012; Yıldırım 2015; Parlak 2016; Nurlu et al., 2016; Awalt and Whitney 2018; Beyarslan et al. 2018; Bingöl et al. 2018;). These geochemical data contributed significantly to the available field evidence (Yılmaz 1993; 2019; Yiğitbaş and Yılmaz 1995) to reassess critical tectonic problems associated with the development of the SAOB.

The Southeast Anatolia has also been effected by the post-Miocene indentation tectonics, which formed the major strike-slip faults of the region (Çemen et al., 1993 and Korucu and Çemen 1998; Yılmaz 2017; 2020; 2021)

The main purpose of this paper is to review the tectonic evolution of the orogenic belt based on the analytical data and our geologic data from the region.

2-Geological outlines of the Southeast Anatolian Orogenic Belt

The SAOB is subdivided into approximately three east-west trending zones. From South to North, they are Arabian Platform, the Imbricated zone, and the Nappes. The zones are separated by major thrusts (Yılmaz 1993) (Fig1).

2-1-The Arabian Platform

The Arabian Platform represents the northwestern part of the Arabian Plate, where a thick sedimentary succession was deposited, mostly in the marine environment from Cambrian to present (Fig 2) (Tuna 1973; Perinçek 1979; Yiğitbaş 1989; Yılmaz 1984; 1990; Yılmaz et al. 1987, 1988; Siyako et al. 2013; Robertson et al. 2012, 2016b). The succession contains several regional unconformities. However, regional unconformities correspond to the three nappe emplacement stages (Figs 2A and 2B). (Yılmaz 1993). The sequence is therefore, divided into three autochthonous successions with respect to the nappes (the allochthonous units) (Fig 2B) (Yılmaz 2021). The first period of sediment deposition ended when the first ophiolite nappe package (the lower ophiolite nappe; LN) was tectonically emplaced onto the Arabian Platform during the Late Campanian–Early Maastrichtian period (Fig 2A and B) (Yılmaz 1993). The ophiolites of this period display the supra subduction zone (SSZO) affinities (Pearce 1985; Dilek and Thy 1992; Parlak et al. 2004). They were developed above the northerly subducting Tethyan oceanic lithosphere (Robertson 2012; Dilek 2019; Yılmaz 2019, 2021).

Overlying unconformably the nappes is a marine transgressive sequence of Maastrichtian to Middle Miocene age (Fig 2) (Tuna 1973; Yılmaz 1984, 1993; Robertson et al. 2012; Siyako et al. 2013). The basal clastic rocks of the transgressive unit transit to neritic limestones (Fig.2 A), which pass upward to shales (the Germav Formation) of Late Maastrichtian- Paleocene age (Fig 2 A). A thick neritic limestone succession of Eocene age (the Midyat Group) grades into carbonate flysch of Upper Eocene-Oligocene age (the Fırat Formation) (Fig 2 A) (Tuna, 1973; Yilmaz et al. 1987).

A new ophiolite nappe was tectonically emplaced above the Arabian platform during the Middle Eocene (the middle ophiolite nappe; MN) (Yılmaz 1984; 2019). Above the ophiolite slab is an epiophiolitic pelagic chalk-radiolarite sequence of Upper Cretaceous-Lower Eocene age range (the Cona Group of Yılmaz 1993). Basal sandstones of late Eocene transgression rest on the middle nappes and transit to a neritic limestone succession (the Midyat Group, Fig 2).

A regional unconformity of the Late Eocene–Oligocene age separates the Eocene marine sediments from the overlying Upper Eocene-Oligocene terrestrial and shallow marine clastics rocks. They grade laterally into the Lower Miocene flysch unit (the Lice Fm) (Fig 2B). A regressive sequence of late Early Miocene-Middle

Miocene age follows the flysch beginning with thick (>500 m) olistostromes (Azgıt Fm in Fig 2B).

A giant nappe pile (UN) was thrust over the Lower-Middle Miocene clastic units during the Middle-Late Miocene (Fig 2B) (Yılmaz 1993; 2019; 2021). The south-vergent compressional stress severely deformed the units of the imbricated zone, which were compressed between the Arabian Plate and the southerly transporting nappes.

2-2-The Zone of Imbrication

This east-west trending belt (Fig 4A) (Yıldırım and Yılmaz 1991; Yılmaz 1993; 2019) is 500m to 2 km wide and consists of south-vergent thrust sheets (Fig 3). The successions are complimentary within the imbricated zone, revealing a continuous sequence before the imbrication (Yılmaz 1993). The sequence is Upper Cretaceous to Early Miocene in age (Fig 3).

There is a deep-sea sedimentary succession of the Upper Cretaceous to Lower-Middle Eocene in age that conformably overlies the ophiolite at the top of the imbricated zone. The pelagic sediments consist of limestone (chalk), chert, clayey limestone, marl, and calciturbidites. The pelagic sedimentary sequence is identical to the succession overlying the middle nappe (the Cona Group, Yılmaz 1984). Intermediate and felsic volcanic rocks (the Helete volcanics) alternate with the pelagic sediments (Aktaş and Robertson 1985, 1991; Yilmaz 1993; Bağcı 2013). Above an unconformity surface, Upper Eocene-Oligocene olistostromes overlie the deep-sea sequence. A nappe pile (< 8 km thick) tectonically overlies the imbricated zone consisting of metamorphic and ophiolitic thrust sheets (Figs 4 and 5).

2-3-The Nappes

Five metamorphic and ophiolite thrust sheets are recognized in the nappe zones based on their lithological and tectonostratigraphic features and the stratigraphic order. Fig 4 displays the main components of the SAOB. From the bottom to the top, they are 1) the lower ophiolite nappes (LO), 2) the middle (MO) ophiolite nappes, 3) the lower (southern) metamorphic massifs (LM), 4) the upper ophiolite nappe (UO), and 5) the upper (northern) metamorphic massifs (UM). During the first two nappe emplacement stages, ophiolite slabs were thrust over the Arabian Platform (Fig 2A and B). The present orogenic belt was developed in the last phase when a nappe pile consisting of the ophiolite nappes and the overlying metamorphic massifs were tectonically emplaced onto the Arabian Plate in Miocene (Figs 2; 4 and 5) (Yılmaz 2019; 2021).

Within the SAOB, two approximately E-W trending metamorphic belts may be differentiated as the northern (the Binboğa-Malatya-Keban metamorphic massifs) and the southern (the Engizek-Pötürge-Bitlis metamorphic massifs) metamorphic belts (Fig 1). The former is tectonically above the latter (Fig 4B and 5). Both metamorphic massifs consist of two major litho-stratigraphic components; a Paleozoic core and a Mesozoic cover (O. Yılmaz 1975; Yılmaz et al. 1993, Yılmaz 2019). Within the cover rocks, metamorphic grade decreases steadily upward in the sequence, where the primary sedimentary features may be identified in the thick recrystallized limestones (Hall 1974; O. Yılmaz 1971; Yılmaz et al. 1993). The age of the cover rocks ranges from Triassic to Upper Cretaceous-Paleocene (?) (Hall 1974; Perinçek and Kozlu 1984; Hempton 1985; Yılmaz 1993; Yılmaz et al. 1993; Yiğitbaş and Yılmaz 1996; Robertson et al. 2016B). The ages and lithological characteristics of the core and the cover units correlate closely with the pre-Mesozoic basement and the overlying Mesozoic carbonate platform succession of the Taurus Range (Şengör and Yılmaz 1981; Göncüoğlu and Turhan 1984; Yılmaz 2019) leading to the interpretation that both have a common origin, and they were rifted off and drifted away from the Arabian Plate during the Triassic (Şengör and Yılmaz 1981). The metamorphic massifs underwent the major phase of metamorphism after the development of the complete sedimentary succession. In that sense, the metamorphic massifs do not fit the classical term of a massif in an orogenic belt representing tectonically elevated or protruded bodies of basement rocks consolidated during earlier orogeneses.

Genetically associated with the nappe emplacements, two belts of basins are also differentiated as the lower (LB) and the upper (UB) basins. Concerning their tectonic connections with the nappes and the distance from the Arabian Platform, the upper basins may also be subdivided into two belts as inner (UB1) and outer (UB2) upper basins (Figs 4A and B). Geological characteristics of the nappes and the basins are outlined in the following section.

2-3-1-The lower ophiolite nappe and the Inner Basin

Development of the lower basin (LB) is spatially, temporally, and genetically related to the lower ophiolite (LO) nappe's emplacement. The LO is a nappe stack consisting of two major groups of related rocks. Large outcrops of a thick (<4000m) ordered ophiolite slab are exposed at the Cilo and Kızıldağ Mountains (Fig1) (Yılmaz 1994; Dilek and Delaloye 1992; Dilek and Delaloye 1992). Their ages vary between 92-80 Ma (Bağcı et al. 2005; 2008; Parlak et al. 2010; Karaoğlan et al. 2013 A). In the Cilo Mountains, an upper basaltic lava layer is seen above the ophiolite, followed upward by an intermediate volcanic suite. Felsic plutonic rocks cut the entire volcanic association. Collectively, they form an intrusive-extrusive complex (Yilmaz, 1985).

The geochemical and isotope studies on the SE Anatolian, Tauride and Cyprus ophiolites are consistent with a supra-subduction zone origin (Pearce 1975; Dilek et al. 1990; Dilek and Eddy 1992; Dilek and Thy 1998; Dilek et al. 2007, Parlak et al. 2009; Parlak 2016; Dilek and Furnes; 2019; Robertson et al. 2012a; Karaoğlan et al., 2013 A, D;) indicating that the older NeoTethyan oceanic lithosphere was eliminated and its demise by intra-oceanic subduction generated a younger SSZ ophiolite during the Late Cretaceous (92-73 Ma) (Karaoğlan et al. 2013, Dilek and Furnes 2019 and the references therein).

Dragged under the LO, there are two distinctly different sub-ophiolitic thrust sheets, separated by thrust faults. An ophiolitic mélange of Upper Cretaceous age, the Koçali Complex, is underlain tectonically by a flysch-wild flysch succession, the Karadut Complex (Fig 2A) (Yılmaz 1984). The Karadut Complex is a severely sheared and internally commonly chaotic sedimentary unit whose age ranges from Late Triassic to Campanian. The lower part of the succession consists of a hemipelagic limestone and calcareous turbidite unit followed by a flysch and an overlying pelagic limestone, red chert, radiolarite, radiolarian mudstone unit (the Şebker Fm). The Karadut Complex represents outer-shelf and continental-slope environments. Towards the top, the Complex contains multiple debris-flow deposits of Upper Campanian age, containing limestone fragments and calci-turbidites derived from the Arabian carbonate platform.

The Koçali Complex (Fig 2 A) is an ophiolitic mélange composed of blocks of ophiolite and pelagic sedimentary rocks. Its matrix comprises sheared serpentinite and multicolored radiolarian mudstone, shale, and splitized basaltic lavas.

Basal clastics of Upper Maastrichtian transgressive succession unconformably overly the LO.

2-3-2-The Metamorphic Massifs

The metamorphic massifs of southeastern Anatolia (LM and UM) display polyphase metamorphism (O. Yılmaz. 1975; Okay et al. 1985; Parlak et al. 2012; Oberhänsli et al. 2012; 2014 and Awalt and Whitney 2018). Initially, they underwent HP metamorphism followed by an HT metamorphism (Yılmaz 2019 and the references therein). Oberhänsli et al. (2012; 2014) described blueschist facies metamorphic rocks from the Bitlis Massif's cover units and estimated the peak conditions about ca. 480–540 °C/1.9–2.4 Gpa. They calculated the age of blueschist 79-71 Ma old. The Bitlis-Pötürge-Engizek massifs were later experienced a retrograde greenschist facies metamorphism, possibly during the Paleocene (Yılmaz 2019).

2-3-3- The Middle (MO) and Upper Ophiolite (UO) nappes and the Upper Basins (UB1 and UB2)

Away from the thrust front to the north, the middle ophiolite nappe is exposed in a tectonic window (Fig 4A). The MO consists of three thrust sheets (Fig 4B), which contain the following rock units: 1-The lower thrust sheet is represented by a low grade metamorphic basaltic lava and its metasedimentary cover (the Kızılkaya Metamorphics KM in fig 4B and5A; Yılmaz et al. 1987, 1993). The metamorphic grade does not extend beyond the lower limit of the greenschist facies. 2-The middle thrust sheet is a non-metamorphic volcano-sedimentary sequence of Middle Eocene age known as the Maden complex or Maden Group (Maden in Fig 4B and M in Fig 5A) (Aktaş and Robertson 1985; Yılmaz et al. 1993; Yiğitbaş and Yılmaz 1996A and 1996B), which developed fragmenting a nappe package during the Middle Eocene (Yılmaz et al. 1993; Yiğitbaş and Yılmaz 1996 A and B). 3- The upper thrust sheet is the major component of the lower nappe pile represented by a thick (< 3km) metamorphic ophiolite slab (the Berit metaophiolite) (MO in Figs 4 A and B and Fig 5A) (Genç et al. 1993; Yılmaz et al. 1993; Yiğitbaş and Yılmaz 1996A and 1996B; Robertson et al. 2006; Karaoğlan et al. 2013D; Awalt and Whitney 2018) consisting of several thrust slices. Each one of these thrust sheets exhibits an apparent ophiolite stratigraphy representing the mantle and crustal layers of an ordered ophiolite (Genç et al.,1993; Yılmaz et al., 1993). However, the ophiolite stratigraphy was reversed across the thrust sheets (Genç and Yılmaz 1993).

The Berit ophiolite displays polyphase metamorphism, the initial granulite-eclogite facies followed by the amphibolite facies. A retrograde greenschist facies metamorphism superimposed on the earlier metamorphic phases (Yiğitbaş 1989; Genç et al. 1993; Candan et al. 2012; Oberhänsli et al. 2012; 2014; Awalt and Whitney 2018).

In the northern part of the SAOB, across the Göksun-Sürgü Fault (Fig 4A), an ordered non-metamorphic ophiolite slab is exposed (UO in Fig 5B). The ophiolite is referred to as Göksun Ophiolite (GO in Fig 5 A) and its epi-ophiolitic cover, the Elbistan volcano-sedimentary sequence of Cretaceous-Paleocene age (AV and UB2 in Fig 4 A). In the epiophiolitic sequence, the pelagic sedimentary rocks are overlain by andesite–dacite lavas of island arc affinity (Yılmaz et al.1993; Yiğitbaş and Yılmaz 1996A; Parlak et al. 2004; 2020; Karaoğlan et al. 2013 C). The lavas are followed upward by the Paleocene-Lower Eocene flysch (Yılmaz et al. 1987; Yılmaz 1993; Robertson et al. 2006). The Binboğa–Keban–Malatya metamorphic Massifs (UM) tectonically overlies the UO and AV (Figs 4 A: B and Fig 5).

3-Time constraints on the amalgamation of the nappes

Fig 4B shows field relations of the time and order of piling of the nappes. Thrusting of the Binboğa-Malatya Metamorphic Massif (UM) above the Göksun Ophiolite- Elbistan volcanic arc pair (UO and UB2) may be tightly constrained to the late Ypresian-Lutetian. This is based on the following lines of field evidence.

> 1-Olistostrome deposits resting stratigraphically above the Elbistan volcano-sedimentary sequence are Middle Eocene in age (Perinçek and Kozlu 1984; Yılmaz et al. 1987). The source of the rapid influx of the internally chaotic sediment is the Binboğa-Malatya Massif. The olistostromes may thus be interpreted as the precursor of the approaching metamorphic nappe.
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> 2- The post thrusting granites that intruded into the Binboğa Massif and the underlying Göksun Ophiolite-Elbistan volcanic arc sequence (Yılmaz et al. 1987) yield 51-45 Ma radiometric ages (Parlak 2006; Karaoğlan et al. 2013D).

Tectonic emplacement of the Engizek-Pötürge-Bitlis Massif (LM) onto the middle ophiolite nappe pile (MO) is also tightly constrained to a narrow time span corresponding to the late Middle Eocene-early Late Eocene because a) the OM (the Maden Complex) comprises the Middle Eocene units (Yiğitbaş and Yılmaz 1996; Yılmaz et al. 2017), and b) the oldest marine sediments deposited above the LM are Upper Eocene sandstones (Yılmaz 1978; Perinçek and Kozlu 1984; Yiğitbaş 1989; Yılmaz 1993; Yılmaz et al. 1981, 1987, 1993; Yılmaz and Yıldırım 1996).

The amalgamation of the northern and the southern nappe piles corresponds to the period between the end of the Middle Eocene and the beginning of the late Eocene because the youngest rocks under the nappe package are the Middle Eocene volcano-sedimentary unit, and the first cover sediments that seals the nappe package is the Upper Eocene sandstones (Fig 4B). From the late Eocene onward, the nappe pile moved as a coherent body (Figs 5 A and B).

4- Discussion on the major tectonic event leading to the development of the SAOB

In this section, we discuss a tectonic evolution model based on our many years of field work in Southeast Anatolia (Figs 6 and 7), which provide lines of evidence leading to this model. The supra subduction ophiolite origin of the lower ophiolite (LO) (Fig. 4) suggests that an older oceanic lithosphere was consumed by northward subduction of the Arabian Plate and generated a supra subduction ophiolite in the upper plate during the Cenomanian (95-73 Ma), Karaoğlan et al. 2013 B, and C) (Fig 6A).

The stratigraphy in the thrust slices (Fig 2A) indicates that an ophiolitic slab was detached from its root, dragged underneath the ophiolitic mélange assemblage, began to move southward toward the Arabian Continent (Fig 6B). The nappe hit the leading edge of the Arabian Continent during Turonian and then synchronously obducted onto the northwestern margin of the Arabian Plate during the Late Campanian-Early Maastrichtian period (Yılmaz 1993, 2019) when the Tethyan subduction system from west to east possibly extended for more than 8000 kilometers. The consumption of the oceanic crust along this subduction zone caused the generation of the wide accretionary prism. The remnant of this accretionary prism is the present day Makran Accretionary prism and the Late Cretaceous SSZ ophiolites, observed along with the northeastern periphery of the Arabian Plate. The Cilo ophiolite in the SE Turkey (Yılmaz 1994), the Neyriz Ophiolite in NW Iran (Moghadam et al. 2014) and the Semail Ophiolite in the Oman Mountains (Searle and Cox 1999) represent part of this ophiolitic belt. The tectonic interaction between the ophiolite nappe and the Arabian Plate is considered as forearc-continent collision (Figs 6B and C). The initial stage of the collision is recorded in a regional unconformity caused by uplift of the Arabian Platform (Figs 2 and 6C) (Yılmaz 1993; 2019).

The stratigraphic data from the Arabian Platform together with the rapid facies changes from the northern to the southern parts of the region (Fig 2A) may be interpreted as follows: a coeval foredeep and a forebulge were developed in front of the nappe pile (Figs 6B and C). Under the nappe pile's heavy load, the foredeep subsided below the CCD (the Şebker Fm). The blocks and olistostromes derived from the steep slope, and the outer-shelf areas were deposited rapidly into the foredeep (Fig 6 B). The elevated land supplied olistoliths and olistostrome deposits into the foredeep basin (Figs 2A and 6C).

Generations of the two internally chaotic assemblages defined as mélanges in the previous studies owe their origins to sedimentary (the Karadut Complex) and tectonic processes (the Koçali Complex). The former was developed throughout the Mesozoic on the continental slope and then slid into the foredeep developed in front of the ophiolite nappe. The latter is an ophiolitic mélange generated during the demise of the ocean along the subduction zone. The forearc-continent collision and the following events, the thickening of continental crust, and the consequent elevation of the topography are synchronously developed all along the Arabian Plate margin from the SAOB to the Oman Mountains.

The nappes' continuing advance rapidly lowered the formerly elevated and eroded platform areas beneath the sea level. This formed a progressively deepening foreland basin (the Sayındere Fm in Fig 2). The thick nappe pile rising above the sea-level formed a structural barrier along the continental platform's outer margin.

Basal sandstones of new transgression were deposited above the LO during the Late Maastrichtian (Fig 2), indicating that the thickened continental crust collapsed rapidly (Fig 6 D), and the sea transgressed onto the Arabian Plate once again (Fig 2 A). The overlying neritic limestone, which grades into the Upper Maastrichtian-Paleocene pelagic limestone and shale interbedded sequence (Germav Fm in Fig.2), reveals that the north-facing passive continental margin reestablished during the late Maastrichtian (Fig 6 D).

Despite the emplacement of the LO onto the Arabian continent, the oceanic environment continued to exist in the northern regions of the SAOB throughout the late Cretaceous (Figs 7A to C) (Yılmaz 2019). This is supported by the presence of uninterrupted Upper Cretaceous-Lower Eocene epi-ophiolitic deep-sea sedimentary sequence transported above the MO during the late Middle Eocene (Yılmaz 2019; 2021).

The geochemical and isotope data on the SE Anatolian-Tauride and Cyprus ophiolites consistent with a supra-subduction zone origin (Pearce 1975; Dilek et al. 1990; Dilek and Eddy 1992; Dilek and Thy 1998; Robertson et al. 2012a; Karaoğlan et al. 2013; Dilek and Furnes 2019). The isotope ages support further that the older NeoTethyan oceanic lithosphere was eliminated, and younger SSZ ophiolites were continually generated in an intra-oceanic environment toward the end of the Late Cretaceous (Fig 6A) (i.e.,83-73; Ma; Bağcı et al. 2008; Parlak et al. 2010; Karaoğlan et al. 2013 A to D, Karaoğlan et al. 2013, Dilek and Furnes 2019) Ages of the fragments from the ophiolitic mélange show that the demise of the oceanic lithosphere by the subduction processes continued till the end of the Middle Eocene (Figs 6D and 7A) (Yılmaz 2019).

Following the rifting from the Arabian Plate, the continental slivers that were located between the Taurus and the Arabian Plate (Şengör and Yılmaz 1981) underwent metamorphism and formed the metamorphic massifs during the progression of the orogen between the late Cretaceous-early Cenozoic (Fig 7B, C, and D) (Şengör and Yılmaz 1981; Yılmaz 2019 and the references therein). The Berit metaophiolite (HP/HT) and the Bitlis Massif (HP) underwent penecontemporaneous, synkinematik metamorphisms (Fig 7D) (O. Yılmaz 1975; Okay et al. 1985; Pourteau et al. 2013; Oberhansli et al. 2014; Yılmaz 2019). For the eclogite and blueschist metamorphic facies, Oberhänsli et al. (2014) inferred a burial of 65 km and 35 km (Fig 7 D) and calculated the peak conditions of the blueschist metamorphism around 79-74 Ma. The P/T path (Oberhänsli et al. 2014) indicates that the continental slab was attached to the subducting oceanic lithosphere and deeply buried along a subduction zone (Fig 7D) (Yılmaz (2019). The Amphibolite facies minerals developed on the HP metamorphic rocks require an unexpectedly high temperature, possibly added by the asthenospheric wedge injection into the space created due to the subducting plate's rollback (Figs 7 D) (Dilek and Flower 2003). The seismic images of the southern Tethyan oceanic slab under the eastern Anatolia display the rollback and associated retreat (Piromallo and Regard 2006: Şengör et al. 2008; Özaçar et al. 2010).

The Göksun-Sürgü Fault (Figs 1 and 4) presently separates the subduction involved HP lower Plate associations (the LM and MO) from the nonmetamorphic ophiolitic association of the upper plate units (the UO and EV) (Figs 7B and 7C). Therefore, this fault may be viewed as a large-scale detachment fault, part of which was taken up later by a strike-slip fault during the Neotectonic period in Pleistocene-Holocene (Yılmaz 2017, 2019). The structural fabrics of ductile to brittle deformation recorded within the metamorphosed mafic-ultramafic rocks were developed during lithospheric-scale detachment faulting associated with upper mantle exhumation. These events may be compared closely to the oceanic core complex formation documented from the modern and ancient oceanic lithosphere such as the western and southern Alpine ophiolites (Miranda and Dilek 2010, Festa et al. 2015, Escartin et al.2017, Pohl et al. 2018; and references therein).

Following the metamorphism that occurred during the Late Cretaceous-early Eocene period, several kilometers thick rock column were exhumed. The Engizek-Bitlis Massif and the Berit metaophiolite reached the surface in a relatively short period during the end of the Early Eocene. For this, the following data may be given; the metamorphic nappes were thrust above the Middle Eocene Maden Basin units (Fig 4B), and Upper Eocene marine sandstones were deposited above the nappe package (Fig 4B).

The thrusting of the northern metamorphic belt over the Göksun ophiolite-magmatic arc pair may be evaluated as an arc-continent collision (Fig 7B, C and D), which occurred between the end of the Early Eocene and early Middle Eocene. The post tectonic granites which intruded into this nappe pile (Fig 7D) (Yılmaz et al. 1987; Rızaoğlu et al. 2006) (Fig 7B) were dated 51-45 Ma old

(Karaoğlan et al. 2013 D). From this time onward, the nappe package moved as a coherent body (Figs 7D and E). The data summarized above refutes the previous claims that the metamorphic massifs were old and collided with the Arabian Plate during the late Cretaceous (Yazgan 1984).

The geological record indicates that a remnant oceanic basin survived in the South of the nappe pile until the end of the Middle Miocene (Figs 7D and 8A) (Yiğitbaş 1989; Yiğitbaş and Yılmaz 1996A; Yılmaz 1993; 2019). During this period, the arc front migrated to the South due possibly to the subducting slab's rollback (Fig 7C) (Dilek and Furnes 2009). The arc volcanic succession continued to grow in the southern region until the Late Eocene (Figs 7E; F). A thick calc-alkaline andesitic-dacitic volcanic sequence was built above an ophiolite foundation (Figs 7B-C and 7E) (Yılmaz 1993; 2019). The volcanic rocks were gradually replaced upward by shallowing marine sandstone-siltstone and reefal limestones (Fig 7E) (Yılmaz 1993; 2019; Yiğitbaş and Yılmaz, 1996A and B; Kuşcu et al. 2010). At higher layers, olistostromes fluxed into the sandstones of the Upper Eocene-Oligocene age (Fig 7F). The stratigraphic order of the units in the volcanic arc sequence may be interpreted that the volcanic activity waned, and the oceanic lithosphere was possibly totally obliterated before the Late Eocene (Fig.7F) (Yılmaz 1993; Şengör et al. 2003; Rolland et al. 2012; Karaoğlan et al. 2016.

The nappes thrusted over the Helete volcanic arc sequence during the Late Eocene-Oligocene when the nappe pile collided with the southerly migrated younger magmatic arc (Fig 7F). The nappes elevated above the sea-level and began supplying coarse clastics into the basin in front of the southerly advancing nappes (Figs 7F). Southward, the coarse clastics graded into sandstones and flysch of the Lower Miocene Lice Formation (Figs 7F and G).

The platform carbonates deposited above the Arabian Plate throughout Eocene (the Midyat Group in Fig 2 A) are replaced upward by shallow marine sandstone-conglomerates, debris flow deposits, and continental red beds of the Late Eocene-Oligocene age (Figs 2A and 7G). Basal clastics of a new transgressive sequence rest above the Oligocene sediments over a marked unconformity. They pass rapidly to a flysch sequence of Early Miocene age (the Lice Fm) (Figs 3 and 7G) (Yılmaz 1987; Derman and Atalık, 1993; Siyako et al. 2013; Özdoğan et al. 2011). The rapid transition from the time-regressive to the time-transgressive successions from the North to South indicates a flexural foredeep (the linear flysch basin: The Lice Formation was developed in front of the southerly transporting nappe pile (Fig 7G). As the nappe pile transportation continued, the flysch and the underlying units were severely deformed, tightly folded, and imbricated by the south-vergent compressional stress (Fig 7H). These are the initial phases of the continent-continent collision between the nappes and the Arabian Plate (Yılmaz 1993; 2017,2019; Hüsing et al., 2009; Silja et al., 2009).

After development of the imbricated zone (Figs 1 and 7H), the nappes were thrust over the Arabian Plate's leading edge during the Middle-Late Miocene period. This event is the collision of the nappe pile with the Arabian Plate.

During the continuing N-S convergence, the suture zone began to rise and formed the Southeast Anatolian suture mountains (Fig 7H and I), which started to develop during the late Miocene is continuing today (Yılmaz 1993; Yılmaz et al. 1987; 1988; Akıncı et al. 2016; Yılmaz 2017). Consequently, the sea retreated from the orogenic belt toward the Mediterranean (Özdoğan et al., 2011; Siyako et al., 2013; Yılmaz, 2017; 2019), which remains as the surviving part of the ocean that extended to the Indian ocean before the development of the Bitlis-Zagros Orogenic Belt (inset in fig 1).

The northward advance of the Arabian Plate continued after the collision. The resulting compression has been initially accommodated along the Arabian Platform's northern boundary with the development of a wide fold and thrust belt (Fig 8) (Yılmaz 2017). Later, when the compressional deformation reached an excessive stage, the shortening deformation was replaced by escape tectonics (Perinçek and Çemen 1990; Yiğitbaş and Yılmaz 1997; Elmas and Yılmaz 2003; Boulton and Robertson 2008; Yilmaz 2017; 2020). Several E-W trending left-lateral strike-slip faults cut and displaced the fold and thrust belt (Fig 8) and began to transfer the stress to the SW direction (Yılmaz 2020).

5-Concluding Summary

The SAOB was developed due to the collisional events that followed the demise of the NeoTethyan Ocean and its dependencies such as back-arc/inter arc and remnant basins. The following successive major events are differentiated in the tectonic development of the SAOB.

1-Collision of the forearc (the Koçali and Karadut complexes and the overlying ophiolite slab) with the Arabian continent during the Late Cretaceous. Similar coeval events were recorded along the northern boundary of the Arabian Plate from the Amanos Mountains of southern Turkey (Fig 1) (Yılmaz 1984) to the Oman Mountains (Searle and Cox 1999; Goodenough et al. 2014).

2 A-Development of new northward subduction in the surviving ocean.

2 B-Involvement of a continental crust into the subduction zone, which formed the southern metamorphic belt: (the Engizek- Pötürge-Bitlis Massifs) during the Maastrichtian-Early Eocene period.

2 C-Fragmentation of south Taurus platelet (development of the Göksun ophiolite and Elbistan volcanic arc) during the Maastrichtian-Middle Eocene.

3-Collison of the Elbistan intra-oceanic magmatic arc with the northerly located continent (the northern metamorphic belt; the Malatya- Pötürge Massifs) during the Middle Eocene.

4-Collision of the southern and the northern nappe piles (the continent-continent collision) during the late middle Eocene.

5-The southward advance of the amalgamated nappe pile and the destruction of the remnant basin during the Late Eocene.

6-Emplacement of the nappes onto the Arabian Plate during the early Late Miocene, the final stage of the collisional development of the SAOB.

7 -Development of a wide fold and thrust belt along the nappe front of the Arabian Plate during Plio-Pleistocene.

8- Replacement of the orthogonal shortening by the escape tectonics and formation of strike-slip faults that transfer the N-S shortening deformation to W and SW during Pleistocene to present.

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Figure Captions

Fig 1-Inset- Location map of the Bitlis Suture Mountains within the Bitlis -Zagros orogenic belt showing the NeoTethyan suture (the black strip) along the northern margin of the Arabian Plate.

Fig 1-Geological Map of Southeast Anatolian region. The white and yellow squares show the location of the maps in figs 4 A and 5A, 5B.

Figure 2A- Generalized stratigraphic section of the Arabian

Platform in southeastern Anatolia, from the suture mountains

to the north of the Arabian Platform.

The lithology and age of the rock units shown in the figure are as follows.

Bitlis-Pötürge Massif represents the nappe of the metamorphic massifs of the southeast Anatolia. Ordered Ophiolite represents the ophiolite nappe. IZ; the imbricated zone. Azgıt Formation (coarse clastic rocks; Middle-Lower Miocene. Horu and Atlık limestones (reefal limestone; Middle Miocene). Adıyaman Formation (fluvial and lacustrine sedimentary rocks; Middle-Upper Miocene). Lice flysch; (Lower Miocene), Gaziantep Formation (pelagic limestone; Upper Eocene-Lower Miocene), Fırat Formation (reefal limestone; Oligocene-Lower Miocene), Midyat Formation (platform carbonate succession; Middie-Upper Eocene), Gergüş Formation (basal conglomerate and sandstone; Lower-Middle Eocene), Belveren Formation (pelagic limestone; Paleocene-Lower Eocene), Germav Formation (shale; Lower Maastrichtian-Paleocene).

Besni Formation (reefal limestone; Upper Maastrichtian), Terbüzek Formation (basal sandstone-conglomerate; Upper Maastrichtian), ordered ophiolite sequence; (Upper Cretaceous), Koçali Complex (ophiolitic mélange association; Upper Cretaceous), Karadut complex (wild flysch-flysch; Upper Triassic-Upper Cretaceous), Kastel Formation (flysch and

olistostrome; Upper Campanian-Lower Maastrichtian), Bozova Formation

(limestone-marl alternations; Campanian-Lower Maastrichtian),

Sayındere Formation (clayey limestone; Campanian), Mardin Group

(platform carbonate succession; Aptian-Cenomanian), Areban Formation

(basal sandstone, limestone; Aptian-Albian), Cudi Group (platform carbonate succession; Triassic-Upper Jurassic), Uludere Formation (siltstone-marl-limestone alternations; Triassic), Atlık Formation (quartzite.

Lower Triassic), Gomaniibrik Formation (limestone; Djulfian), Hazro

Formation (sandstone, siltstone; Upper Permian), Bedinan Formation (shale and clastic rocks; Upper Ordovician), Seydişehir Formation (shale, sandstone; Upper Cambrian-Lower Ordovician), Sosink Formation (shale-sandstone alternations; Upper Cambrian), Koruk Dolomite (Middle Cambrian), Zabuk Formation (arkosic sandstone; Lower-Middle Cambrian?), Sadan Formation (shale-slate; Precambrian? -Lower Cambrian?) Telbesmi Formation (metamorphosed tuff and felsic lava; Precambrian?). Names of the rock stratigraphic units were adopted from the Turkish Petroleum Company (revised from Yılmaz 1993).

Fig 2B- Columnar section showing three nappe emplacement stages and the consequent subdivisions of the Arabian Platform sequence into allochthonous and autochthonous successions. Abbreviations: LN, ON and UP are lower, middle, and upper nappes

Fig 3- Major tectonostratigraphic units of the zone of Imbrication. Lithologies and ages of the tectonostratigraphic units within the imbricated zone are as follows: the overturned syncline at the top of the Arabian Platform sequence is the Lower Miocene Lice Flysch and the regressive Middle Miocene sandstones. The coarse clastics-Oligocene are wild flysch grading into the Lower Miocene flysch. The flysch in the imbricated zone is the distal equivalent of the Lice Flysch. The Helete Formation represents the volcanic arc consisting mainly of andesitic lavas and pyroclastic rocks of the middle Eocene age. UB1; the cover sediments of the arc sequence formed during the late stage of the arc development in the Middle-Late Eocene. Pelagic sediments of Upper Cretaceous-Middle Eocene ages above the ophiolite represent epiophiolitic deep-sea sediments, the Cona Grp. Upp. Eoc-Olig. coarse clastics are the post nappe cover sediments that sealed the amalgamated nappe pile. The Engizek Massif represents the lower metamorphic nappe (LN).

Fig 4A- Geological map of the western part of the Southwest Anatolian Orogenic Belt showing major tectonic zones and structural elements of

the region (modified after Yılmaz 1993). The white line is the cross-section direction displayed in Fig. 4B. The Sürgü Fault (The Göksun–Sürgü strike-slip fault) is one of the prominent faults of the orogenic belt, which separates the nonmetamorphic Göksun Ophiolite (Upper Ophiolite nappe; UO) and the Elbistan Arc (UB2) from the metamorphic nappes (MO and LM.

Abbreviations; UM; Upper Metamorphic massifs (the Binboğa Massif), UB2; the Upper basin (Upper part of the Elbistan Arc succession), UO; the Upper Ophiolite nappe (Göksun Ophiolite), MO; the Middle Ophiolite nappe (Berit meta-ophiolite), LM; The Lower metamorphic massif (Engizek Massif), LO; (Lower ophiolite nappe), LB; Lower basin, Maden; Maden basin. UB1;(The Kızılkaya, the weakly metamorphic upper Cretaceous-Lower Eocene volcanic arc unit, Small red letters accompanying the trusts indicate thrusting order of the nappes, Eoc1; late Early Eocene, Eoc2; late Early Eocene–Middle Eocene, Eo3; late Middle Eocene-early Late Eocene, Mio1; Early Miocene, Mio2; Middle-Late Miocene, Eoc; late Middle Eocene, Maa; Late Campanian-Early Maastrichtian, Q; Quaternary.

Fig 4B- Geologic cross-section across the Southeastern Anatolian Orogenic Belt. Abbreviations are the same as in Fig 4A.

Arrows and numbers indicate the stacking order of the nappes; main thrusting stages; 1: late Early Eocene, 2: late Middle Eocene, 3: early Miocene, 4: Middle-Late Miocene

Figs 5A and B- Block diagrams from the western and central part of the nappe regions of the SAOB showing order of the nappe piles. Locations of figures A and B are shown in the figure 1A,

Abbreviations black letters and red letters indicate names and tectonic orders of the nappes. In fig A, red letters; LM; the Lower Metamorphic Massifs, MO; the Middle Ophiolite Nappe, UO; the Upper Ophiolite Nappe, UM; the Upper Ophiolite Nappe, LB; the Lower Basin, UB1; the Upper Internal Basin, IZ; the Zone of imbrication, EAF; The east Anatolian Transform Fault, SF; the Sürgü Fault, FFTB; Foreland fold and thrust belt. The black letters, PM; Pötürge Metamorphic Massif, MM; Malatya Metamorphic Massif, KM; Keban Metamorphic Massif. In figure B, the red letters, EM; Engizek Metamorphic Massif, GO; Göksun Ophiolite, BM; Binboğa Metamorphic Massif, AV; Elbistan Arc volcanics. M; the Maden Basin, KM; Kızılkaya Metamorphics. The red letters are the same as the fig A.

Fig 6- Cartoons showing tectonic evolution of the Southeastern Anatolia during the Late Cretaceous

A-Cenomanian-A north-facing passive continental margin was developed on the Arabian Platform. The northward intra-oceanic subduction generated a young SSZO. Following the total consumption of the old ocean the

young oceanic lithosphere reached the leading edge of the Arabian Plate

B- Turonian. An ophiolitic slab detached from its root. The ophiolite and the mélange drugged underneath were thrust over the Arabian Plate's leading-edge. This tectonic event may be interpreted as a forearc (accretionary complex)-continent (the Arabian Plate) collision**.** In front of the nappe pile, a foredeep and an accompanying forebulge formed. The rectangle defines the region detailed in fig C (inspired from Casey 1980).

C-Late Campanian-Maastrichtian. The foredeep subsided beneath the CCD. Blocks and olistostromes derived from the continental slope, and the outer-shelf areas were deposited rapidly into this foredeep. The adjacent forebulge was eroded (the Turonian unconformity in Fig 2). The nappes' continuing advance rapidly lowered the formerly elevated and eroded platform areas beneath sea level and formed a deep basin (the Sayındere basin in Fig 2A). The thick nappe pile gradually reached above sea level and formed a structural high along the continental platform's outer margin. Debris flows and blocks, derived mostly from this high, were deposited rapidly into this basin lying in front of the nappes. Therefore, the basin where the pelagic limestone was formerly deposited turned gradually into an environment of clastic deposition (Kastel basin in Fig 2A) (inspired from Robertson,1987, Fig.14).

Fig.7- Block diagrams showing the subsequent stages of southeast Anatolian orogenic evolution from late Maastrichtian to Present (modified after Yilmaz 1993).

A.-Maastrichtian. After the Late Campanian ophiolite obduction onto the Arabian Platform, a north-facing passive margin formed once again during late Maastrichtian and continued uninterruptedly to the middle Eocene epoch. This was the marine invasion's resumption from the north, where the open marine environment remained. The abyssal-plain sedimentary sequence (the Cona Fm) formed during this period are presently seen among the tectonic slices of the imbricated zone and at the top of the middle ophiolite nappe (the MO) (Fig 2B). The ocean separating the Arabian continent from the northern continental fragment (the metamorphic massifs) began to be consumed by northward subduction, which generated a younger ensimatic island arc.

B- Later periods of Maastrichtian. Due to the retreat of the subducting slab, the northerly located continent was split into two continental slivers. They were later incorporated in the orogeny and turned into the southern and northern metamorphic massifs. A younger SSZO (the Göksun Ophiolite; GO) and an ensimatic magmatic arc (the Elbistan Arc, EV) was developed between them.

C- Late Maastrichtian-Paleocene, Retreat of the subducting ocean lithosphere continued, which caused southward migration of the arc front. Volcanic activity in the southern arc continued until the Late Eocene (the Helete volcanics).

D- Paleocene-Early Eocene. The southerly located continental sliver attached to the oceanic slab involved in the subduction zone. They underwent HP and HP metamorphisms. Partly simultaneously, the subducting oceanic slab retreated (rollback). Hot asthenosphere wedged into the space generated by the rollback. The asthenospheric inflow contributed unusually high heat, which caused HT metamorphism, which superimposed on the previous HP metamorphism. The rollback also promoted the exhumation. The oceanic and continental fragments, when exhumed, formed the Bitlis Massif and the Berit metaophiolite. The northerly located continental sliver hit and moved onto the Göksun ophiolite (GO) and the overlying Elbistan arc (EV) during the late Eocene (the continent-arc collision). The 51-45 my old post tectonic granites (Gr) intruded into the nappe package.

E- Middle Eocene. Volcanoes of the magmatic arc rose above sea level, and fringing carbonate reefs formed. A short-lived back-arc/ interarc basin, the Maden Basin, opened fragmenting the nappe package. **F-Late Eocene-Oligocene**. As a result of the continuing southward transport, the nappes moved over and destroyed the Maden basin to the end of the middle Eocene. Different tectonostratigraphic units: the northerly located metamorphic massifs, the ophiolite nappes (The MO, UO), the Elbistan and Helete volcanic arcs, and UB2 were tectonically amalgamated. This event may be considered as the magmatic arc-continent collision The Oceanic basin was totally consumed. The development of the subduction mélange and the deep-sea sediment deposition ended before the Late Eocene. Above the elevated nappe pile formed a rugged topography, which supplied olistostrome deposits and coarse clastics into the adjacent lowlands. The Upper Eocene-Oligocene sediments deposited above the nappes as a first common cover. From this time onward, the nappe pile began to move as a coherent body.

G-Early Miocene. The remnant sea left after the oceanic lithosphere consumption was initially filled with coarse-grained sediment accumulation from the adjacent topographic highs. They were gradually replaced by more orderly flysch deposition during the early Miocene. A transition from the shallow sea to a linear flysch basin (the Lice Flysch) may be observed from the Miocene sections across the mountain range (Yılmaz et al. 1987; 1988).

H-Middle-Late Miocene. The flysch basin was severely deformed under the southerly transported nappes, which also caused the imbrication of the belts squeezed between the nappes and the Arabian Plate (the imbricated zone). The nappes were then trust on to the Arabian Plate; (the latest phase of the Continent-Continent collision).

I-Late Miocene–Present. Further convergence due to the continuing southward advance of the nappes and northward movement of the Arabian Plate caused elevation of the suture mountains. Consequently, the sea retreated from the Arabian Platform toward the Mediterranean. The continental foredeep (the Maraş Basin in fig 4A) began to be filled with terrestrial deposits.

Fig. 8- The physiographic map of western regions of the Southeastern Anatolian Orogenic Belt (SAOB) and the adjacent areas. The red arrows indicate the motion directions of the Arabian and Anatolian Plates. The

brown curvilinear lines show the trend lines of the mountain ranges, which correspond to the axes of the regional folds formed due to the compressional forces exerted by the escape regime, which also generated strike-slip faults (the white lines). The double headed black arrows indicate prominent foreland folds displaced by left-lateral strike-slip faults.

Abbreviations: SSF; the fault bundle in the Sarız-Saimbeyli Mega Shear zone comprises several fault-bound blocks or tectonic wedge transferring the compressional stress to the South. SF: the Sürgü Fault, which connects the East Anatolian Transform Fault zone (EATF) to the Mediterranean Region. DSF; the Dead Sea Fault.

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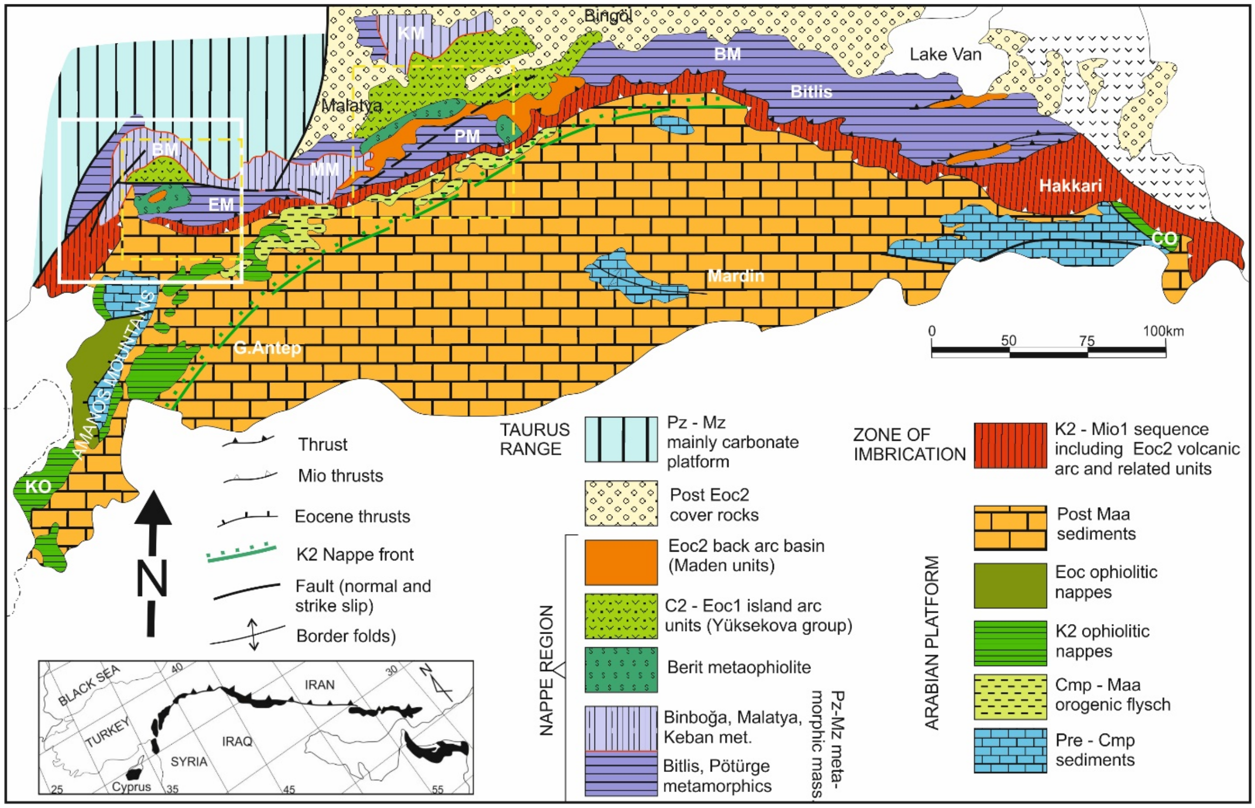


Figure 1. Geology Map of Southeast Anatolian regions. The squares show the location of the maps in Figures 4 A and 5A, 5B. The black strip in the inset map shows the suture mountains (Yılmaz 1993) of the Bitlis -Zagros Orogenic Belt.

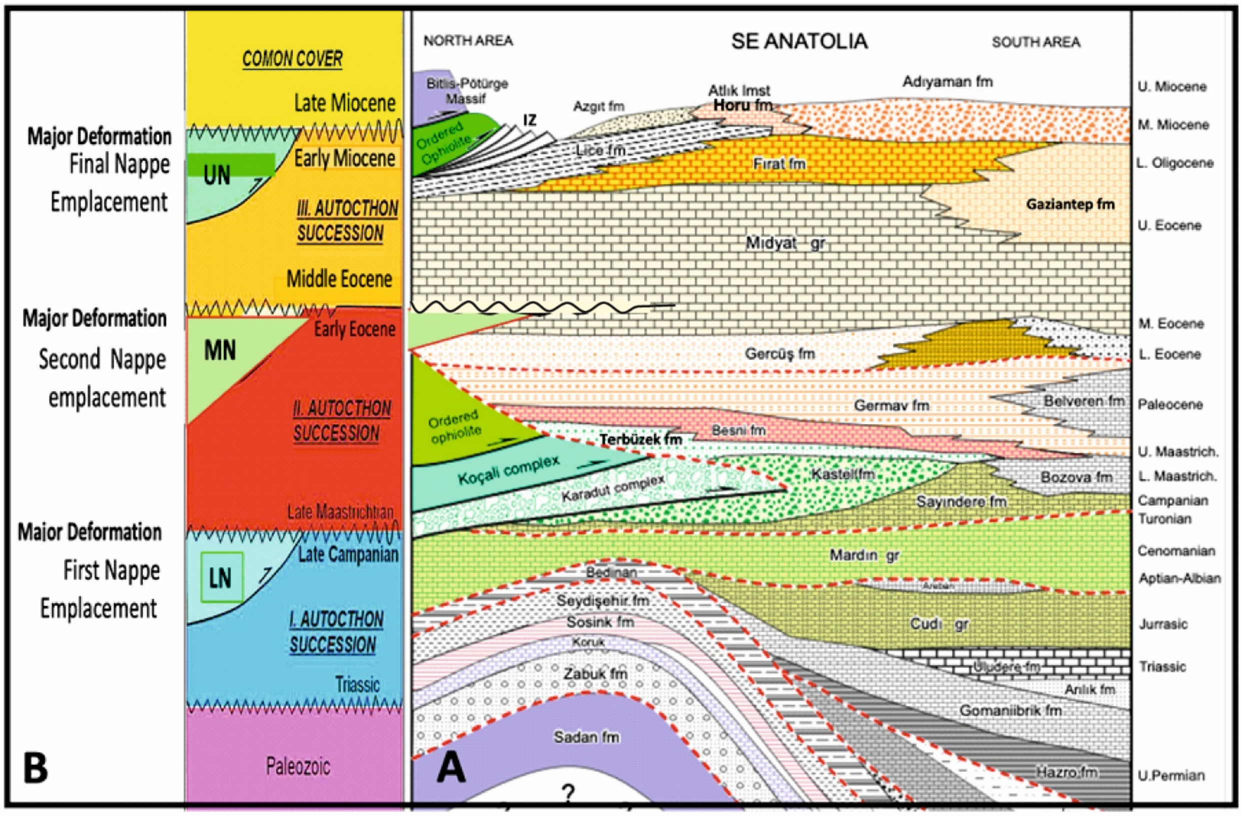


Figure 2 A. Generalized stratigraphic section of the Arabian Platform in southeastern Anatolia, from the suture mountains to the north of the Arabian Platform. The lithology and age of the rock units shown in the figure are as follows.

The Bitlis-Pötürge Massif represents a nappe of the metamorphic massifs of the Southeast Anatolia. The ordered Ophiolite represents ophiolite nappe. IZ; the imbricated zone. Azgıt Formation (coarse clastic rocks; Middle-Lower Miocene. Horu and Atlık limestones (reefal limestone; Middle Miocene). Adıyaman Formation (fluvial and lacustrine sedimentary rocks; Middle-Upper Miocene). Lice fm (flysch unit; Lower Miocene). Gaziantep Formation (pelagic limestone; Upper Eocene-Lower Miocene). Fırat Formation (reefal limestone; Oligocene-lower Miocene). Midyat Formation (platform carbonate succession; Middle-Upper Eocene). Gergüş Formation (basal conglomerate and sandstone; Lower-Middle Eocene). Belveren Formation (pelagic limestone; Paleocene-Lower Eocene). Germav Formation (shale; Lower Maastrichtian-Paleocene). Besni Formation (reefal limestone; Upper Maastrichtian). Terbüzek Formation (basal sandstone-conglomerate; Upper Maastrichtian). ordered ophiolite sequence; (Upper Cretaceous). Koçali Complex (ophiolitic mélange association; Upper Cretaceous). Karadut complex (wild flysch-flysch; Upper Triassic-Upper Cretaceous). Kastel Formation (flysch and olistostrome; Upper Campanian-Lower

Maastrichtian). Bozova Formation (limestone-marl alternations; Campanian-lower Maastrichtian). Sayındere Formation (clayey limestone; Campanian). Mardin Group (platform carbonate succession; Aptian-Cenomanian), Areban Formation (basal sandstone, limestone; Aptian-Albian). Cudi Group (platform carbonate succession; Triassic-Upper Jurassic). Uludere Formation (siltstone-marl-limestone alternations; Triassic). Atlık Formation (quartzite, Lower Triassic), Gomaniibrik Formation (limestone; Djulfian). Hazro Formation (sandstone, siltstone; Upper Permian). Bedinan Formation (shale and clastic rocks; Upper Ordovician). Seydişehir Formation (shale, sandstone; Upper Cambrian-Lower Ordovician). Sosink Formation (shale-sandstone alternations; Upper Cambrian). Koruk Dolomite (Middle Cambrian). Zabuk Formation (arkosic sandstone; Lower-Middle Cambrian?). Sadan Formation (shale-slate; Precambrian? -Lower Cambrian). Names of the rock stratigraphic units were adopted from the Turkish Petroleum Company (revised from Yılmaz 1993). **Figure 2B.** Columnar section showing three nappe emplacement stages and the consequent subdivisions of the Arabian Platform sequence into allochthonous and autochthonous successions. **Abbreviations:** LN, MN and UN are lower, middle, and upper nappes, respectively.

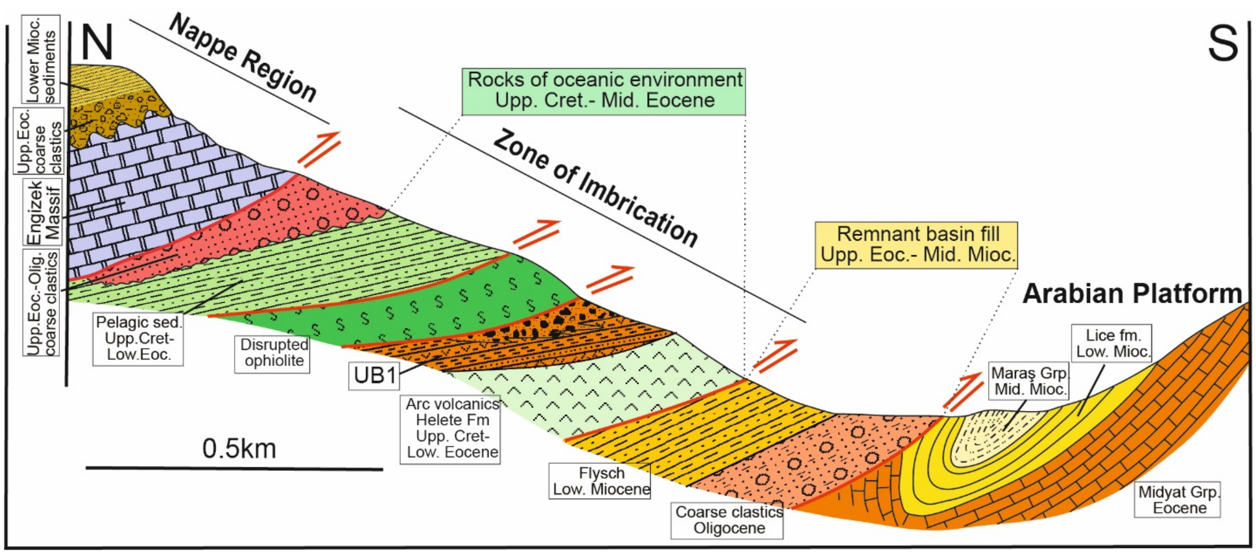


Figure 3. Structural order of the major tectonostratigraphic units of the Zone of Imbrication. Lithologies and ages of the tectonostratigraphic units within the imbricated zone are as follows: the overturned syncline at the top of the Arabian Platform sequence is the Lower Miocene Lice Flysch (Lice Formation) and the Middle Miocene sandstones. The coarse clastics-Oligocene are wild flysch grading into the Lower Miocene flysch. The flysch-Low. Miocene in the imbricated zone is the distal equivalent of the Lice Flysch. The Helete Formation represents the volcanic arc unit consisting mainly of andesitic lavas and pyroclastic rocks of the Upper Cret. to Low-Middle Eocene age. UB1;

Middle-Late Eocene cover sediments of the volcanic arc sequence. Resting above the ophiolite pelagic are the sediments of Upper Cretaceous-Middle Eocene age range; epiophiolitic deep-sea sediments, the Cona Grp. Upp Eoc-Olig coarse clastics are the post nappe units that sealed the amalgamated nappe pile. The Engizek Massif represents the lower metamorphic nappe (LM in Figure 4).

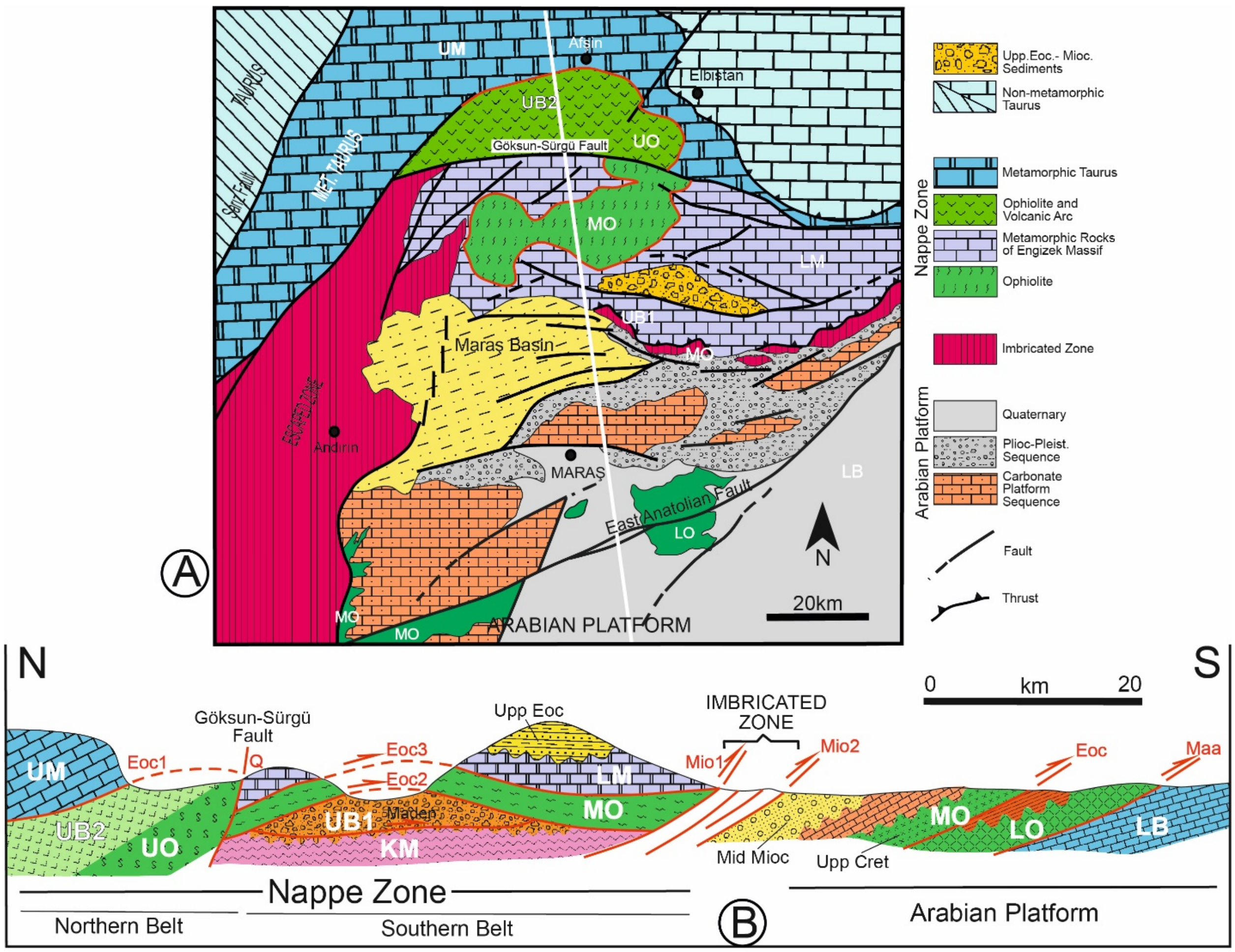


Figure 4A. Geological map of the western regions of the Southwest Anatolian Orogenic Belt showing major tectonic zones and units (modified after Yılmaz 1993). The white line is the cross-section direction displayed in Figure 4B. The Göksun–Sürgü Fault (or the Sürgü Fault) is one of the prominent strike-slip faults of the orogenic belt, which separates the nonmetamorphic Göksun Ophiolite (Upper Ophiolite nappe; UO)- Elbistan Arc (UB2) pair from the metamorphic nappes (MO and LM.

Abbreviations; UM; Upper metamorphic massifs (the Binboğa Massif), UB2; the upper basin represents upper part of the Elbistan Arc sequence), UO; the upper ophiolite nappe (the Göksun Ophiolite), MO; the middle ophiolite nappe (the Berit Meta-ophiolite), LM; the lower metamorphic massif (the Engizek Massif), LO; Lower ophiolite nappe, UB1; the internal upper basin, Maden; the Maden Basin. KM; The Kızılkaya Metamorphics; a weakly metamorphosed upper Cretaceous-Lower Eocene volcanic arc unit. Red letters on the trust faults indicate time of thrusting, Eoc1; late Early Eocene, Eoc2; late Early–Middle Eocene, Eo3; late Middle Eocene-early Late Eocene, Mio1; Early Miocene, Mio2; Middle-Late Miocene, Eoc; late Middle Eocene, Maa; Late Campanian-Early Maastrichtian, Q; Quaternary. **Figure 4B.** Geologic cross-section across the Southeastern Anatolian Orogenic Belt. Abbreviations are the same as in Figure 4A.

Arrows and numbers indicate main thrusting stages; 1) late Early Eocene, 2) late Middle Eocene, 3) Early Miocene, 4: Middle-Late Miocene

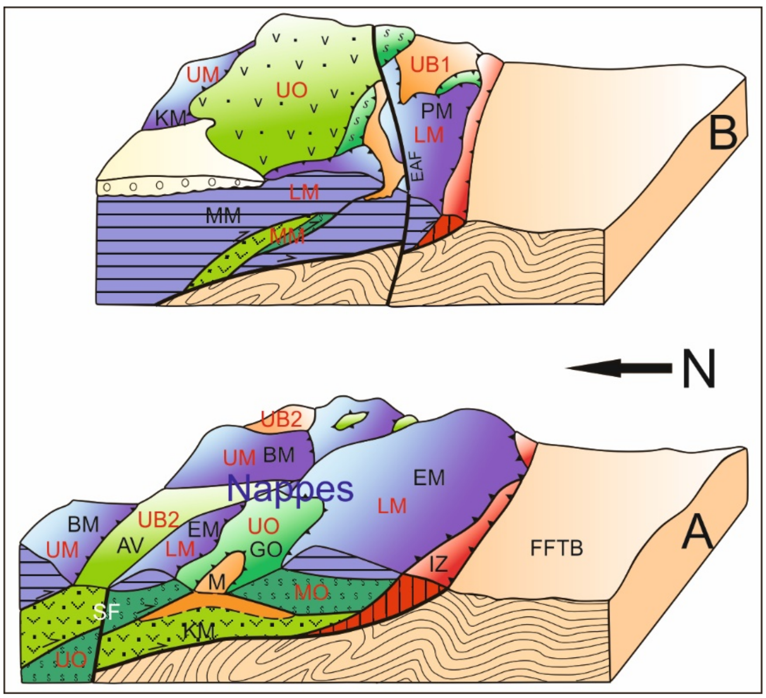


Figure 5A and B. Block diagrams representing the western and central parts of the nappe regions of the SAOB showing structural order of the nappes. Locations of figures A and B are displayed in the Figure 1A. **Abbreviations:** LM; the lower metamorphic massifs, MO; the middle ophiolite nappe, UM; the upper ophiolite nappe, UB 1; the internal upper basins, UB2; the external upper basins. IZ; the Zone of Imbrication. EAF; the East Anatolian Transform Fault, SF; the Sürgü Fault, FFTB; Foreland fold and thrust belt, PM; Pötürge Metamorphic Massif, MM; Malatya Metamorphic Massif., KM; Keban Metamorphic Massif. EM: Engizek Metamorphic Massif, GO; Göksun Ophiolite, BM; Binboğa Metamorphic Massif, AV; Elbistan Arc volcanics. M; the Maden Basin, KM; Kızılkaya Metamorphics.

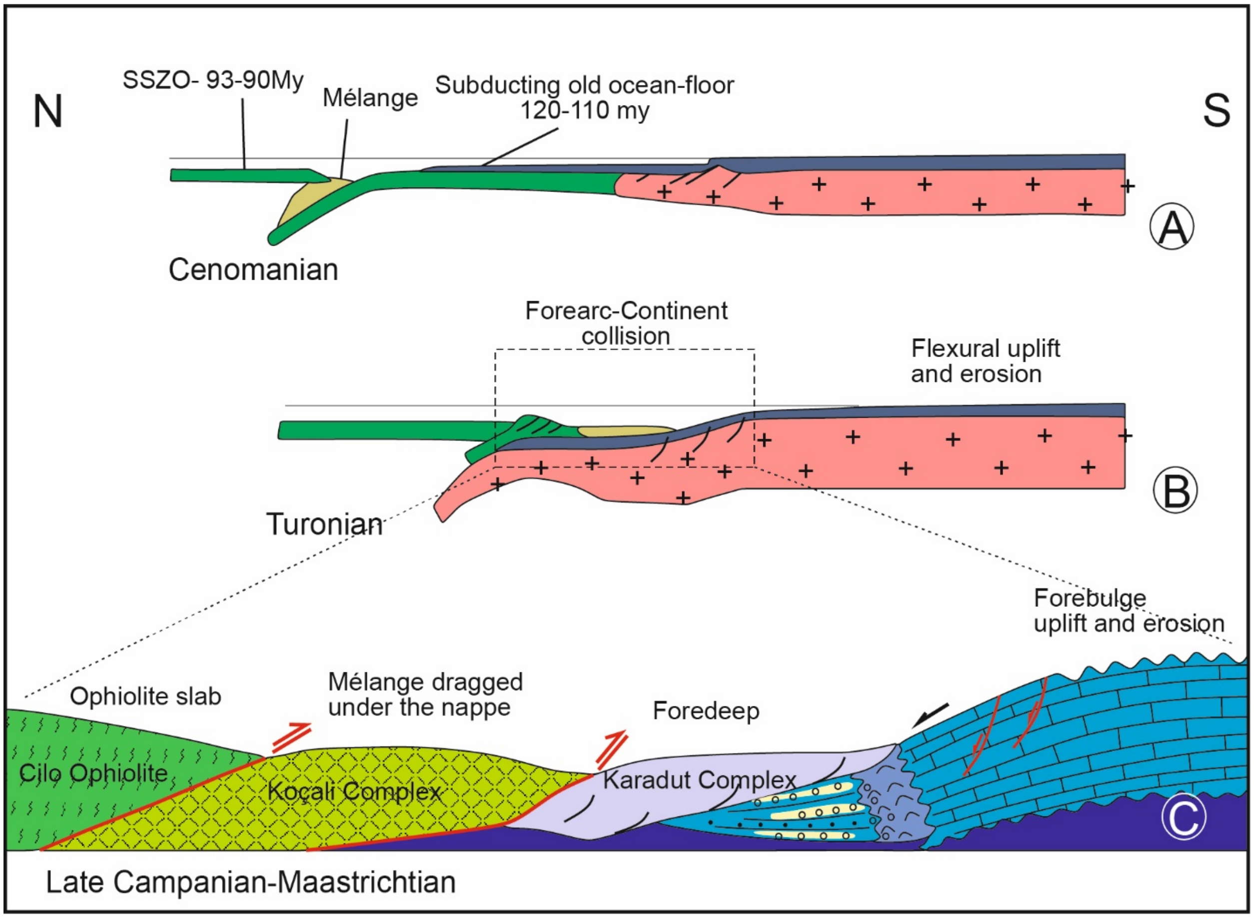
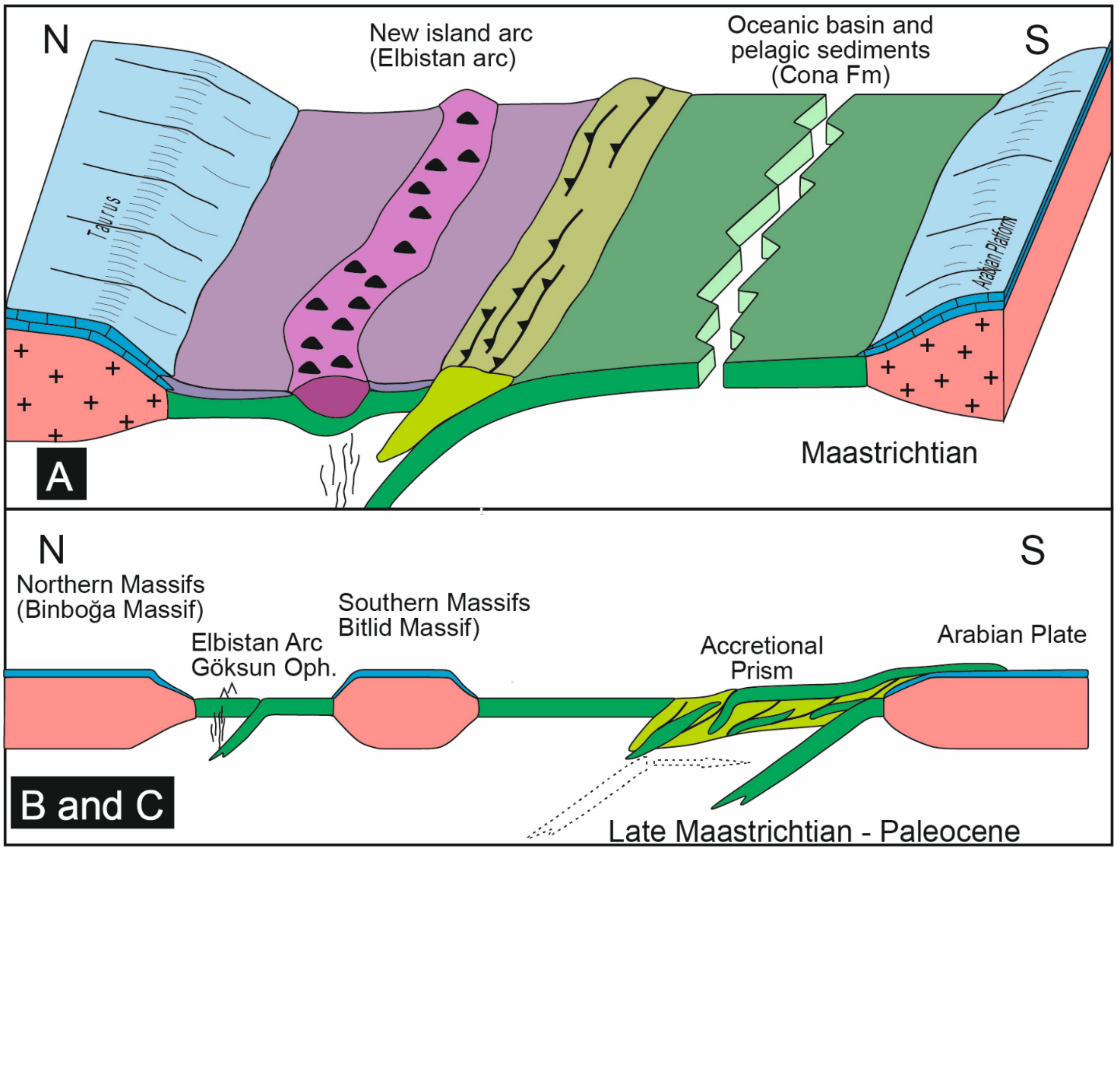
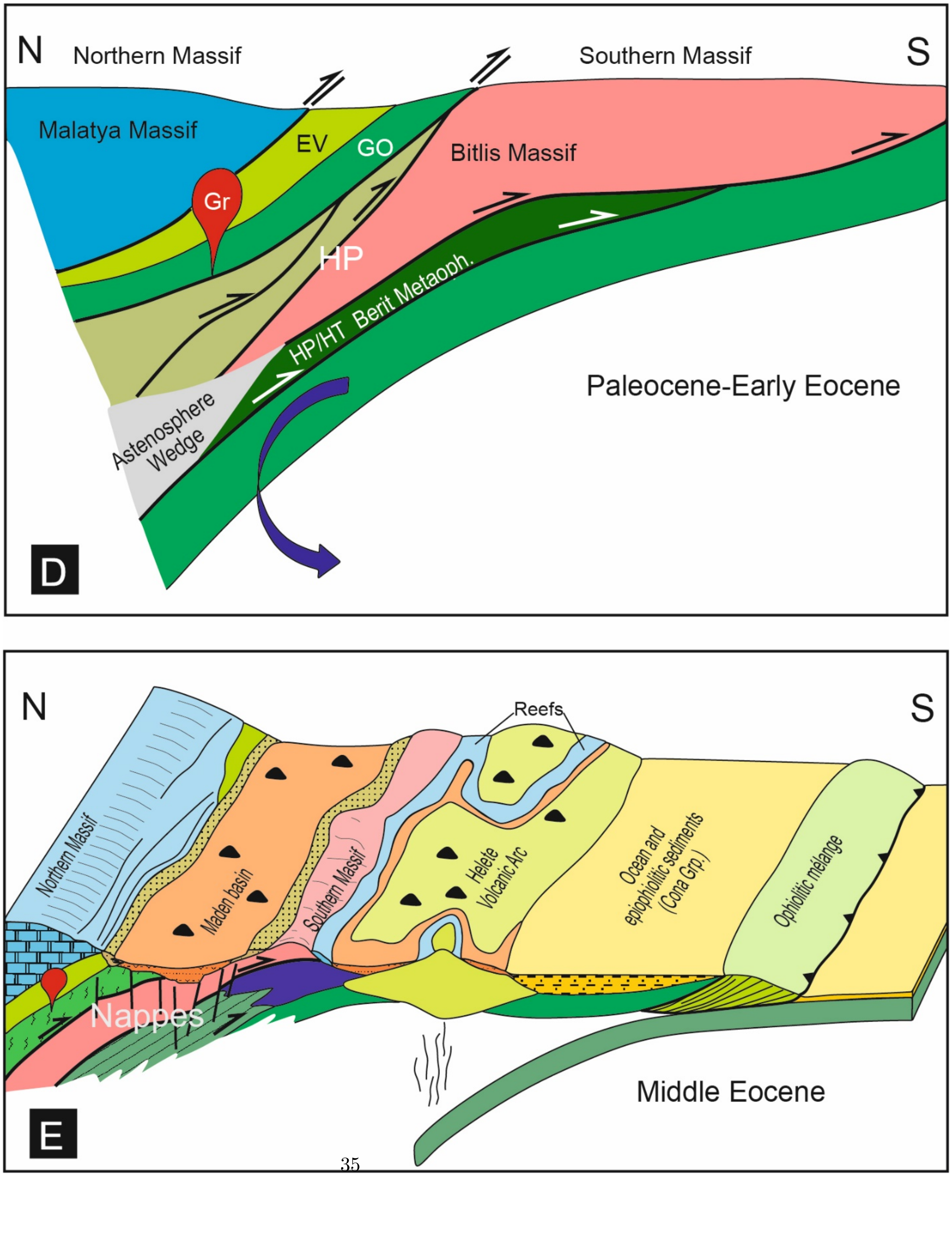
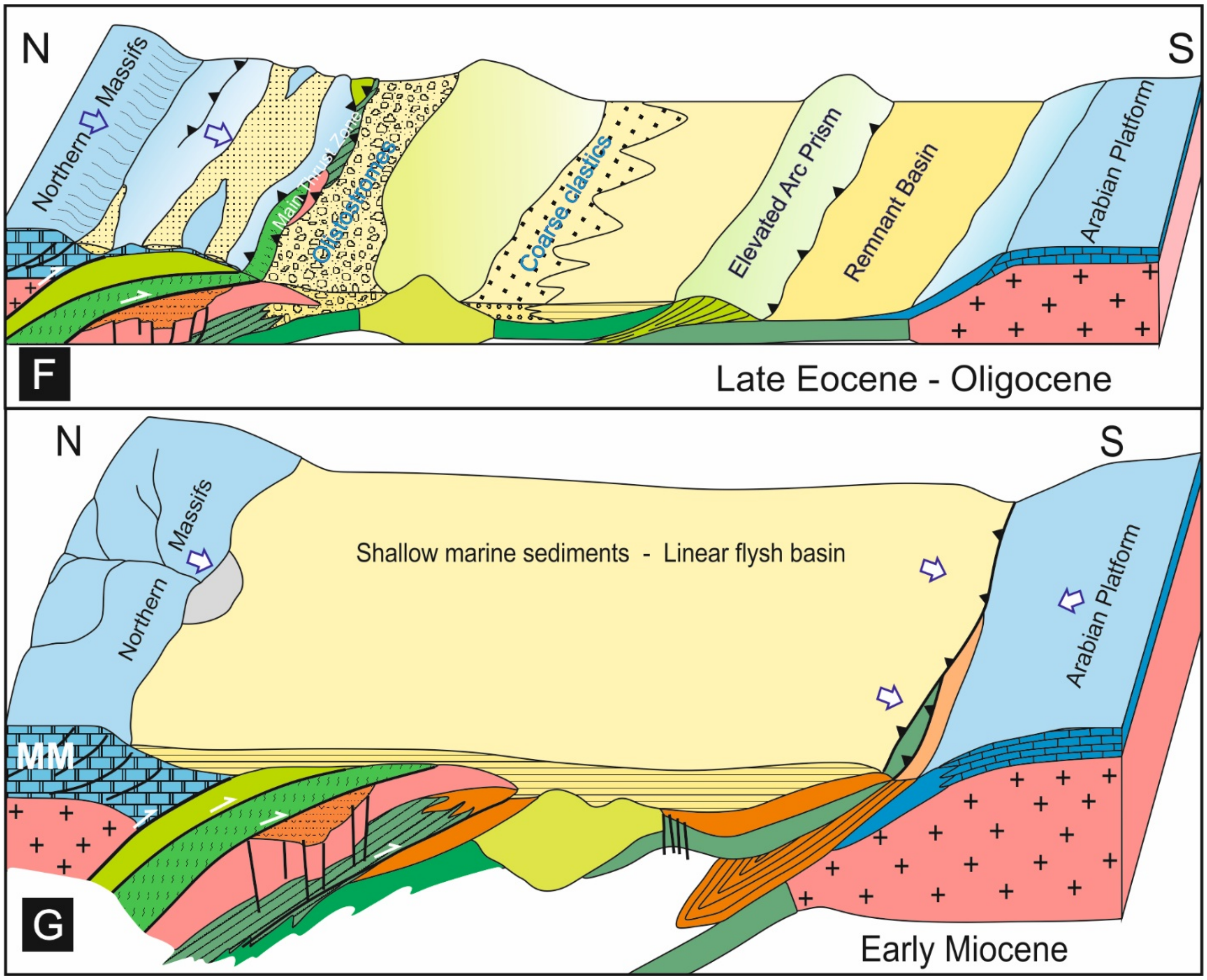


Figure 6. Cartoons showing Late Cretaceous tectonic evolution of the South-eastern Anatolia. **Figure 6A.** Cenomanian- A north-facing passive continental margin was developed on the Arabian Platform. The northward intra-oceanic subduction generated a young SSZO. **Figure 6B.** Turonian**-**An ophiolitic slab detached from its root together with an ophiolitic mélange drugged underneath began thrusting over the Arabian Plate. This is a **forearc** (accretionary complex)-**continent collision** (the Arabian Plate). Infront of the nappe pile, a foredeep and an accompanying forebulge (the Turonian unconformity in Figure 2A) were formed. The rectangle defines the region detailed in Figure 6C (inspired from Casey 1980). **Figure 6C.** Late Campanian-Maastrichtian- The foredeep subsided beneath the CCD. Blocks and olistostromes derived from the continental slope, and the outer-shelf areas were deposited rapidly into this foredeep. The adjacent forebulge was eroded (the Turonian unconformity in Figure 2). The nappes' continuing advance rapidly lowered the formerly elevated and

eroded platform areas beneath sea level and formed a deep basin (the Sayındere basin in Figure 2A). The thick nappe pile gradually reached above sea-level and formed a structural high along the continental platform's outer margin. Debris flows and blocks, derived mostly from this high were deposited rapidly into this basin lying in front of the nappes. Therefore, the basin where the pelagic limestone was formerly deposited turned into an environment of clastic deposition (the Kastel Basin in Figure 2A) (inspired from Robertson, 1987, Figure 14).




N
Northern Massif
Southern Massif
S
Malatya Massif
EV
GO
Bitlis Massif
Gr
HP
HP/HT Berit Metaoph.
Astenosphere Wedge
Paleocene-Early Eocene
D
N
Reefs
S
Northern Massif
Maden basin
Southern Massif
Helete Volcanic Arc
Ocean and epiophiolitic sediments (Cona Grp.)
Ophiolitic mélange
Nappes
Middle Eocene
E


N
S
Northern Massifs
Main Thrust Zone
Olistostromes
Coarse clastics
Elevated Arc Prism
Remnant Basin
Arabian Platform
F
Late Eocene - Oligocene
N
S
Northern Massifs
Shallow marine sediments - Linear flysh basin
Arabian Platform
MM
G
Early Miocene

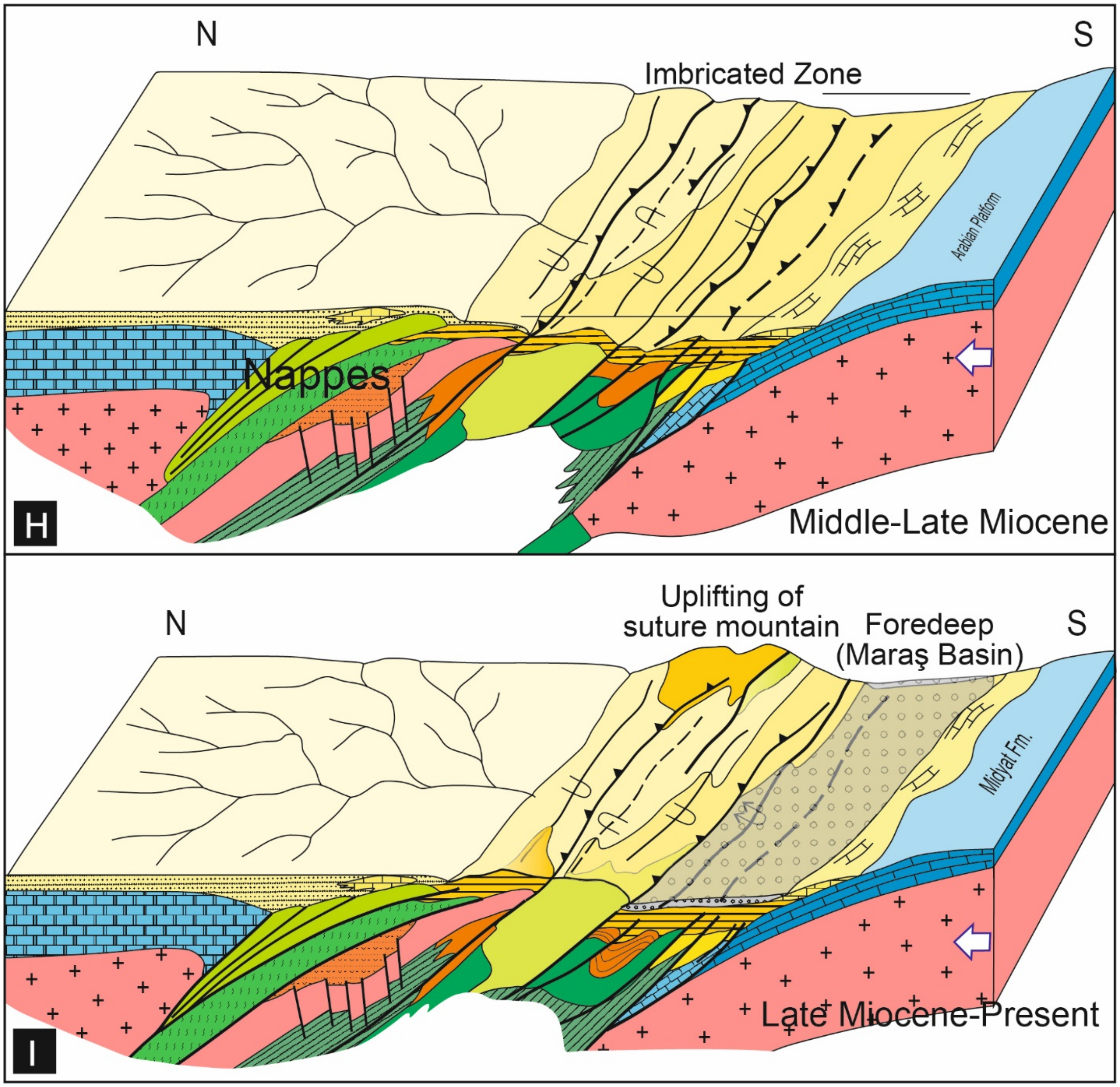


Figure 7. Block diagrams showing evolutionary stages of the Southeast Anatolian Orogenic Belt from Late Maastrichtian to Present (modified after Yilmaz 1993). **Figure 7A.** Maastrichtian- Following the Late Campanian ophiolite obduction, a north-facing passive continental margin was formed on the Arabian Plate during Late Maastrichtian, which continued till the Middle Eocene. This was the marine invasion's resumption from the north, where the open marine environment remained. The abyssal-plain sedimentary sequence (the Cona

Fm) formed during this period are presently seen among the tectonic slices of the Imbricated Zone and at the top of the middle ophiolite nappe (the MO) (Figure 2B). The ocean separating the Arabian Continent from the northern continental fragment began to be consumed by northward subduction, which generated a younger ensimatic island arc. **Figure 7B.** Late Maastrichtian-Paleocene**-** Due to the retreat of the subducting slab, the northerly located continent was split into two continental slivers. Between them a younger SSZO (the Göksun Ophiolite; GO) and an ensimatic magmatic arc (the Elbistan Arc, EV) were developed. The continental slivers were later incorporated in the orogeny and turned into the southern and northern metamorphic massifs. Retreat of the subducting oceanic lithosphere caused southward migration of the arc front. Volcanic activity in the southern arc continued until the late Eocene (the Helete volcanics). **Figure 7C.** Late Maastrichtian-Paleocene-The remaining ocean was continually eliminated in the south until the Middle Eocene. **Figure 7D.** Paleocene-Early Eocene- The southerly located continental sliver attaching to the oceanic slab involved in the subduction zone. They underwent HP and HP/HT metamorphisms. Partly simultaneously, the subducting oceanic slab retreated (rollback). Hot asthenosphere wedged into the space generated by the rollback. The asthenospheric inflow contributed unusually high heat, which caused HT metamorphism, which superimposed on the previous HP metamorphism. The rollback also promoted the exhumation. The oceanic and continental fragments, when exhumed, formed the Bitlis Massif and the Berit metaophiolite. The northerly located continental sliver was thrust onto the Göksun Ophiolite (GO) and the overlying Elbistan Arc (EV) during the late Early Eocene. This is **the continent-arc collision**. The 51-45 my old post tectonic granites (Gr) intruded into the nappe package. **Figure 7E.** Middle Eocene-The volcanic arc migrated to the south of the nappes consisting of the Bitlis Massif and the underlying Berit Metaophiolite. Volcanoes of the magmatic arc rose above the sea-level, around which fringing carbonate reefs were formed. The nappe package was fragmented to form a short-lived back-arc/interarc basin, the Maden Basin during the Middle Eocene. **Figure 7F.** Late Eocene-Oligocene-As a result of the continuing southward transport, the nappes moved onto, and destroyed the Maden Basin toward the end of the Middle Eocene. Different tectonic belts: the northerly located metamorphic massifs, the ophiolite nappes (the MO, UO), the Elbistan and Helete volcanic arcs, and UB2 were tectonically amalgamated. This event is **the magmatic arc-continent collision.** Development of the subduction mélange and the deep-sea sediment deposition ended before the late Eocene indicating that the oceanic lithosphere was totally consumed. Above the elevated nappe pile a rugged topography was formed, which supplied olistostrome deposits and coarse clastics into the adjacent lowlands. The Upper Eocene-Oligocene sediments deposited above the nappes are the first common cover. From this time onward, the nappe pile began to move as a coherent mass. **Figure 7G.** Early Miocene-The remnant oceanic basin was filled with coarse-grained sediment accumulation from the adjacent topographic highs. The coarse clastics were gradually replaced by more orderly flysch units during the Early Miocene. A transition from the shallow sea to a linear flysch basin (the Lice Flysch) may be traced across the Miocene successions from the North to the South (Yılmaz et al. 1987; 1988). **Abbreviations:** MM; Malatya Metamorphic Massif, GE; Geben Fm., BM; Binboğa Metamorphic Massif, Brt; Berit metaophiolite, KM; Kızılkaya Metamorphics, M; Maden Group, C-H; Cona Fm and Helete volcanic arc transitional units; HV; Helete volcanic arc. **Figure 7H.** Middle-Late Miocene-The flysch basin was severely deformed under the southerly transported nappes, which also caused the imbrication of the belts squeezed between the nappes and the Arabian Plate (the Imbricated Zone). The nappes were then trust on to the Arabian Plate (the later phases of **the Continent-Continent collision). Figure 7I.** Late Miocene–Present-Further convergence due to the continuing southward transport of the nappes and northward advance of the Arabian Plate caused elevation of the suture zone. Consequently, the sea retreated from the Arabian Platform toward the Mediterranean. A continental foredeep (the Maraş Basin in Figure 4A) was formed in the nappe front and began to be filled with terrestrial deposits.

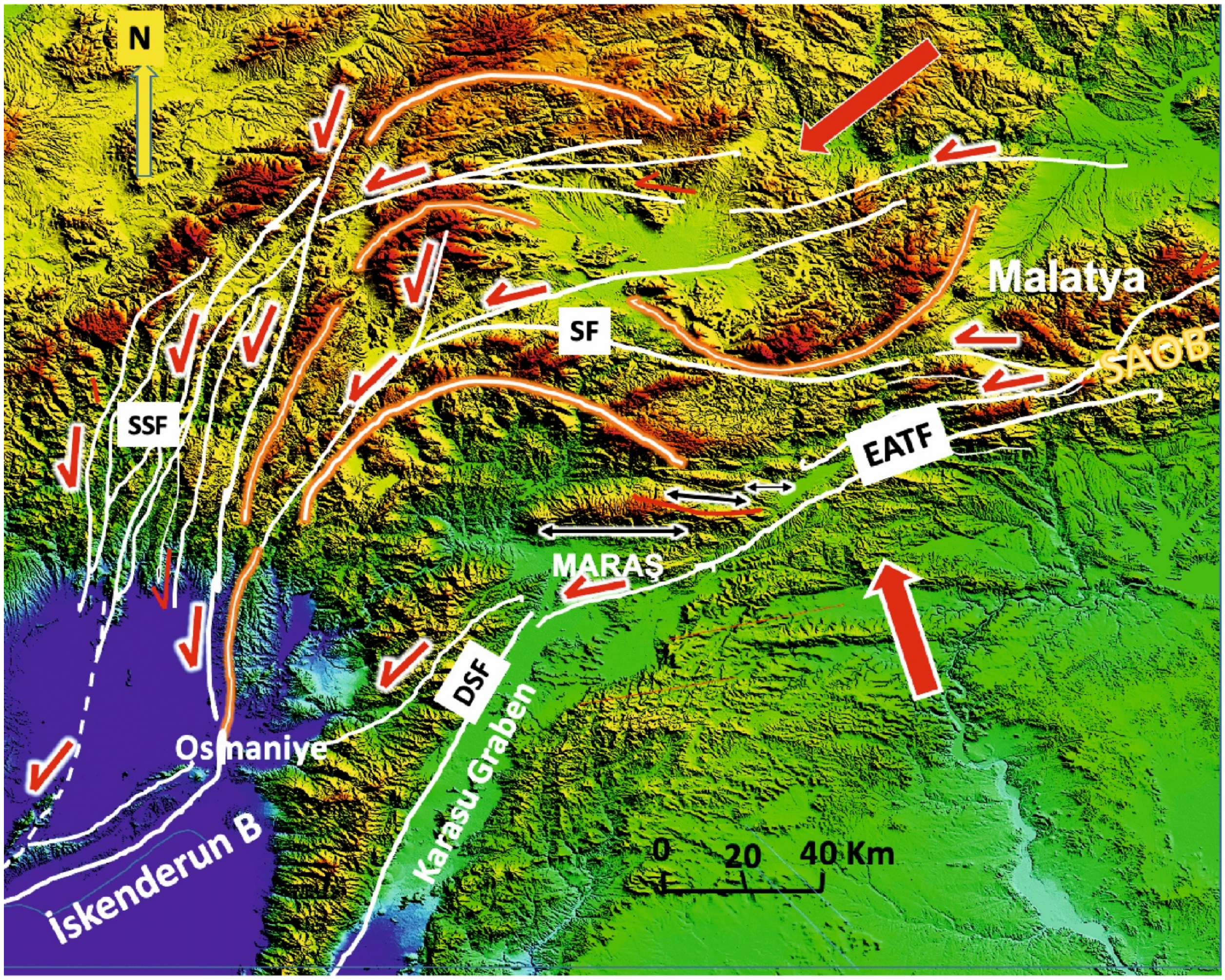


Figure 8. The physiographic map of western regions of the (SAOB) and the adjacent areas. The red arrows indicate the motion directions of the Arabian and Anatolian Plates. The brown curvilinear lines show the trend lines of the mountain ranges, which correspond to the axes of the regional folds formed due to the compressional forces exerted by the escape regime, which also generated strike-slip faults (the white lines). The double headed black arrows indicate prominent foreland folds displaced by left-lateral strike-slip faults (modified after Yılmaz 2021). **Abbreviations:** SSF; the fault bundle in the Sarız-Saimbeyli Mega Shear zone comprises several fault-bound blocks or tectonic wedge transferring the compressional stress to the south. SF: the Göksun-Sürgü Fault, which connects the East Anatolian Transform Fault zone (EATF) to the Mediterranean Region. DSF: the Dead Sea Fault.