Tectonics of Eastern Anatolian Plateau; Final Stages of Collisional Orogeny in Anatolia

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Abstract

The East Anatolian High Plateau, part of the Alpine-Himalayan orogen, is a 200 km wide, approximately E-W trending belt surrounded by two peripheral mountains of the Anatolian Peninsula. The plateau is covered by a thick, interbedded Neogene volcanic and sedimentary rocks. Outcrops of the underlying rocks are rare. Therefore, contrasting views were proposed on the nature of the basement rocks. New geological and geophysical data suggest the presence of an ophiolitic mélange-accretionary complex under cover rocks of Eastern Anatolia. The cover units began to be deposited during the closure of the NeoTethyan Ocean that was located between the Pontide arc to the north, and the continental slivers drifted away from the Arabian Plate to the south. The surrounding orogenic belts experienced different orogenic evolution. The Eastern Anatolian orogen was formed during the later stages of the development of the surrounding orogenic belts. In this period, the melange-accretionary prism that occupied a large terrain behaved like a wide and thick cushion, which did not allow a head-on collision of the bordering continents. NeoTethyan oceanic lithosphere was eliminated from entire eastern Turkey by the Late Eocene. The eastern Anatolia began to rise when the northern advance of the Arabian Plate continued after the total demise of the oceanic lithosphere. The present stage of the elevation of the East Anatolian Plateau as a coherent block started during the Late Miocene.

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The East Anatolian High Plateau, part of the Alpine-Himalayan orogen, is a 200 km wide, approximately E-W trending belt surrounded by two peripheral mountains of the Anatolian Peninsula. The plateau is covered by a thick, interbedded Neogene volcanic and sedimentary rocks. Outcrops of the underlying rocks are rare. Therefore, contrasting views were proposed on the nature of the basement rocks.

New geological and geophysical data suggest the presence of an ophiolitic mélange-accretionary complex under cover rocks of Eastern Anatolia. The cover units began to be deposited during the closure of the NeoTethyan Ocean that was located between the Pontide arc to the north, and the continental slivers drifted

away from the Arabian Plate to the south. The surrounding orogenic belts experienced different orogenic evolution. The Eastern Anatolian orogen was formed during the later stages of the development of the surrounding orogenic belts. In this period, the mélange-accretionary prism that occupied a large terrain behaved like a wide and thick cushion, which did not allow a head-on collision of the bordering continents.

NeoTethyan oceanic lithosphere was eliminated from entire eastern Turkey by the Late Eocene. The eastern Anatolia began to rise when the northern advance of the Arabian Plate continued after the total demise of the oceanic lithosphere. The present stage of the elevation of the East Anatolian Plateau as a coherent block started during the Late Miocene.

1-Introduction

The Eastern Anatolian region is part of the Alpine-Himalayan belt. It is usually referred to as an East Anatolian High Plateau because it is on average 2000 m in elevation. The region is a 200 km wide belt between the Pontide Mountains to the North and the Bitlis-Zagros suture mountains to the south (Fig 1).

The Pontides were formed during consecutive collisions between the Andean-type volcanic arcs and continental blocks of Gondwanan origin (Yılmaz et al., 1997) (see an accompanying paper on the Pontide in this volume). The Bitlis-Zagros suture mountains were formed as a result of the continent-continent collision (Yılmaz 2019 and the references therein) (see the accompanying paper on the Southeast Anatolian Orogenic Belt in this volume). The Eastern Anatolian orogen was formed during the later stages of development of the surrounding orogenic belts.

The most significant structural features of Eastern Anatolia are the North Anatolian Transform Fault (NATF) and the East Anatolian Transform Fault (EATF) (Figs 1 and 2). The two faults converge in the Karlıova junction (KJ in Fig 1) and define the Anatolian Plate. The transform faults are long recognized as the major manifestation of the escape tectonics and associated lateral extrusion of the Anatolian Plate (e.g., Şengör 1979; Şengör and Yilmaz, 1981; Çemen et al. 1993; Yılmaz 2017).

The eastern Anatolia is covered by a thick, interbedded Neogene volcanic and sedimentary rocks and contains many conical peaks and ENE and WNW trending hills (Figs 1 and 2). The individual peaks correspond to volcanic cones (Fig 1) (Yılmaz et al. 1987, 1998; Pearce et al. 1990; Yılmaz 2017). The volcanoes produced a wide range of edifices from plateau basalts to ignimbrite deposits (Yılmaz et al. 1998; Kaygusuz et al. 2018).

The Neogene sedimentary cover rocks of Eastern Anatolia extend mainly along with two separate stripes of depressions adjacent to the peripheral mountains (Figs 1 and 2) (Yılmaz 2017). Rates of uplift in the bordering mountains are greater (0.2- 0.3 mm/y; Keskin et al. 2011) than the plateau's uplift (0.1-0.2 mm/y; Mc Nab et al. 2018). Therefore, headword erosion across the peripheral mountains cannot keep pace with the elevation increase in Eastern Anatolia. Consequently, major rivers in the plateau flow generally in east-west directions (Fig 1).

The thick Neogene cover sequence is commonly flat but is locally tightly folded and faulted. The morphological pattern of Eastern Turkey resembles a sheave of wheat tied at the center (the inset in Fig 1), reflecting strict structural control of the ongoing tectonics. The peripheral mountains on both sides curve around a central dome, which determines the regional structures and the present drainage network (Şaroğlu and Güner 1981; Maggie and Priestley 2005; Yılmaz 2017) (Figs 1 and 1 inset). The hills, depressions, and rivers fan out from the central high (Fig.1).

Outcrops of the basement rocks below the thick Neogene volcano-sedimentary layer are rare. As a result, contrasting views were proposed on the nature of the basement rocks, which made the orogenic evolution of the belt controversial. This paper aims to document new data leading to clarify the nature of basement rocks in Eastern Anatolia and discuss the orogenic development based on the new data.

2-Geologic Overview

In this section, we will summarize stratigraphic, structural, and igneous features of the eastern Anatolia.

2-1-Stratigraphy

Stratigraphic columnar sections covering the entire Eastern Anatolian region are displayed in Fig 3. The sections summarize the data gathered mainly from our field work together with the TPAO reports, and the previous studies (Kurtman and Akkuş 1971; Özdemir 1981; Şenel et al 1984; Koçyiğit et al 1985; Şaroğlu and Yılmaz 1984;1986; 1987;1991; Uysal 1986; Gedik 1986; Yılmaz et al 1987 A and B; Yılmaz A. et al 1988; Tarhan 1997A; B; 1998 A, B; Akay et al 1989; Bozkuş 1990; Temiz et al 2002; MTA 2002; Konak and Hakyemez 2008; Yılmaz 2107; Bedi and Yusufoğlu 2017; 2018; Yılmaz A and Yılmaz 2019; Üner 20121) enabling correlations and comparisons along and across the east Anatolian Plateau possible.

The generalized stratigraphic columnar section of eastern Anatolia (GSS in Fig 3 A) shows the presence of an ophiolitic mélange below the Neogene cover in most outcrops (MTA 2002; Özdemir 1981; Şenel et al. 1984; Konak and Hakyemez 2008; Elitok and Dolmaz 2008; Yılmaz A and Yılmaz 2019; Üner 2021; TPAO field reports and drilling data, and our field observations). The overlying Neogene cover is represented commonly by terrestrial sedimentary rocks. However, the stratigraphy in the northeastern part of the East Anatolia (i.e., N of the Kars province; Fig 1) is entirely different (the Karst region in Fig 3A). It consists of two major components, an old metamorphic basement and an overlying thick Paleozoic, Mesozoic, and Cenozoic successions. This is shown in the stratigraphic column of the Kars region in Fig 3A, where the succession is identical to that of the eastern Pontide Region (see the accompanying paper by Yılmaz et al. in this volume). The western and northwestern parts of the Kars province are thus considered easterly continuation of the eastern Pontide.

There is no detailed study on the eastern Anatolian ophiolitic mélange-accretionary complex. The previous works generally outline its major constituents (Altınlı1966; Yılmaz A. et.al.1988; Tarhan1989;1997A and B;1998 A and B; Önal and Kaya 2009; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019). A pelagic sedimentary succession consisting of limestone (chalk), radiolarite, and siltstone of the Upper Cretaceous to Lower Eocene age range is observed in association with the mélange. They are either blocks incorporated into the mélange or deep-sea sedimentary sequences deposited above the mélange foundation. Altınlı (1966), Şenel, et al. 1984; Tarhan (1989; 1997A; B;1998 A; B; Kaya (2009), Bedi et al. (2017), and Bedi and Yusufoğlu (2018) documented Upper Cretaceous, Paleocene, and Eocene fossil lists from the pelagic sediments. In some exposures, Upper Cretaceous-Eocene shallow sea sediments are also observed lying stratigraphically over the ophiolitic mélange (Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019).

The Neogene cover succession consists of four major rock groups separated by angular unconformities corresponding to: 1-Late Eocene-Oligocene (the lower unconformity), 2-Late Oligocene-Early Miocene (the middle unconformity), and 3-Late Pliocene (the upper unconformity). The lower unconformity separates the ophiolitic mélange-accretionary complex from the Upper Eocene-Oligocene terrestrial units consisting mainly of coarse clastic deposits (1 to 9 in Fig 3B and 3C). The middle unconformity separates the terrestrial sediments from the overlying Upper Oligocene-Lower Miocene transgressive sequence. The marine sediments begin with fine-grained sandstone-siltstones-marl alternations followed by reefal limestone and Lower-Middle Miocene neritic limestone (the Adilcevaz limestone; Şaroğlu and Yılmaz 1986). The limestone unit is observed in the entire eastern Anatolian region (Şaroğlu and Yılmaz 1986; 1987; Tarhan 1998; Kaya 2009; Gedik 2010., Yılmaz 2017; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019).

The shallow marine sediments grades upward into evaporites (Akkuş 1970; Yılmaz 2017; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019; Helvacı 2021) and lacustrine limestone, shale-sandstone alternations of Upper Miocene-Lower Pliocene age (Akkuş. 1970; 19071; Tarhan 1998., Nazik et al. 2008; Yılmaz 2017; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019). Thick Pleistocene-Holocene lacustrine-fluvial conglomerates and sandstones unconformably overlie them.

The upper unconformity marks a critical change in the region's morphotectonics (Yılmaz 2017 and the references therein). The field data obtained from regional geological mapping in eastern Anatolia (unpublished maps of Turkish Petroleum Association) shows that the Miocene and Pliocene sediments are regionally distributed. However, the post-Pliocene deposits are confined to the local depressions and display abrupt vertical-lateral facies changes within the basins (Şaroğlu and Yılmaz 1987; Tarhan 1989; 1997A, 1998A; Yılmaz 2017; Bedi and Yusufoğlu 2018).

The stratigraphic data outlined above reveal that the final stage of the uplift in eastern Anatolia began during the Late Miocene (Yılmaz 2017; Bedi and Yusufoğlu 2018). This event is also coeval with the elevation of the Central Anatolia, which leads to assume that the rise of eastern Anatolia also accelerated the uplift and magmatism in Central Anatolia (Schildgen et al. 2014; Bartol and Govers, 2014; Govers and Fichtner, 2016; McNab et al. 2018).

Stratigraphic and isotopic age data reveal that volcanic activity in the eastern Anatolian plateau began sporadically during the Late Miocene, possibly about 13-11 my ago (Şaroğlu and Yılmaz 1984; Yılmaz et al. 1987A; B; 1998; Yılmaz 2017). The volcanic edifices increased in the northern regions around 7-8 my ago and then migrated to the central areas around 5-4 m years ago (Pearce et al. 1990; Yılmaz et al. 1998; Keskin 2003; 2006; 2007; 2012). However, the volcanic activity intensified in the central and the southern regions about 3 my ago and has continued almost uninterruptedly to the present (Yılmaz et al. 1987 A; B.,1998; Yılmaz, 1990; Pearce et al., 1990; Keskin, 2003; 2007; Keskin et al., 2006; 2012). As a result, a thick volcanic blanket covered the entire eastern Anatolian plateau. Thick lava pile reaching up to 2 km in thickness was measured and drilled in the Kars plateau (unpublished TPAO data). The major volcanic centers, the Nemrut, Süphan, Tendürek, and Ağrı volcanoes, were built during the Quaternary (Yılmaz et al. 1988).

2-2-Structural Geology

Eastern Anatolia displays most of the geological features of a collisional orogen, which is similar in many respects to the Tibetan Plateau (Şengör and Kidd 1979; Şengör 1979; Şengör and Yılmaz 1981; Dewey et al 1986; Şaroğlu and Yılmaz 1984; Barazangi 1989; Şengör and Natalin 1996; Şengör et al 2003; 2008) (Fig 4A). The GPS measurements of crustal displacements (Fig 4B) (Reilenger et al. 2006; Şengör et al. 2008), focal mechanism of the earthquakes, and the distribution of active faults (Figs 1, 2, 4 A) (Şengör et al. 2003; Bozkurt 2001; Yılmaz 2017) confirm that the eastern Turkey experiences an ongoing north-directed compressional stress (Fig 4 A) (Yılmaz 2017 and the references therein).

The present-day morphology in eastern Anatolia was developed under a significant structural control (Yılmaz 2017) (Figs 1 and 2). The major morphotectonic features, northeast, and northwest-trending hills, and depressions (Fig 1) correspond to anticlines and synclines, respectively (Fig.1) (Yılmaz 2017). There is a centrally located structural dome, which may be regarded as the center of virgation (Fig 1), the maximum indentation location. The peripheral mountains on both sides make curves around the virgation (inset in Fig 1). The strike-slip faults disperse away from this high (Figs 1, 2). The arrangement and interactions of the structures demonstrate that eastern Anatolia has undergone a complex tectonic evolution (Şengör and Kidd 1979; Şengör and Yılmaz 1981; Şaroğlu and Yılmaz 1986; Copley and Jackson 2006; Yılmaz 2017) from the time of collision along with the southeastern Anatolian suture zone in the Late Eocene. This event corresponds to a wholesale elevation reflected in eastern Anatolian stratigraphy as a marked angular unconformity (Fig 3) (Yılmaz 2019) (see the accompanying paper in this volume by Yılmaz et al.).

In the East Anatolian High Plateau, the following major groups of structures are readily observed (Fig 4A);

1- NE and NW striking strike-slip faults (Figs.1and 4A) forming conjugated pairs (Şengör and Kidd 1979; Şaroğlu and Yılmaz 1984; Bozkurt 2001; Seyitoğlu et al. 2017; Yılmaz et al. 2017). The NE Striking faults are commonly longer and more prominent (Fig. 1) (Bozkurt 2001; Seyitoğlu et al. 2017). Most of these faults are young and active that generate frequent earthquakes (i.e., the Elazığ earthquake, on the 24 January 2020, Mw= 6.7, the Iran-Turkey border earthquake on the 23 February 2020, Mw=6.0, and the Malatya earthquake on the 24 January 2020 Mw=6,7).

2- Approximately E-W or ESE-WNW- striking reverse faults (Fig 4A),

3- E-W trending open and tight folds (Şaroğlu et al 1980; Şaroğlu and Yılmaz 1984;1986;1987; Koçyiğit et al. 2001; Yılmaz 2017).

4- N-S trending extensional structures (Fig 4A) (Şengör and Kidd 1979; Şaroğlu and Yılmaz 1984;1987; Yılmaz 2017).

The trends of all these structures are compatible with the N-S compressional stress field (Fig. 4A) generated from the northward advance of the Arabian Plate (Fig, 4B), which also caused the peripheral mountains to thrust over the eastern Anatolian plateau (Fig 2; 5A and 5C). Along the thrust boundary, the basement metamorphic rocks are exposed on the hanging walls (Figs 2 and 5C). As a result, the crust along the overthrust zones is thicker than the average, reaching up to 50 km (48 km beneath the Bitlis-Pötürge massifs in the south and 50 km under the Pontide Range (Barazangi et al. 2006; Şengör et. 2003; 2008: Tezel et al. 2013; Pamukçu et al. 2007; Medved et al. 2021).

Two narrow, fault-bounded chains of depressions were formed between the central high and the peripheral mountains during Pleistocene (Figs 1, 2, 5 A and 5B). The boundary faults give the young basins their distinct rhombohedral or parallelogram geometrical patterns (Fig. 5B). The transpressional faults with the major strike-slip, coupled with reverse slip components, strike parallel with, and determine the basins' long axes (Fig 5B). Due to the reverse slip displacements along the boundary faults, the depressions may be viewed as ramp basins or intermontane basins (Figs 5A and 5C) as exemplified from the Muş, Bingöl, Murat, Elazığ, Malatya basins to the south (Figs 1 and 5B) and the Tercan-Aşkale, Pasinler, Kağızman basins to the north (Figs 1 and 5B). The Eastern Anatolian High Plateau may also be regarded as a giant ramp basin between the thrust elevated peripheral mountains (Fig 5A).

Within the rhombohedral depressions where normal faults define the releasing bends, the local basins were alternatively described as pull-apart basins (Keskin et al. 1998). Some volcanos were built above the extensional openings (Fig 1) (Dewey et al., 1986; Pearce et al., 1990; Keskin et al., 1998; Yılmaz 2017).

The two transform faults, the North Anatolian Transform Fault and the East Anatolian Transform Fault define the Anatolian Plate (Figs 1 and 2), which protrudes away from the area of convergence in the Karlıova Junction (KJ in Fig 1) (McKenzie 1972; Şengör et al. 1975; Şengör and Yılmaz 1981; McKenzie and Yılmaz 1991; Şaroğlu and Yılmaz 1991; Çemen et al., 1993; Aktuğ et al. 2012; Karaoğlu et al. 2017) (Figs 1, 2, and 5B). The area where the transform faults intersect is a wedge shape depression (Fig 5 B), which widens progressively as the Anatolian Plate moves away from the point of convergence (Şaroğlu and Yılmaz 1991; Karaoğlu et al. 2016) (Fig 5 B). The oldest lateral fan deposits sourced from the basin boundary faults (Fig 5 B) is Upper Pliocene (?)- Pleistocene in age (Şaroğlu and Yılmaz 1991), which sets a lower limit to the time of the westerly escape of the Anatolian Plate. The escape tectonics partitions the N-S compressional stress (Yılmaz 2017).

Associated with the development of the two transform faults and the consequent escape tectonics of Anatolia, a new tectonic regime, the Neo Tectonics, began and has drastically changed the morphotectonic character of the Anatolia and surrounding regions (e.g., Şengör 1979; Şengör and Yılmaz 1981; Çemen et al., 1993; Yılmaz 2017).

The GPS vectors in Fig 4B shows that the eastward motion of Eastern Anatolia is slower than its westward movement. Field and earthquake data indicate that the N-S compressional stress is accommodated in this region along with several small-size strike-slip faults with right-lateral displacements (Fig 2).

2-3-Thickness of Crust and Lithosphere

Geophysical data suggest that the eastern Anatolian crust is thick (Çınar and Alkan 2015; Pamukçu et al. 2007; Cırmık 2018; Medved et al. 2021), but the uppermost mantle below the crust is very thin because it strongly attenuates Sn waves (Barazangi et al 2006). The Pn velocities are also low (-7.6 km/Sn) (Turkelli et al., 2003; Sandvol et al., 2003 A; 2003 B; Zor et al.,2003; Gök et al 2003; 2007; Maden and Öztürk 2005; Angus et al., 2015; Barazangi et al., 2006; Özaçar et al 2008; Göğüş and Pysklywec, 2008; Biryol et al 2011; Zor 2008; Elitok and Dolmaz 2008; Bartol et al., 2012; Warren et al 2013; Tezel et al 2013; Skobeltsyn et al 2016; Cırmık 2018). The heat flow is high (Tezcan 1987; Tezcan and Turgay 1989; Dolmaz et al. 2005; Ateş et al. 2005; İlkışık 1995; Bektaş et al 2007; Bektaş 2013; Pamukçu et al 2014: Cırmık et al 2018) and the Curie point depth is around 12-13 km below surface (Ateş et al 2005; Bektaş 2013; Pamukçu et al 2014; Cırmık 2018).

Based on data from the East Anatolian seismic experiment, Barazangi et al. (2006) proposed that the East Anatolian crust floats on a partly molten asthenosphere. Almost the whole thickness of the mantle lithosphere was removed from the overlying crust (Piromallo and Regard 2006; Barazangi et al. 2006; Gök et al. 2007; Lei and Zhao 2007: Zor et al. 2008; Medved et al. 2021). The following mechanisms were proposed to explain the obliteration of the lithospheric upper mantle.

1-the delamination of upper mantle (Al-Lazki et al 2003; Göğüş and Pysklywec 2008; Biryol et al 2011; Bartol et al 2012).

2- the steepening and break-off of the subducting slab (Davies and Blackenburg1995; Piromallo and Morelli, 2003; Piromallo and Regard 2006; Facenna et al. 2006) Lei and Zhao 2007; Gans et al. 2009; Dilek and Sandvol 2009; Govers and Fithcher 2016).

3-Combination of both mechanisms that are listed above (Mahatsente et al., 2018).

The space created by the removal of the mantle lithosphere was filled with a hot, upwelling asthenosphere or asthenospheric wedge (Şengör et al., 2003; Piromallo and Regard 2006), which caused adiabatic decompression. It is the hot mantle considered responsible for the high heat flow, the consequent regional uplift, and coeval volcanism (Pearce et al. 1990; Keskin, 2003; Piromallo and Regard 2006; Lei and Zhao, 2007; Şengör et al., 2008. Yılmaz 2017; 2019),

3-Discussion

In the following paragraphs, the two contrasting views proposed on the nature of the eastern Anatolian crust are discussed based on geological, geophysical, and geochemical data;

1-an ophiolitic mélange-accretionary complex forms the basement, which was developed during the demise of the Neo-Tethyan Ocean. Later, it was trapped between the approaching continents (Fig 6A) (Şengör and Kidd 1979; Şengör et al. 2008).

2- The entire eastern Anatolia is underlain by an old and thick continental crust (Fig 6 B) (Topuz et al., 2017).

Both views listed above were based on inconclusive evidence. The following critical data set are needed to provide verifications for the two hypotheses:

a-detailed geological data to examine the applicability of the view on the regional scale, including comparative data to correlate the eastern Anatolian geology with the neighboring tectonic belts (i.e., with the Southeastern Anatolian Orogenic Belt to the south and the Pontide Belt to the north to provide evidence how each hypothesis fits with the geology and tectonic evolution of the neighboring regions in a time-space reference.

b-geophysical data, particularly seismic data, to enlighten the nature of the basement.

The hypothesis proposed by Topuz et al. (2017), is based on the observations basically from two metamorphic rock inliers in eastern Anatolia (Fig 2) and the following interpretations; on the SE Anatolia and Pontide

1- ''Metagranite obtained from the metamorphic rock outcrops have a Late Ordovician–Early Silurian protolith and were therefore connected with the Menderes Massif of western Anatolia, which displays a similar protolith".

The old metamorphic minerals obtained from eastern Anatolia's metamorphic inliers are expected to be similar to those obtained from the Menderes Massif because the metamorphic massifs of Western, Central, and SE Anatolian orogenic belts share the Pan African-Gondwanan origin (Şengör and Yılmaz 1981).

2- ''Multiple continental fragments separated by oceanic accretionary complexes are absent in eastern Anatolia".

This interpretation dismisses the essential characteristics of the Anatolian orogen, including the eastern Turkey where the orogen was developed by accretions of small continental fragments following the closure of the separating oceans (Şengör and Yılmaz 1981; Yılmaz and Şengör,1985; Dercourt et al. 1986; Dilek, 2006; Robertson et al. 2012; Barrier et al. 2018; McNab et al. 2018). Regional heating generated during the plate reorganization is stated to have caused major obduction of these ophiolites (Hassig et al. 2013, 2016 a, b; Roland 2020).

3- ''the metamorphic mineral assemblages that crop out in the metamorphic rocks of the region, display medium to high T metamorphisms, but not high-pressure metamorphism".

This interpretation disregards the critical geological data obtained from the neighboring orogenic belts (see the two accompanying papers in this volume on the Pontide and SE Anatolian orogenic belts by Yılmaz et al.). Particularly the recent studies on the SE Anatolian metamorphic massifs indicate that the ophiolitic rocks and the Bitlis Massif underwent an initial HP metamorphism, followed by an HT metamorphic phase during the Late Cretaceous-Early Eocene period (Roland et al. 2012; Oberhansli et al. 2012; 2014; Pourteau et al. 2013; Awalt and Whitney 2018; Yılmaz 2019). The Bitlis Massif, a fragment of continental crust involved in northward subduction together with the oceanic lithosphere (the Berit metaophiolite; Yılmaz 2019) under the Eastern Anatolia where, they were buried down to 35-65 km at depths (Oberhansli et al., 2014). Their exhumation occurred mainly during the Early Eocene period (Roland et al., 2012; Oberhansli et al., 2014; Yılmaz, 2019). A transgressive sequence was deposited above the elevated metamorphic massifs during the Middle Eocene (Yiğitbaş 1989; Yiğitbaş and Yılmaz 1996; Yılmaz 1993; Yılmaz 2019). The metamorphic massifs were then thrust over the ophiolitic mélange during the Late Eocene before they were tectonically emplaced as a giant nappe package onto the Arabian Plate in the Late Miocene (Yılmaz 2019). Consequently, the southeast Anatolian metamorphic massifs represent allochthonous belts (Fig 7B) resting tectonically on the Late Cretaceous-Middle Eocene metamorphic ophiolites (the Kızılkaya Metamorphics and the Berit Metaophiolite), and non-metamorphic ophiolites (The Göksun Ophiolite) and an accretionary complex (Fig 7B) extending from the eastern Anatolia (Fig 7A). Tens of kilometers of the nappe transport of the metamorphic massifs may be estimated from the Muş region in the North to the Sason region in the South (Figs 7A and B) (Yılmaz 2019 and the references therein).

3-1- Geological Data

Based on limited geological data, Topuz et al. (2017) state that the metamorphic rocks and the overlying ophiolitic layer of eastern Anatolia were exhumed during the Late Cretaceous, above which the sediments of Maastrichtian transgression were deposited. This view necessitates two highly improbable consequences.

a)-the continental crust must have remained buried under the thick, dense ophiolitic layer for more than 60-70 Ma period, which seems physically highly unlikely, and does not fit with tectonic behavior of the Alpine-Himalayan Mountain ranges,

b)-the stratigraphic data documented in Fig 3 display that the wholesale elevation of the eastern Anatolia above the sea level occurred during the Late Eocene-Oligocene. The bulk of eastern Anatolia became emergent in Neogene (Şengör and Yılmaz 1981; Bedi and Yusufoğlu 2018; Okay et al 2020; McNab et al 2018).

Moreover, geological data from the neighboring orogenic belts, the Pontide, and the Southeastern orogens reveal also that the oceanic environment survived in these regions until the Middle Eocene (Dilek and Sandvol 2009; Hassig et al. 2013; Nikishin et al. 2015; Sosson et al. 2017; Meijers et al. 2017; Yılmaz 2019, see also the accompanying papers by Yılmaz et al. in this volume). Elevation of fragments of the accretionary complex, reaching somewhere above the sea during the Late Cretaceous-Early Eocene period does not rule out the ocean's existence in the region, similar to many growing accretionary prisms of the world today, such as the Aegean-Eastern Mediterranean region (Robertson et al. 1996).

The hypothesis by Topuz et al. (2017) is based essentially on the presence of the metamorphic inliers surrounded by the accretionary complex located between the towns of Tekman, Hınıs, Karayazı and Aktuzla

(Figs 2 and 8A). They argue that these metamorphic assemblages represent fragments of the elevated old metamorphic basement. The following evidence questions validity of this hypothesis. Figure 8B illustrates a geological cross-section along the largest metamorphic inlier (A-B section in Fig 8 B). The cross-section and the aerial photos in Fig 8 C and Figs 9 A and B show that the outcrops do not represent intact rock masses. They are observed either as tectonic wedges imbricated with the accretionary complex (Figs 9 A and 9 B) or as thrust sheets resting above the ophiolitic mélange (Fig 8 A, B, and C).

Furthermore, the data summarized below do not favor the presence of an old metamorphic basement under the ophiolitic mélange:

a)- The field evidence from the northern (the Çayırlı-Tercan-Aşkale-Pasinler basins), central (the Tekman-Hınıs-Malazgirt-Tekman basins), and southern (the Muş-Bingöl-Gevaş basins) (Fig 2) regions of the East Anatolia, particularly from the basin boundaries where the base rocks are exposed, reveal that there is almost always an ophiolitic mélange under the Neogene cover (Figs 3 and 5C).

b)- All the wells drilled by the oil and gas industry in the region cutting through the Neogene succession penetrated the ophiolitic mélange (unpublished TPAO data).

3-2- Geophysical Data

The distributions of seismic b-values from the entire eastern Anatolia, and the major high-wave number magnetic anomaly values favor high-density rocks under the Neogene successions matching the density of an ophiolite association (Bektaş et al. 2007; Bektaş 2013; Mahatsente et al.; 2018; Cırmık et al. 2018). The seismic waves down to 5-6 km at depths display a relatively uniform pattern (Figs 10 A and B) without abrupt vertical changes to infer a lower density layer under the ophiolitic rocks.

Maden and Öztürk (2015), examining rich data derived from the entire eastern Anatolia and the surrounding areas, concluded that the eastern Anatolian crust is thick, where the large negative gravity anomalies and low b-values are observed.

Fowler (2004) calculated a Bouguer gravity anomaly of -300 mgal in the case of 100% isostatic equilibrium (roc=2.85 gr/cm3, rum=3.3 gr/cm3) in a region with a topographic height of 1 km. The eastern Anatolia region has an average topography of 2 km. Therefore, it would be expected to yield gravity values lower than -300 mgal. However, the values observed in eastern Anatolia range between -100 and -200 mgal. This may be explained by the rapid uplift of the eastern Anatolian region due to delamination of the mantle lithosphere (see the discussion in the following paragraphs), insufficient immersion of the root of the lithosphere in the mantle, and the consequent isostatic disequilibrium.

3-3-Geochemical data from the Neogene volcanic rocks

The eastern Anatolian lavas' modal and normative compositions show a broad spectrum from nepheline normative basalts to quartz normative felsic lavas (Yılmaz et al. 1987A.B; 1998; Pearce et al. 1990; Keskin 2003;). The southern volcanic centers produced large quantities of basic and intermediate lavas. The northern volcanoes extruded voluminous intermediate volcanic edifices in which pyroclastic rocks dominate, particularly in the northeast of the Erzurum city (Fig 2).

Based on the geochemistry of the Eastern Anatolian Neogene lavas, the previous studies (e.g., Yılmaz et al. 1987A; B 1988; Yılmaz 1990; Pearce et al. 1990; Notsu et al. 1995; Keskin et al. 1998; 2003; 2006; 2007;2012; Lustrino et al. 2012; Özdemir and Güleç 2014; Oyan et al. 2016 A; 2016 B; Lebedev et al. 2016 A and B; Kaygusuz et al. 2018; Açlan et al. 2020; Üner 2021) reached the following conclusions on the magma compositions.

1-The magmas were derived from the heterogeneous mantle source and retained their compositions during the transit with minor modifications.

2- Magma chemistry of the alkaline, mildly alkaline, and calc-alkaline lavas displays distinct enrichment by the subduction components (enriched in LILE and LREE and depleted in HFSE) (e.g., Pearce et al. 1990;

Jean et al. 2010; Lebedev et al. 2018 A and B. Kaygusuz et al. 2018; Üner 2021 and the references therein) and also boninitic enrichment (Üner 2021). In accordance with this conclusion, the seismic images obtained by various analytical methods demonstrate a remnant subducted oceanic lithosphere that is broken into pieces underneath Eastern Anatolia (Piromallo and Morelli 2003; Piromallo and Regard 2006; Facenna et al. 2006; Gans et al., 2009; Warren et al., 2013) (for the discussion on the time, place, and role of the subducting events in the development of the surrounding orogenic belts, see the two accompanying papers by Yılmaz et al. in this volume). The enriched mantle source generated a wide compositional range in the consecutive magma batches.

3- The Sr 86/ Sr 87 ratios of lavas of the eastern Anatolian volcanic provinces are on an average of 0.704, which varies in a narrow range commonly between 0.703 and 0.705. The Nd 143 Nd/144 Nd ratio ranges between 0.5127 and 0.5128 (e.g., Kaygusuz 2018 and the references therein). The isotope values plot in the mantle array (Kaygusuz et al. 2018). The isotope ratios together with the magma composition compare favorably with the OIB lavas (Üner 2021; Yang et al 2019; McNabb et al. in 2018).

4- The petrochemical characteristics indicate that the eastern Anatolian magmas were derived from an ophiolitic host and underwent significant fractionation in the magma chamber and during the transit.

5-Upper crustal contribution into the magmas is negligible (Kaygusuz et al., 2018; Üner 2021).

The petrochemical data derived from the Eastern Anatolian magmas may be used to test the validity of the hypothesis that assumes the presence of a thick continental crust under eastern Anatolia. Substantial chemical modifications would be expected in the magma composition if they passed through the thick and hot continental crust. These may be listed as follow; 1-higher Sr and Nd isotope values, 2-increasing amount of continental crustal components, 3-large volumes of magmas of continental crust origin (granitic magmas), 4-mixing and mingling of magmas of diverse compositions.

The petrochemical properties of the lavas from the entire eastern Anatolian region show boninitic or metasomatic enrichment but do not confirm these alternatives and thus do not support presence of a thick continental crust.

4-Concluding Summary

Geological field observations and the geophysical data suggest the presence of an ophiolitic mélange-accretionary complex under the cover sequence of eastern Anatolia (A in fig 11-I). The eastern Anatolian volcanic and sedimentary cover units were piled up during the closure of the NeoTethyan Ocean that was located between the Pontide arc to the north, and the continental slivers drifted away from the Arabian Plate to the south (e.g., Şengör and Yılmaz1981). The Upper Cretaceous-Lower-Middle Eocene deep-sea sedimentary rocks, associated genetically with the ophiolitic mélange, indicate that the NeoTethyan oceanic lithosphere survived during this period and was finally eliminated from entire eastern Turkey by the Late Eocene. Continental fragments of various sizes were tectonically incorporated into the mélange prism, possibly during the growth of the accretionary complex.

The northward advance of the Arabian Plate continued after the elimination of the oceanic environment. The mélange-accretionary prism that occupied a large terrain behaved like a wide and thick buffer unit, which did not allow a head-on collision of the bordering continents (cf., the Turkic type orogen of Şengör and Natalin 1996). The northward advance of the Arabian Plate that continued after the initial stage of the collision caused shortening deformation. It began squeezing the eastern Anatolian accretionary complex. As a result, eastern Anatolia was elevated above the sea during the Late Eocene-Oligocene. An irregular topography was developed on the elevated land as indicated by coarse-grained thick Upper Eocene-Oligocene terrestrial conglomerates deposited in irregularly developed narrow depressions) (B in Fig 11-I). The rough topography was smoothened, and the region subsided steadily during the Late Oligocene-Early Miocene when an epeiric sea invaded the region again (Yılmaz 2017 and the references therein). This is evidenced by the low-energy marine sediments laid down on the Upper Eocene-Oligocene terrestrial sedimentary rocks. The smooth topography survived during the Early-Middle Miocene. Shallow marine limestones (the Adilcevaz

Limestone) were deposited above the fine-grained marine sediments (C in Fig 11-I) (Şaroğlu and Yılmaz 1986; Bedi and Yusufoğlu 2018). The limestones graded upward into evaporates and lacustrine limestones during the Late Miocene (Fig 3 and D in Fig 11-I). The gradual transition observed in the entire eastern Anatolian region reveals that interconnected lakes were developed over the elevated land following the disappearance of the sea (Şaroğlu and Yılmaz 1986; Yılmaz 2017). This event may also be interpreted that the eastern Anatolia began to rise as a coherent block (en mass) during the Late Miocene (Phase I, Fig.11-I). Following the disappearance of the interconnected lakes, the elevated land underwent a severe denudation phase, which formed a flat-lying erosional surface above the Upper Miocene lacustrine limestones (ES in Figs.11-I and the accompanying photo A1) (Yılmaz 2017). The smooth topography disappeared after this period. Various sediment packages were formed in separate depressions from this Late Pliocene onward (Phase II, Figs 11-II).

Entire eastern Turkey, including the Pontide and the Arabian Platform has behaved as an interconnected tectonic entity since their tectonic amalgamation. Paleomagnetic studies and the GPS data support this conclusion, which show that eastern Anatolia has been deformed together with the surrounding tectonic entities since the Late Miocene following the collision of the Arabian plate with the Anatolian blocks (Reilenger et al. 2006; Şengör et al 2008; Çinku et al. 2014; 2016; Gürer et al 2017; Bakkal et al 2019).

The continuing N-S compressional stress caused a complex pattern of structures in the Eastern Turkey (Fig. 4A). The rigid continental crust underlying the peripheral mountains accommodated the N-S compression by elevating faster (0.2-0.3 mm/y) than the eastern Anatolian plateau (0.1-0.2 mm/y). This is possibly because of the blocks and matrix of the ophiolitic mélange underlying eastern Anatolia partly absorbed the compression.

Starting from the Late Pliocene-Pleistocene big scale folds and thrusts began to form in the eastern Anatolia (phases III and IV; Figs 11-III and 11-IV) and the accompanying photos C1 and D1). The peripheral mountains were thrust over the eastern Anatolian plateau (Fig 2; 5A and 5C). Two narrow, fault-bound chains of E-W trending depressions were formed along the thrust fronts as intermountain or ramp basins (Fig1 and Figs 5A; 5B and 5C). The boundary faults give the young basins their distinct rhombohedral or parallelogram geometrical patterns (Fig 5B).

When the N-S compression and associated shortening reached an excessive stage, which could no longer be accommodated within the volume of eastern Anatolia, the stress permutation occurred. This led to the development of two transform faults, the North Anatolian Transform Fault (NATF) and the East Anatolian Transform Fault (EATF) (Figs 1 and 2) (Şengör 1979; Şengör and Kidd 1979; Şengör and Yılmaz 1981; Çemen et al.,1993 and Yılmaz 2017). They defined an independent tectonic entity, the Anatolian Plate, which began escaping away from the area of convergence to transfer part of the north-south compressional stress to the west (Mc Kenzie 1972; 1978; Şengör 1979; Şaroğlu and Yılmaz 1991; Şengör and Yılmaz 1981). The escape tectonics and associated lateral extrusion initiated a new tectonic regime in Anatolia and the surrounding regions known as the Neotectonics, which determined the development of the major morphotectonic entities in the peripheral mountains and the eastern Anatolian High Plateau (Yılmaz 2017). This event also caused anticlockwise rotations of the semi-independent fault-bounded blocks of Central Anatolia (Yılmaz 2017).

According to geophysical data lithospheric mantle under East Anatolia is very thin. Almost the whole thickness of the mantle lithosphere was removed from the overlying thickened crust (e.g., Barazangi et al., 2003). The space created was filled with a hot, upwelling asthenosphere, which produced mantle-derived magmas. The volcanic activity began sporadically during the Late Miocene and intensified about 5–6 Ma ago. The volcanoes were commonly developed above the extensional openings associated with the basin boundary faults. The volcanic edifices covered the entire plateau as a thick blanket (Yılmaz, 1990; Yılmaz et al., 1987, 1998; Pearce et al., 1990; Keskin, 2007; Keskin et al., 2012).

The north-directed compressional stress is actively deforming eastern Turkey. This is evidenced by GPS measurements (e.g., Reilenger et al., 2002) indicating that the high plateau and the peripheral mountains are still elevating, and the Anatolian Plate's westward escape is continuing at an about 20 mm/y rate. This continuing deformation may be regarded as the late-post tectonic phase of the orogenic development.

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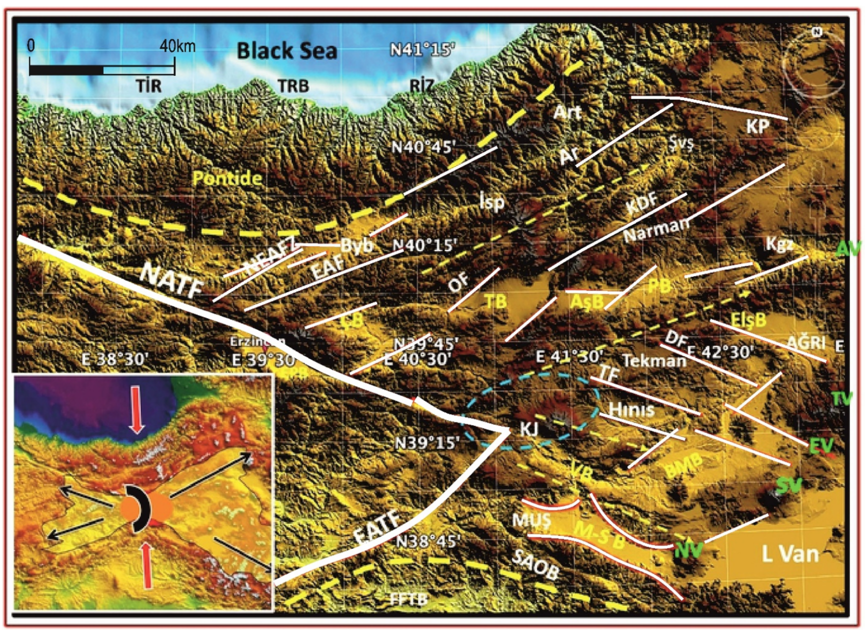

Figure 1- Morphotectonic map of eastern Anatolia showing major faults (straight lines) and trend lines of the mountain ranges (broken lines). Thick, broken, curvilinear lines represent trendlines of the peripheral orogenic belts, the Pontide, and the Southeastern Anatolian Orogenic Belt (SAOB). The white lines with the black glove are reverse faults. The inset map shows the central high resembling sheaved wheat and the dispersing major morphological features. **Abbreviations:**NATF; the North Anatolian Transform Fault, EATF; the East Anatolian Transform Fault, EAF; East Anatolian fault zone, NEAFZ; Northeast Anatolian fault zone, OF; Olur fault, DF; Doğu Beyazıt fault; TF; Tutak fault, the ellipse represents the center of the Virgation, KJ; The Karlıova Junction, FFTB; Foreland fault and thrust belt of the Southeastern Anatolian

Orogen. Basins: ÇB; Çayırlı basin, TB; Tercan basin, AşB; Aşkale basin, PB; Pasinler basin, VB; Varto basin, BMB; Bulanık-Malazgirt basin, M-SB; Muş- Solhan Basin

Volcanoes; NV; Nemrut, SV; Süphan, EV; Etrüsk, TV; Tendürek, AV; Ağrı (Ararat). Towns and cities (Black letters along the coastal zone)

; TİR; Tirebolu; TRB; Trabzon, RİZ; Rize, White letters inland; Art; Artvin, Ar; Ardanuç; Byb; Bayburt, İsp; İspir, Şvş; Şavşat, KP; The Karst Plateau, LVan; the lake Van.

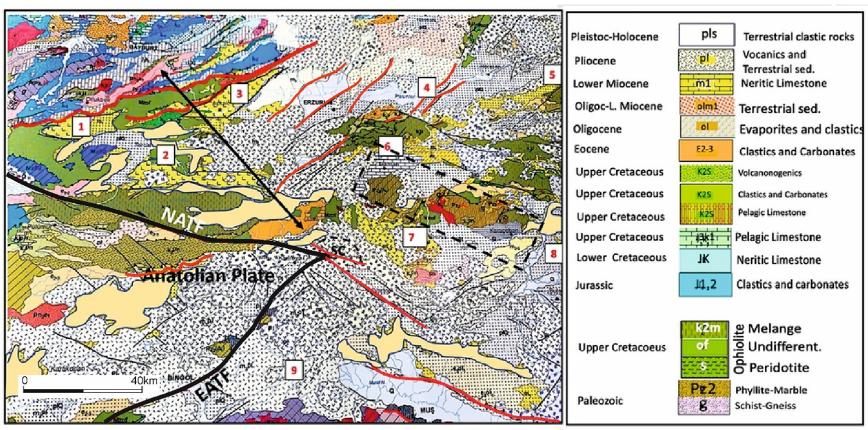

Figure 2. Geology map of the Eastern Anatolia (modified after MTA 1/500 000 scale geology map of Turkey covering regions from the Erzurum, Van, Diyarbakır, and Trabzon sheets). Numbers 1 to 10 show approximate locations of the young continental basins; 1; Çayırlı, 2; Tercan, 3; Aşkale, 4; Pasinler, 5; Kağızman, 6; Tekman, 7; Hınıs, 8; Bulanık-Malazgirt 9; Muş-Bingöl. Straight lines are major strike-slip faults. Curvilinear lines along the northern and southern edges of eastern Anatolia are the major thrusts separating eastern Anatolia from the neighboring orogenic belts.

The rectangle defined by black broken lines shows the location of the map in fig 8A. The black line with arrows at both ends indicates the direction of the cross-section in Figure 5C. **Abbreviations:** SC; the Solhan volcano's caldera, broken black half-circle defines the caldera's northern half.

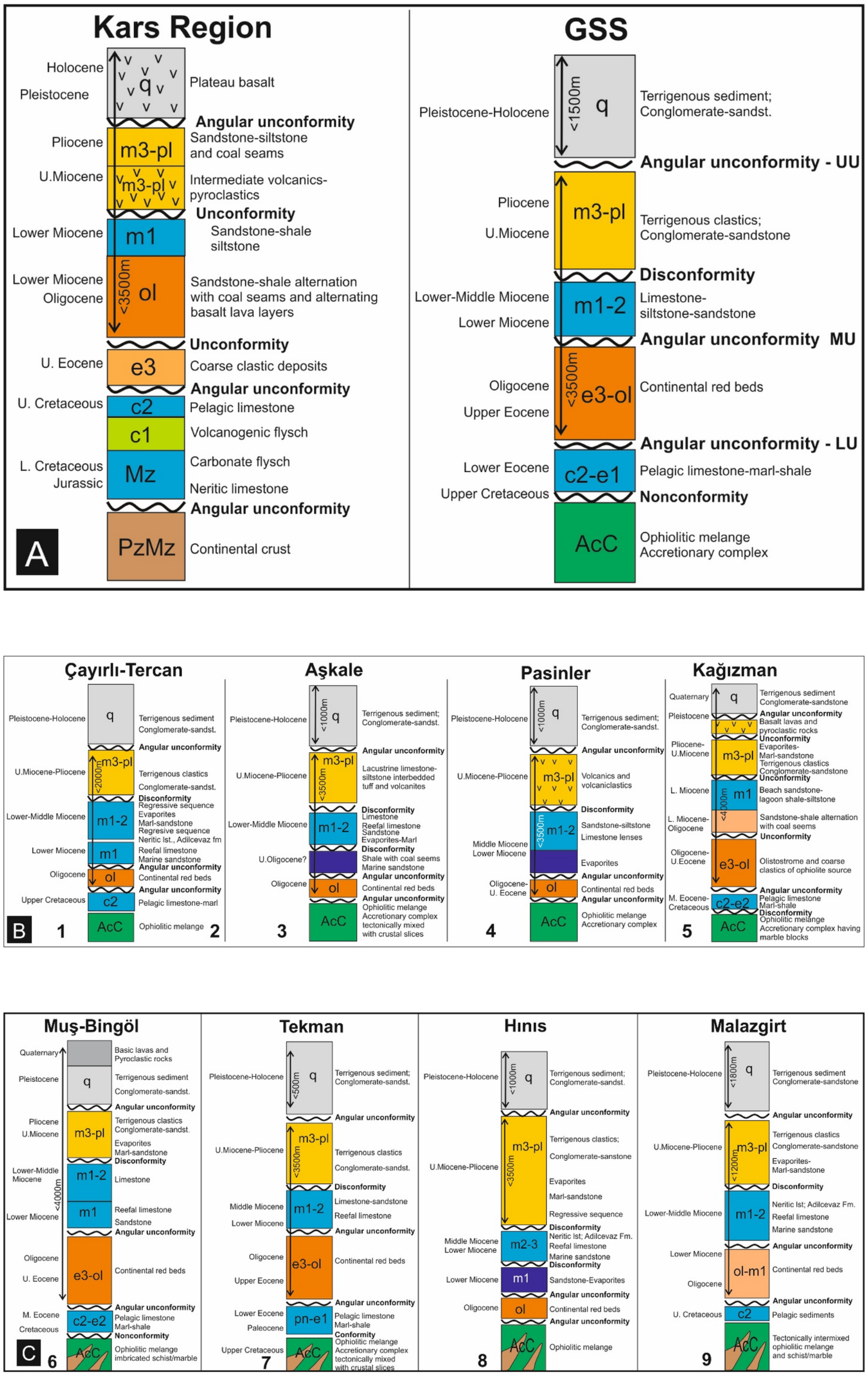

Figure 3A . GSS; Generalized stratigraphic section representing the eastern Anatolian basins. Abbreviations, LU; Lower unconformity, Middle Unconformity, UU; Upper Unconformity. Kars Region; Stratigraphic section representing the northeastern part of eastern Anatolia, the Kars Region, and surroundings. **Figure 3B and 3C.** Stratigraphic columnar sections of the major basins of eastern Anatolia. Locations of the basins are shown in Figure 2.

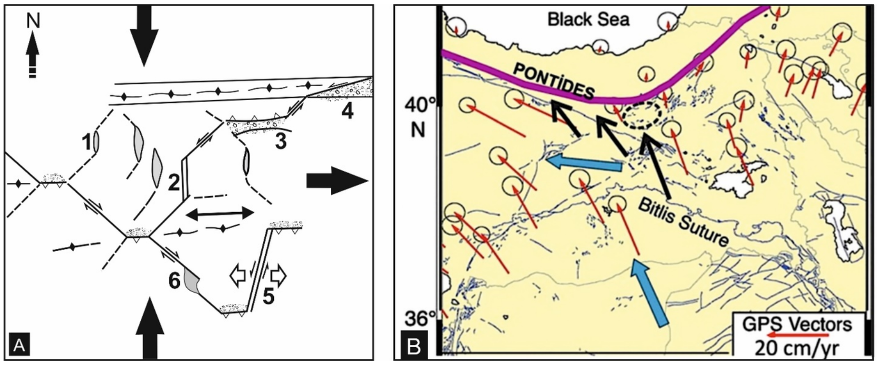

Figure 4 A. Schematic diagram showing types and trends of the major structures of eastern Anatolian Plateau.1 and 2; tensional openings, 3 and 4 ramp basins formed between reverse fault and oblique-slip faults. 5 and 6; extensional opening associated with pull-apart basins. The large arrows indicate compression and extension directions. **Figure 4 B.** The GPS vectors measured in eastern Anatolia (modified after Şengör et al., 2008). The thick line displays the crest line of the Pontide Range. The wide arrows; the motion directions of the Arabian and Anatolian plates. The black arrows: the major stress direction deforming southern regions of the Pontides.

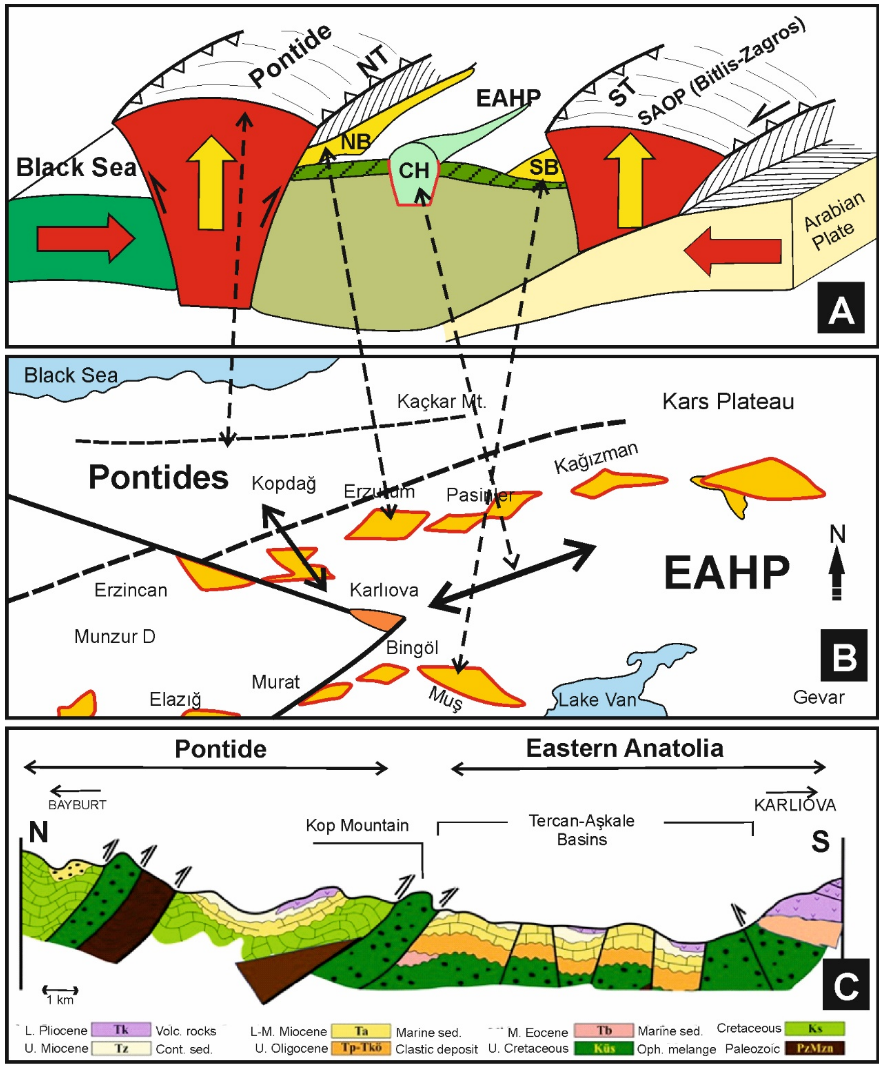

Figure 5 A. Schematic block diagram displaying major tectonic belts and morphotectonic features of eastern Turkey. Eastern Anatolia is squeezed (the dark arrows) between the northward advance of the Arabian Plate, and the resisting old oceanic lithosphere under the Black Sea is shortened, thickened, and elevated. The Pontide Range and the Southeastern Anatolian Orogenic Belt (SAOB) (the Bitlis-Zagros Mountains) underlain by old and rigid continental crust were thrust over eastern Anatolia and elevated with a higher rate (the pale arrows) because the ophiolitic mélange-accretionary complex underlying eastern Anatolia absorbs the bulk of N-S compression. Along the trust fronts, two narrow chains of fault-bound basins (NB and SB) were formed. The oblique faults (major strike-slip coupled with reverse slip displacements) give the basins their distinct parallelogram shapes and ramp basin characters (Fig 5B). The center of eastern Anatolia responded to the N-S compressional stress by protruded upward to form a central high (CH). Abbreviations: EAHP; the East Anatolian High Plateau, SAOB; the Southeast Anatolian Orogenic belt-the Bitlis-Zagros Mountains, SB, NB, the southern and northern basins, ST and NT; the southern and northern thrusts along with the peripheral mountains were thrust over the young basins. **Figure 5 B.** Schematic structural map of eastern Anatolia showing fault-bound chains of basins and centrally located structural high (the black line with arrows at both ends in Fig 5 B). The broken lines correspond to the trend lines of the mountain ranges. The short arrow between Kopdağ and Karlıova shows the direction of the geological cross-section in Fig 5C. The thin broken vertical lines connect the structural elements between the map and the block diagram in fig

5A and 5B. Abbreviations: Munzur D: The Munzur Mountains, Mt; mountains. **Figure 5 C.** Geological cross-section from eastern Anatolia to the Pontide Mountains along the cross-section direction shown in Figs 2 and 5B (modified from the cross-section provided by Ö. Şahintürk).

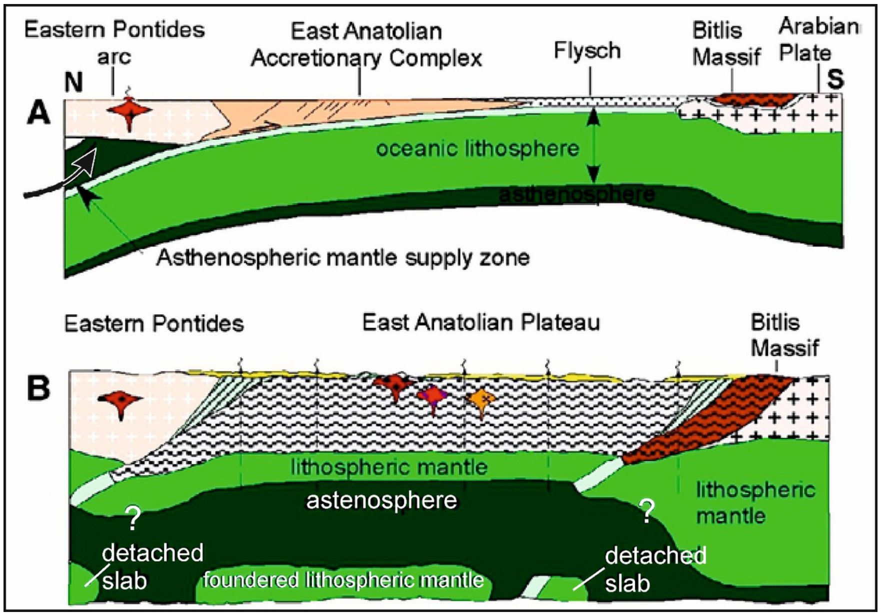

Figure 6. Two alternative geological models proposed for the nature of eastern Anatolia's basement (after Topuz et al. 2017).**Figure 6 A.** An ophiolitic mélange-accretionary complex forms the basement. **Figure 6 B.** An old metamorphic basement underlies eastern Anatolia.

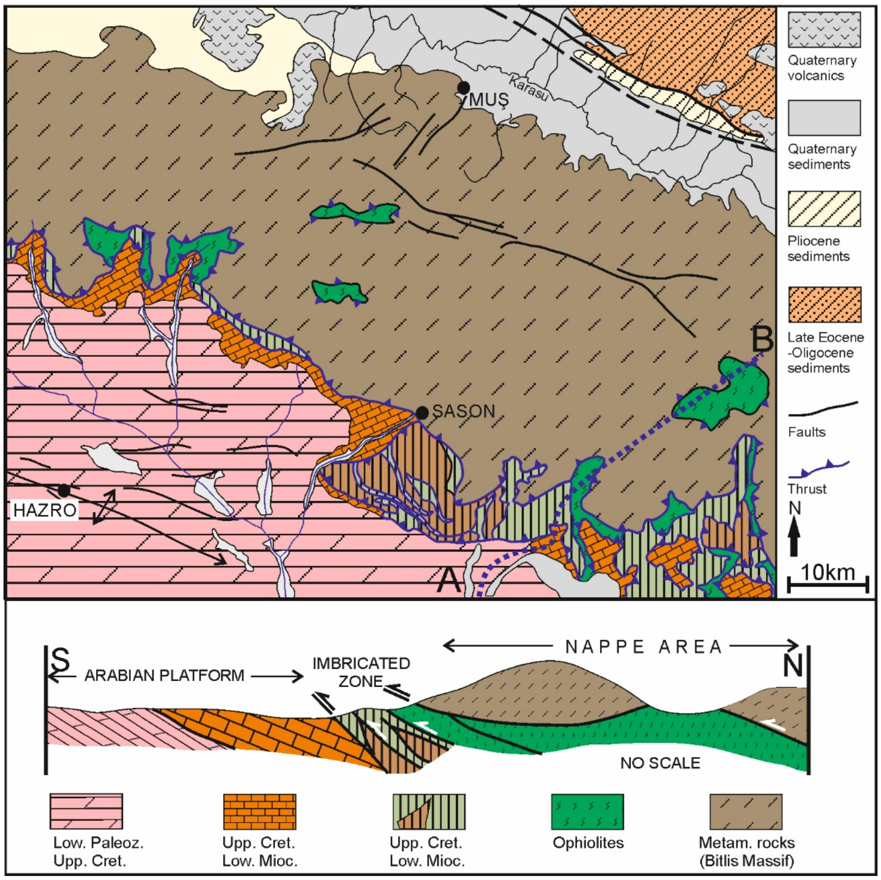

Figure 7A. The Geology map of the Southeast Anatolian Orogenic Belt (SAOB) (Modified after the MTA 1/500 000 scale geology map of the Erzurum sheet). **Figure 7B.** Geological cross-section across the SAOB along the direction indicated by the A-B broken line in the map. The cross-section showing metamorphic massifs as thrust sheets above the ophiolitic mélanges (modified after Yılmaz 1993).

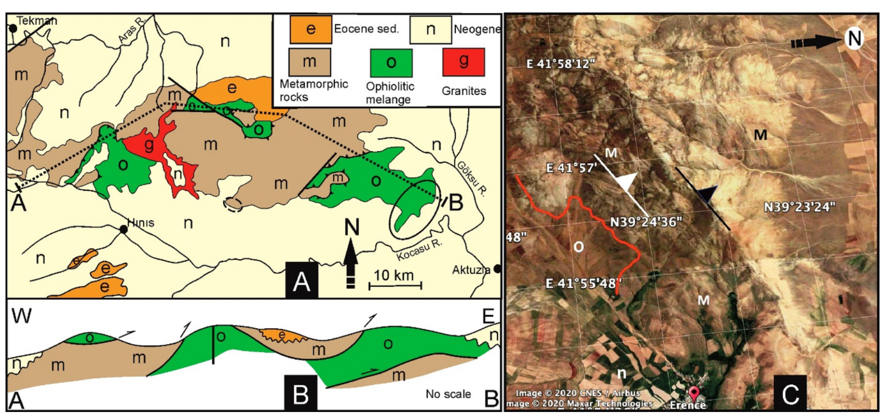

Figure 8A. Simplified geology Map of the region between towns of Tekman-Varto and Aktuzla where large metamorphic inliers (m) and the surrounding ophiolite-accretionary complexes (o) crop out (modified after MTA 1/500 000 scale Turkish geology maps, Erzurum and Van sheets). Both are overlain by Neogene cover rocks (n). The map location is shown in figure 2. The broken line connecting A and B indicates the direction of the cross-section in Figure 8 B. The small and big ellipses show the location of the aerial photos in Figure 8 C and 9A, respectively.**Figure 8 B.** A schematic geological cross-section along the direction of A and B in Fig 8A showing the structural arrangement of the metamorphic rocks (m) and the accretionary complex (o). **Figure 8 C.** Arial photo showing the metamorphic rocks tectonically overlying the accretionary complex. The north of the Erence village, the northwest of Varto. The small ellipse in Figure 8A marks the location of Figure 8B

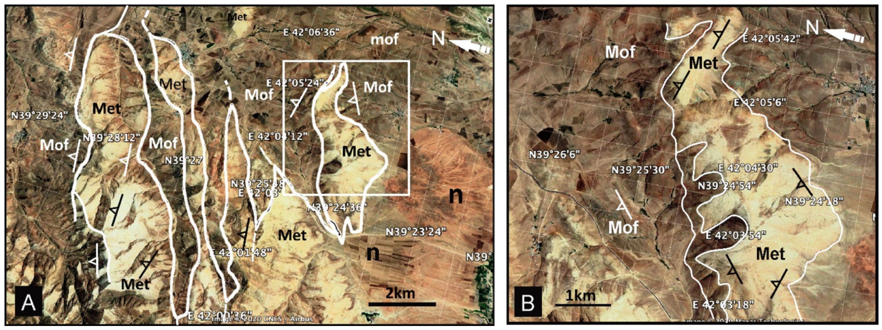

Figure 9A. Arial photo of the area marked with the big ellipse in Figure 8 A, the northwest of Aktuzla showing tectonically intermixed metamorphic rocks (Met) and the ophiolitic mélange (Mof). The white rectangle indicates the location of the aerial photo in Figure 9B. n; the Neogene cover rocks. **Figure 9B.** Arial photo showing a slice of metamorphic rocks (Met) tectonically sandwiched between the ophiolitic mélange (Mof) units.

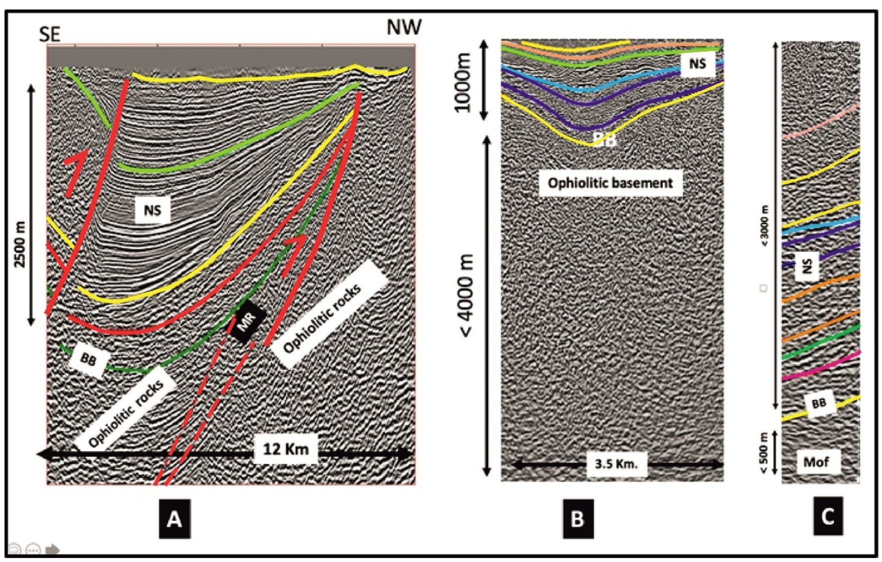

Figure 10. Seismic profiles across the young basins of eastern Anatolia from northern, southern, and central regions showing the ophiolitic rocks under the Neogene succession (seismic sections provided by Ö. Şahintürk). **Figure 10A.** From the Hınıs Basin, central Eastern Anatolia, located between 7 and 8 in Figure 2. **Figure 10B.** From the southern central region of Eastern Anatolia to the west of no 8 in figure 2.

Figure 10C. From the Pasinler Basin, the northern region of the Eastern Anatolia, 4 in Figure 2. **Abbreviations:** NS; The Neogene sequence. BB; Basement boundary, MR; Metamorphic rocks, Mof; Ophiolitic rocks.

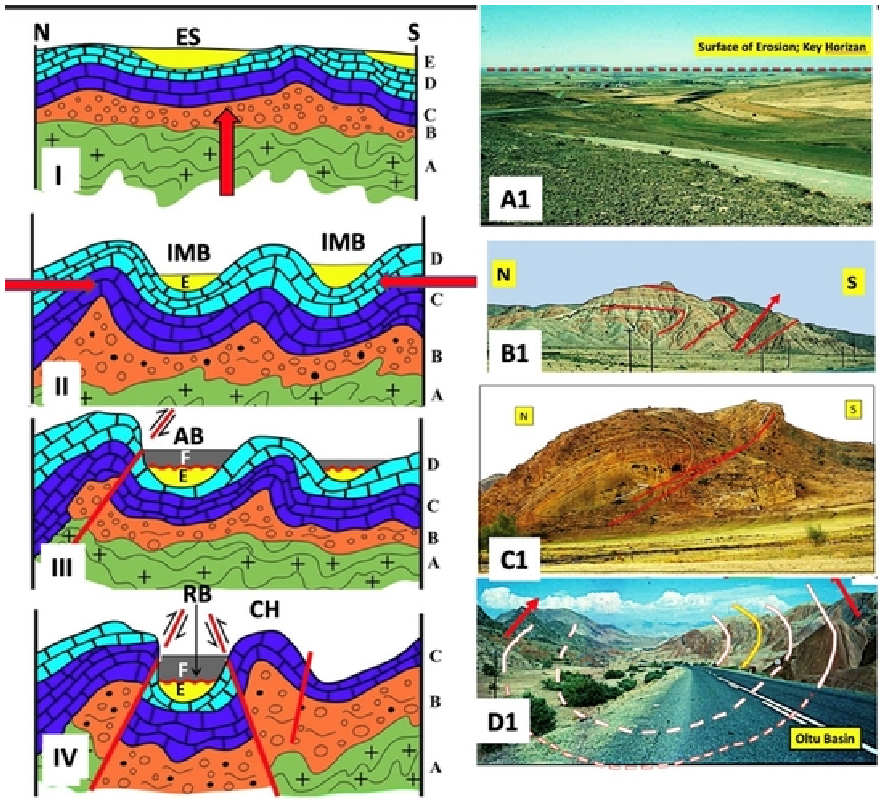

Figure 11. Schematic geological cross-sections illustrating consecutive stages of tectonic development of eastern Anatolia. Legend for Figures I to IV. A; Ophiolitic mélange-accretionary complex, B; Upper Eocene-Oligocene terrestrial coarse-grained sedimentary rocks, C; Lower-Middle Miocene shallow marine limestone, D; Upper Miocene-Lower Pliocene lacustrine limestone, E (in Figs II, III and IV); Upper Pliocene terrestrial sediments, and F (in Figs III and IV); Pleistocene -Holocene fluvial conglomerates.

Figure I showing eastern Anatolia during the Late Oligocene-Early Miocene. Following the denudation phase, a regionwide flat-lying erosional surface (ES) was developed (photo A1). Figure II showing the continuing N-S compression that caused large-scale folds (photo B1), Figure III showing tight folds and thrusts that were developed in the following periods (photo C1). Figure IV showing big-scale tight folds accompanied by thrusts from the opposite directions that caused the development of ramp basins (photo D1) during the more advanced stage of the compressional stress, Abbreviations; ES; Erosional surface, IMB; intermountain basins. AB; asymmetrical basins, RB; Ramp basin, CH; The Central High. Photos A1 to C1 are folds and thrusts from different eastern Anatolian regions showing the deformed Neogene sequence under the N-S compressional stress. A1; A northerly view from the southwest of Erzurum, B1 and C1; Kağızman-Tuzluca areas, D1; Oltu-Olur city road.

Tectonics of Eastern Anatolian Plateau; Final Stages of Collisional Orogeny in Anatolia

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Abstract.

The East Anatolian High Plateau, part of the Alpine-Himalayan orogen, is a 200 km wide, approximately E-W trending belt surrounded by two peripheral mountains of the Anatolian Peninsula. The plateau is covered by a thick, interbedded Neogene volcanic and sedimentary rocks. Outcrops of the underlying rocks are rare. Therefore, contrasting views were proposed on the nature of the basement rocks.

New geological and geophysical data suggest the presence of an ophiolitic mélange-accretionary complex under cover rocks of Eastern Anatolia. The cover units began to be deposited during the closure of the NeoTethyan Ocean that was located between the Pontide arc to the north, and the continental slivers drifted away from the Arabian Plate to the south. The surrounding orogenic belts experienced different orogenic evolution. The Eastern Anatolian orogen was formed during the later stages of the development of the surrounding orogenic belts. In this period, the mélange-accretionary prism that occupied a large terrain behaved like a wide and thick cushion, which did not allow a head-on collision of the bordering continents.

NeoTethyan oceanic lithosphere was eliminated from entire eastern Turkey by the Late Eocene. The eastern Anatolia began to rise when the northern advance of the Arabian Plate continued after the total demise of the oceanic lithosphere. The present stage of the elevation of the East Anatolian Plateau as a coherent block started during the Late Miocene.

1-Introduction

The Eastern Anatolian region is part of the Alpine-Himalayan belt. It is usually referred to as an East Anatolian High Plateau because it is on average 2000 m in elevation. The region is a 200 km wide belt between the Pontide Mountains to the North and the Bitlis-Zagros suture mountains to the south (Fig 1).

The Pontides were formed during consecutive collisions between the Andean-type volcanic arcs and continental blocks of Gondwanan origin (Yılmaz et al., 1997) (see an accompanying paper on the Pontide in this volume). The Bitlis-Zagros suture mountains were formed as a result of the continent-continent collision (Yılmaz 2019 and the references therein) (see the accompanying paper on the Southeast Anatolian Orogenic Belt in this volume). The Eastern Anatolian orogen was formed during the later stages of development of the surrounding orogenic belts.

The most significant structural features of Eastern Anatolia are the North Anatolian Transform Fault (NATF) and the East Anatolian Transform Fault (EATF) (Figs 1 and 2). The two faults converge in the Karlıova junction (KJ in Fig 1) and define the Anatolian Plate. The transform faults are long recognized as the major manifestation of the escape tectonics and associated lateral extrusion of the Anatolian Plate (e.g., Şengör 1979; Şengör and Yilmaz, 1981; Çemen et al. 1993; Yılmaz 2017).

The eastern Anatolia is covered by a thick, interbedded Neogene volcanic and sedimentary rocks and contains many conical peaks and ENE and WNW trending hills (Figs 1 and 2). The individual peaks correspond to volcanic cones (Fig 1) (Yılmaz et al. 1987, 1998; Pearce et al. 1990; Yılmaz 2017). The volcanoes produced a wide range of edifices from plateau basalts to ignimbrite deposits (Yılmaz et al. 1998; Kaygusuz et al. 2018).

The Neogene sedimentary cover rocks of Eastern Anatolia extend mainly along with two separate stripes of depressions adjacent to the peripheral mountains (Figs 1 and 2) (Yılmaz 2017). Rates of uplift in the bordering mountains are greater (0.2- 0.3 mm/y; Keskin et al. 2011) than the plateau's uplift (0.1-0.2 mm/y; Mc Nab et al. 2018). Therefore, headword erosion across the peripheral mountains cannot keep pace with the elevation increase in Eastern Anatolia. Consequently, major rivers in the plateau flow generally in east-west directions (Fig 1).

The thick Neogene cover sequence is commonly flat but is locally tightly folded and faulted. The morphological pattern of Eastern Turkey resembles a sheave of wheat tied at the center (the inset in Fig 1), reflecting strict structural control of the ongoing tectonics. The peripheral mountains on both sides curve around a central dome, which determines the regional structures and the present drainage network (Şaroğlu and Güner 1981; Maggie and Priestley 2005; Yılmaz 2017) (Figs 1 and 1 inset). The hills, depressions, and rivers fan out from the central high (Fig.1).

Outcrops of the basement rocks below the thick Neogene volcano-sedimentary layer are rare. As a result, contrasting views were proposed on the nature of the basement rocks, which made the orogenic evolution of the belt controversial. This paper aims to document new data leading to clarify the nature of basement rocks in Eastern Anatolia and discuss the orogenic development based on the new data.

2-Geologic Overview

In this section, we will summarize stratigraphic, structural, and igneous features of the eastern Anatolia.

2-1-Stratigraphy

Stratigraphic columnar sections covering the entire Eastern Anatolian region are displayed in Fig 3. The sections summarize the data gathered mainly from our field work together with the TPAO reports, and the previous studies (Kurtman and Akkuş 1971; Özdemir 1981; Şenel et al 1984; Koçyiğit et al 1985; Şaroğlu and Yılmaz 1984;1986; 1987;1991; Uysal 1986; Gedik 1986; Yılmaz et al 1987 A and B; Yılmaz A. et al 1988; Tarhan 1997A; B; 1998 A, B; Akay et al 1989; Bozkuş 1990; Temiz et al 2002; MTA 2002; Konak and Hakyemez 2008; Yılmaz 2107; Bedi and Yusufoğlu 2017; 2018; Yılmaz A and Yılmaz 2019; Üner 20121) enabling correlations and comparisons along and across the east Anatolian Plateau possible.

The generalized stratigraphic columnar section of eastern Anatolia (GSS in Fig 3 A) shows the presence of an ophiolitic mélange below the Neogene cover in most outcrops (MTA 2002; Özdemir 1981; Şenel et al. 1984; Konak and Hakyemez 2008; Elitok and Dolmaz 2008; Yılmaz A and Yılmaz 2019; Üner 2021; TPAO field reports and drilling data, and our field observations). The overlying Neogene cover is represented commonly by terrestrial sedimentary rocks. However, the stratigraphy in the northeastern part of the East Anatolia (i.e., N of the Kars province; Fig 1) is entirely different (the Karst region in Fig 3A). It consists of two major components, an old metamorphic basement and an overlying thick Paleozoic, Mesozoic, and Cenozoic successions. This is shown in the stratigraphic column of the Kars region in Fig 3A, where the succession is identical to that of the eastern Pontide Region (see the accompanying paper by Yılmaz et al. in this volume). The western and northwestern parts of the Kars province are thus considered easterly continuation of the eastern Pontide.

There is no detailed study on the eastern Anatolian ophiolitic mélange-accretionary complex. The previous works generally outline its major constituents (Altınlı1966; Yılmaz A. et.al.1988; Tarhan1989;1997A and B;1998 A and B; Önal and Kaya 2009; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019). A pelagic sedimentary succession consisting of limestone (chalk), radiolarite, and siltstone of the Upper Cretaceous to Lower Eocene age range is observed in association with the mélange. They are either blocks incorporated into the mélange or deep-sea sedimentary sequences deposited above the mélange foundation. Altınlı (1966), Şenel, et al. 1984; Tarhan (1989; 1997A; B;1998 A; B; Kaya (2009), Bedi et al. (2017), and Bedi and Yusufoğlu (2018) documented Upper Cretaceous, Paleocene, and Eocene fossil lists from the pelagic sediments. In some exposures, Upper Cretaceous-Eocene shallow sea sediments are also observed lying stratigraphically over the ophiolitic mélange (Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019).

The Neogene cover succession consists of four major rock groups separated by angular unconformities corresponding to: 1-Late Eocene-Oligocene (the lower unconformity), 2-Late Oligocene-Early Miocene (the middle unconformity), and 3-Late Pliocene (the upper unconformity). The lower unconformity separates the ophiolitic mélange-accretionary complex from the Upper Eocene-Oligocene terrestrial units consisting mainly of coarse clastic deposits (1 to 9 in Fig 3B and 3C). The middle unconformity separates the terrestrial sediments from the overlying Upper Oligocene-Lower Miocene transgressive sequence. The marine sediments begin with fine-grained sandstone-siltstones-marl alternations followed by reefal limestone and Lower-Middle Miocene neritic limestone (the Adilcevaz limestone; Şaroğlu and Yılmaz 1986). The limestone unit is observed in the entire eastern Anatolian region (Şaroğlu and Yılmaz 1986; 1987; Tarhan 1998; Kaya 2009; Gedik 2010., Yılmaz 2017; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019).

The shallow marine sediments grades upward into evaporites (Akkuş 1970; Yılmaz 2017; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019; Helvacı 2021) and lacustrine limestone, shale-sandstone alternations of Upper Miocene-Lower Pliocene age (Akkuş. 1970; 19071; Tarhan 1998., Nazik et al. 2008; Yılmaz 2017; Bedi and Yusufoğlu 2018; Yılmaz A and Yılmaz 2019). Thick Pleistocene-Holocene lacustrine-fluvial conglomerates and sandstones unconformably overlie them.

The upper unconformity marks a critical change in the region's morphotectonics (Yılmaz 2017 and the references therein). The field data obtained from regional geological mapping in eastern Anatolia (unpublished maps of Turkish Petroleum Association) shows that the Miocene and Pliocene sediments are regionally distributed. However, the post-Pliocene deposits are confined to the local depressions and display abrupt vertical-lateral facies changes within the basins (Şaroğlu and Yılmaz 1987; Tarhan 1989; 1997A, 1998A; Yılmaz 2017; Bedi and Yusufoğlu 2018).

The stratigraphic data outlined above reveal that the final stage of the uplift in eastern Anatolia began during the Late Miocene (Yılmaz 2017; Bedi and Yusufoğlu 2018). This event is also coeval with the elevation of the Central Anatolia, which leads to assume that the rise of eastern Anatolia also accelerated the uplift and magmatism in Central Anatolia (Schildgen et al. 2014; Bartol and Govers, 2014; Govers and Fichtner, 2016; McNab et al. 2018).

Stratigraphic and isotopic age data reveal that volcanic activity in the eastern Anatolian plateau began sporadically during the Late Miocene, possibly about 13-11 my ago (Şaroğlu and Yılmaz 1984; Yılmaz et al. 1987A; B; 1998; Yılmaz 2017). The volcanic edifices increased in the northern regions around 7-8 my ago and then migrated to the central areas around 5-4 m years ago (Pearce et al. 1990; Yılmaz et al. 1998; Keskin 2003; 2006; 2007; 2012). However, the volcanic activity intensified in the central and the southern regions about 3 my ago and has continued almost uninterruptedly to the present (Yılmaz et al. 1987 A; B.,1998; Yılmaz, 1990; Pearce et al., 1990; Keskin, 2003; 2007; Keskin et al., 2006; 2012). As a result, a thick volcanic blanket covered the entire eastern Anatolian plateau. Thick lava pile reaching up to 2 km in thickness was measured and drilled in the Kars plateau (unpublished TPAO data). The major volcanic centers, the Nemrut, Süphan, Tendürek, and Ağrı volcanoes, were built during the Quaternary (Yılmaz et al. 1988).

2-2-Structural Geology

Eastern Anatolia displays most of the geological features of a collisional orogen, which is similar in many respects to the Tibetan Plateau (Şengör and Kidd 1979; Şengör 1979; Şengör and Yılmaz 1981; Dewey et al 1986; Şaroğlu and Yılmaz 1984; Barazangi 1989; Şengör and Natalin 1996; Şengör et al 2003; 2008) (Fig 4A). The GPS measurements of crustal displacements (Fig 4B) (Reilenger et al. 2006; Şengör et al. 2008), focal mechanism of the earthquakes, and the distribution of active faults (Figs 1, 2, 4 A) (Şengör et al. 2003; Bozkurt 2001; Yılmaz 2017) confirm that the eastern Turkey experiences an ongoing north-directed compressional stress (Fig 4 A) (Yılmaz 2017 and the references therein).

The present-day morphology in eastern Anatolia was developed under a significant structural control (Yılmaz 2017) (Figs 1 and 2). The major morphotectonic features, northeast, and northwest-trending hills, and depressions (Fig 1) correspond to anticlines and synclines, respectively (Fig.1) (Yılmaz 2017). There is a centrally located structural dome, which may be regarded as the center of virgation (Fig 1), the maximum indentation location. The peripheral mountains on both sides make curves around the virgation (inset in Fig 1). The strike-slip faults disperse away from this high (Figs 1, 2). The arrangement and interactions of the structures demonstrate that eastern Anatolia has undergone a complex tectonic evolution (Şengör and Kidd 1979; Şengör and Yılmaz 1981; Şaroğlu and Yılmaz 1986; Copley and Jackson 2006; Yılmaz 2017) from the time of collision along with the southeastern Anatolian suture zone in the Late Eocene. This event corresponds to a wholesale elevation reflected in eastern Anatolian stratigraphy as a marked angular unconformity (Fig 3) (Yılmaz 2019) (see the accompanying paper in this volume by Yılmaz et al.).

In the East Anatolian High Plateau, the following major groups of structures are readily observed (Fig 4A);

1- NE and NW striking strike-slip faults (Figs.1and 4A) forming conjugated pairs (Şengör and Kidd 1979; Şaroğlu and Yılmaz 1984; Bozkurt 2001; Seyitoğlu et al. 2017; Yılmaz et al. 2017). The NE Striking faults are commonly longer and more prominent (Fig. 1) (Bozkurt 2001; Seyitoğlu et al. 2017). Most of these faults are young and active that generate frequent earthquakes (i.e., the Elazığ earthquake, on the 24 January 2020, Mw= 6.7, the Iran-Turkey border earthquake on the 23 February 2020, Mw=6.0, and the Malatya earthquake on the 24 January 2020 Mw=6,7).

2- Approximately E-W or ESE-WNW- striking reverse faults (Fig 4A),

3- E-W trending open and tight folds (Şaroğlu et al 1980; Şaroğlu and Yılmaz 1984;1986;1987; Koçyiğit et al. 2001; Yılmaz 2017).

4- N-S trending extensional structures (Fig 4A) (Şengör and Kidd 1979; Şaroğlu and Yılmaz 1984;1987; Yılmaz 2017).

The trends of all these structures are compatible with the N-S compressional stress field (Fig. 4A) generated from the northward advance of the Arabian Plate (Fig, 4B), which also caused the peripheral mountains to thrust over the eastern Anatolian plateau (Fig 2; 5A and 5C). Along the thrust boundary, the basement metamorphic rocks are exposed on the hanging walls (Figs 2 and 5C). As a result, the crust along the overthrust zones is thicker than the average, reaching up to 50 km (48 km beneath the Bitlis-Pötürge massifs in the south and 50 km under the Pontide Range (Barazangi et al. 2006; Şengör et. 2003; 2008: Tezel et al. 2013; Pamukçu et al. 2007; Medved et al. 2021).

Two narrow, fault-bounded chains of depressions were formed between the central high and the peripheral mountains during Pleistocene (Figs 1, 2, 5 A and 5B). The boundary faults give the young basins their distinct rhombohedral or parallelogram geometrical patterns (Fig. 5B). The transpressional faults with the major strike-slip, coupled with reverse slip components, strike parallel with, and determine the basins' long axes (Fig 5B). Due to the reverse slip displacements along the boundary faults, the depressions may be viewed as ramp basins or intermontane basins (Figs 5A and 5C) as exemplified from the Muş, Bingöl, Murat, Elazığ, Malatya basins to the south (Figs 1 and 5B) and the Tercan-Aşkale, Pasinler, Kağızman basins to the north (Figs 1 and 5B). The Eastern Anatolian High Plateau may also be regarded as a giant ramp basin between the thrust elevated peripheral mountains (Fig 5A).

Within the rhombohedral depressions where normal faults define the releasing bends, the local basins were alternatively described as pull-apart basins (Keskin et al. 1998). Some volcanos were built above the extensional openings (Fig 1) (Dewey et al., 1986; Pearce et al., 1990; Keskin et al., 1998; Yılmaz 2017).

The two transform faults, the North Anatolian Transform Fault and the East Anatolian Transform Fault define the Anatolian Plate (Figs 1 and 2), which protrudes away from the area of convergence in the Karlıova Junction (KJ in Fig 1) (McKenzie 1972; Şengör et al. 1975; Şengör and Yılmaz 1981; McKenzie and Yılmaz 1991; Şaroğlu and Yılmaz 1991; Çemen et al., 1993; Aktuğ et al. 2012; Karaoğlu et al. 2017) (Figs 1, 2, and 5B). The area where the transform faults intersect is a wedge shape depression (Fig 5 B), which widens progressively as the Anatolian Plate moves away from the point of convergence (Şaroğlu and Yılmaz 1991; Karaoğlu et al. 2016) (Fig 5 B). The oldest lateral fan deposits sourced from the basin boundary faults (Fig 5 B) is Upper Pliocene (?)- Pleistocene in age (Şaroğlu and Yılmaz 1991), which sets a lower limit to the time of the westerly escape of the Anatolian Plate. The escape tectonics partitions the N-S compressional stress (Yılmaz 2017).

Associated with the development of the two transform faults and the consequent escape tectonics of Anatolia, a new tectonic regime, the Neo Tectonics, began and has drastically changed the morphotectonic character of the Anatolia and surrounding regions (e.g., Şengör 1979; Şengör and Yılmaz 1981; Çemen et al., 1993; Yılmaz 2017).

The GPS vectors in Fig 4B shows that the eastward motion of Eastern Anatolia is slower than its westward movement. Field and earthquake data indicate that the N-S compressional stress is accommodated in this region along with several small-size strike-slip faults with right-lateral displacements (Fig 2).

2-3-Thickness of Crust and Lithosphere

Geophysical data suggest that the eastern Anatolian crust is thick (Çınar and Alkan 2015; Pamukçu et al. 2007; Cırmık 2018; Medved et al. 2021), but the uppermost mantle below the crust is very thin because it strongly attenuates Sn waves (Barazangi et al 2006). The Pn velocities are also low (−7.6 km/Sn) (Türkelli et al., 2003; Sandvol et al., 2003 A; 2003 B; Zor et al.,2003; Gök et al 2003; 2007; Maden and Öztürk 2005; Angus et al., 2015; Barazangi et al., 2006; Özaçar et al 2008; Göğüş and Pysklywec, 2008; Biryol et al 2011; Zor 2008; Elitok and Dolmaz 2008; Bartol et al., 2012; Warren et al 2013; Tezel et al 2013; Skobeltsyn et al 2016; Cırmık 2018). The heat flow is high (Tezcan 1987; Tezcan and Turgay 1989; Dolmaz et al. 2005; Ateş et al. 2005; İlkışık 1995; Bektaş et al 2007; Bektaş 2013; Pamukçu et al 2014: Cırmık et al 2018) and the Curie point depth is around 12-13 km below surface (Ateş et al 2005; Bektaş 2013; Pamukçu et al 2014; Cırmık 2018).

Based on data from the East Anatolian seismic experiment, Barazangi et al. (2006) proposed that the East Anatolian crust floats on a partly molten asthenosphere. Almost the whole thickness of the mantle lithosphere was removed from the overlying crust (Piromallo and Regard 2006; Barazangi et al. 2006; Gök et al. 2007; Lei and Zhao 2007: Zor et al. 2008; Medved et al. 2021). The following mechanisms were proposed to explain the obliteration of the lithospheric upper mantle.

1-the delamination of upper mantle (Al-Lazki et al 2003; Göğüş and Pysklywec 2008; Biryol et al 2011; Bartol et al 2012).

2- the steepening and break-off of the subducting slab (Davies and Blackenburg1995; Piromallo and Morelli, 2003; Piromallo and Regard 2006; Facenna et al. 2006) Lei and Zhao 2007; Gans et al. 2009; Dilek and Sandvol 2009; Govers and Fithcher 2016).

3-Combination of both mechanisms that are listed above (Mahatsente et al., 2018).

The space created by the removal of the mantle lithosphere was filled with a hot, upwelling asthenosphere or asthenospheric wedge (Şengör et al., 2003; Piromallo and Regard 2006), which caused adiabatic decompression. It is the hot mantle considered responsible for the high heat flow, the consequent regional uplift, and coeval volcanism (Pearce et al. 1990; Keskin, 2003; Piromallo and Regard 2006; Lei and Zhao, 2007; Şengör et al., 2008. Yılmaz 2017; 2019),

3-Discussion

In the following paragraphs, the two contrasting views proposed on the nature of the eastern Anatolian crust are discussed based on geological, geophysical, and geochemical data;

1-an ophiolitic mélange-accretionary complex forms the basement, which was developed during the demise of the Neo-Tethyan Ocean. Later, it was trapped between the approaching continents (Fig 6A) (Şengör and Kidd 1979; Şengör et al. 2008).

2- The entire eastern Anatolia is underlain by an old and thick continental crust (Fig 6 B) (Topuz et al., 2017).

Both views listed above were based on inconclusive evidence. The following critical data set are needed to provide verifications for the two hypotheses:

a-detailed geological data to examine the applicability of the view on the regional scale, including comparative data to correlate the eastern Anatolian geology with the neighboring tectonic belts (i.e., with the Southeastern Anatolian Orogenic Belt to the south and the Pontide Belt to the north to provide evidence how each hypothesis fits with the geology and tectonic evolution of the neighboring regions in a time-space reference.

b-geophysical data, particularly seismic data, to enlighten the nature of the basement.

The hypothesis proposed by Topuz et al. (2017), is based on the observations basically from two metamorphic rock inliers in eastern Anatolia (Fig 2) and the following interpretations; on the SE Anatolia and Pontide

1- ‘ ’Metagranite obtained from the metamorphic rock outcrops have a Late Ordovician–Early Silurian protolith and were therefore connected with the Menderes Massif of western Anatolia, which displays a similar protolith’ ’.

The old metamorphic minerals obtained from eastern Anatolia’s metamorphic inliers are expected to be similar to those obtained from the Menderes Massif because the metamorphic massifs of Western, Central, and SE Anatolian orogenic belts share the Pan African-Gondwanan origin (Şengör and Yılmaz 1981).

2- ‘ ’Multiple continental fragments separated by oceanic accretionary complexes are absent in eastern Anatolia’ ’.

This interpretation dismisses the essential characteristics of the Anatolian orogen, including the eastern Turkey where the orogen was developed by accretions of small continental fragments following the closure of the separating oceans (Şengör and Yılmaz 1981; Yılmaz and Şengör,1985; Dercourt et al. 1986; Dilek, 2006; Robertson et al. 2012; Barrier et al. 2018; McNab et al. 2018). Regional heating generated during the plate reorganization is stated to have caused major obduction of these ophiolites (Hassig et al. 2013, 2016 a, b; Roland 2020).

3- ‘ ’the metamorphic mineral assemblages that crop out in the metamorphic rocks of the region, display medium to high T metamorphisms, but not high-pressure metamorphism’ ’.

This interpretation disregards the critical geological data obtained from the neighboring orogenic belts (see the two accompanying papers in this volume on the Pontide and SE Anatolian orogenic belts by Yılmaz et al.). Particularly the recent studies on the SE Anatolian metamorphic massifs indicate that the ophiolitic rocks and the Bitlis Massif underwent an initial HP metamorphism, followed by an HT metamorphic phase during the Late Cretaceous-Early Eocene period (Roland et al. 2012; Oberhansli et al. 2012; 2014; Pourteau et al. 2013; Awalt and Whitney 2018; Yılmaz 2019). The Bitlis Massif, a fragment of continental crust involved in northward subduction together with the oceanic lithosphere (the Berit metaophiolite; Yılmaz 2019) under the Eastern Anatolia where, they were buried down to 35-65 km at depths (Oberhansli et al., 2014). Their exhumation occurred mainly during the Early Eocene period (Roland et al., 2012; Oberhansli et al., 2014; Yılmaz, 2019). A transgressive sequence was deposited above the elevated metamorphic massifs during the Middle Eocene (Yiğitbaş 1989; Yiğitbaş and Yılmaz 1996; Yılmaz 1993; Yılmaz 2019). The metamorphic massifs were then thrust over the ophiolitic mélange during the Late Eocene before they were tectonically emplaced as a giant nappe package onto the Arabian Plate in the Late Miocene (Yılmaz 2019). Consequently, the southeast Anatolian metamorphic massifs represent allochthonous belts (Fig 7B) resting tectonically on the Late Cretaceous-Middle Eocene metamorphic ophiolites (the Kızılkaya Metamorphics and the Berit Metaophiolite), and non-metamorphic ophiolites (The Göksun Ophiolite) and an accretionary complex (Fig 7B) extending from the eastern Anatolia (Fig 7A). Tens of kilometers of the nappe transport of the metamorphic massifs may be estimated from the Muş region in the North to the Sason region in the South (Figs 7A and B) (Yılmaz 2019 and the references therein).

3-1- Geological Data

Based on limited geological data, Topuz et al. (2017) state that the metamorphic rocks and the overlying ophiolitic layer of eastern Anatolia were exhumed during the Late Cretaceous, above which the sediments of Maastrichtian transgression were deposited. This view necessitates two highly improbable consequences.

a)-the continental crust must have remained buried under the thick, dense ophiolitic layer for more than 60-70 Ma period, which seems physically highly unlikely, and does not fit with tectonic behavior of the Alpine-Himalayan Mountain ranges,

b)-the stratigraphic data documented in Fig 3 display that the wholesale elevation of the eastern Anatolia above the sea level occurred during the Late Eocene-Oligocene. The bulk of eastern Anatolia became emergent in Neogene (Şengör and Yılmaz 1981; Bedi and Yusufoğlu 2018; Okay et al 2020; McNab et al 2018).

Moreover, geological data from the neighboring orogenic belts, the Pontide, and the Southeastern orogens reveal also that the oceanic environment survived in these regions until the Middle Eocene (Dilek and Sandvol 2009; Hassig et al.

2013; Nikishin et al. 2015; Sosson et al. 2017; Meijers et al. 2017; Yılmaz 2019, see also the accompanying papers by Yılmaz et al. in this volume). Elevation of fragments of the accretionary complex, reaching somewhere above the sea during the Late Cretaceous-Early Eocene period does not rule out the ocean's existence in the region, similar to many growing accretionary prisms of the world today, such as the Aegean-Eastern Mediterranean region (Robertson et al. 1996).

The hypothesis by Topuz et al. (2017) is based essentially on the presence of the metamorphic inliers surrounded by the accretionary complex located between the towns of Tekman, Hınıs, Karayazı and Aktuzla (Figs 2 and 8A). They argue that these metamorphic assemblages represent fragments of the elevated old metamorphic basement. The following evidence questions validity of this hypothesis. Figure 8B illustrates a geological cross-section along the largest metamorphic inlier (A-B section in Fig 8 B). The cross-section and the aerial photos in Fig 8 C and Figs 9 A and B show that the outcrops do not represent intact rock masses. They are observed either as tectonic wedges imbricated with the accretionary complex (Figs 9 A and 9 B) or as thrust sheets resting above the ophiolitic mélange (Fig 8 A, B, and C).

Furthermore, the data summarized below do not favor the presence of an old metamorphic basement under the ophiolitic mélange:

a)- The field evidence from the northern (the Çayırlı-Tercan-Aşkale-Pasinler basins), central (the Tekman-Hınıs-Malazgirt-Tekman basins), and southern (the Muş-Bingöl-Gevaş basins) (Fig 2) regions of the East Anatolia, particularly from the basin boundaries where the base rocks are exposed, reveal that there is almost always an ophiolitic mélange under the Neogene cover (Figs 3 and 5C).

b)- All the wells drilled by the oil and gas industry in the region cutting through the Neogene succession penetrated the ophiolitic mélange (unpublished TPAO data).

3-2- Geophysical Data

The distributions of seismic b-values from the entire eastern Anatolia, and the major high-wave number magnetic anomaly values favor high-density rocks under the Neogene successions matching the density of an ophiolite association (Bektaş et al. 2007; Bektaş 2013; Mahatsente et al.; 2018; Cırmık et al. 2018). The seismic waves down to 5-6 km at depths display a relatively uniform pattern (Figs 10 A and B) without abrupt vertical changes to infer a lower density layer under the ophiolitic rocks.

Maden and Öztürk (2015), examining rich data derived from the entire eastern Anatolia and the surrounding areas, concluded that the eastern Anatolian crust is thick, where the large negative gravity anomalies and low b-values are observed.

Fowler (2004) calculated a Bouguer gravity anomaly of -300 mgal in the case of 100% isostatic equilibrium (roc=2.85 gr/cm3, rum=3.3 gr/cm3) in a region with a topographic height of 1 km. The eastern Anatolia region has an average topography of 2 km. Therefore, it would be expected to yield gravity values lower than -300 mgal. However, the values observed in eastern Anatolia range between -100 and -200 mgal. This may be explained by the rapid uplift of the eastern Anatolian region due to delamination of the mantle lithosphere (see the discussion in the following paragraphs), insufficient immersion of the root of the lithosphere in the mantle, and the consequent isostatic disequilibrium.

3-3-Geochemical data from the Neogene volcanic rocks

The eastern Anatolian lavas' modal and normative compositions show a broad spectrum from nepheline normative basalts to quartz normative felsic lavas (Yılmaz et al. 1987A.B; 1998; Pearce et al. 1990; Keskin 2003;). The southern volcanic centers produced large quantities of basic and intermediate lavas. The northern volcanoes extruded voluminous intermediate volcanic edifices in which pyroclastic rocks dominate, particularly in the northeast of the Erzurum city (Fig 2).

Based on the geochemistry of the Eastern Anatolian Neogene lavas, the previous studies (e.g., Yılmaz et al. 1987A; B 1988; Yılmaz 1990; Pearce et al. 1990; Notsu et al. 1995; Keskin et al. 1998; 2003; 2006; 2007;2012; Lustrino et al. 2012; Özdemir and Güleç 2014; Oyan et al. 2016 A; 2016 B; Lebedev et al. 2016 A and B; Kaygusuz et al. 2018; Açlan et al. 2020; Üner 2021) reached the following conclusions on the magma compositions.

1-The magmas were derived from the heterogeneous mantle source and retained their compositions during the transit with minor modifications.

2- Magma chemistry of the alkaline, mildly alkaline, and calc-alkaline lavas displays distinct enrichment by the subduction components (enriched in LILE and LREE and depleted in HFSE) (e.g., Pearce et al. 1990; Jean et al. 2010; Lebedev et al. 2018 A and B. Kaygusuz et al. 2018; Üner 2021 and the references therein) and also boninitic enrichment (Üner 2021). In accordance with this conclusion, the seismic images obtained by various analytical methods demonstrate a remnant subducted oceanic lithosphere that is broken into pieces underneath Eastern Anatolia (Piromallo and Morelli 2003; Piromallo and Regard 2006; Facenna et al. 2006; Gans et al., 2009; Warren et al., 2013) (for the discussion on the time, place, and role of the subducting events in the development of the surrounding orogenic belts, see the two accompanying papers by Yılmaz et al. in this volume). The enriched mantle source generated a wide compositional range in the consecutive magma batches.

3- The Sr 86/ Sr 87 ratios of lavas of the eastern Anatolian volcanic provinces are on an average of 0.704, which varies in a narrow range commonly between 0.703 and 0.705. The Nd 143 Nd/144 Nd ratio ranges between 0.5127 and 0.5128 (e.g., Kaygusuz 2018 and the references therein). The isotope values plot in the mantle array (Kaygusuz et al. 2018). The isotope ratios together with the magma composition compare favorably with the OIB lavas (Üner 2021; Yang et al 2019; McNabb et al. in 2018).

4- The petrochemical characteristics indicate that the eastern Anatolian magmas were derived from an ophiolitic host and underwent significant fractionation in the magma chamber and during the transit.

5-Upper crustal contribution into the magmas is negligible (Kaygusuz et al., 2018; Üner 2021).

The petrochemical data derived from the Eastern Anatolian magmas may be used to test the validity of the hypothesis that assumes the presence of a thick continental crust under eastern Anatolia. Substantial chemical modifications would be expected in the magma composition if they passed through the thick and hot continental crust. These may be listed as follow; 1-higher Sr and Nd isotope values, 2-increasing amount of continental crustal components, 3-large volumes of magmas of continental crust origin (granitic magmas), 4-mixing and mingling of magmas of diverse compositions.

The petrochemical properties of the lavas from the entire eastern Anatolian region show boninitic or metasomatic enrichment but do not confirm these alternatives and thus do not support presence of a thick continental crust.

4-Concluding Summary

Geological field observations and the geophysical data suggest the presence of an ophiolitic mélange-accretionary complex under the cover sequence of eastern Anatolia (A in fig 11-I). The eastern Anatolian volcanic and sedimentary cover units were piled up during the closure of the NeoTethyan Ocean that was located between the Pontide arc to the north, and the continental slivers drifted away from the Arabian Plate to the south (e.g., Şengör and Yılmaz1981). The Upper Cretaceous-Lower-Middle Eocene deep-sea sedimentary rocks, associated genetically with the ophiolitic mélange, indicate that the NeoTethyan oceanic lithosphere survived during this period and was finally eliminated from entire eastern Turkey by the Late Eocene. Continental fragments of various sizes were tectonically incorporated into the mélange prism, possibly during the growth of the accretionary complex.

The northward advance of the Arabian Plate continued after the elimination of the oceanic environment. The mélange-accretionary prism that occupied a large terrain behaved like a wide and thick buffer unit, which did not allow a head-on collision of the bordering continents (cf., the Turkic type orogen of Şengör and Natalin 1996). The northward advance of the Arabian Plate that continued after the initial stage of the collision caused shortening deformation. It began squeezing the eastern Anatolian accretionary complex. As a result, eastern Anatolia was elevated above the sea during the Late Eocene-Oligocene. An irregular topography was developed on the elevated land as indicated by coarse-grained thick Upper Eocene-Oligocene terrestrial conglomerates deposited in irregularly developed narrow depressions) (B in Fig 11-I).

The rough topography was smoothened, and the region subsided steadily during the Late Oligocene-Early Miocene when an epeiric sea invaded the region again (Yılmaz 2017 and the references therein). This is evidenced by the low-energy marine sediments laid down on the Upper Eocene-Oligocene terrestrial sedimentary rocks. The smooth topography survived during the Early-Middle Miocene. Shallow marine limestones (the Adilcevaz Limestone) were deposited above the fine-grained marine sediments (C in Fig 11-I) (Şaroğlu and Yılmaz 1986; Bedi and Yusufoğlu 2018). The limestones graded upward into evaporates and lacustrine limestones during the Late Miocene (Fig 3 and D in Fig 11-I). The gradual transition observed in the entire eastern Anatolian region reveals that interconnected lakes were developed over the elevated land following the disappearance of the sea (Şaroğlu and Yılmaz 1986; Yılmaz 2017). This event may also be interpreted that the eastern Anatolia began to rise as a coherent block (en mass) during the Late Miocene (Phase I, Fig.11-I). Following the disappearance of the interconnected lakes, the elevated land underwent a severe denudation phase, which formed a flat-lying erosional surface above the Upper Miocene lacustrine limestones (ES in Figs.11-I and the accompanying photo A1) (Yılmaz 2017). The smooth topography disappeared after this period. Various sediment packages were formed in separate depressions from this Late Pliocene onward (Phase II, Figs 11-II).

Entire eastern Turkey, including the Pontide and the Arabian Platform has behaved as an interconnected tectonic entity since their tectonic amalgamation. Paleomagnetic studies and the GPS data support this conclusion, which show that eastern Anatolia has been deformed together with the surrounding tectonic entities since the Late Miocene following the collision of the Arabian plate with the Anatolian blocks (Reilenger et al. 2006; Şengör et al 2008; Çinku et al. 2014; 2016; Gürer et al 2017; Bakkal et al 2019).

The continuing N-S compressional stress caused a complex pattern of structures in the Eastern Turkey (Fig. 4A). The rigid continental crust underlying the peripheral mountains accommodated the N-S compression by elevating faster (0.2-0.3 mm/y) than the eastern Anatolian plateau (0.1-0.2 mm/y). This is possibly because of the blocks and matrix of the ophiolitic mélange underlying eastern Anatolia partly absorbed the compression.

Starting from the Late Pliocene-Pleistocene big scale folds and thrusts began to form in the eastern Anatolia (phases III and IV; Figs 11-III and 11-IV) and the accompanying photos C1 and D1). The peripheral mountains were thrust over the eastern Anatolian plateau (Fig 2; 5A and 5C). Two narrow, fault-bound chains of E-W trending depressions were formed along the thrust fronts as inter-mountain or ramp basins (Fig1 and Figs 5A; 5B and 5C). The boundary faults give the young basins their distinct rhombohedral or parallelogram geometrical patterns (Fig 5B).

When the N-S compression and associated shortening reached an excessive stage, which could no longer be accommodated within the volume of eastern Anatolia, the stress permutation occurred. This led to the development of two transform faults, the North Anatolian Transform Fault (NATF) and the East Anatolian Transform Fault (EATF) (Figs 1 and 2) (Şengör 1979; Şengör and Kidd 1979; Şengör and Yılmaz 1981; Çemen et al.,1993 and Yılmaz 2017). They defined an independent tectonic entity, the Anatolian Plate, which began escaping away from the area of convergence to transfer part of the north-south compressional stress to the west (Mc Kenzie 1972; 1978; Şengör 1979; Şaroğlu and Yılmaz 1991; Şengör and Yılmaz 1981). The escape tectonics and associated lateral extrusion initiated a new tectonic regime in Anatolia and the surrounding regions known as the Neotectonics, which determined the development of the major morpho-tectonic entities in the peripheral mountains and the eastern Anatolian High Plateau (Yılmaz 2017). This event also caused anticlockwise rotations of the semi-independent fault-bounded blocks of Central Anatolia (Yılmaz 2017).

According to geophysical data lithospheric mantle under East Anatolia is very thin. Almost the whole thickness of the mantle lithosphere was removed from the overlying thickened crust (e.g., Barazangi et al., 2003). The space created was filled with a hot, upwelling asthenosphere, which produced mantle-derived magmas. The volcanic activity began sporadically during the Late Miocene and intensified about 5–6 Ma ago. The volcanoes were commonly developed above the extensional openings associated with the basin boundary faults. The volcanic edifices covered the entire plateau as a thick blanket (Yılmaz, 1990; Yılmaz et al., 1987, 1998; Pearce et al., 1990; Keskin, 2007; Keskin et al., 2012).

The north-directed compressional stress is actively deforming eastern Turkey. This is evidenced by GPS measurements (e.g., Reilenger et al., 2002) indicating that the high plateau and the peripheral mountains are still elevating, and the Anatolian Plate's westward escape is continuing at an about 20 mm/y rate. This continuing deformation may be regarded as the late-post tectonic phase of the orogenic development.

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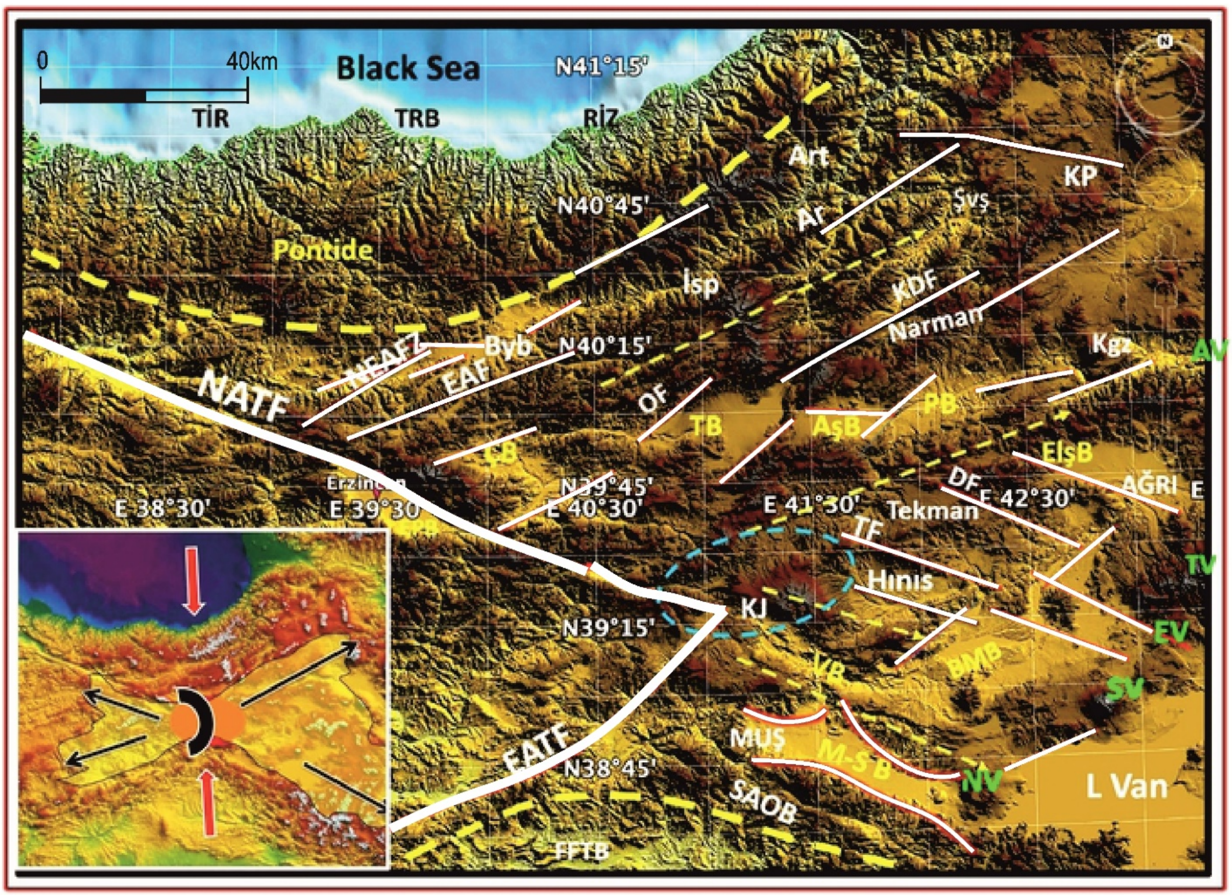


Figure 1- Morphotectonic map of eastern Anatolia showing major faults (straight lines) and trend lines of the mountain ranges (broken lines). Thick, broken, curvilinear lines represent trendlines of the peripheral orogenic belts, the Pontide, and the Southeastern Anatolian Orogenic Belt (SAOB). The white

lines with the black glove are reverse faults. The inset map shows the central high resembling sheaved wheat and the dispersing major morphological features. **Abbreviations:** NATF; the North Anatolian Transform Fault, EATF; the East Anatolian Transform Fault, EAF; East Anatolian fault zone, NEAFZ; Northeast Anatolian fault zone, OF; Olur fault, DF; Doğu Beyazıt fault; TF; Tutak fault, the ellipse represents the center of the Virgation, KJ; The Karlıova Junction, FFTB; Foreland fault and thrust belt of the Southeastern Anatolian Orogen. Basins: ÇB; Çayırlı basin, TB; Tercan basin, AşB; Aşkale basin, PB; Pasinler basin, VB; Varto basin, BMB; Bulanık-Malazgirt basin, M-SB; Muş-Solhan Basin

Volcanoes; NV; Nemrut, SV; Süphan, EV; Etrüsk, TV; Tendürek, AV; Ağrı (Ararat). Towns and cities (Black letters along the coastal zone)

; TİR; Tirebolu; TRB; Trabzon, RİZ; Rize, White letters inland; Art; Artvin, Ar; Ardanuç; Byb; Bayburt, İsp; İspir, Şvş; Şavşat, KP; The Karst Plateau, LVan; the lake Van.

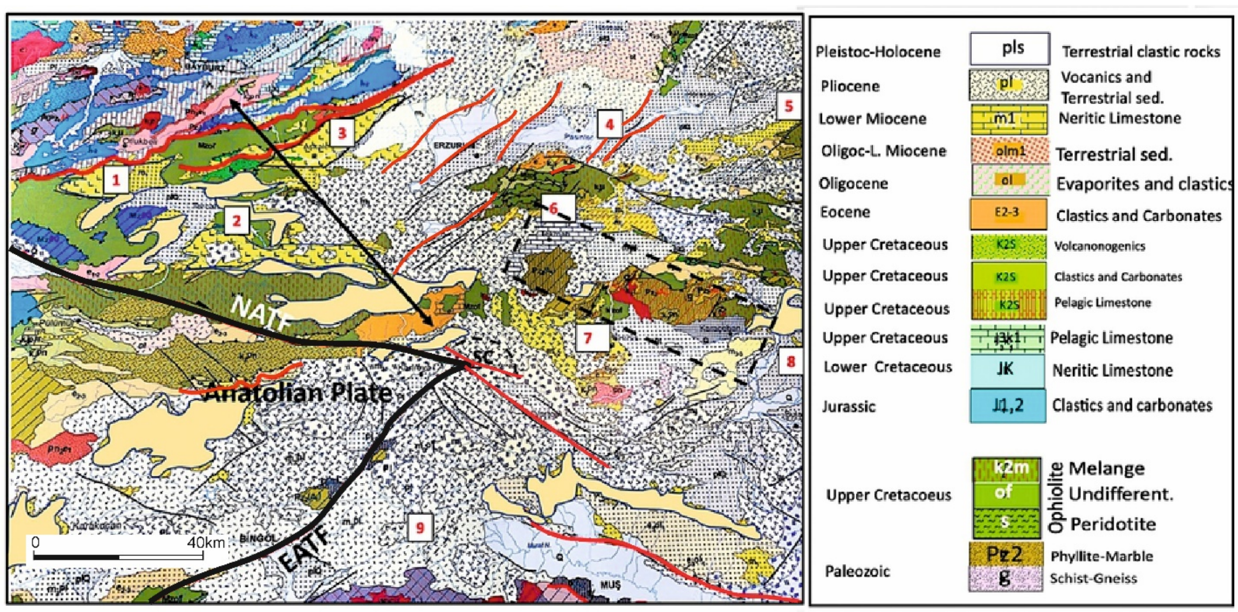
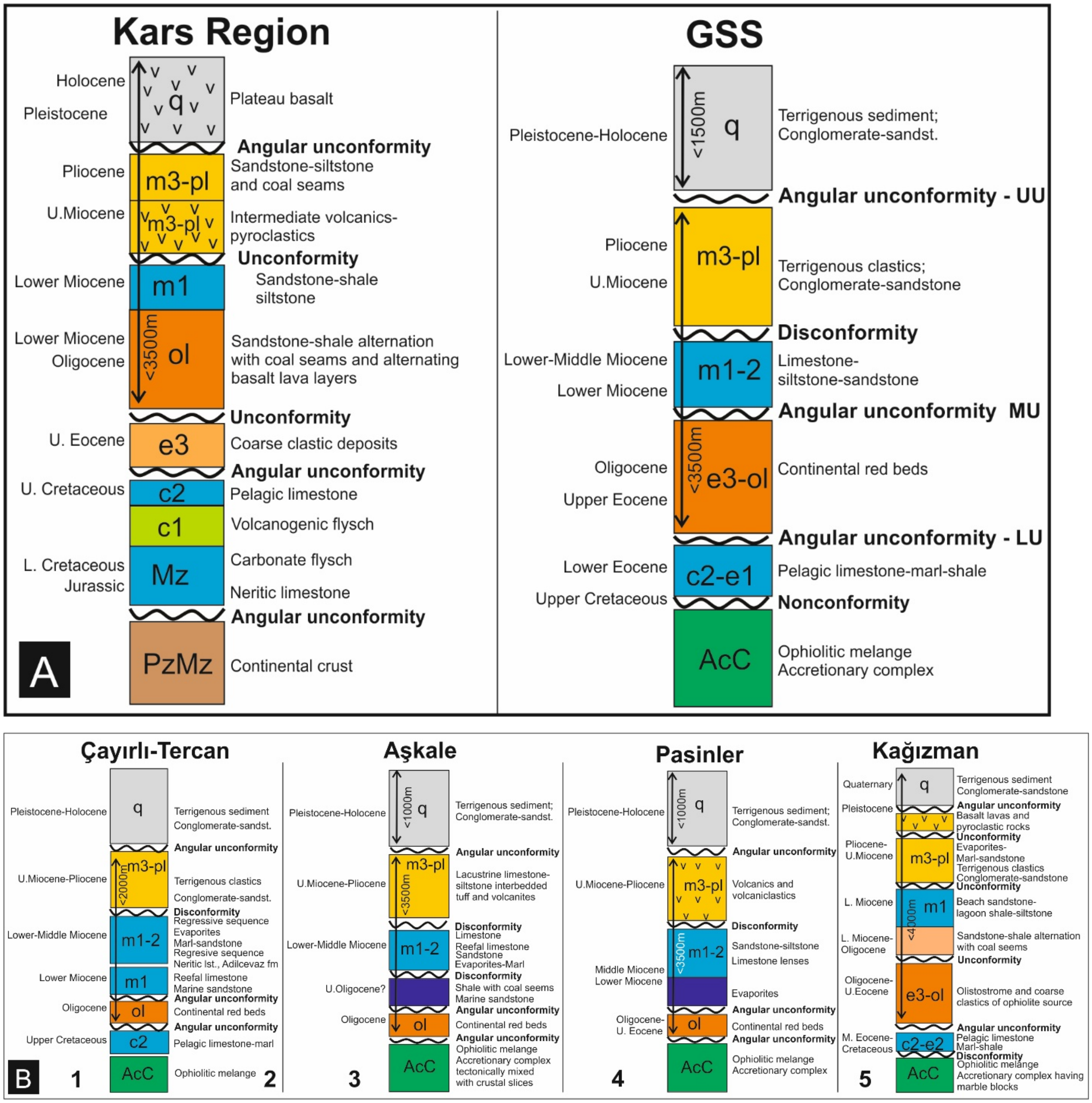


Figure 2. Geology map of the Eastern Anatolia (modified after MTA 1/500 000 scale geology map of Turkey covering regions from the Erzurum, Van, Diyarbakır, and Trabzon sheets). Numbers 1 to 10 show approximate locations of the young continental basins; 1; Çayırlı, 2; Tercan, 3; Aşkale, 4; Pasinler, 5; Kağızman, 6; Tekman, 7; Hınıs, 8; Bulanık-Malazgirt 9; Muş-Bingöl. Straight lines are major strike-slip faults. Curvilinear lines along the northern and southern edges of eastern Anatolia are the major thrusts separating eastern Anatolia from the neighboring orogenic belts.

The rectangle defined by black broken lines shows the location of the map in fig 8A. The black line with arrows at both ends indicates the direction of the cross-section in Figure 5C. **Abbreviations:** SC; the Solhan volcano's caldera, broken black half-circle defines the caldera's northern half.



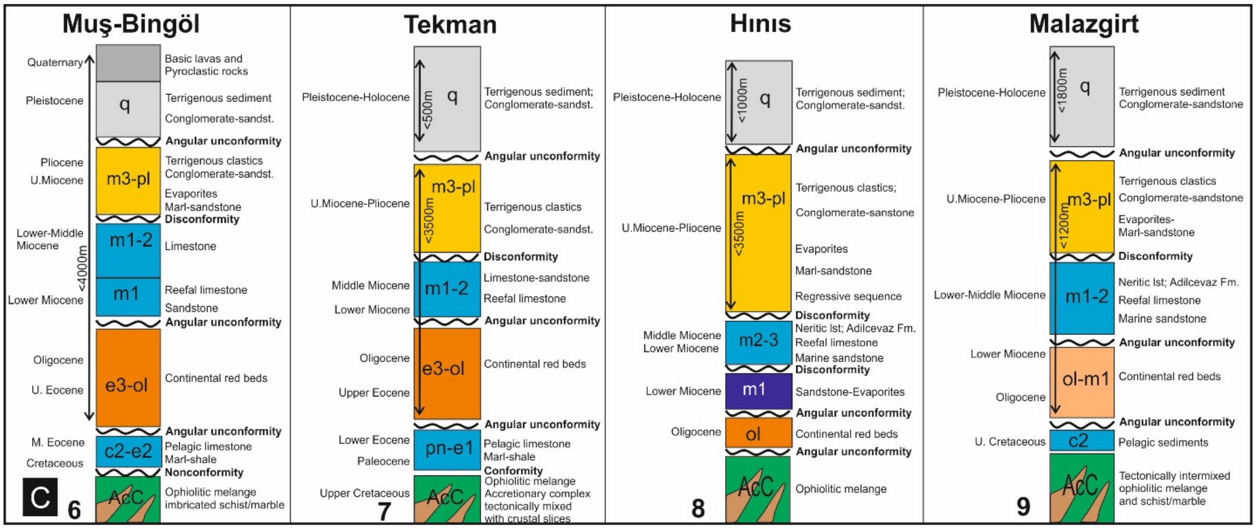


Figure 3A. GSS; Generalized stratigraphic section representing the eastern Anatolian basins. Abbreviations, LU; Lower unconformity, Middle Unconformity, UU; Upper Unconformity. Kars Region; Stratigraphic section representing the northeastern part of eastern Anatolia, the Kars Region, and surroundings. **Figure 3B and 3C.** Stratigraphic columnar sections of the major basins of eastern Anatolia. Locations of the basins are shown in Figure 2.

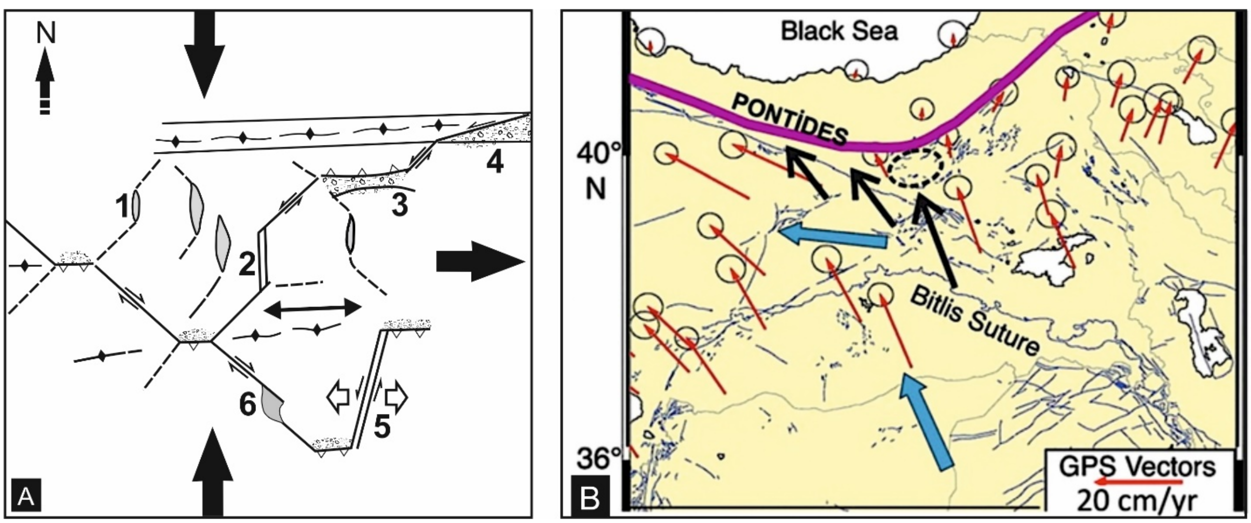


Figure 4 A. Schematic diagram showing types and trends of the major structures of eastern Anatolian Plateau.1 and 2; tensional openings, 3 and 4 ramp basins formed between reverse fault and oblique-slip faults. 5 and 6; extensional opening associated with pull-apart basins. The large arrows indicate compression and extension directions. **Figure 4 B.** The GPS vectors measured in

eastern Anatolia (modified after Şengör et al., 2008). The thick line displays the crest line of the Pontide Range. The wide arrows; the motion directions of the Arabian and Anatolian plates. The black arrows: the major stress direction deforming southern regions of the Pontides.

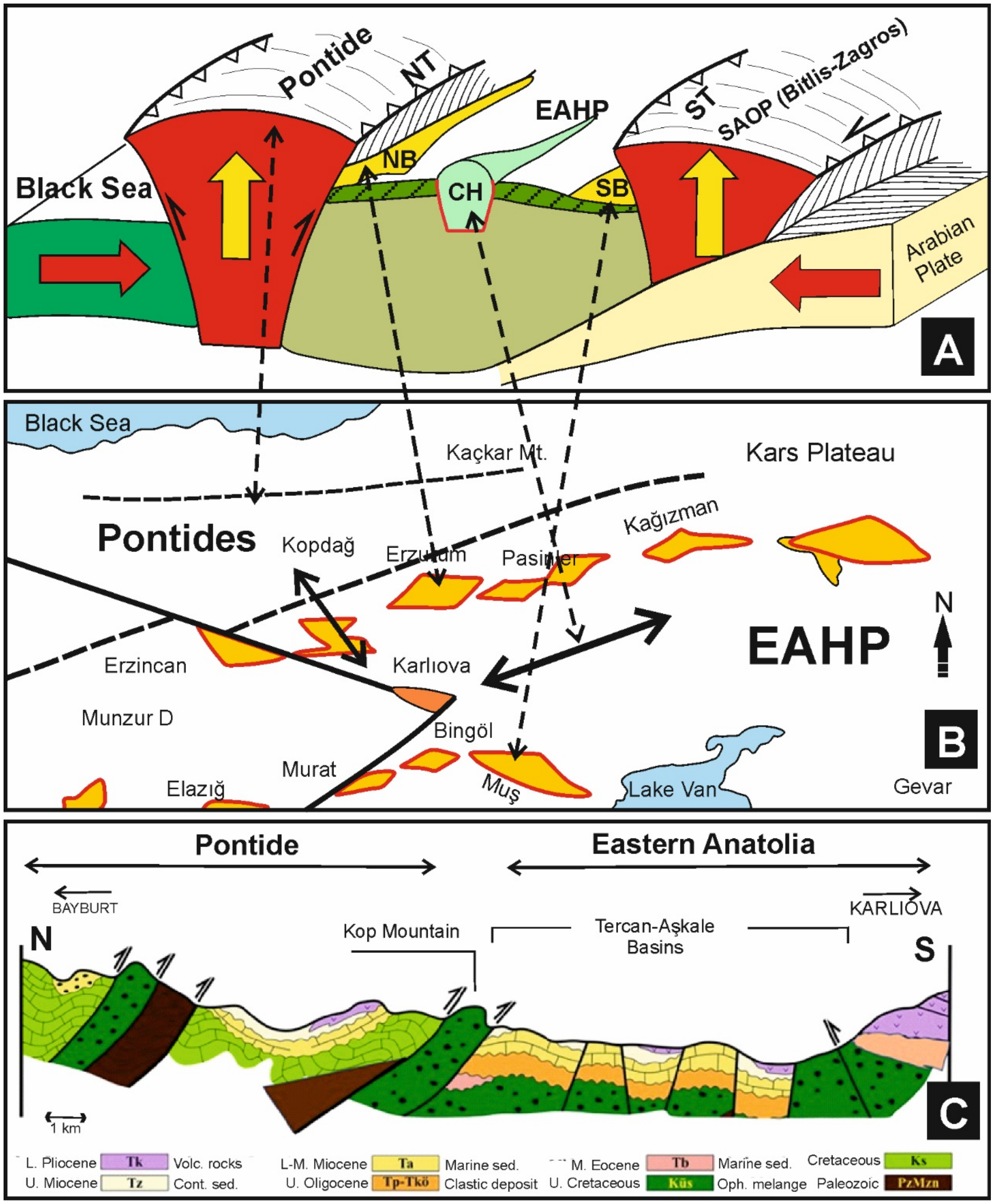


Figure 5 A. Schematic block diagram displaying major tectonic belts and morphotectonic features of eastern Turkey. Eastern Anatolia is squeezed (the dark arrows) between the northward advance of the Arabian Plate, and the resist-

ing old oceanic lithosphere under the Black Sea is shortened, thickened, and elevated. The Pontide Range and the Southeastern Anatolian Orogenic Belt (SAOB) (the Bitlis-Zagros Mountains) underlain by old and rigid continental crust were thrust over eastern Anatolia and elevated with a higher rate (the pale arrows) because the ophiolitic mélange-accretionary complex underlying eastern Anatolia absorbs the bulk of N-S compression. Along the trust fronts, two narrow chains of fault-bound basins (NB and SB) were formed. The oblique faults (major strike-slip coupled with reverse slip displacements) give the basins their distinct parallelogram shapes and ramp basin characters (Fig 5B). The center of eastern Anatolia responded to the N-S compressional stress by protruded upward to form a central high (CH). Abbreviations: EAHP; the East Anatolian High Plateau, SAOB; the Southeast Anatolian Orogenic belt-the Bitlis-Zagros Mountains, SB, NB, the southern and northern basins, ST and NT; the southern and northern thrusts along with the peripheral mountains were thrust over the young basins. **Figure 5 B.** Schematic structural map of eastern Anatolia showing fault-bound chains of basins and centrally located structural high (the black line with arrows at both ends in Fig 5 B). The broken lines correspond to the trend lines of the mountain ranges. The short arrow between Kopdağ and Karlıova shows the direction of the geological cross-section in Fig 5C. The thin broken vertical lines connect the structural elements between the map and the block diagram in fig 5A and 5B. Abbreviations: Munzur D: The Munzur Mountains, Mt; mountains. **Figure 5 C.** Geological cross-section from eastern Anatolia to the Pontide Mountains along the cross-section direction shown in Figs 2 and 5B (modified from the cross-section provided by Ö. Şahintürk).

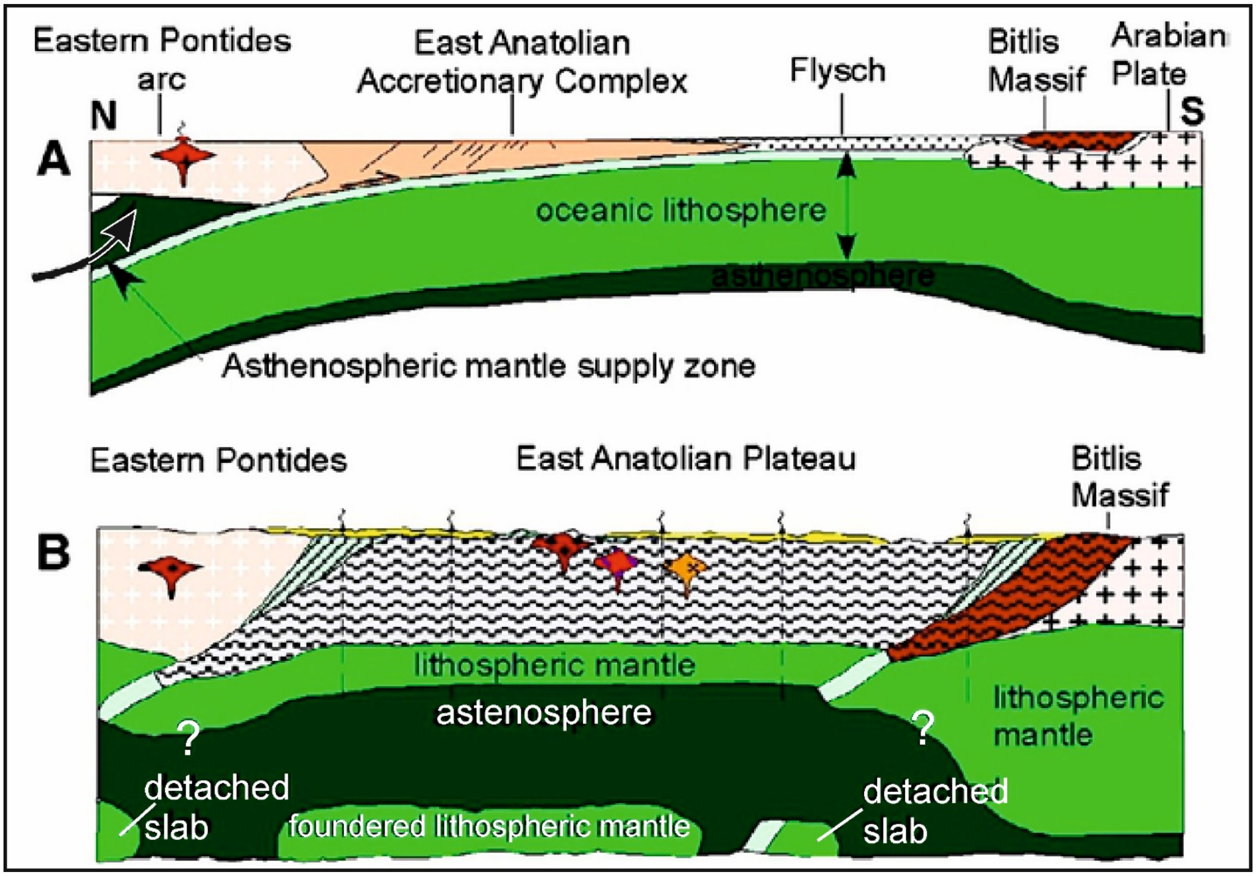


Figure 6. Two alternative geological models proposed for the nature of eastern Anatolia's basement (after Topuz et al. 2017). **Figure 6 A.** An ophiolitic mélange-accretionary complex forms the basement. **Figure 6 B.** An old metamorphic basement underlies eastern Anatolia.

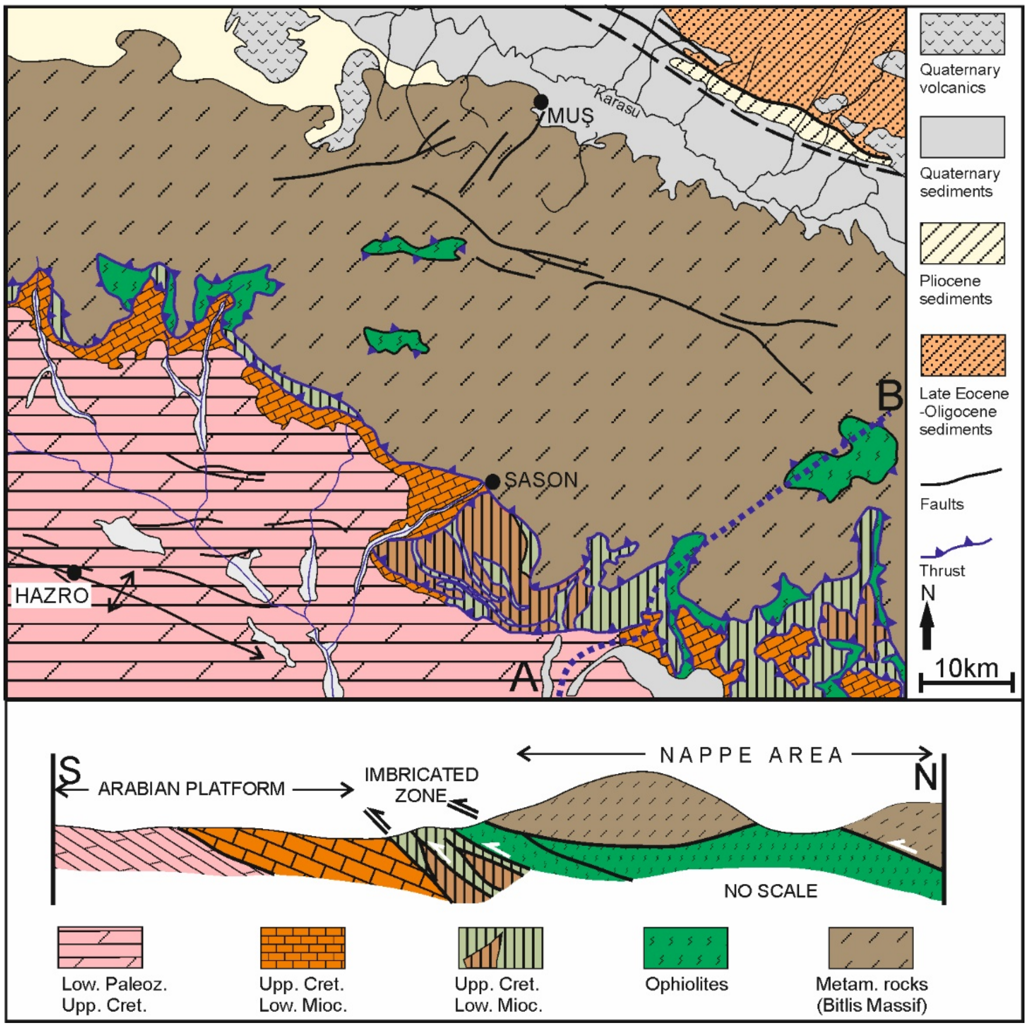


Figure 7A. The Geology map of the Southeast Anatolian Orogenic Belt (SAOB) (Modified after the MTA 1/500 000 scale geology map of the Erzurum sheet). **Figure 7B.** Geological cross-section across the SAOB along the direction indicated by the A-B broken line in the map. The cross-section showing metamorphic massifs as thrust sheets above the ophiolitic mélanges (modified after Yılmaz 1993).

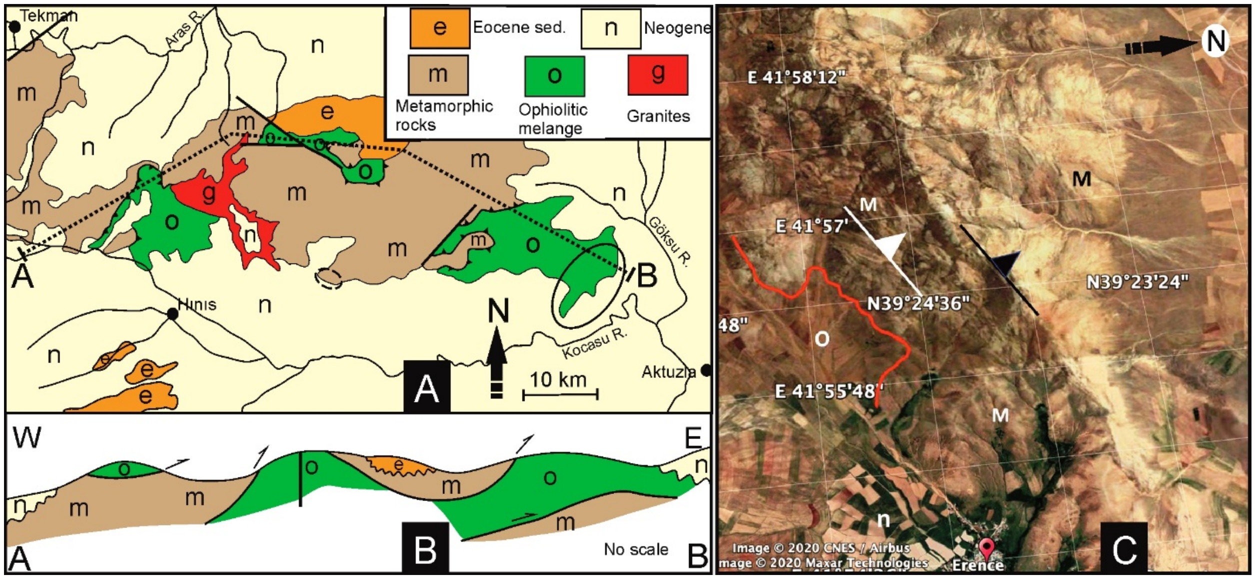


Figure 8A. Simplified geology Map of the region between towns of Tekman-Varto and Aktuzla where large metamorphic inliers (m) and the surrounding ophiolite-accretionary complexes (o) crop out (modified after MTA 1/500 000 scale Turkish geology maps, Erzurum and Van sheets). Both are overlain by Neogene cover rocks (n). The map location is shown in figure 2. The broken line connecting A and B indicates the direction of the cross-section in Figure 8 B. The small and big ellipses show the location of the aerial photos in Figure 8 C and 9A, respectively. **Figure 8 B.** A schematic geological cross-section along the direction of A and B in Fig 8A showing the structural arrangement of the metamorphic rocks (m) and the accretionary complex (o). **Figure 8 C.** Arial photo showing the metamorphic rocks tectonically overlying the accretionary complex. The north of the Erence village, the northwest of Varto. The small ellipse in Figure 8A marks the location of Figure 8B

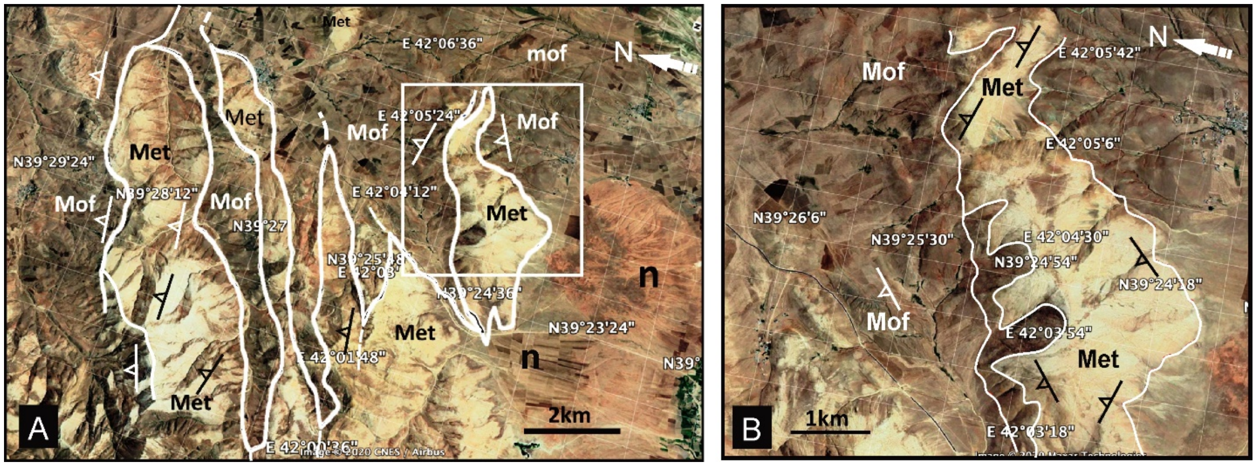


Figure 9A. Arial photo of the area marked with the big ellipse in Figure 8 A, the northwest of Aktuzla showing tectonically intermixed metamorphic rocks (Met) and the ophiolitic mélange (Mof). The white rectangle indicates the location of the aerial photo in Figure 9B. n; the Neogene cover rocks. **Figure 9B.** Arial photo showing a slice of metamorphic rocks (Met) tectonically sandwiched between the ophiolitic mélange (Mof) units.

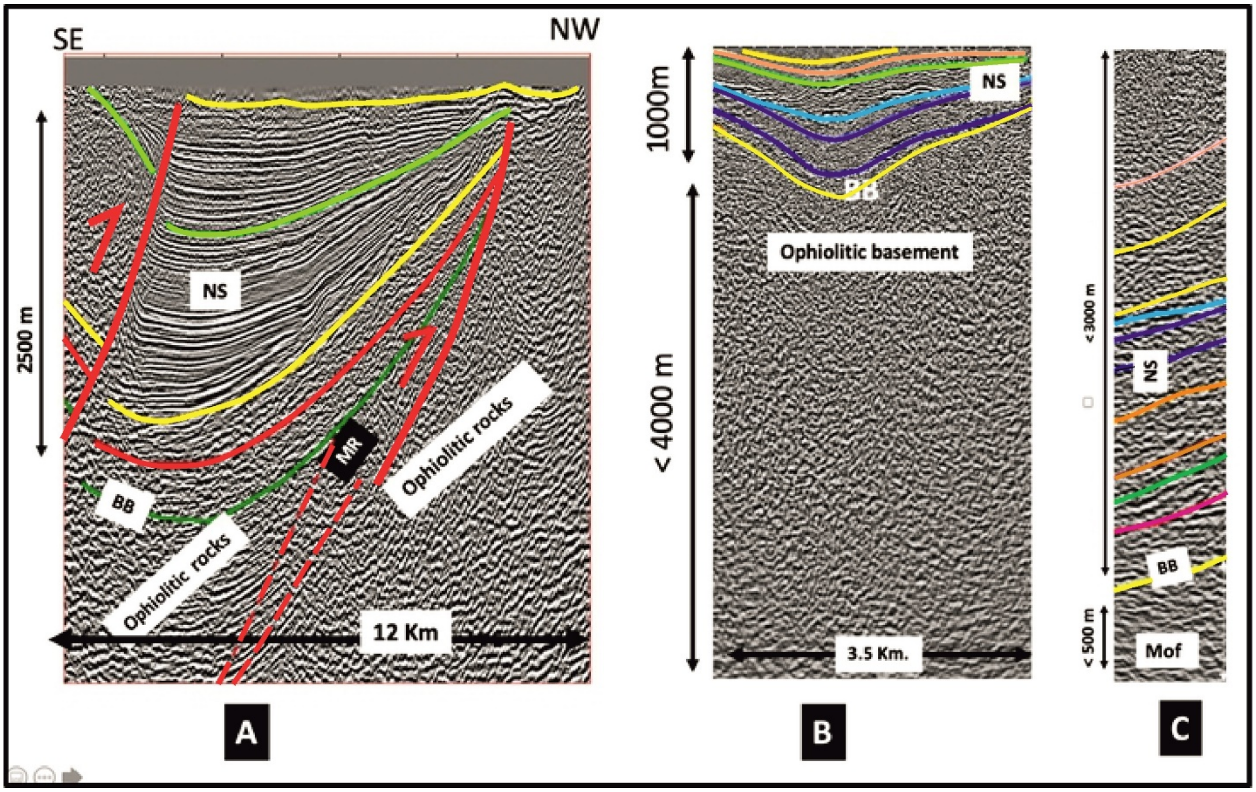


Figure 10. Seismic profiles across the young basins of eastern Anatolia from northern, southern, and central regions showing the ophiolitic rocks under the Neogene succession (seismic sections provided by Ö. Şahintürk). **Figure 10A.** From the Hınıs Basin, central Eastern Anatolia, located between 7 and 8 in Figure 2. **Figure 10B.** From the southern central region of Eastern Anatolia to the west of no 8 in figure 2.

Figure 10C. From the Pasinler Basin, the northern region of the Eastern Anatolia, 4 in Figure 2. **Abbreviations:** NS; The Neogene sequence. BB; Basement boundary, MR; Metamorphic rocks, Mof; Ophiolitic rocks.

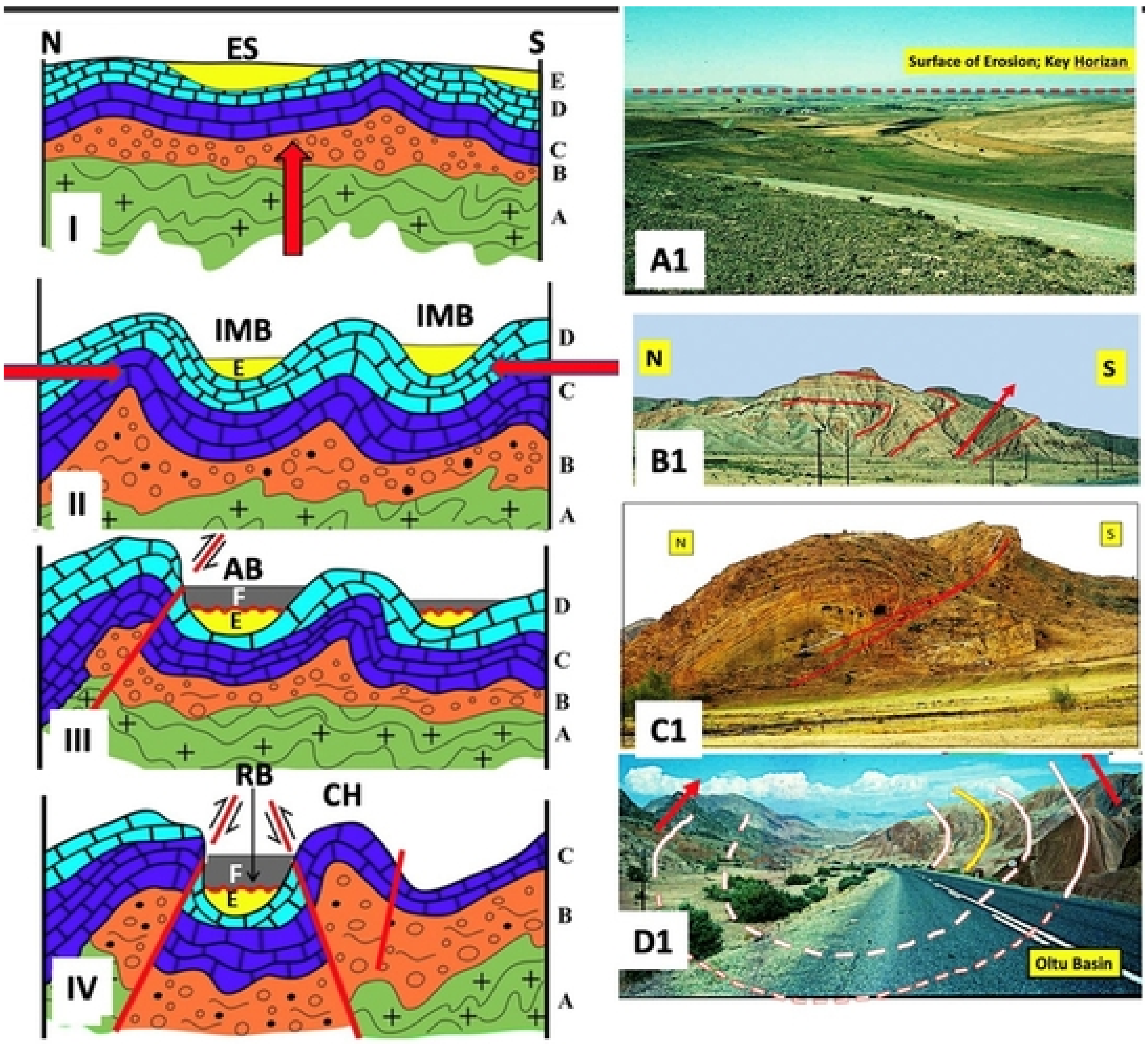


Figure 11. Schematic geological cross-sections illustrating consecutive stages of tectonic development of eastern Anatolia. Legend for Figures I to IV. A; Ophiolitic mélange-accretionary complex, B; Upper Eocene-Oligocene terrestrial coarse-grained sedimentary rocks, C; Lower-Middle Miocene shallow marine limestone, D; Upper Miocene-Lower Pliocene lacustrine limestone, E (in Figs II, III and IV); Upper Pliocene terrestrial sediments, and F (in Figs III and IV); Pleistocene -Holocene fluvial conglomerates.

Figure I showing eastern Anatolia during the Late Oligocene-Early Miocene. Following the denudation phase, a regionwide flat-lying erosional surface (ES) was developed (photo A1). Figure II showing the continuing N-S compression that caused large-scale folds (photo B1), Figure III showing tight folds and thrusts that were developed in the following periods (photo C1). Figure IV showing big-scale tight folds accompanied by thrusts from the opposite directions that caused the development of ramp basins (photo D1) during the more advanced stage of the compressional stress, Abbreviations; ES; Erosional surface, IMB; intermountain basins. AB; asymmetrical basins, RB; Ramp basin, CH; The Central High. Photos A1 to C1 are folds and thrusts from different eastern Anatolian regions showing the deformed Neogene sequence under the N-S compressional stress. A1; A northerly view from the southwest of Erzurum, B1 and C1; Kağızman-Tuzluca areas, D1; Oltu-Olur city road.