

Geology of the Eastern Anatolian Plateau (Turkey): a synthesis

Ali YILMAZ¹, Gültekin TOPUZ², Tuna EKEN³,
Osman CANDAN⁴, Hüseyin YILMAZ⁵

¹Ümit Mahallesi, 2497. Sokak, Çamlıca Vadi Sitesi, Çankaya, Ankara, Turkey

²Eurasia Institute of Earth Sciences, İstanbul Technical University, İstanbul, Turkey

³Department of Geophysical Engineering, İstanbul Technical University, İstanbul, Turkey

⁴Department of Geophysical Engineering, Dokuz Eylül University, İzmir, Turkey

⁵Eğriköprü Mahallesi, Şehit Melih Çimen Caddesi, Akademi, Sivas, Turkey

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Abstract: The Eastern Anatolian Plateau (EAP), approximately 2000 m above sea level, is located between the Eastern Pontides to the north, the Arabian Platform to the south, and the Iranian Plateau to the east. It is characterized by approximately 6 km-thick Maastrichtian to Quaternary volcano-sedimentary cover which unconformably overlies continental and oceanic basement units. Overall, the outcrops of the pre-Maastrichtian basement are rare and include both continental and oceanic units. This led to drastically different interpretations of the nature of the pre-Maastrichtian basement as (i) the oceanic accretionary complex or (ii) continental crust and overlying ophiolitic mélange. This synthesis deals with the relationships between continental and oceanic units in light of the recent geological, geophysical, and geochemical studies. Geophysical studies consistently indicate the presence of a spatially thickened continental crust with a lateral variation ranging from 38 to 52 km. Seismological models estimate lithospheric thicknesses to be in the range of 70–80 km, suggesting the presence of a rather thinned lithosphere. The pre-Maastrichtian continental units include late Cretaceous high-*T*/low-*P* metamorphic rocks, which are intruded by late Cretaceous basic to acidic intrusions at the base. Protoliths of the high-*T*/low-*P* metamorphic rocks can be closely correlated with those of the Anatolide-Tauride Block, probably representing the metamorphosed equivalents of the Anatolide-Tauride Block. The continental crustal nature is also testified by the presence of metasyenite to -granite with igneous crystallization ages of 430–440 Ma. The Late Cretaceous ophiolitic mélanges with locally intact tracks of ophiolite and overlying forearc deposits tectonically sit over the Late Cretaceous high-*T*/low-*P* metamorphic rocks. These ophiolitic mélanges probably form part of the North Anatolian ophiolitic belt, related to the İzmir-Ankara-Erzincan suture. Maastrichtian to Quaternary volcano-sedimentary rocks overlie both the continental crustal and tectonically overlying oceanic units, representing probably collisional and postcollisional basin fills. Available geological, geochemical, and geophysical data suggest a pre-Maastrichtian basement that comprises a continental crustal domain and an overlying ophiolitic mélange beneath the Maastrichtian to Quaternary cover.

Keywords: Eastern Anatolian Plateau, accretionary complex, continental crust, high-*T*/low-*P* metamorphism, Turkey

1. Introduction

The Eastern Anatolian Plateau (EAP) has an average elevation of 2000 m above sea level, and is bound by the Eastern Pontides to the north, the Arabian Platform to the south, the Iranian Plateau to the east, and Central Anatolian Plateau to the west (Figure 1). The northern and southern boundaries of the plateau are defined by the Neotethyan sutures such as the İzmir-Ankara-Erzincan suture to the north, and the Bitlis suture to the south. There is a decrease in the elevation towards Central Anatolia (approximately 1000 m) to the west and Central Iran (approximately 1500 m) to the east. The age of the youngest marine deposits in the Plateau is Middle Miocene (e.g., Okay et al., 2020),

suggesting that the attainment of the high elevation and formation of the Plateau occurred within the last 15 Ma.

The EAP, parts of the Eastern Pontides, and the Lesser Caucasus are extensively covered by Neogene to Quaternary volcano-sedimentary units (Yilmaz et al., 1987a, b; Pearce et al., 1990; Keskin, 2003; Keskin et al., 2006; Yilmaz et al., 2007). The pre-Neogene rock associations are largely concealed beneath these volcanic-sedimentary covers. The volcanic rocks are represented by calc-alkaline to alkaline basaltic to rhyolitic rocks and their pyroclastic rocks. The Neogene-Quaternary magmatism is probably related to mantle-crust interactions in a postcollisional setting which were probably caused by progressive slab peel-back

* Correspondence: ylmazali06@gmail.com

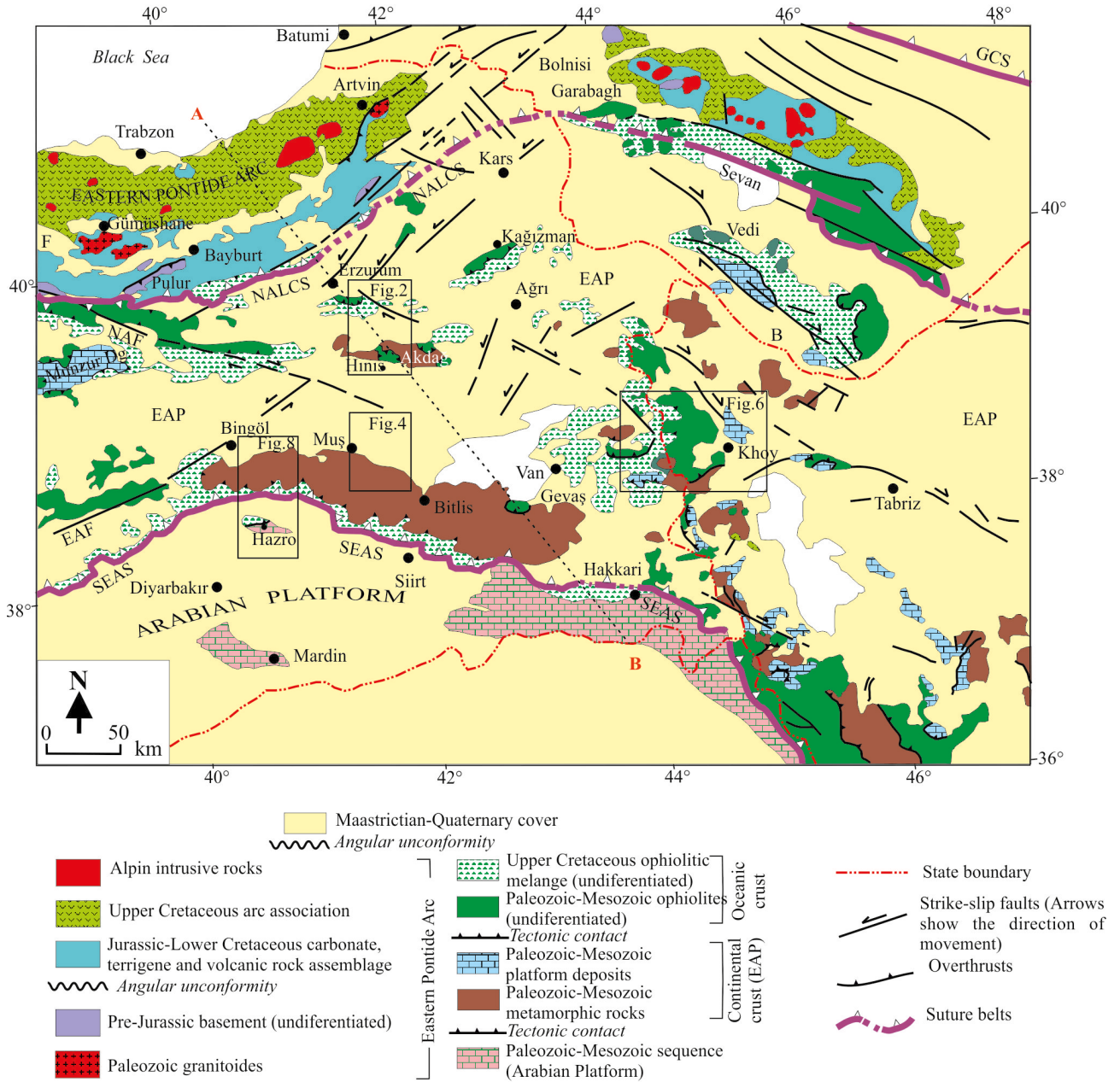


Figure 1. Geological map of the East Anatolian Plateau and adjacent continental blocks (modified from Yılmaz et al., 2014).

(e.g., Memiş et al., 2020). The youngest intrusions exposed are dated 19 to 24 Ma, suggesting that the latest significant uplift/exhumation occurred during the Early Miocene (e.g., Topuz et al., 2019). Therefore, exposures of the pre-Miocene rock associations are rare and confined to four isolated localities.

Two entirely different models have been proposed for the nature of the pre-Maastrichtian basement of Eastern Anatolia: It either consists (i) entirely of oceanic

accretionary complexes (Şengör and Yılmaz, 1981; Şengör et al., 2003, 2008; Yılmaz et al., 2022), or (ii) of a continental crust comprised of Late Cretaceous high- T /middle to low- P metamorphic rocks intruded by basic to acidic intrusions of the Late Cretaceous age and tectonically overlying Late Cretaceous ophiolitic mélanges (Yılmaz, 1989; Yılmaz et al., 2010; Topuz et al., 2017, 2021). For the reasons presented above, the well-exposed paleotectonic outcrops and overlying basin fills in the

Hınıs-Akdağ region, Muş Basin, Van, Bingöl-Hazro, and Gevaş regions (Figure 1) are evaluated in detail. The main aim of this paper is to reassess both models in light of field relationships not only between the pre-Maastrichtian basement rocks but also their cover. In addition, the Maastrichtian-Quaternary cover and structural units of the region have been evaluated in the framework of the geological, geophysical, and geochemical studies.

2. Regional geological studies

The pre-Maastrichtian rock associations and their cover are exposed primarily in the Hınıs-Akdağ region, Muş Basin, Van, Bingöl-Hazro and Gevaş regions (Figure 1). The geological features of these regions are described in detail below.

2.1. The Hınıs-Akdağ region

The Hınıs-Akdağ area represents the largest exposure of the pre-Maastrichtian basement of the EAP (Figures 1 and 2). The area has been mapped by Yılmaz et al. (1988, 1990, 2010) in detail and includes both the high-*T*/middle- to low-*P* metamorphic rocks and Late Cretaceous ophiolitic mélange and overlying pelagic forearc deposits. The Late Cretaceous ophiolitic mélange tectonically sits over the high-*T*/middle- to low-*P* metamorphic rocks (Figure 2) and is regarded as a part of large ophiolitic mélange and ophiolite obducted over the Anatolite-Tauride Block and south Armenian Block (Rolland et al., 2020). The tectonic contact is sealed by a basal conglomerate and overlying Maastrichtian reefal limestone (Yılmaz et al., 1988; Topuz et al., 2017). This unconformity is characteristic of the whole East Anatolian Plateau and Transcaucasus (Yılmaz et al. 2014; Yılmaz and Yılmaz, 2019). Figure 3A shows the tectonic contact between the high-*T*/middle- to low-*P* metamorphic rocks and the tectonically overlying diabase dyke complex, which is part of an ophiolite, and the unconformably overlying Maastrichtian reefal limestone (Figure 3B) to the north of Akdağ. In addition, detailed field mapping revealed the presence of several unconformities of pre-Middle Eocene, pre-Oligo-Miocene, and pre-Late Miocene ages in addition to the pre-Maastrichtian one (Yılmaz et al. 1988, 1990; Koçyiğit et al., 2001). These unconformities can be followed in the Eastern Anatolia in many places. This suggests that the emergence above the sea level and subsidence below the sea level occurred several times after Maastrichtian and the last one occurred during Middle Miocene. Relationships among the different rock types can be seen in the N-S cross-section across the Hınıs-Akdağ area (Figure 2).

The high-*T*/middle- to low-*P* metamorphic rocks comprise mainly marble (over 70% of the outcrop area), and subordinate garnet-cordierite-sillimanite migmatite, amphibolite, and calc-silicate gneiss (Yılmaz et al. 1988, 1990; Topuz et al., 2017). Pressure and temperature

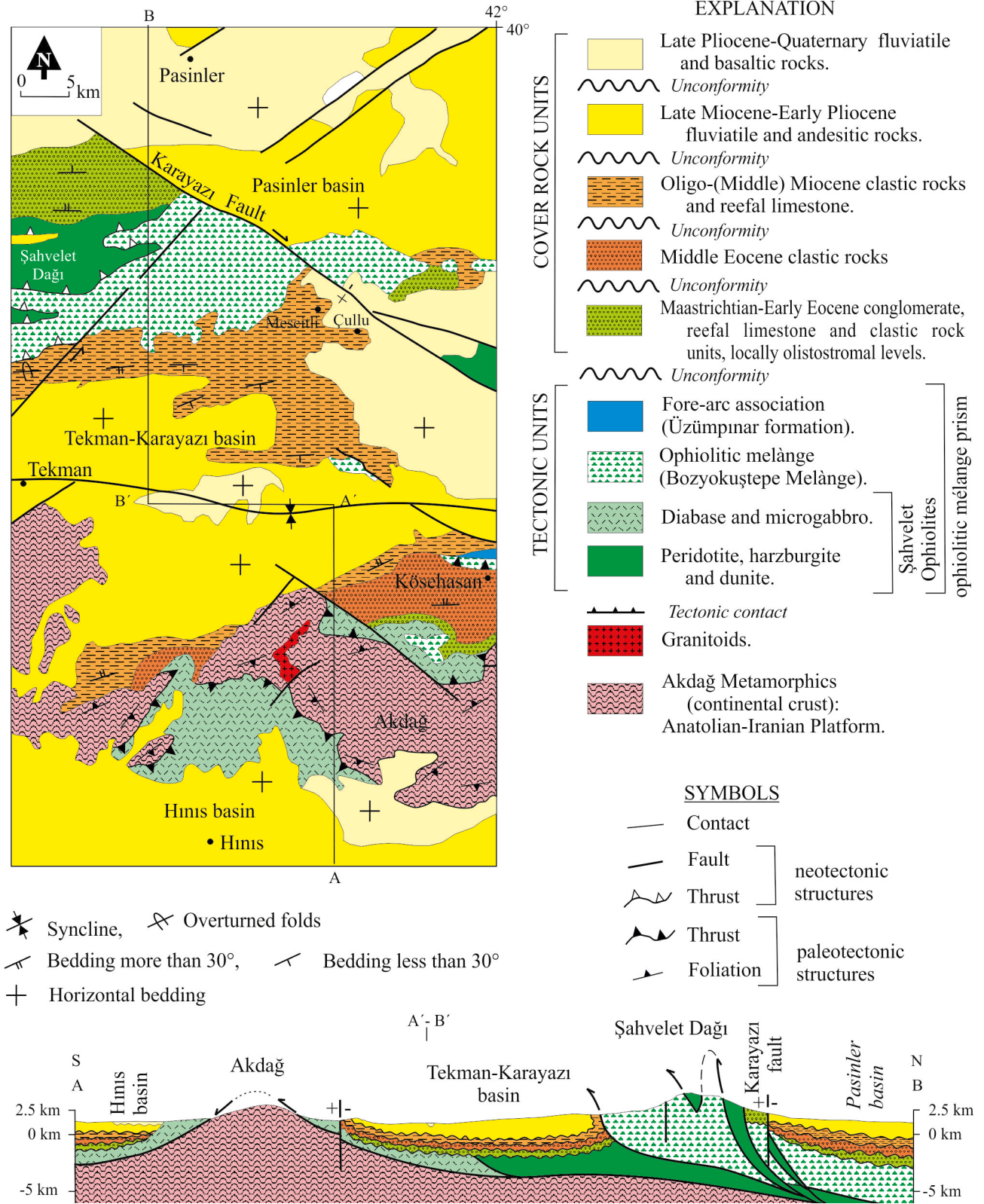
conditions are constrained as approximately 820 °C and 0.6 GPa (Topuz et al. 2017). The metamorphic rocks do not contain any evidence of a former high-pressure metamorphism. U-Pb dating of metamorphic zircon and rutile indicate that the metamorphism occurred at 82–85 Ma (Santonian, Late Cretaceous). Yılmaz and Yılmaz (2019) report on a granite body from the Akdağ area with Ar-Ar age of 84 ± 2 Ma (Santonian, Late Cretaceous). Seeing that the metamorphic rocks and tectonically overlying ophiolitic mélanges are unconformably overlain by Maastrichtian reefal limestone, several geological processes, such as (i) exhumation of the metamorphic rocks and (ii) emplacement of the ophiolitic mélanges, should have occurred within a time interval of 12–15 Ma. Gün et al. (2021, 2022) suggested that the exhumation of the metamorphic rocks was facilitated by the precollisional extension due to slab pull force along the İzmir-Ankara-Erzincan suture.

The Taşlıca metamorphic rocks, which occupy a comparable tectonic position as the Hınıs-Akdağ metamorphic rocks include a large Silurian anorogenic metasyenite to -granite with igneous crystallization age of 430–440 Ma (Silurian) (Topuz et al. 2021). They intruded into a clastic-carbonate rock assemblage of the Late Neoproterozoic to Early Paleozoic age. To sum up, both high-*T*/middle- to low-*P* metamorphic rocks represent part of a continental crust that can be lithologically correlated with the Anatolide-Tauride Block (Topuz et al., 2017, 2021). Metaquartzite in the Taşlıca area contains a significant population of Late Neoproterozoic zircons, suggesting that the protolith of the metaquartzite was deposited at the northern margin of Gondwana.

2.2. The Muş Basin

The Muş Basin is located in the southern part of the East Anatolian Plateau and to the north of the Bitlis Massif (Figure 1) and is approximately 85 km long and 15 km across. Figure 4 shows a simplified geological map of the Muş Basin and a roughly NW-SE striking cross-section (compiled from Uysal, 1986; Akay, 1989; Akay et al., 1989; MTA, 2002; Yılmaz and Yılmaz, 2019). The stratigraphic columnar section of the basin is given in Figure 5.

The basin is dominated by Oligo-Miocene sedimentary rocks, starting with continental reddish conglomerate (the Ahlat formation) and ending with reefal limestone (the Adilcevaz limestone) (Figure 4). The Middle Eocene clastic rocks are mostly in tectonic contact with the Oligo-Miocene sedimentary rocks, and probably underlie the Oligo-Miocene sedimentary rocks with a major unconformity. In the basin, there is no direct contact between the Oligo-Miocene basin fill and the Late Cretaceous ophiolitic mélange. Şengör et al. (2008) interpreted the basin fill as a part of the accretionary complex. On the other hand, field relations and the coherent stratigraphic sequence



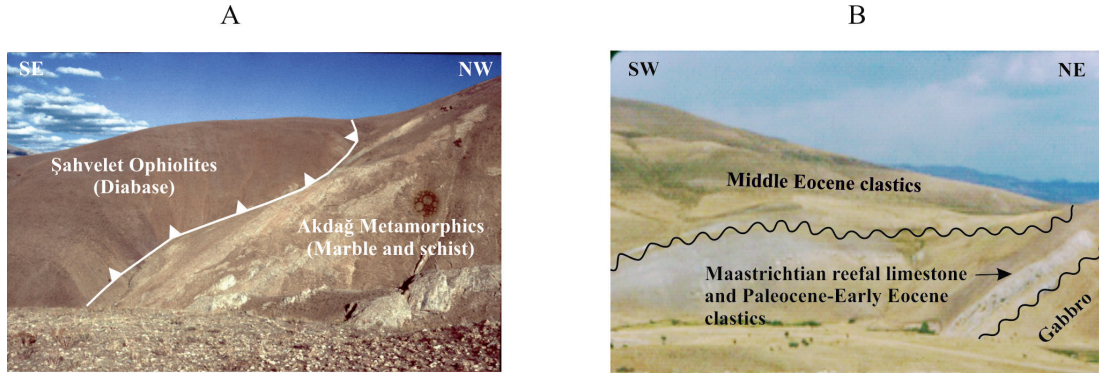


Figure 3. Field views from the Erzurum- Hınıs area. (A) The Akdağ Metamorphics and tectonically overlying diabase dike complex (ophiolite). (B) Ophiolite (gabbro) and unconformably overlying Maastrichtian reefal limestone and Eocene clastic rocks (Dündar village and İbo kom to the north of Akdağ).

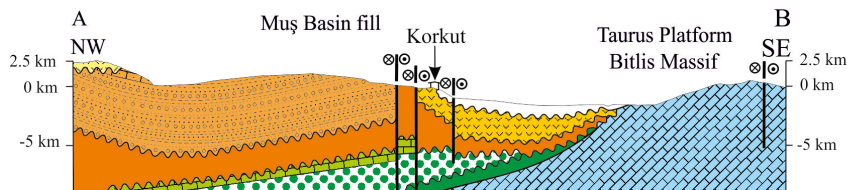
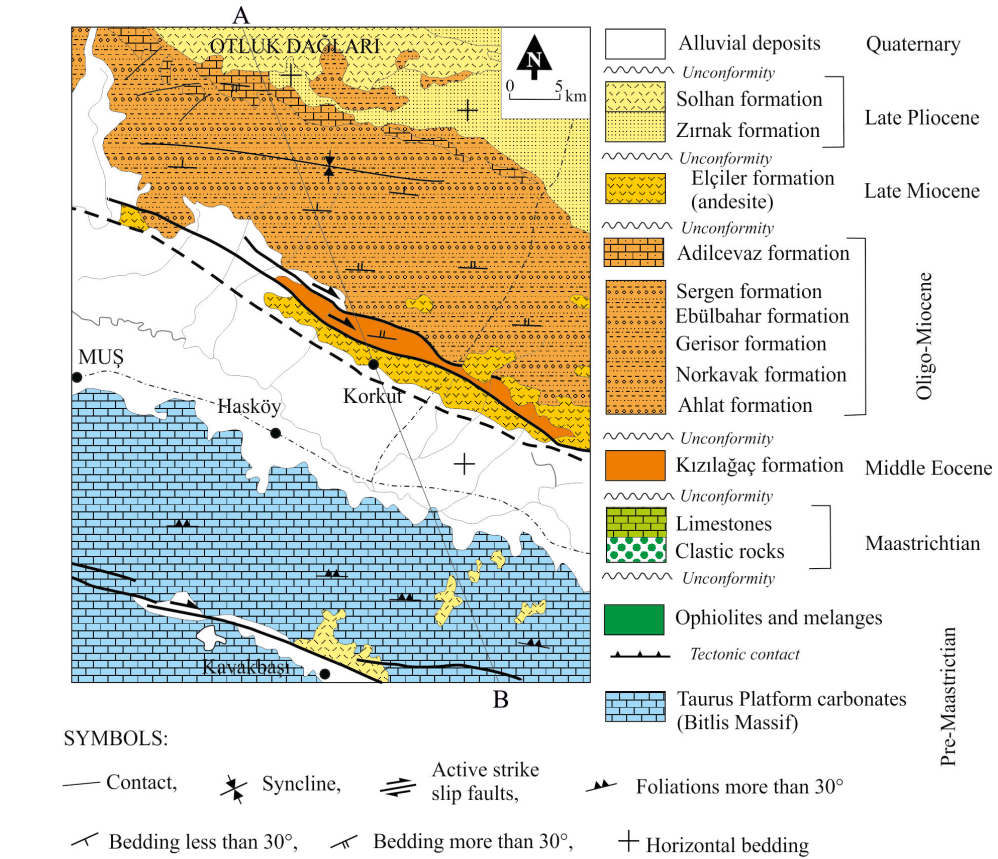


Figure 4. Geological map of the Muş Basin. The map is based on the studies by Uysal (1986), Akay (1989), Akay et al. (1989), MTA (2002), and Yılmaz and Yılmaz (2019). See Figure 1 for location.

Geological age	Formations	Lithology	Thickness (m)	Descriptions	Fossils
Quaternary	Solhan Zırnak		500	Unconformity: Basaltic lavas with clastics Clastic rocks association Unconformity	<i>Mimomys hajnackensis</i> , <i>M. stehlini</i> <i>M. pliocaenicus</i> , <i>Micromys</i> sp.
Pliocene	L E Elçiler		1000	Andesitic lavas and pyroclastic rocks, in places, fluvial deposits Unconformity	
Miocene	L M E Adilcevaz		4000	Reefal limestone	<i>Triquetrorhabdulus carinatus</i> Martini <i>Cyclicargolithus abisectus</i> (Müller) <i>Helicopontophaera recta</i> (Haq) <i>H. intermedia</i> Martini <i>H. euphratis</i> (Bramlette and Wilcoxon) <i>H. obliqua</i> (Bramlette and Wilcoxon) <i>Sphenolithus ciperoensis</i> (Bramlette and Wilcoxon)
Oligocene	Sergen Ebülbahar Gerisor Norkavak Ahlat			Reefal limestone and clay stone alternation Sandstone and conglomerate alternation Claystone and siltstone Unconformity: Reddish conglomerate Unconformity: Alternation of shale, claystone, sandstone and conglomerate Unconformity: Conglomerate and limestone Unconformity	<i>Cyclicargolithus floridanus</i> (Rot and Hay) <i>C. abisectus</i> (Müller) <i>Sphenolithus predistentus</i> (Bram. and Will.)
Middle Eocene	Kızılağaç		500		<i>Nummulites</i> sp. <i>Discocyclina</i> sp. <i>Assilina</i> sp. <i>Alveolina</i> sp.
Paleocene Maastrichtian					
Pre-Maastrichtian				Metamorphic rocks and ophiolites with melanges	

Figure 5. Stratigraphic columnar section for the Muş Basin and surrounding areas compiled from studies by Uysal (1986), Akay et al. (1989), and Yılmaz and Yılmaz (2019).

suggest that the Muş Basin is not a part of an accretionary complex. Akay (1989) suggests that the Muş Basin evolved as a typical intracratonic basin. We infer that the Muş Basin has probably developed on the pre-Maastrichtian rock associations, as can be seen in Figures 4 and 5. This inference is based on the field relations observed in the Bitlis-Mutki and Gevaş areas (Yılmaz et al. 1981; Göncüoğlu and Turhan, 1983; Yılmaz and Yılmaz, 2019). In these areas, there are major unconformities between the Maastrichtian-Early Paleocene and older units and between Maastrichtian-Early Paleocene and Middle Eocene units.

2.3. The Van region

The geology of the Van region and that of northwest Iran are summarized together below. Figure 6 shows a combined geological map of the Van region and the Ishgeh Su and Khoy areas of northwest Iran which is based on Şenel (1987) and Dizaj sheet at a scale 1/100,000, of the Geological Survey of Iran (1985). Pre-Maastrichtian, post-Eocene and neotectonic structures have been differentiated on the map. Figure 7 shows correlative columnar sections of the Van region and the Ishgeh Su-Khoy areas in Iran. Metamorphic rocks and platform-type carbonates

represent the oldest rocks in both the Van region and the Ishgeh Su-Khoy areas (Figure 6). These are in tectonic contact with the ophiolites and ophiolitic mélanges. Both are unconformably overlain by Maastrichtian-Eocene volcano-sedimentary rocks. The origin of the obducted ophiolites and ophiolitic mélanges is contentious. Topuz et al. (2017) regard large tracts of ophiolites along the Turkish-Iranian border as vestiges of an oceanic seaway that once separated the Anatolide-Tauride Block and the NW Iran. On the other hand, most researchers relate them to the İzmir-Ankara-Erzincan suture and metamorphic rocks as the metamorphosed equivalents of the Anatolide-Tauride Block (Yılmaz and Yılmaz, 2013). The N-S cross-section across the Van region shows the relationships between the different rock associations and unconformably overlying Maastrichtian-Eocene basin fills. Platform-type carbonates crop out to the north of Khoy and to the south of Saray and show similar stratigraphic and facies features as well as fossil contents (Figure 7). Şenel (1987) correlates platform-type carbonates of the region with those in the Anatolide-Tauride Block. Thus, we infer that the Anatolide-Tauride Block continues up to the northwest of Iran.

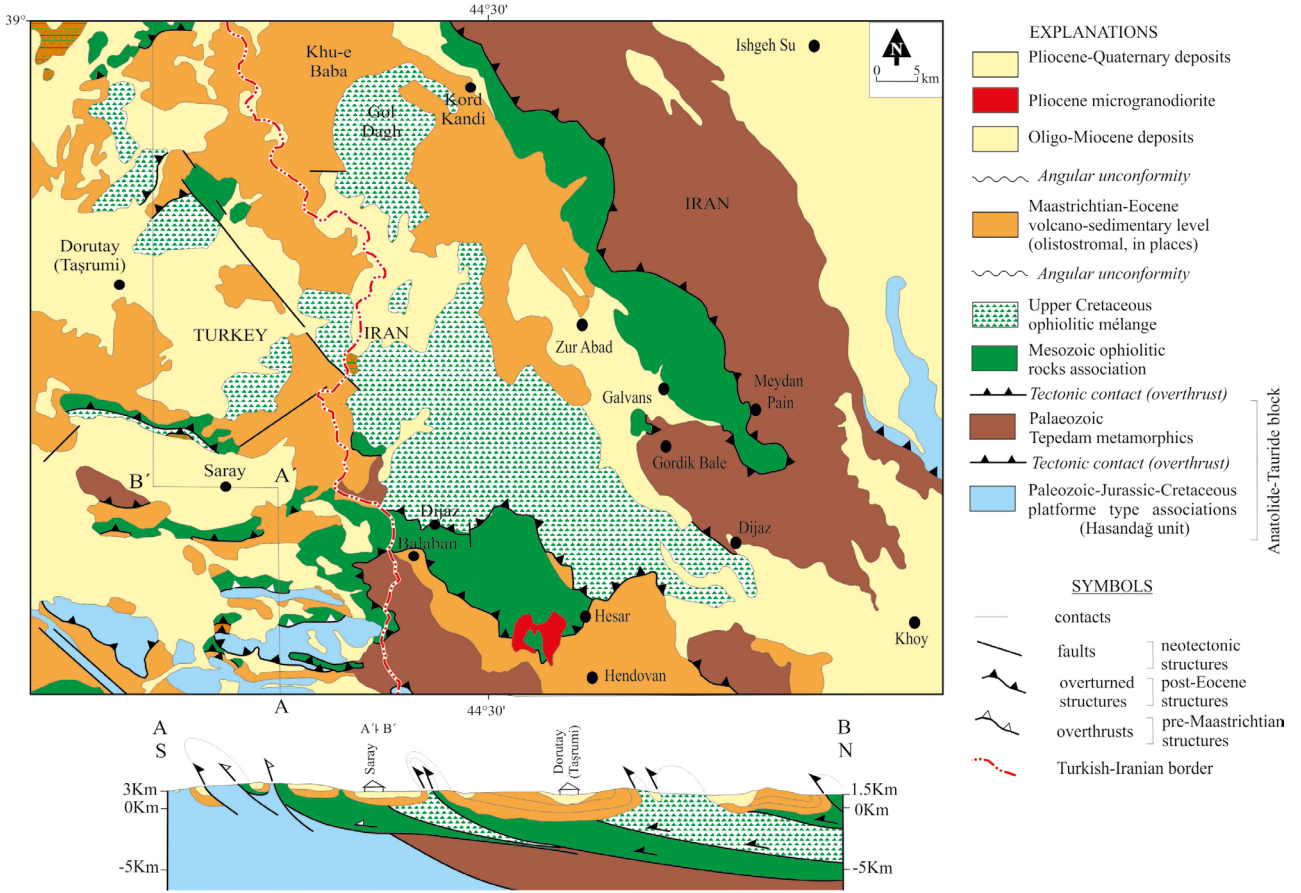


Figure 6. Geological map of the area between Van and Khoy (modified after Şenel 1987; Geological Survey of Iran, 1985; Azizi and Tsuboi, 2021). See Figure 1 for location.

2.4. The Bingöl-Hazro region

The tectonic setting of the Bitlis Massif is important for the basement rocks and basin fills of the EAP. There are conflicting ideas as to the setting of the suture zone between the Anatolide-Tauride Block and the Arabian Platform to the south. Figure 8 shows a geological map and cross-section of the area between Bingöl and Hazro (Diyarbakır). The Bitlis Massif is interpreted as the metamorphic equivalent of the Anatolide-Tauride Block, which is similar to the Keban-Malatya metamorphic rocks, representing the continental crust to the north of the suture. Figure 9A shows the Bitlis Massif with a Triassic volcano-sedimentary layer between carbonates near Tütü village at Kampos Tepe. On the other hand, some researchers suggest that the Bitlis Massif corresponds to the northern metamorphosed margin of the Arabian Platform and/or the suture runs in front of the Bitlis Massif.

The Hazro region is located approximately 15 km to the south of the Bitlis suture. We focus on the field relations in the Hazro region and farther north to discuss the relationship between the basement and the basin

fill. The Hazro region is made up of the carbonate rocks of the Arabian Platform and tectonically overlain by Late Cretaceous mélangé (Figures 1 and 8). Both are, in turn, unconformably overlain by Late Miocene to Quaternary sedimentary rocks (see cross-section in Figure 8). The southern boundary of the Bitlis Massif is characterized by a thrust fault. With this thrust, the Bitlis Massif is thrust over ophiolite/ophiolitic mélangé and Lower to Middle Eocene volcanoclastic rocks.

Whether the Bitlis Massif can be regarded as an equivalent of the high- T /middle to low- P metamorphic rocks of the East Anatolian Plateau is contentious. In clear difference to the high- T /middle to low- P metamorphic rocks in the Hınıs-Akdağ areas, the Bitlis Massif locally contains relicts of Late Cretaceous high-pressure rocks such as eclogite and blueschist (Oberhänsli et al., 2010, 2013). This suggests that the Bitlis Massif was involved in subduction. On the other hand, the Bitlis Massif includes greenschist-facies marbles and Triassic metavolcanosedimentary interlayers (Figure 9A) which can be correlated with the stratigraphy of the Anatolide-Tauride Block.

Geological Age	Turkish Side (Başkale Map) 1/100 000 series by General Directorate of MTA		Iran Side (Dizaj Map) 1/100 000 series by Geological Survey of Iran
Quaternary	Alluvium – terraces and fans, travertine		Alluvium – terraces and fans, travertine
Pliocene	Basaltic lava and pyroclastic rocks Andesitic lava flows (Saray formation)		Andesitic lava flows in general and microgranodiorite
Oligo-Miocene	Dacitic volcanics in places Shallow marine with continental deposits		Andesitic -trachyandesitic and dasitic volcanics
Eocene	Mendikdere formation Yücelendere formation		Basaltic lava flows with shale and limestone Grey and reddish imestone
Paleocene	Şehittepe unit	Volcano sedimentary level (olistostromal in places)	Sandstone with shale and colored shale with green conglomerate
Maastrichtian			Alternation of shale, sandstone with intercalations of conglomerate and limestone
~~~~~ <i>Angular unconformity</i> ~~~~~			
E. Cretaceous Jurassic (?)	Ophiolites with ophiolitic melanges (Mehmetalán Peridotite and Bakışık Melange)		Ophiolitic complex including ultramafic rocks, harzburgite and dunite, serpentinite, pelagic limestone, basaltic lava flows partly with radiolarian chert.
Mesozoic Paleozoic (?)	Tepedam Metamorphics: Green metavolcanics with schists and crystallized limestone		Metamorphic rocks: Green metavolcanics with green schists and crystallized limestone
Jurrassic Triassics Paleozoic	Hasandağ Unit: Grey crystallized limestone and in places dolomitic levels		Dark grey crystallized limestone with Fusulins and dolomitic limestones

**Figure 7.** Correlative columnar section of the Van region (after Şenel, 1987; Yılmaz et al., 2010) and Khoy area (Dizaj sheet, 1/100,000, Geological Survey of Iran, 1985).

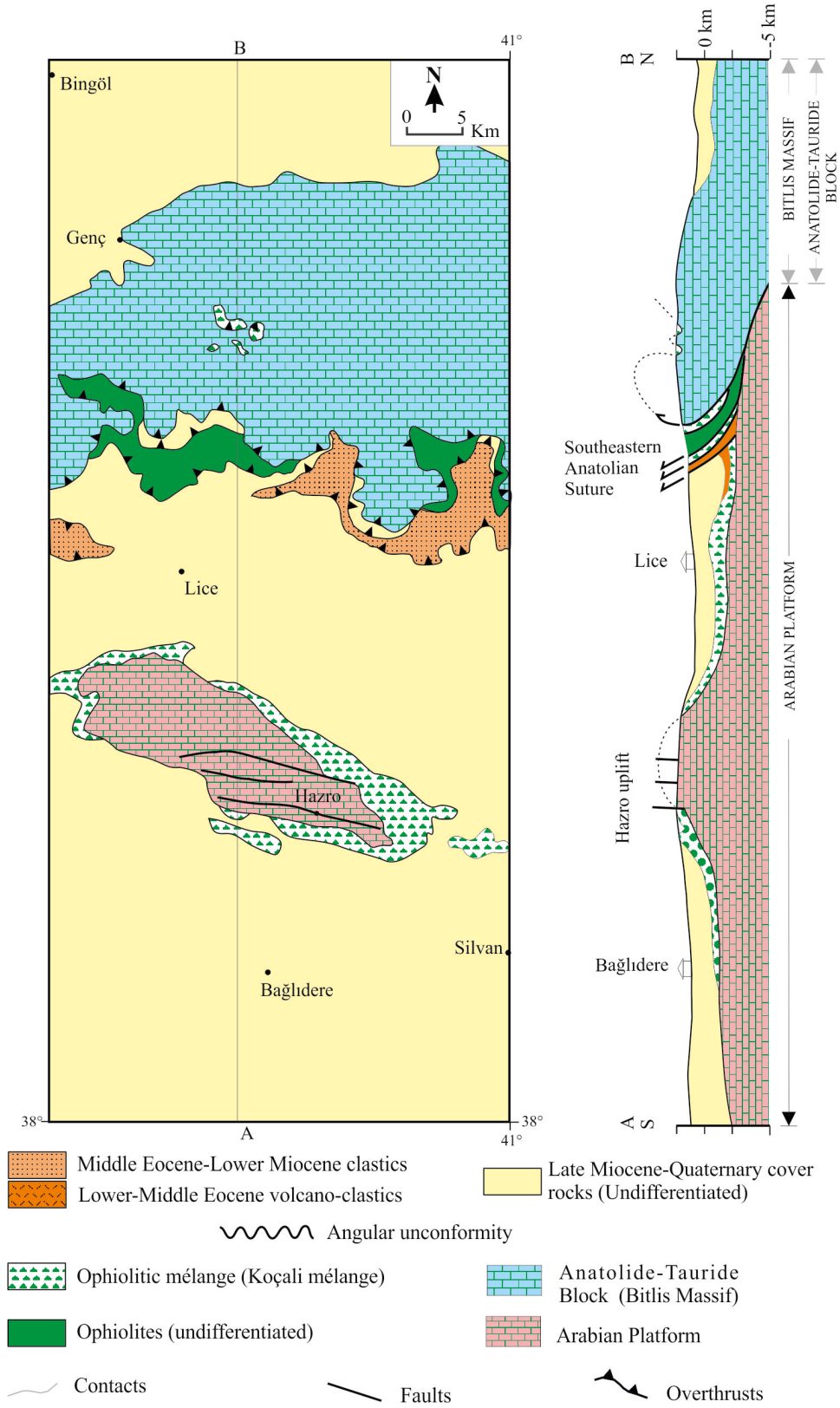
## 2.5. The Gevaş region

The Gevaş region is a critical area to evaluate the relationships between the ophiolites and metacarbonates of the Bitlis Massif. This region is located to the southeast of Lake Van and is made up of the greenschist-facies rocks of the Bitlis Massif and the Gevaş Ophiolite (Figure 1). In clear contrast to the ophiolitic rocks to the south of the Bitlis Massif (Figure 8), the Gevaş Ophiolite is thrust over the Bitlis Massif (Figure 9B). The Bitlis Massif representing a typical continental crust is at the base and the ophiolite tectonically sits on the top in the Gevaş region, as seen in the Hınıs-Akdağ area and in other places of EAP. The

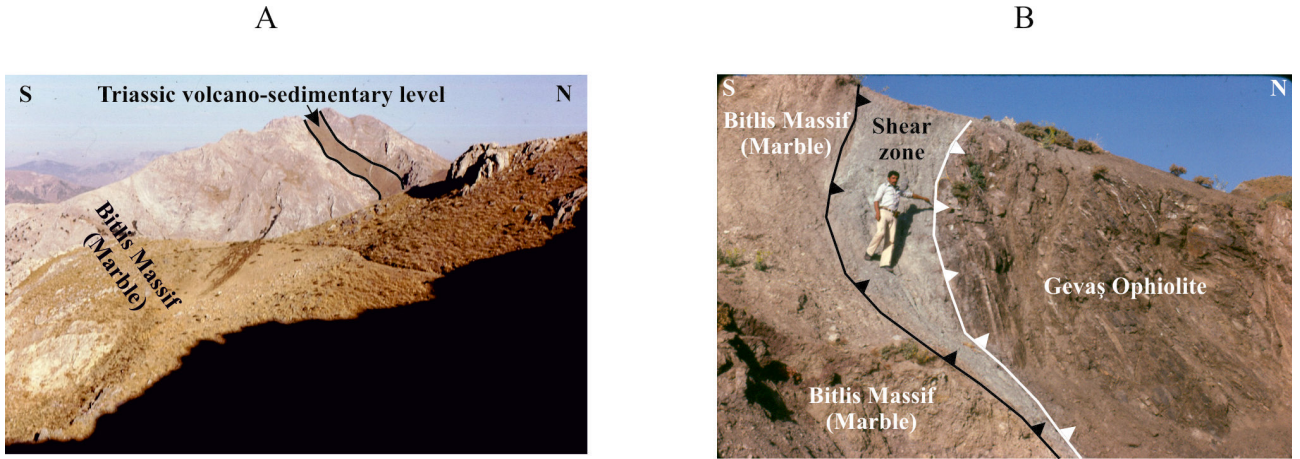
structures in Figure 8 may have resulted from the ophiolite emplacement during subduction. In addition, there are major unconformities between the Maastrichtian-Early Paleocene, Middle Eocene and Oligo-early Miocene, late Miocene-Pliocene units of the EAP around the Gevaş area (Yılmaz et al. 1981; Göncüoğlu and Turhan, 1983; Yılmaz and Yılmaz, 2019).

## 2. Geophysical studies

In Eastern Anatolia, controlled source seismic profiles presented by Yılmaz et al. (2022) across the basin fills of the East Anatolian Plateau were capable of resolving only



**Figure 8.** Geological map of the area between the Bingöl and Silvan (modified after MTA, 2002; Yılmaz and Yılmaz, 2013). See Figure 1 for location.



**Figure 9.** (A) Triassic metavolcano-sedimentary level within marble in the Bitlis Massif (Tütü village, Kampos tepe). (B) The Gevaş Ophiolite is thrust over the Bitlis Massif (the Gevaş area).

1000–2500-m deep structures. In fact, the thickness of the Maastrichtian-Quaternary sequence is at least more than 4000 m and the thickness of *mélange*-related units is more than 1500 m in the eastern Anatolia (Yılmaz et al., 2010). Hence, a complementary tool to verify the geophysical evidence requires the drilling process down to a depth of 7–8 km at suitable locations in Eastern Anatolia.

In the last two decades, a number of geophysical studies (e.g., Dehghani and Makris, 1984; Maggi et al., 2000; Al-Lazki et al., 2003; Gök et al., 2003; Zor et al., 2003; Maggi and Priestley, 2005; Angus et al., 2006; Zor, 2008; Pamukçu et al., 2007; Pamukçu and Akçığ, 2010; Fichtner et al., 2013; Vanacore et al., 2013; Pamukçu et al., 2014, 2015; Maden and Öztürk, 2015; Oruç et al., 2017; Zhu 2018; Confal et al., 2018, 2020; Wang et al., 2020; Eken et al., 2021) have been conducted on the East Anatolian Plateau to understand the deeper sections of crust and mantle. According to their findings, the EAP is characterized by the highest topography and the deepest Moho in all of Turkey. Early analyses using gravity, magnetic, and topographic data estimated a crustal thickness variation of 38 to 52 km in the region (Pamukçu et al., 2007). Recently, modeling of teleseismic P-coda autocorrelation function in Eken et al. (2021) has suggested a range of Moho depths (crustal thicknesses) between 40 and 58 km. All these estimates suggest that the EAP has a relatively thickened crust. However, these crustal thicknesses are less than an isostatically compensated thick crust (Dewey et al., 1986).

The P- and S-receiver function models (Angus et al., 2005; Kind et al., 2015) together with surface wave inversions (Gök et al., 2008) showed a relatively thinned lithospheric mantle (about 70–80 km), suggesting that the high elevation of the plateau is supported by asthenosphere

(Şengör et al., 2003). The significantly thinned mantle lithosphere is also confirmed by low Pn velocities and high Sn attenuation (Al-Lazki et al. 2003; Gök et al. 2003) as well as by the logarithmic amplitude spectra of Bouguer anomalies in Oruç et al. (2017) constraining an average depth of the lithosphere-asthenosphere boundary (LAB) at 84 km. The extensive magma generation is presumably due to the mechanical removal of the mantle lithosphere in the form of delamination (Göğüş and Pysclewec, 2008; Topuz et al., 2017) or slab break-off (Zor, 2008). Confal et al. (2018) showed the validity of the detachment process within the Arabian plate (break-off) through a 3-D petrological-thermo-mechanical modeling.

Slow P- and S-wave speeds beneath volcanic fields (Zhu 2018; Wang et al., 2020; Eken et al., 2021) that are correlated with high Vp/Vs down to uppermost mantle depths likely reflect high temperature in relation to Neogene–Quaternary magmatism. The shallow Curie point depths vary between 6 and 24 km inferred from the spectral analysis of magnetic anomalies (Pamukçu et al., 2014). These observations together with low-resistivity geo-electrical features modeled via the inversion of long-period magnetotelluric data (Türkoğlu et al., 2008) imply pockets of local melt accumulation in the lower crust that is underlain by anomalously low resistivity and low seismic velocity asthenosphere containing a few percent partial melts in the Eastern Anatolia. An overall increase in Vp/Vs variation in the region may hint toward mafic lower crustal rocks or melts/fluids.

### 3. Geochemical studies

As pointed out above, the East Anatolian Plateau is extensively covered by Neogene to Quaternary volcanic

sedimentary rocks (e.g., Yılmaz et al., 1987a,b; Pearce et al., 1990; Keskin et al., 1998; Keskin, 2003; Keskin et al., 2006; Özdemir and Güleç, 2014; Oyan et al., 2016; Lebedev et al., 2016; Kaygusuz et al., 2018; Açlan et al., 2020; Üner, 2021). Comparable volcanic rocks were also reported from the Eastern Pontides and Transcaucasus (Yılmaz et al., 2000). These volcanic sequences overlie Eocene- Oligocene-Early Miocene sequences in the Eastern Pontide-Southern Transcaucasus magmatic arc. During the field mapping, two clearly different horizons of volcanic rocks are differentiated: The early one is represented by late Miocene andesitic lavas with volcano-sedimentary rocks, while the second one is Pliocene basalt lavas with its pyroclastic rocks (Figure 5, the horizons indicated as the letters A and B in the columnar section), respectively. The thickness of the volcanic cover is estimated to be around 1 km. The high-volume volcanism occurred between 12 Ma and present. Late Oligocene-Early Miocene magmatic rocks (19–23 Ma) are represented mainly by shallow-level granitoids and minor gabbroids with high-K calc-alkaline affinity (Oyan, 2018; Topuz et al., 2019; Rabayrol et al., 2019). The absence of younger intrusions is ascribed to the absence of a significant uplift and exhumation after the Middle Miocene (Topuz et al., 2019). Middle to Late Miocene volcanic rocks range from middle- to high-K calc-alkaline basalt to rhyolite with minor alkaline basalt, trachybasalt, and trachyandesite. Özdemir et al. (2022) report on minor tholeiitic basalts of Late Miocene age. The Pliocene and Quaternary volcanic rocks are variably alkaline, ranging from tephrite/basanite to phonolite and alkaline basalt to trachyte, while high-K calc-alkaline intermediate to felsic rocks are subordinate (Özdemir and Güleç, 2014; Oyan et al., 2016; Rabayrol et al., 2019; Özdemir et al., 2022).

All these volcanic rocks carry geochemical characteristics with a variable amount of subduction components and/or crustal assimilation. Asthenospheric melts with OIB-type geochemical signatures are only documented from the Quaternary volcanic rocks on the Bitlis Massif and on the Arabian Platform (Özdemir et al., 2019). Likewise, melts that can be interpreted as products of the continental crustal melting are unknown on the plateau.

#### 4. Discussion

There is no consensus on the geological setting of eastern Anatolia among proponents of continental and oceanic models. In addition to the disadvantage of limited paleotectonic outcrops, there is no agreement on the tectonic processes or on the separation of tectonic phases. In the present paper, the relationships between tectonic units and tectonic phases were evaluated on the geological maps (Figures 2, 4, 6, and 8). In this context, the following results have been highlighted after evaluating both models that

were inferred from different geological, geophysical, and geochemical evidence. In fact, a model should, first and foremost, be based on reliable geological relationships. If there is no agreement on the geological relationships, no further step can be taken. Below, we focus on the field relations where continental crust, ophiolitic units, and basin fills crop out.

The Hınıs-Akdağ region is a critical region for the age of the basin fill and the boundary relationship between the tectonic units. The different rock units and contact relationships have been interpreted as a component of the ophiolitic mélange-accretionary complex by Yılmaz et al., (2022) (Figures 8A–8C, 9A, and 9B). The map shows a tectonic alternation of the continental metamorphic rocks and ophiolitic rocks overlain unconformably by the Eocene units. In the study, both field mapping and aerial photos have been used for the determination of contact relationships. Figure 2 shows the detailed geological map and cross-section of the Hınıs-Akdağ region. Figure 3A displays the boundary relationships between continental metamorphic rocks and ophiolites, and Figure 3B the contact relationships between the basement and the oldest basin fill. The field relationships clearly suggest that the continental metamorphic rocks represent the basement, and ophiolitic rocks tectonically sit over the metamorphic rocks. The Maastrichtian reefal limestone and middle Eocene units unconformably overlie the basement, respectively.

The Muş Basin is another key locality for differences and contradictions involving both models. Şengör et al. (2008; Figure 24: Geological map of the Muş Basin) interpreted the Oligocene-early Miocene deposits of the Muş Basin as a component of the ophiolitic mélange-accretionary complex. On the other hand, Yılmaz et al. (2022) suggested that the Neo-Tethyan oceanic lithosphere was eliminated from the entire eastern Turkey by the late Eocene. This is the only difference between Şengör et al. (2008) and Yılmaz et al. (2022). On the basis of both studies, there are purely oceanic accretion complexes beneath the EAP. It is not possible to define the age of the accretionary complex directly in the Muş Basin, as the basin fill consists of shallow marine and continental deposits that are interpreted as molasse deposits in this study. Similar to cover units in the Bitlis, Mutki, and Gevaş areas, there are unconformities between Maastrichtian-early Paleocene and older basement units, and Maastrichtian-early Paleocene and Eocene units (Yılmaz et al., 1981; Göncüoğlu and Turhan, 1983; Yılmaz and Yılmaz, 2019).

The Van region is another interesting area where metamorphosed and unmetamorphosed equivalents of the Anatolide-Tauride Block are exposed. Figures 6 and 7 show the relationships among different units including metamorphic rocks, unmetamorphosed crustal

rocks, and the Neogene to Quaternary cover rocks. The unmetamorphosed units to the south of Saray (in Turkey) and to the north of Khoy (in Iran) comprise comparable rock types and stratigraphies. Maastrichtian-Quaternary rocks unconformably overlie the pre-Maastrichtian rock associations in both Saray and Khoy areas. Thus, both the pre-Maastrichtian rock associations and the cover units can be correlated with each other.

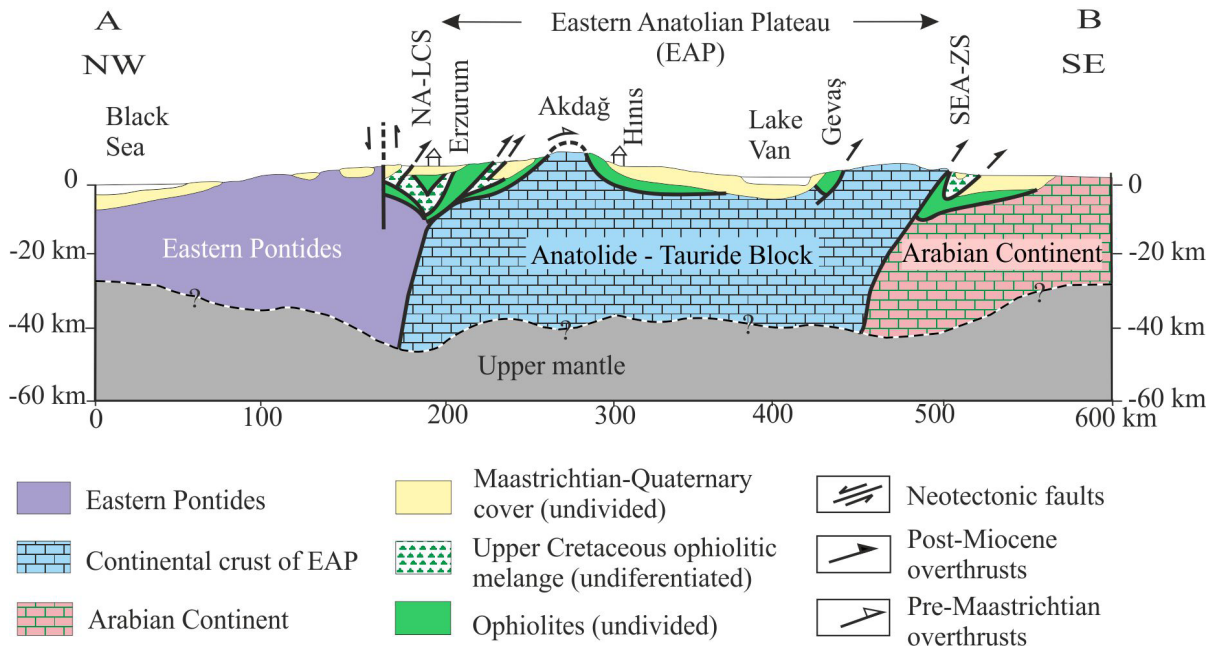
At depth of 50–60 km beneath the EAP, there are regions of high  $V_p/V_s$  distributions ( $>2.2$ , corresponding to low S-wave speeds) (Zhu, 2019; Eken et al., 2021). These zones likely imply regions of partial melt in the lowermost crust and lithospheric mantle beneath volcanoes in Eastern Anatolia. This is not surprising given the presence of Quaternary high-volume volcanism in the region. As pointed out above, the various geophysical observations and relevant models indicated relatively large Moho depths corresponding to a thick crust (reaching up to 58 km) across the entire EAP. Such large crustal thicknesses are not expected to be made up entirely of oceanic accretionary complexes.

The majority of the strike-slip faults in the EAP are active and postdate the formation of the ophiolitic mélanges (Figure 10). The Plio-Quaternary sequences are mostly horizontal and unfolded across the entire region and are inclined close to the active faults (Koçyiğit et al., 2001). The neotectonic structures in the plateau as a

whole represent the rhomboidal cell model in the internal deformation of the Turkish-Iranian Plateau (Seyitoğlu et al., 2018).

## 5. Conclusion

Two contrasting models have been proposed for the nature of the basement of the East Anatolian Plateau: (i) oceanic accretionary complexes, and (ii) a continental basement forming an eastward extension of the Anatolide-Tauride Block. In this paper, these models have been reassessed within the framework of recent geological, geophysical, and geochemical studies. Field relations among the rock units indicate the presence of Late Cretaceous high- $T$ / middle- to low- $P$  metamorphic rocks. These metamorphic rocks do not contain any evidence of involvement in subduction-zone metamorphism and locally include metasyenite to granite with Silurian igneous crystallization ages. The high- $T$ / middle- to low- $P$  metamorphic rocks can be correlated with those of the Anatolide-Tauride Block in terms of lithology. Such a correlation is also supported by the local presence of the platform-type carbonates in the Van region and NW Iran, which were a common component of the Anatolide-Tauride Block. The late Cretaceous (pre-Maastrichtian) ophiolitic mélanges and ophiolites tectonically overlie both high- $T$ / middle- to low- $P$  metamorphic rocks and platform-type carbonate rocks and were interpreted as obducted vestiges of the Neo-



**Figure 10.** Simplified synthetic cross-section showing the nature of the crustal structure of the East Anatolian Plateau (EAP) and its relationships with neighboring tectonic units (NA-LCS: North Anatolian-Lesser Caucasus Suture zone; SEA-ZS: South Eastern Anatolian-Zagros Suture zone). See Figure 1 for location.

Tethyan seaways. Obduction of the ophiolites and ophiolitic mélanges as well as the exhumation of the metamorphic rocks were completed before Maastrichtian time.

The post-Maastrichtian rocks show the presence of several unconformities, suggesting that East Anatolia emerged above sea level and subsided below sea level several times. The last marine deposits are of the Early to Middle Miocene age. The development of the Plateau occurred in the last 15 Ma. Extensive Neogene magmatism occurred in a postcollisional setting, as a consequence of the interaction of subducting slab/crust-mantle interactions.

In conclusion, after evaluating of the recent geological, geophysical, and geochemical studies and also reevaluating

both hypotheses, Figure 10 has been presented as a synthesis.

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