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Postcollisional extensional tectonics and exhumation of the Menderes massif in the Western Anatolia extended terrane, Turkey

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ABSTRACT

The Western Anatolia extended terrane in Turkey is bounded by the North Anatolian fault zone to the north, the Lycian nappes to the south. It contains the Menderes massif, one of the post-collisional Alpine metamorphic core complexes. Field data and available radiometric ages suggest that the north-directed Cenozoic extension in the terrane is the product of three consecutive, uninterrupted stages, and that it is still continuing today. The first stage was initiated in the Late Oligocene along a north-dipping extensional simple-shear zone with a listric geometry at depth. The shear zone is named here as the Southwest Anatolian shear zone and marks the southern and southwestern boundary of the Western Anatolia extended terrane. Evidence for the presence of this shear zone includes (1) the dominant top to the north-northeast shear sense indicators in the Menderes massif and (2) a series of Oligocene extensional basins located adjacent to the shear zone that contain carbonate and ophiolitic rock clasts, but no high-grade metamorphic rock fragments. During this stage, erosion and extensional unroofing brought high-grade metamorphic rocks of the Central Menderes massif to the surface by the early Miocene. The second stage of extension produced the north-dipping Alasehir and the south-dipping Büyük Menderes detachment surfaces in the early Miocene. The detachments control the Miocene sedimentation in the Alasehir and Büyük Menderes grabens, containing high-grade metamorphic rock fragments that were already at the surface in the Central Menderes massif in the early Miocene. The third stage of extension may have started ca. 5 Ma, when the North Anatolian fault was initiated. This extensional phase produced faults within the Alasehir and Büyük Menderes grabens and possibly the Kucuk Menderes graben.

Keywords: extensional tectonics, Menderes massif, Turkey, metamorphic core complexes

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INTRODUCTION

The Aegean region of southeastern Europe and southwestern Asia is one of the best-developed examples of postcollisional extended terranes in the world. The region is part of the Alpine-Himalayan belt (Fig. 1), and it experienced a series of continental collisions from the Late Cretaceous to the Eocene that led to the formation of the Izmir-Ankara-Erzincan and Tauride suture zones (e.g., Şengör and Yılmaz, 1981; Tankut et al., 1998; Dilek et al., 1999; Stampli, 2000). Although its age and origin are controversial, postcollisional extension in the Aegean region caused the exhumation of several Alpine metamorphic massifs, including the Menderes, Crete, Cyladic, Rhodop, and Kazdag massifs (Fig. 1).

Most of the extended Aegean region coincides with the Aegean Sea, where extensional features are difficult to study because they are exposed above water only on the Aegean Islands. The extensional features, however, are well exposed in the Western Anatolia extended terrane in Turkey (Figs. 1 and 2). That terrane is bounded by the North Anatolian fault zone to the north, the Lycian nappes to the south, and an ENE- to northeast-trending fault zone to the southeast (Figs. 1 and 2) that is here named the Southwest Anatolian shear zone.

The Western Anatolia extended terrane occupies an area of >50,000 km^2 and contains exposures of the metamorphic and igneous rocks of the Menderes massif, which has been recognized as a metamorphic core complex (e.g., Bozkurt and Park, 1994; Hetzel et al., 1995a,b; Emre and Sözbilir, 1997; Isik and Tekeli, 2001). The Menderes massif is divided into northern, central, and southern sections by east-west-trending grabens. The region to the north of the Alasehir graben is referred to as the Northern (Gördes) Menderes massif, and it contains the north-trending Gördes, Demirci, and Usak-Selendi basins. The area between the Alasehir and Büyük Menderes grabens is recognized as the Central Menderes massif. The region between the Büyük Menderes graben and the ENE-trending Gökova and Kale-Tavas basins is called the Southern (Çine) Menderes massif (Fig. 2).

The objectives of this article are to (1) describe the geologic history of the Menderes massif via both geochronology and thermobarometry; (2) discuss the structural features of the Western Anatolia extended terrane, including microstructural shear sense indicators; (3) describe the synextensional sedimentary rocks in Cenozoic extensional basins in the northern and central parts of the Menderes massif and along the Southwest Anatolian shear zone; and (4) propose a three-stage continuous extension model for the structural development of the terrane.

REVIEW OF CENOZOIC EXTENSION IN WESTERN ANATOLIA

Since the early 1900s, western Anatolia and the Aegean region have been recognized as being formed by crustal extension. High-angle crust-penetrating normal faults were discovered and documented in the region throughout the early and middle parts of the twentieth century (e.g., Phillipson, 1910–1915; Erinc, 1955). The discovery of low-angle normal faults (e.g., Wright and Troxel, 1973; Wernicke, 1981) and strike-slip shear zones (Çemen et al., 1985), together with the recognition of metamorphic core complexes in the Basin and Range province of North America (e.g., Davis, 1980), changed our understanding of the geometry and evolution of extensional features worldwide and assisted modern geological studies in extended terranes. Although the metamorphic core complex origin of the Central Menderes massif is generally accepted today (e.g., Bozkurt and Park, 1994; Hetzel et al., 1995a,b; Emre and Sözbilir, 1997; Gessner et al., 2001a; Ring and Collins, 2005), the origin, timing of initiation, geometry, and evolution of the major extensional features in western Anatolia remain controversial.

Models proposed for the origin of extension in western Anatolia include (1) tectonic escape (e.g., Dewey and Şengör, 1979; Şengör, 1979; Şengör and Yılmaz, 1981; Şengör et al., 1985) and its modification, the lateral extrusion (Çemen et al., 1993, 1999); (2) back-arc extension (e.g., McKenzie, 1978; Le Pichon and Angelier, 1979, 1981) in response to subduction roll-back (e.g., Meulenkamp et al., 1988; Spakman et al., 1988); and (3) orogenic collapse (e.g., Dewey, 1988; Seyitoğlu and Scott, 1996; Dilek and Whitney, 2000). These models imply different timing for initiation of extension in western Anatolia. Tectonic escape models require initiation of extension in the Tortonian (late Miocene) commensurate with westward movement of the Anatolia plate along the North Anatolian fault zone (Fig. 1), whereas back-arc extension and subduction roll-back models suggest that the extension started in the early Miocene as subduction along the Hellenic arc shifted southwest. The orogenic collapse model suggests that extension might have started as early as the Oligocene after Eocene thickening subsided.

Radiometric age determinations have been used in attempts to solve this controversy. Hetzel et al. (1995a,b) proposed that extension along the Alasehir detachment began in the early Miocene (19.5 ± 1.4 Ma) based on the $^{40}Ar/^{39}Ar$ amphibole age from a "synextensional" granodiorite that they interpreted as intruding prior to brittle deformation along the detachment surface. This widely cited age (e.g., Hetzel et al., 1995a; Seyitoğlu and Scott, 1996; Gessner et al., 2001a; Lips et al., 2001) is the sole evidence for early Miocene extension. However, the extensional origin of the granodiorite is controversial. Yılmaz et al. (2000) interpreted it as the product of crustal thickening during the formation of the Izmir-Ankara suture zone. In addition, the age spectrum and correlation diagram show that the amphibole is affected by excess argon, so its apparent age may be spuriously old.

A bivergent rolling hinge model for the Central Menderes massif was developed based on the oppositely dipping Alasehir and Büyük Menderes detachments (Fig. 2; Gessner et al., 2001a). In this model, the two detachments developed as high-angle normal faults in the early Miocene. The Alasehir graben of the Central Menderes massif may have been formed by a process similar to the rolling hinge or flexural bending model of extension proposed for the Death Valley graben of the Basin and Range

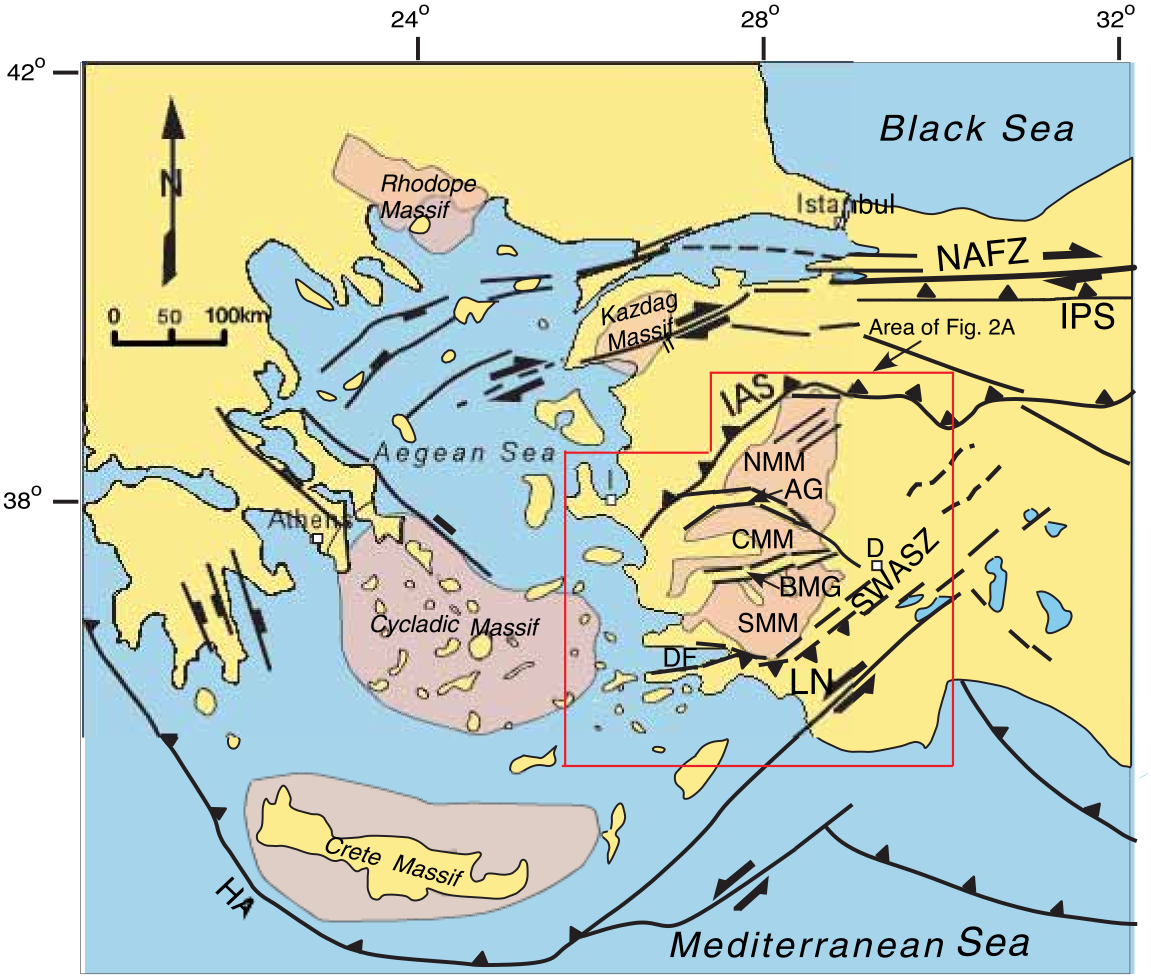
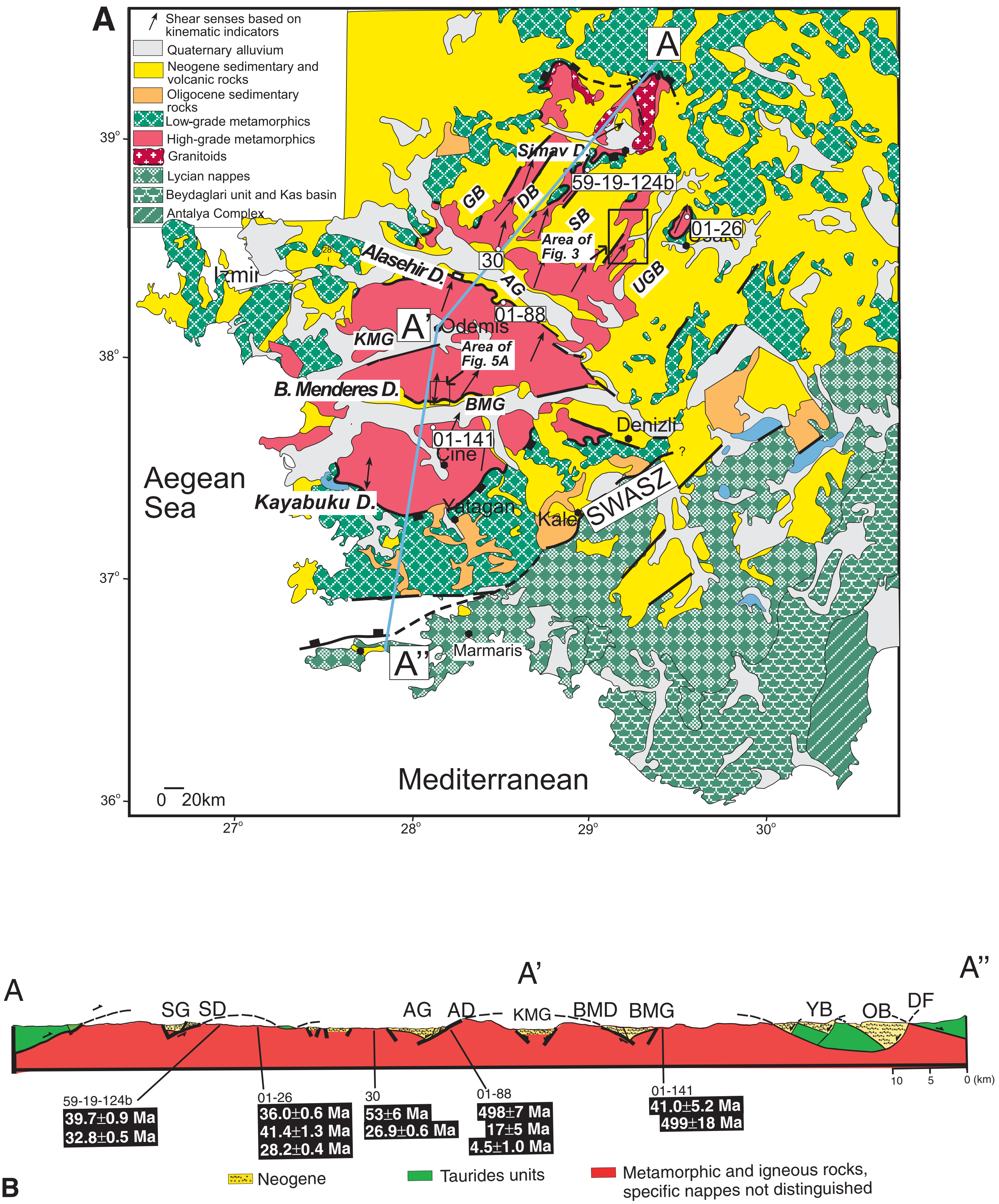


Figure 1. Generalized map of the Aegean region showing the location of major structural elements and Alpine metamorphic belts shaded in pink. The red box outlines the Menderes massif in western Anatolia, Turkey (see Fig. 2). Abbreviations: Towns: D—Denizli; I—Izmir. Structural elements: AG—Alasehir graben; BMG—Büyük Menderes graben; CMM—Central Menderes massif; DF—Datça fault; HA—Hellenic arc; IAS—Izmir-Ankara suture; IPS—Intra-Pontide suture; LN—Lycian nappes; NAFZ—North Anatolian fault zone, NMM—Northern Menderes massif; SMM—Southern Menderes massif; SWASZ—Southwest Anatolian shear zone.

province (see Seyitoğlu et al., 2002; e.g., Hamilton, 1988; Wernicke, 1988, 1992; Wernicke et al., 1988; Holm et al., 1992).

Ring et al. (2003) proposed that extension in western Anatolia was initiated in the late Oligocene along two oppositely dipping symmetric deep-seated detachment surfaces that unroofed the high-grade metamorphic rocks of the Menderes massif in the late Miocene in a process similar to the flexural rotation and deep-seated normal fault model processes (e.g., Buck, 1988). They also proposed that a second episode of extension started around the Miocene-Pliocene boundary, again along two oppositely dipping symmetric, deep-seated high-angle normal faults. Alternatively, extension in the Menderes massif may have been initiated by a north-dipping listric main breakaway in the late Oligocene as proposed by Seyitoğlu et al. (2004). In this scenario, the Alasehir and Büyük Menderes detachments were initiated in the early Miocene as high-angle normal faults and became low-angle normal faults in response to footwall rotation as Cenozoic extension has continued (Seyitoğlu et al., 2002, 2004). Based on their Monazite ages, Catlos and Çemen (2005) also proposed that extension in western Anatolia may have occurred in two uninterrupted, continuous stages. The first stage started in the Oligocene and lasted until the early Miocene. The second stage started in the early Miocene and continues today.

Purvis and Robertson (2004) proposed a "pulsed extension" model for western Turkey. This model suggests that the Cenozoic extension in western Turkey was produced in three phases.


A
Shear senses based on kinematic indicators
Quaternary alluvium
Neogene sedimentary and volcanic rocks
Oligocene sedimentary rocks
Low-grade metamorphics
High-grade metamorphics
Granitoids
Lycian nappes
Beydaglari unit and Kas basin
Antalya Complex
A
Simav D.
59-19-124b
GB
DB
SB
Area of Fig. 3
01-26
Usak
30
Alasehir D.
AG
UGB
Izmir
01-88
A'
Odemis
KMG
Area of Fig. 5A
B. Menderes D.
BMG
Denizli
01-141
Cine
Aegean Sea
Kayabuku D.
Yatagan
Kale
SWASZ
?
A''
Marmaris
Mediterranean
0 20km
39°
38°
37°
36°
27°
28°
29°
30°
A
A'
A''
SG
SD
AG
AD
KMG
BMD
BMG
YB
OB
DF
10
5
0 (km)
59-19-124b
39.7±0.9 Ma
32.8±0.5 Ma
01-26
36.0±0.6 Ma
41.4±1.3 Ma
28.2±0.4 Ma
30
53±6 Ma
26.9±0.6 Ma
01-88
498±7 Ma
17±5 Ma
4.5±1.0 Ma
01-141
41.0±5.2 Ma
499±18 Ma
Neogene
Taurides units
Metamorphic and igneous rocks, specific nappes not distinguished
B

These authors related the first two phases to roll-back of the Aegean subduction zone and the third phase to the tectonic escape of Anatolia.

THE MENDERES MASSIF

The earliest field observations divided the metamorphic rocks of the Menderes massif into a "core" and a "cover" sequence (Fig. 2; e.g., Akkök, 1983; Şengör et al., 1984). The core of high-grade metamorphic rocks was thought to have formed during the Pan African orogeny (Cambro-Ordovician; Şengör et al., 1984), whereas the cover contains Paleozoic schist and Mesozoic–Cenozoic marble that experienced regional metamorphism during the Alpine orogeny (Şengör et al., 1984). More recent field studies have documented the presence of nappes that formed during the formation of the Izmir-Ankara suture zone (see Ring, 1999; Gessner et al., 2001b). The Bayindir nappe is structurally the lowest, and it consists of Paleozoic–Mesozoic rocks deformed and metamorphosed at least once in the Cenozoic. This metamorphism, often referred to as the "main Menderes metamorphism," is commonly assumed to be Paleocene–Eocene in age and to have been pervasive throughout the massif. The overlying Bozdag nappe is composed of metapelite with intercalated amphibolite, eclogite, and marble lenses. The Çine nappe is made up of orthogneiss and paragneiss with intercalated metabasite. The Selimiye nappe, Cycladic blueschists, and Lycian nappes overlie the Çine and Bozdag such as nappes and contain high-*P*, low-*T* assemblages such as Mg carpholite (e.g., Oberhänsli et al., 1998).

In the following sections, we summarize the work previously done to understand the geologic history of the Menderes massif via geochronology, thermobarometry, and field observations. Other structural, metamorphic, and geochronologic summaries include those of Bozkurt and Oberhänsli (2001), Gessner et al. (2001b), Regnier et al. (2003), and Rimmele et al. (2003).

Figure 2. (A) Simplified Geologic map of the Western Anatolia extended terrane. The monazite ages of Catlos and Çemen (2005) are indicated in the white boxes adjacent to their locations. The two rectangles in the northern and central Menderes massif show the locations of Figures 3 and 5A, respectively. Abbreviations: AG—Alasehir graben; BMG—Büyük Menderes graben; DB—Demirci basin; GB—Gordes basin; KMG—Kucuk Menderes graben; SB—Selendi basin; SWASZ—Southwestern Anatolia shear zone; UGB—Usak-Gure basin (modified from Seyitoğlu et al., 2004). (B) Geologic cross-section along the line A-A′-A″. See panel A for the line of section. Th-Pb ion microprobe monazite ages (±1σ) are indicated (Catlos and Çemen, 2005). Abbreviations from north to south: SG—Simav graben; SD—Simav detachment; AG—Alasehir graben; AD—Alasehir detachment; KMG—Kucuk Menderes graben; BMD—Büyük Menderes detachment; BMG—Büyük Menderes graben; YB—Yatagan basin; OB—Ören basin; DF—Datça fault.

Geochronology and Thermobarometry

In the Northern Menderes massif, rocks experienced peak metamorphic conditions of ~5.3 to ~9.2 kilobars and ~572 to ~712 °C (Table 1), which have been correlated to metamorphism during the Pan African orogeny (Candan et al., 2001) or perhaps correspond to the closure of the northern Karakaya marginal basin (e.g., Akkök, 1983). The presence of Late Cambrian metamorphism or magmatism in the Northern Menderes massif is based on six whole-rock Rb-Sr analyses that yield ages of 471 ± 9 Ma (Satir and Friedrichsen, 1986) and in situ ion microprobe ^{207}Pb-^{206}Pb zircon ages that average 508 ± 92 Ma (Catlos and Çemen, 2005; Table 2). However, the *P-T* conditions could record more recent metamorphism, for the Th-Pb ion microprobe ages of monazites from the Bozdag and Çine nappes in the Northern Menderes massif range from 52.9 ± 5.7 Ma to 26.9 ± 0.6 Ma (Fig. 2B; Catlos and Çemen, 2005). The K-Ar and ^{40}Ar/^{39}Ar ages of muscovite and biotite are early to middle Miocene and have typically been related to regional metamorphism (see Table 2). The apatite and zircon fission track ages in the Northern Menderes massif average 19.5 ± 1.3 Ma (Gessner et al., 2001a; Ring et al., 2003), suggesting that the rocks were near the surface by the early Miocene.

The Central Menderes massif consists largely of three major lithological units: gneiss, schist, and marble (e.g., Akkök, 1983; Gessner et al., 2001a). The gneiss underlies the schist and marble and is composed of porphyroblastic and augen gneisses with minor amounts of banded gneiss and massive granite gneisses, whereas the schist contains garnet-mica schist, quartzite, and augen schist and is intruded by the Dede Dagi granite, which contains lenses of serpentinite (e.g., Akkök, 1983). The northern segment of the Central Menderes massif may have experienced a more complicated history than the southern segment due to its proximity to the Pontides and the Anatolide-Tauride platform. The schist and marble in the north have been speculated to have experienced three major phases of metamorphism (Akkök, 1983).

The first major phase, which occurred during the Cambro-Ordovician (Pan African), is recorded by U-Pb zircon and Th-Pb monazite dating (Fig. 2B; Table 3; Hetzel et al., 1998; Catlos and Çemen, 2005). During this time, rocks from the massif may have reached eclogite conditions as high as ~730 °C and ~15.1 kilobars (Table 4; Candan et al., 2001; Ring et al., 2001). However, depending on location, this event may have also resulted in more moderate greenschist facies as low as ~4.9 kilobars and ~512 °C (Candan et al., 2001).

The second phase occurred during late Cretaceous–early Eocene (Alpine) regional metamorphism (Akkök, 1983; Ring et al., 2001; Table 4). Blueschist metamorphism occurred at 39.6 ± 0.4 Ma (Okay et al., 1998) along the western peninsula of the Menderes massif, in which rocks experienced ~10 kilobars and <470 °C (Candan et al., 1997).

The third phase, which occurred during the early to the late Miocene, was a retrograde metamorphic event (e.g., Akkök,

TABLE 1. *P-T* CONDITIONS REPORTED FROM THE NORTHERN MENDERES MASSIF

Event	Unit and location	*P* (kbar)	*T* (°C)	References
1	Marble and schist unit; 20 km S of Kula	5.3–8.3	572–612	CEA (2001)
1	Marble and schist unit; near Salihli	8.0–9.2	588–712	CEA (2001)

References: CEA (2001)—Candan et al. (2001).
Note: Event 1—Pan African–related event.

1983). The muscovite $^{40}Ar/^{39}Ar$ dating of a rock from the north-dipping Alasehir detachment of the Central Menderes massif (Fig. 2) yields an age of 7 ± 1 Ma, whereas muscovite grains of the south-dipping Büyük Menderes detachment (Fig. 2) record $^{40}Ar/^{39}Ar$ ages that are Oligocene to early Miocene (Gessner et al., 2001a; Lips et al., 2001; Ring et al., 2003). Other granodiorites in the region yield late Miocene ages (Table 3).

Like the Central and Northern Menderes massifs, the Southern Menderes massif contains evidence of a Cambro-Ordovician, Eocene–Oligocene to late Miocene geologic history (Table 6). Peak *P-T* conditions ascribed to the Pan African orogeny range from ~8 to ~12 kilobars at ~440 to ~643 °C (Candan et al., 2001; Regnier et al., 2003; Rimmele et al., 2003). However, these conditions are no different from those that have

TABLE 2. AGES REPORTED FROM THE NORTHERN MENDERES MASSIF

Unit (mineral dated)	Age (Ma)	Method	References
Cine Nappe (zircon)	508 ± 92	Pb-Pb	CEA (2005)
Core rocks (igneous rock, bulk)	471 ± 9	Rb-Sr	SF (1986)
Bozdag and Cine nappes (monazite)	53 ± 6 to 26.9 ± 0.6	Th-Pb	CC (2005)
Southern Gördes submassif (muscovite)	24.7 ± 1.2	$^{40}Ar/^{39}Ar$	REA (2003); GEA (2001a)
Tourmaline leucogranite (muscovite)	24.2 ± 0.8 to 21.1 ± 1.1	K-Ar	SEA (1992)
Core series; gneissic mylonite (muscovite)	23.0 ± 1.0	$^{40}Ar/^{39}Ar$	IEA (2004)
Core series; Egrigöz granitoid (biotite)	20.4 ± 0.5	$^{40}Ar/^{39}Ar$	IEA (2004)
Gördes submassif (apatite and zircon)	19.5 ± 1.3	FT	REA (2003); GEA (2001a)
Acid volcanic domes (muscovite)	18.8 ± 0.8 to 16.3 ± 0.5	K-Ar	SEA (1992)

References: CC (2005)—Catlos and Çemen (2005) (see also Fig. 2B); GEA (2001a)—Gessner et al. (2001a); IEA (2004)—Isik et al. (2004); REA (2003)—Ring et al. (2003); SF (1986)—Satir and Friedrichsen (1986); SEA (1992)—Seyitoğlu et al. (1992).
Note: FT—fission track.

TABLE 3. AGES REPORTED FROM THE CENTRAL MENDERES MASSIF

Unit (mineral dated)	Age (Ma)	Method	References
Birgi metagranite (zircon)	551.5 ± 1.4	U-Pb	HEA (1998)
Rock from Alaşehir detachment (monazite)	498 ± 7	Th-Pb	CC (2005)
Cover series; leucocratic orthogneiss (zircon)	241 ± 9	$^{207}Pb/^{206}Pb$	KEA (2001)
Cover series; blueschists (phengite)	39.6 ± 0.4	$^{40}Ar/^{39}Ar$	OEA (1998)
Guney detachment (muscovite)	36 ± 2	$^{40}Ar/^{39}Ar$	LEA (2001)
Southern Büyük Menderes detachment (muscovite)	26.0 ± 1.0	$^{40}Ar/^{39}Ar$	REA (2003b); GEA (2001a)
Salihli granodiorite (amphibole)	19.5 ± 1.4	$^{40}Ar/^{39}Ar$	HEA (1995)
Alasheir graben sediments (sporomorph)	19–20 to 14–15	Paleontology	SS (1996)
Turgutlu granodiorite (biotite)	13.3 ± 0.3	$^{40}Ar/^{39}Ar$	HEA (1995)
Salihli granodiorite (biotite)	12.6 ± 0.4	$^{40}Ar/^{39}Ar$	HEA (1995)
Central Menderes submassif (apatite and zircon)	10.9 ± 1.5	FT	REA (2003b); GEA (2001a)
Alaşehir detachment (muscovite)	7 ± 1	$^{40}Ar/^{39}Ar$	LEA (2001)

References: CC (2005)—Catlos and Çemen (2005) (see also Fig. 2b); GEA (2001a)—Gessner et al. (2001a); HEA (1995)—Hetzel et al. (1995b); HEA (1998)—Hetzel et al. (1998); KEA (2001)—Koralay et al. (2001); LEA (2001)—Lips et al. (2001); OEA (1998)—Oberhänsli et al. (1998); SS (1996)—Seyitoğlu and Scott (1996).
Note: FT—fission track.

TABLE 4. *P-T* CONDITIONS REPORTED FROM THE CENTRAL MENDERES MASSIF

Event	Unit and/or location	*P* (kbar)	*T* (°C)	References
1	Orthogneiss core unit; near Birch	7.7–12.2	521–692	CEA (2001)
1	Lowermost Cine nappe	6.2–6.4	620–730	REA (2001)
1	Orthogneiss core; 20 km S of Kiraz	5.3–15.1	580–645	CEA (2001)
1	Orthogneiss core; 20 km SE of Tire	5.1–11.9	512–674	CEA (2001)
1	Orthogneiss core unit; near Alasheir	4.9–14.6	580–656	CEA (2001)
2	Cover series; western peninsula; blueschists	10	<470	CEA (1997)
2	Middle Bozdag nappe	8.5–10.8	560–590	REA (2001)
2	Upper Bozdag nappe	8.5–10.9	605–665	REA (2001)
2	Garnet-bearing metapelites	8	530	O (2001)
2	Bozdag nappe	6.1–7.6	480–540	REA (2001)
2	Marble and schist unit; Derbent, 20 km S of Alashehir	5–6	600–660	A (1983)
?	Pelites	4–7	450–600	AE (1985)
?	Core series near Birgi and Tire	13	650	OEA (1997)

References: A (1983)—Akkök (1983); AE (1985)—Ashworth and Evirgen (1985); CEA (1997)—Candan et al. (1997); CEA (2001)—Candan et al. (2001); OEA (1997)—Oberhänsli et al. (1997); O (2001)—Okay (2001); REA (2001)—Ring et al. (2001).

Notes: Event 1—Pan African–related event; Event 2—Late Cretaceous/early Eocene event; ?—unknown event timing.

been ascribed to late Cretaceous–early Eocene regional metamorphism (Table 5; ~4 to ~12 kilobars and ~430 to ~675 °C; Whitney and Bozkurt, 2002; Regnier et al., 2003). Oxygen isotope temperatures of ~514 to ~529 °C have been reported from the range (Satir and Taubald, 2001), although the origin of the event that created these conditions remains unknown.

The difficulty in ascribing the peak *P-T* conditions achieved by rocks within the Menderes massif to specific events underscores the region's complicated tectonometamorphic history. Catlos and Çemen (2005) report both Cambro-Ordovician and Eocene–Oligocene monazite inclusions in Menderes massif garnets, indicating that garnet growth events occurred during both the Pan African and the Alpine orogenic events. Garnet-based thermobarometric methods are typically used to generate the *P-T* estimations (e.g., Ashworth and Evirgen, 1984, 1985), and rocks in the massif may have experienced multiple episodes of deformation (Catlos and Çemen, 2005) that could have affected their mineral compositions and thus the reported *P-T* conditions.

TABLE 5. *P-T* CONDITIONS REPORTED FROM THE SOUTHERN MENDERES MASSIF

Event	Unit and/or location	*P* (kbar)	*T* (°C)	References
1	Southern submassif	10–12	440	REA (2003a)
1	Orthogneiss schist unit 20 km NW of Karacasu	9	568	CEA (2001)
1	Orthogneiss schist unit 20 km S of Cine	8.2	624–585	CEA (2001)
1	Çine nappe; 20–30 km N of SSZ	8–11	600–650	REA (2003)
1	Metasedimentary Çine nappe	7.9 ± 0.7 to 9.7 ± 1.1	600 ±13 to 643 ± 21	REA (2003)
2	Gneiss unit; Southern Menderes massif	8.0–8.6	457–462	AE (1984)
2	Selimiye nappe	7.0 ± 0.6 to 11.7 ± 1.2	502 ± 16 to 675 ± 31	REA (2003)
2	Çine submassif	<6 to 8	430–550	WB (2002)
2	Çine nappe beneath the SSZ	7	>550	REA (2003)
2	Metasedimentary Selyime nappe	4	525	REA (2003)
?	Crystalline core of the Çine massif	NR	529 ± 50	ST (2001)
?	Schist belt of the Cine massif	NR	514 ± 67	ST (2001)

References: AE (1984)—Ashworth and Evirgen (1984); CEA (2001)—Candan et al. (2001); REA (2003)—Regnier et al. (2003); REA (2003a)—Rimmele et al. (2003); ST (2001)—Satir and Taubald (2001); WB (2002)—Whitney and Bozkurt (2002).

Notes: Event 1—Pan African–related event; Event 2—Late Cretaceous–early Eocene event; ?—unknown event timing; SSZ—Seliyme shear zone; NR—not reported.

TABLE 6. AGES REPORTED FROM THE SOUTHERN MENDERES MASSIF

Unit (mineral dated)	Age (Ma)	Method	References
Cine submassif; metasediments (zircon)	2094 ± 2	^{207}Pb/^{206}Pb	LR (1999)
Cine submassif; metasediments (zircon)	609.0 ± 5.5	^{207}Pb/^{206}Pb	LR (1999)
Cine nappe; orthogneiss SW of Cine (zircon)	566 ± 9	^{207}Pb/^{206}Pb	GEA (2004)
Cine submassif; granitic gneisses (zircon)	559.1 ± 5.3	^{207}Pb/^{206}Pb	LR (1999)
Deformed orthogneiss SW of Cine (zircon)	547.2 ± 1.0	^{207}Pb/^{206}Pb	GEA (2001b)
Cine submassif; augen gneiss near Sarikaya (zircon)	546.4 ± 0.8	^{207}Pb/^{206}Pb	HR (1996)
Cine submassif; augen gneiss W of Comakdagi (zircon)	546.0 ± 1.6	^{207}Pb/^{206}Pb	HR (1996)
Cine nappe; N of the Selimiye shear zone (zircon)	541 ± 14	^{207}Pb/^{206}Pb	GEA (2004)
Cine submassif; augen gneiss (zircon)	526.6 ± 9.2	^{207}Pb/^{206}Pb	LR (1999)
Core rocks; augen gneiss and migmatites (bulk)	502 ± 10	Rb-Sr	SF (1986)
Core series (zircon)	490 ± 90	Rb-Sr	CEA (2001)
Quartz-mica vein	47 ± 11	Rb-Sr	BS (2000)
Cine submassif; augen gneiss near Sarikaya (muscovite)	38.0 ± 0.9	^{40}Ar/^{39}Ar	HR (1996)
Cine submassif; augen gneiss W of Comakdagi (muscovite)	37.9 ± 0.4	^{40}Ar/^{39}Ar	HR (1996)
Cine submassif; mica schist N of Kafaca (muscovite)	36.7 ± 1.2	^{40}Ar/^{39}Ar	HR (1996)
Core rocks; augen gneiss and migmatites (micas)	35 ± 5	Rb-Sr	SF (1986)
Cine submassif (muscovite)	31.6 ± 1.2	^{40}Ar/^{39}Ar	REA (2003b); GEA (2001a)
Cine submassif; mica schist NW of Ikiztas (muscovite)	29.7 ± 2.0	^{40}Ar/^{39}Ar	HR (1996)
Cine submassif (apatite and zircon)	20.9 ± 1.5	FT	REA (2003b); GEA (2001a)

References: BS (2000)—Bozkurt and Satir (2000); CEA (2001)—Candan et al. (2001); GEA (2001a)—Gessner et al. (2001a); GEA (2001b)—Gessner et al. (2001b); GEA (2004)—Gessner et al. (2004); LR (1999)—Loos and Reischmann (1999); REA (2003b)—Ring et al. (2003); SF (1986)—Satir and Friedrichsen (1986).

Note: FT—fission track.

Structural Geology

Field studies in the Northern, Central and Southern Menderes massif document the presence of four low-angle detachment surfaces (Fig. 2). They are, from north to south, the Simav (Isik and Tekeli, 2001; Isik et al., 2003), Alasehir (Kuzey), Büyük Menderes (Güney), and Kayabükü detachments (Bozkurt and Park, 1994; Hetzel et al., 1995a; Seyitoğlu et al., 2000, 2002, 2004; Isik et al., 2003). In this section, we describe the geometry and shear sense indicators of these structural features.

Simav Detachment. Located along the southern margin of the Simav graben (Fig. 2), the Simav detachment separates Pan African–Paleozoic rocks containing migmatitic banded gneiss, biotite gneiss, high-grade schist, marble, and amphibolite in its footwall from low-grade upper Paleozoic metamorphic rocks, Mesozoic limestone, and ophiolitic mélange in its hangingwall. The footwall rocks experienced low to medium greenschist-facies conditions. Kinematic indicators that developed during cooling and uplift of the footwall indicate top to the north-northeast shear sense (Isik et al., 1997). We have examined and measured the trend and plunge of hundreds of mylonitic stretching lineations in the metamorphic rocks of the Northern Menderes massif between the northern margin of the Alasehir graben and southern margin of the Simav graben (Fig. 2). Our examinations indicate that mylonitic stretching lineations consistently indicate top to the north shear sense direction. Our measurements show that the trends of the lineations range from N10°E to N30°E. Considering that mylonitic lineations form parallel to the direction of extension, the measurements define well-developed N10°E- to N30°E-directed extension.

Systematic strike and dip measurements of foliation surfaces in the Northern Menderes massif indicate the presence of major antiformal and synformal structures. We have mapped these structures in the Usak area (Fig. 3) and determined that their axial surface traces have a northeastward trend. In the Northern Menderes massif, the hinge lines of mesoscopic folds have a trend parallel to the axial surfaces of the major folds. The hinge lines of the major and minor folds trend between N10°E and N30°E (Fig. 4A and B) and are parallel to the trend of the stretching lineations (Fig. 4C). This geometry suggests a genetic relationship between the stretching lineations and the small and large folds. These folds were probably formed by the contractional component of the N30°E-directed extension, because their axes are parallel to the extension direction.

Footwall rocks of the Simav detachment are intruded by the Koyunoba and Egrigöz granodiorites (Table 2). These igneous rocks have generally been considered as intruded during the early stages of extension in the early Miocene (Isik et al., 2003, 2004; Ring et al., 2003).

Alasehir and Büyük Menderes Detachments. Field-oriented geological studies in the Central Menderes massif indicate the presence of the north-dipping Alasehir and the south-dipping low-angle Büyük Menderes detachment surfaces on the northern and southern margins, respectively, of the Central Menderes massif (Fig. 2, e.g., Hetzel et al., 1995b; Emre, 1996;

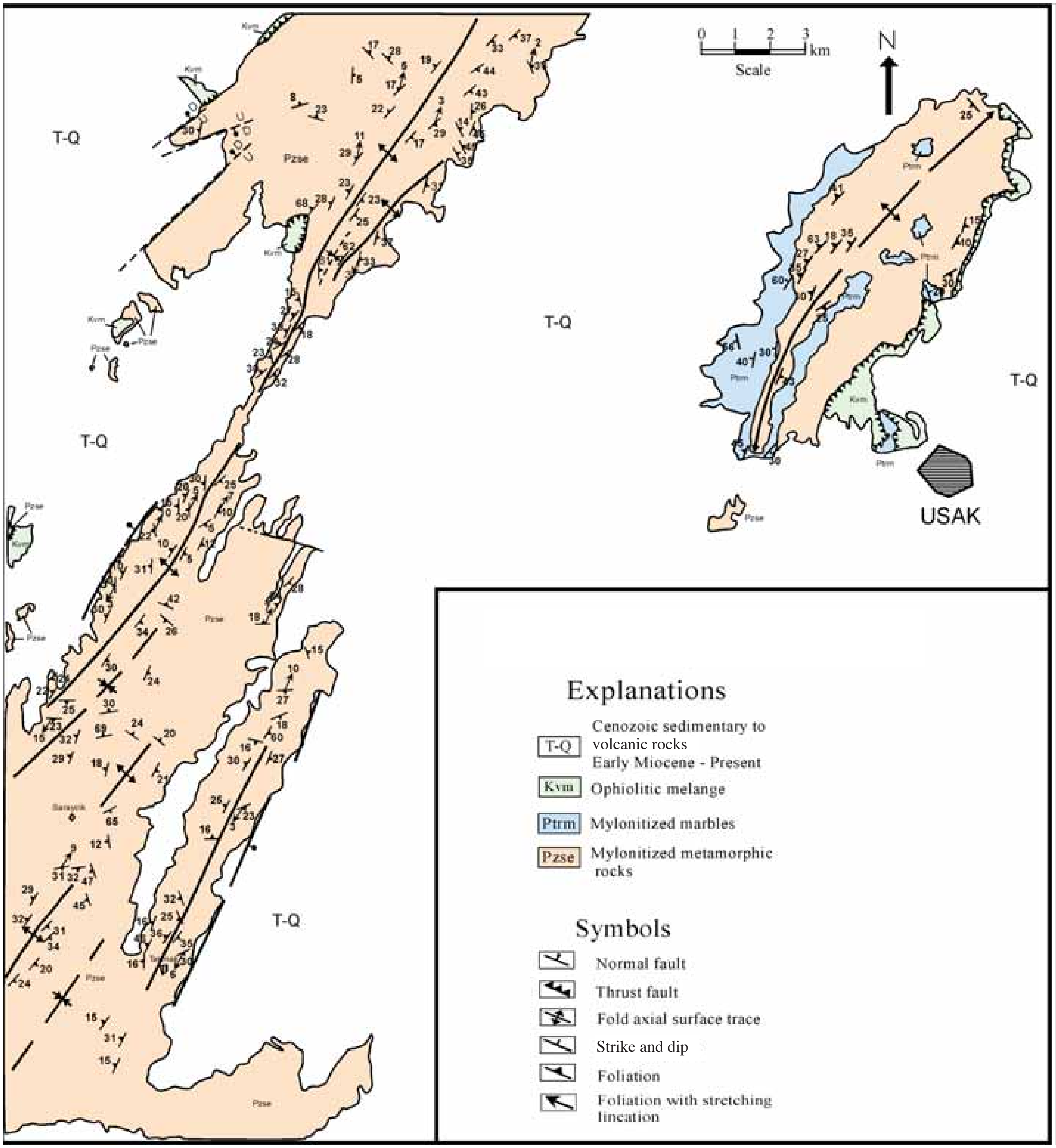


Figure 3. Basement structure map of the Usak-Gure basin area showing large antiforms and synforms trending N10°E to N30°E.

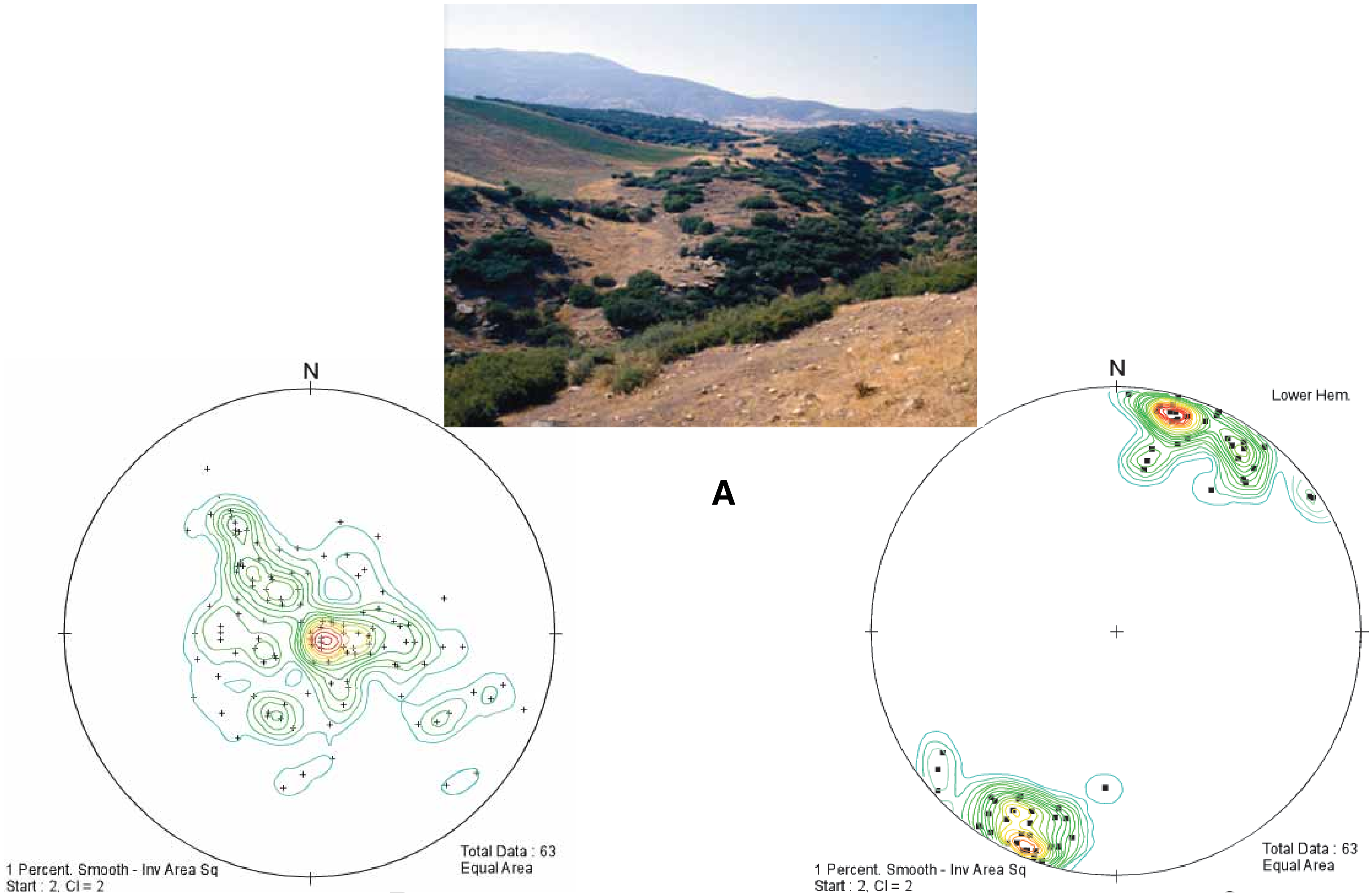


Figure 4. (A) Photo showing an extension parallel antiform and a synform pair to the north of the town of Kula, looking northward. The hinge lines of the antiform and synform trend about N30°E parallel to small-scale antiforms and synforms superimposed onto the large folds. The ductile stretching lineation direction (~N30°E) is parallel to the hinge lines of these folds. (B) 1% contouring of the poles to the foliation planes of small-scale folds in the Northern Menderes massif. The fold axes are striking approximately N30°E. (C) 1% contouring of the trend and plunge of the extensional stretching lineations in the Northern Menderes massif. The trend of the lineations is also about N30°E, parallel to the fold axes, indicating that they are formed in the same stress field. See text for explanation.

Seyitoğlu et al., 2000; Gessner et al., 2001a). In the Central Menderes massif, Hetzel et al. (1995a) and Gessner et al. (2001b) reported the presence of an overall dome-shaped foliation pattern and NNE-trending stretching lineations parallel to the stretching lineations of the Northern Menderes massif. The asymmetry of the shear bands and quartz c-axis fabrics on either side of the structural dome record a top to the north-northeast shear sense across the Alasehir detachment and a top to the north and south-southwest shear sense along the Büyük Menderes detachment surface, although top to the northeast shear sense indicators along the Büyük Menderes detachment are also present (see Hetzel et al., 1995a; Gessner et al., 2001b). Based primarily on the presence of a north-dipping detachment surface with top to the north-northeast shear sense indicators and a south-dipping detachment surface containing both top to the north and top to the south shear sense indicators. Gessner et al. (2001a) proposed a bivergent rolling hinge detachment system as a mechanism of exhumation of the Central Menderes massif in western Turkey.

The footwall of the Alasehir detachment is composed of gneiss, schist, quartzite marble, and igneous rocks referred to as the Salihli granitoid (Hetzel et al., 1995a). The hangingwall of the Alasehir detachment contains Neogene sediments. Ductile deformation of the footwall of the detachment produced mylonitic foliation and stretching lineations. Kinematic indicators include mesoscopic and microscopic features such as mica fish, S-C and C′ fabric, oblique foliation, and fractured and displaced grains. A brittle deformation stage of the shear zone is defined by the development of cataclastic rocks (Isik et al., 2003).

The footwalls of both the Simav and the Alasehir detachments contain well-developed ductilely deformed fault rocks displaying top to the north ductile shear sense indicators that are progressively overprinted by top to the north brittle deformation (Isik et al., 2003). The granitoids show a gradual change structurally upward from undeformed granodiorite converted to protomylonite, mylonite, and ultramylonite with mylonitic foliation and lineation. The metamorphic rocks are also mylonitized structurally upward. The deformed granitoid, in turn, grades into a cataclastic zone, with the uppermost part composed of the brittlely deformed rocks of the Alasehir detachment. This gradual upward change from the undeformed granitoid to the brittlely deformed detachment surface suggests that the Cenozoic extension resulted in a ductile deformation at depth and, as the crust adjusted to the removal of rocks in the hangingwall of the detachment, ductility deformed rocks were brought to shallower depths, where they were brittlely deformed (Isik et al., 2003). Both ductile and brittle shear sense indicators along the Alasehir detachment surface show top to the north-northeast shearing, suggesting that the northeasterly-directed Cenozoic extension produced a large regional extensional shear zone at depth.

The southern margin of the Alasehir graben (Fig. 2) is locally bounded by a turtleback fault surface known as the Horzum turtleback (Çemen et al., 2005). The turtleback is part of the Alasehir detachment, which contains mylonitic lineations trending between N10°E and N30°E. Striations along the detachment surface also trend between N10°E and N30°E and overprint the mylonitic lineations. These observations suggest a structural relationship between the Alasehir detachment, which contains the Horzum turtleback in its footwall, and the Simav detachment surface, which contains large-scale antiformal structures of the Northern Menderes massif in its footwall (Fig. 1). Çemen et al. (2005) suggest that the Horzum turtleback is a large-scale extension-perpendicular antiformal fold similar in origin to the Death Valley turtlebacks.

The Büyük Menderes detachment surface is well exposed along the northern margin of the Büyük Menderes graben. The detachment generally strikes N50°E to N50°W and dips ~15° to 30° southward. It separates a sequence of high-grade metamorphic gneisses and a lower Miocene sedimentary rock succession in its hangingwall from the marble-intercalated mylonitized schists in its footwall (Göğüs et al., 2003; Göğüs, 2004).

The hangingwall of the Büyük Menderes detachment consists of quartzofeldspathic gneiss and the early Miocene sedimentary rocks of the Haskoy formation. The gneiss has an assemblage of K-feldspar + quartz + plagioclase + muscovite + biotite ± garnet. The quartz grains typically form elongate domains and polycrystalline ribbons, suggesting that they experienced ductile conditions. The feldspars commonly have reaction rims of biotite and muscovite, and the plagioclase is altered into sericite. The biotite is typically altered to foliation-parallel chlorite. The foliations in the gneiss sequence are characterized by recrystallized quartz, feldspar, and biotite (Göğüs, 2004).

The presence of high-grade metamorphic gneiss in the hangingwall of the Büyük Menderes detachment has been problematic. The detachment was first mapped by Emre and Sözbilir (1997) as a normal fault surface. Those authors named it the Bascayir detachment because it is well exposed in the vicinity of the Bascayir village. Gessner et al. (2001a) also interpreted this surface as a low-angle normal fault. Okay (2001) mapped the Büyük Menderes detachment surface as a thrust fault based on the apparent field relationship of older rocks over younger ones. He proposed the presence of a large recumbent fold (the Menderes fold) formed during pre-extension tectonism in the region. Okay (2001) suggested that the high-grade gneisses were brought over the marble-intercalated mylonitized schists by a low-angle thrust fault during the Eocene contractional tectonics in the region. However, Gessner et al. (2001b) pointed out that within a structure similar to the Menderes fold, thrust fault and low-angle normal fault geometries can be found together. Consequently, a low-angle normal fault can show older over younger geometry. Moreover, the presence of (1) extensional stretching lineations along the detachment surface and (2) Miocene sedimentary rocks overlying the high-grade metamorphic gneiss in the hangingwall of the Büyük Menderes detachment suggest low-angle faulting. Therefore, we strongly believe that a low-angle normal fault exists along the northern margin of the Büyük Menderes graben. This detachment is here renamed the Büyük Menderes detachment because it controls the early development of the Büyük Menderes graben. The surface

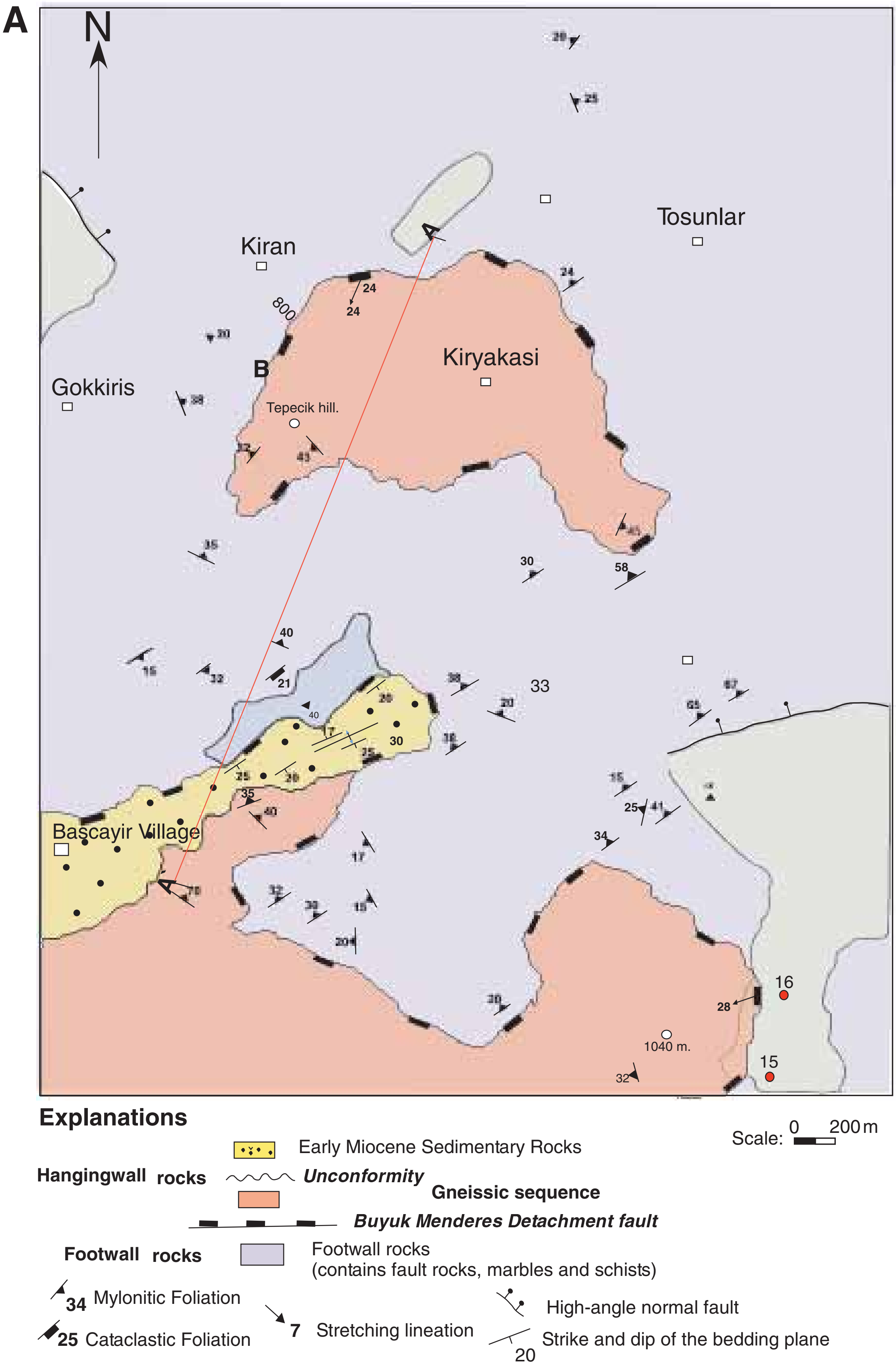


Figure 5. (A) Geologic map of the Büyük Menderes detachment area in the vicinity of Bascayir village. (B) Geologic cross-section along the line A-A′ and two photomicrographs showing top to the north ductile shear sense indicators overprinted by top to the south ductile and brittle shear sense indicators.

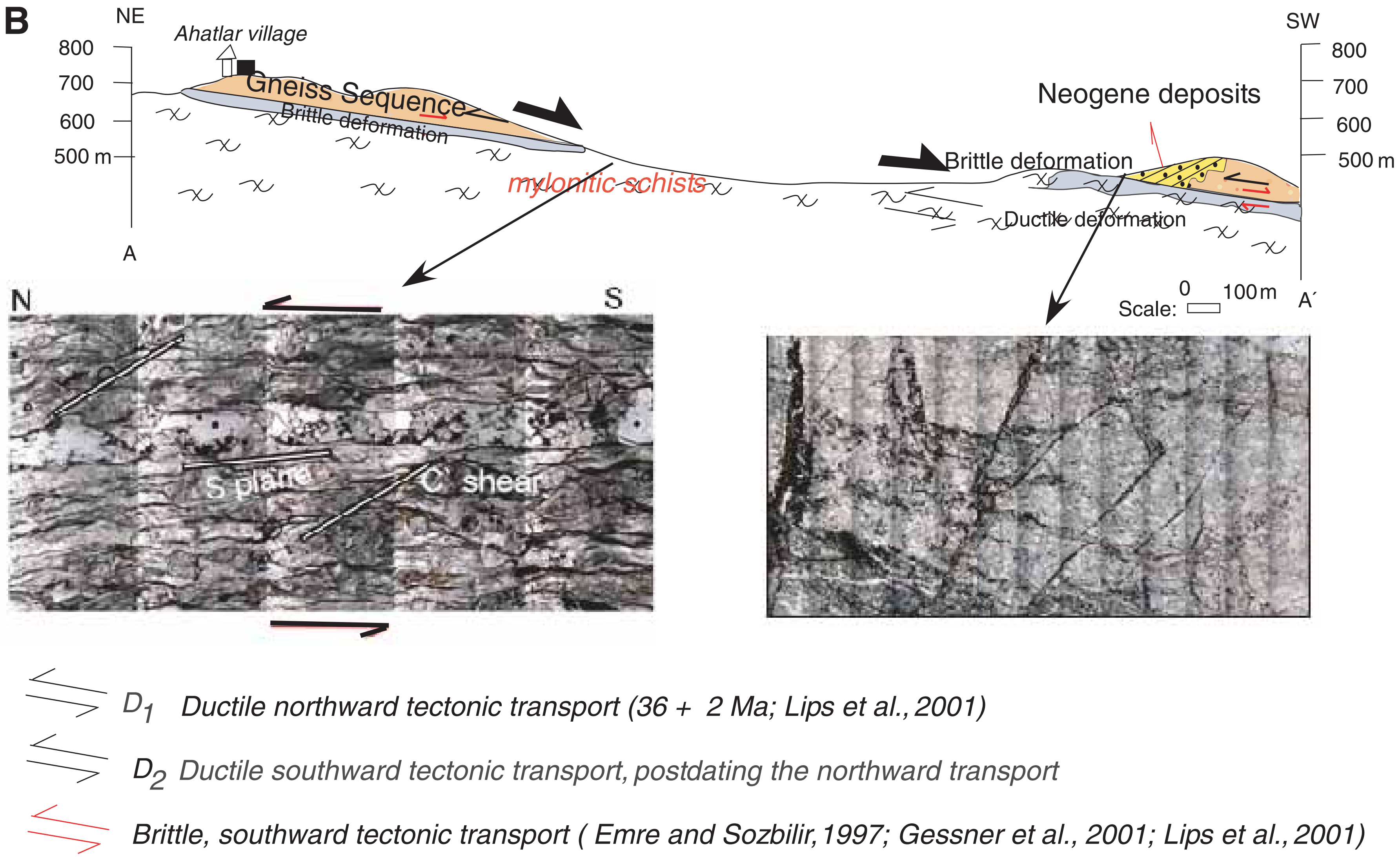


Figure 5. *Continued*

of the Büyük Menderes detachment is typically marked by cataclastic rocks and is well exposed in the vicinity of Bascayir village (Fig. 5). Cataclastic zones are commonly more than 1 m thick and grade into fractured rock adjacent to the fault. Most of the cataclastic rocks are composed of fractured marble, which is derived from the nonmylonitic marble-intercalated schists of the footwall (Fig. 5B).

At structurally lower levels, the fault rocks are ductilely deformed and display S-C and S-C asymmetric structures, schistosity, asymmetric mica fish, isoclinal folds, and asymmetric porphyroclasts. These features suggest top to the north sense of shear. Northward-directed ductile shear sense indicators are overprinted by southward-directed ductile shear sense indicators such as asymmetric porphyroclasts, mica fish, and asymmetric quartzite. These ductile features are overprinted by top to the south brittle shear sense indicators, including Riedel shears (Fig. 5B). These findings suggest that the Büyük Menderes detachment may have developed in more than one stage: earlier ductile extension with top to the north sense of tectonic transport overprinted by top to the south tectonic transport, again under ductile conditions. The top to the south tectonic transport must have continued as the footwall rocks reached the higher crustal levels to produce brittle top to the south shear sense indicators (Göğüs et al., 2003; Göğüs, 2004). The footwall rocks are made of foliated micaschists and marbles (Fig. 5), with the micas showing undulose extinction, indicative of intracrystalline cataclasis.

Kayabükü Detachment. In the Southern Menderes massif, coarse-grained augen gneisses are separated from pelitic schists by a major extensional shear zone, termed the Kayabükü shear zone, that exhibits a moderately dipping mylonitic foliation and a NNE- to SSW-trending mineral lineation (Bozkurt and Park, 1994; Hetzel and Reischmann, 1996; Isik et al., 2003). The augen gneisses display various kinematic indicators (e.g., S-C fabric, extensional shear cleavage, asymmetric feldspar porphyroclasts, and oblique quartz grain-shape foliation), suggesting a top to the south down-dip sense of shear (e.g., Bozkurt and Park, 1994).

Our preliminary investigation and data collection along the surface of the Kayabuku detachment suggest that the surface is characterized by mostly top to the north ductile shear-sense indicators. The detachment surface also contains secondary top to the south shear sense indicators that overprinted the top to the north shear indicators that may have formed during the backslippage along the shear zone. However, further systematic analyses of shear sense indicators along the Kayabükü detachment are necessary to ascertain the validity of this hypothesis.

SEDIMENTARY BASINS OF THE NORTHERN MENDERES MASSIF

The most striking feature of the Northern Menderes massif is the presence of north-south-trending basins. These basins, from west to east, are the Gördes, Demirci, Selendi, and Usak-Güre Basins (Fig. 3). The origin of these basins is controversial. Several workers proposed that these basins were developed under a north-south, post-Paleocene compression related to the terminal closure of the northern branch of Neo-Tethys Ocean that produced the Izmir-Ankara suture zone of Western and Central Anatolia (Şengör and Yılmaz, 1981; Şengör et al., 1985; Şengör, 1987). The basins were later filled by early Miocene sediments, then cut by east-west–trending basins of Tortonian age, and continued their development under the north-south extensional regime. The north-south–trending grabens are "replacement" structures, which continued their development in the hangingwall of the major east-west listric faults with a basin floor dipping into these structures and containing anomalously thick basin fill (e.g., Şengör et al., 1985; Şengör, 1987).

However, the ages of the sedimentary and igneous rocks in the basins appear to be inconsistent with this interpretation. The oldest sedimentary unit in the north-south–trending Gördes, Demirci, Selendi, and Usak-Güre Basins (Fig. 2; see also Fig. 14 later in this chapter) is a locally driven conglomerate unit named the Hacibekir formation (Seyitoğlu, 1997; Seyitoğlu et al., 2002). The formation has been dated as early Miocene by identifying Eskihisar sporomorph association, whose time span is bracketed between 20 and 14 Ma based on the K-Ar ages of volcanic rocks in the Aegean region (Benda et al., 1974; Benda and Meulenkamp, 1979; Seyitoğlu et al., 1994).

The Hacibekir formation unconformably overlies the metamorphic rocks of the Northern Menders massif and is in the same stratigraphic interval as the Alasehir formation of the Alasehir graben and the Haskoy formation of the Büyük Menderes graben (Fig. 6). The lowermost part of the Hacibekir formation contains poorly sorted fragments with very little matrix from the low-grade metamorphic rocks and marbles of the Menderes massif, which constitutes the upper plate of the Lycian nappes (Fig. 7A) together with the poorly sorted augen gneiss fragments of the Menderes massif (Fig. 7B). The conglomerate unit of the Hacibekir formation in the Demirci basin is ~250 m thick and contains large clasts of augen gneiss and high-grade metamorphosed mylonites, together with low-grade metamorphic rocks and marbles.

We interpret the conglomerates of the Hacibekir formation as remnants of coalescing alluvial fans. This interpretation is based on (1) the angularity and commonly imbricate arrangement of the rock fragments, (2) the poor degree of sorting, (3) the large size of some clasts, and (4) the presence of much finer-grained and very little matrix (Fig. 7). The presence of the fragments of both "core" and "cover" rocks of the Menderes massif suggests that there were remnants of the Lycian nappes (cover) in the areas where the conglomerate fragments were derived as part of the coalescing alluvial fans.

Based on the data outlined earlier, we propose that the north-trending basins of the northern Menderes massif started to form in the early Miocene related to the north-directed extension (Fig. 14). We further propose that the basins were initiated

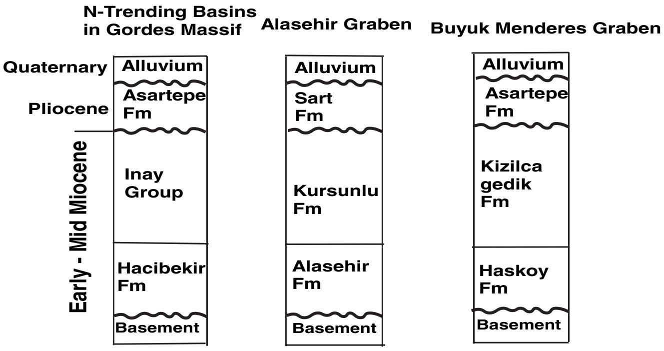


Figure 6. Schematic columnar sections showing the correlation of sedimentary units between Alasehir and Büyük Menderes grabens and the north-trending basins of the Northern Menderes (Gördes) massif.

due to the formation of large antiforms and synforms that are present in the northern Menderes massif (Figs. 3 and 4A). These large folds provided the earlier depressions in the early Miocene for coarse-grained sedimentary rock accumulations of the Hacibekir formation (Fig. 6), the lowest Cenozoic sedimentary unit in these basins. The north-trending faults that control the eastern and western margins of these basins contain well-developed slickenlines, suggesting mostly strike-slip motion as the sense of latest motion along them (Fig. 8). This suggests that they may have been formed as accommodation faults (Şengör, 1987) due to differential stretching during the third stage of the north-directed extension from the late Miocene to the present, because they have a substantial strike-slip component (see Figs. 13 and 14 later in this chapter).

SEDIMENTARY BASINS OF THE CENTRAL MENDERES MASSIF

The Alasehir and Büyük Menderes grabens are two main east-west-trending grabens in the Central Menderes massif. In the eastern part of western Anatolia, the Alasehir graben trends southeasterly and joins the Büyük Menderes graben in the area of the Denizli basin (Figs. 2 and 9).

The sedimentary successions in the Alasehir graben are composed of four different sedimentary units (Fig. 6). The oldest sedimentary unit in the graben fill is the Alasehir formation (Iztan and Yazman, 1990), which is equivalent to the Hacibekir formation (Fig. 6) in the north-trending Demirci, Gördes, and Usak-Selendi basins (Seyitoğlu et al., 2002). The Kursunlu formation conformably overlies the Alasehir formation. These early–middle Miocene units are unconformably overlain by the Pliocene Sart formation. The Kursunlu and Alasehir formations are in fault contact with the basement metamorphic rocks of the Menderes massif along the southern margin of the Alasehir graben (Seyitoğlu et al., 2000, 2002). The Alasehir formation unconformably overlies the metamorphic rocks of the Menderes massif (Fig. 6) in the subsurface as evidenced along the unpublished seismic reflection profiles of the Turkish Petroleum Corporation (TPAO).

Kocyigit et al. (1999) proposed that the east-west–trending folds within the Alasehir graben were formed during north-

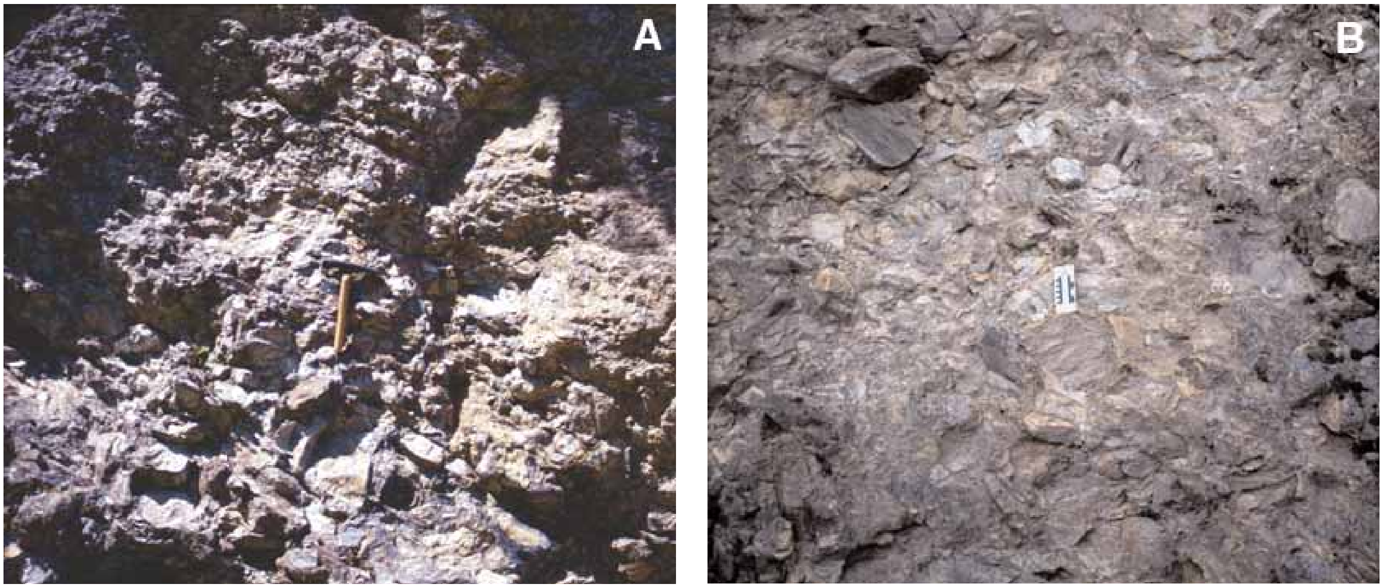


Figure 7. Poorly sorted conglomerates along the eastern margin of the Demirci basin showing rock fragments derived from (A) the low-grade metamorphic rocks and marbles of the upper plate and from (B) the high-grade metamorphic Augen gneisses of the lower plate of the Menderes massif. Note that the conglomerate is very angular and contains very little matrix.

Figure 8. Horizontal slickenlines on the fault along the eastern margin of the Gordes basin, looking east. Fault plane: N65°E, 85°SE Pitch 10S.

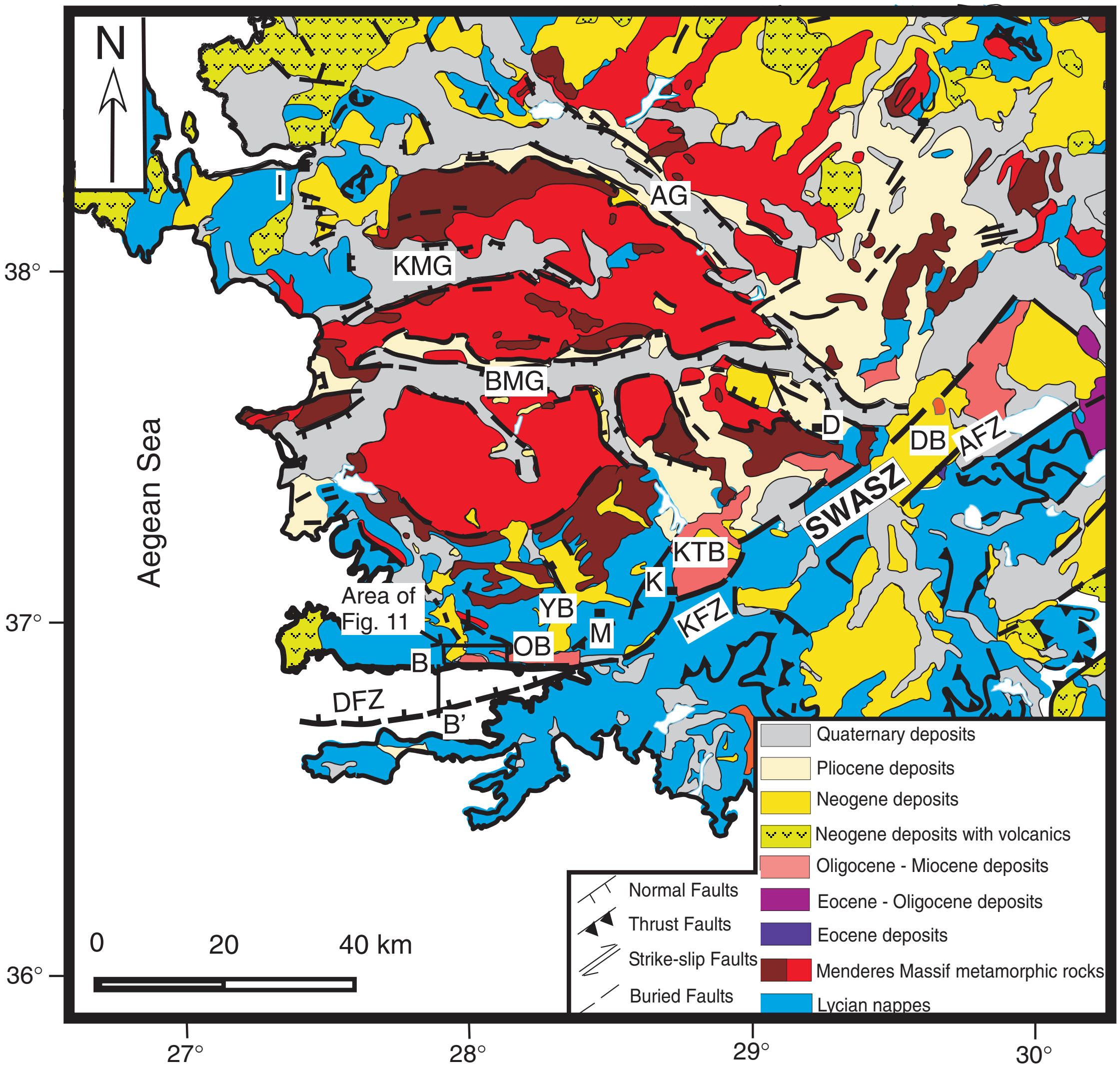


Figure 9. Simplified geologic map showing the sedimentary basins adjacent to the Southwest Anatolian shear zone (SWASZ). Abbreviations: Towns: D—Denizli; I—Izmir; K—Kale; M—Mugla. Structural elements: AFZ—Acigol fault zone; AG—Alasehir graben; BMG—Büyük Menderes graben; DB—Denizli basin; DFZ—Datça fault; KFZ—Kale fault zone; KMG—Kucuk Menderes graben; KTB—Kale-Tavas basin; OB—Ören basin; SWASZ—Southwest Anatolian shear zone; YB—Yatagan basin.

south-directed contraction in the middle Miocene. They suggested that the Alasehir graben and all of western Anatolia experienced two stages of extension separated by a contraction, the first in the early Miocene and the second in the late Miocene, separated by a contraction stage in the middle Miocene. However, these folds are rollover structures related to the north-directed Cenozoic extension (Seyitoğlu et al., 2000). Therefore, there was no middle Miocene contraction in western Anatolia. Purvis and Robertson (2004) interpreted the Alasehir graben in terms of two phases of extension, an early phase lasting from the early Miocene to the late Miocene and a young Plio-Quaternary phase that is still active.

The Hasköy formation is the oldest synextensional sedimentary sequence along the northern margin of the Büyük Menderes graben (Fig. 6). The unit is reddish colored and composed of sandstone, claystone, limestone, and lenses of coal. It is in the same stratigraphic interval as the Alasehir formation of the Alasehir graben and the Hacibekir formation of the north-trending basins (Fig. 6). The Hasköy formation is conformably overlain by the Kizilcagedik formation, which corresponds to the Kursunlu formation of the Alasehir graben. The Kizilcagedik formation is unconformably overlain by the Asartepe formation. All these sedimentary formations are unconformably overlain by Quaternary alluvium (Fig. 6). The oldest sedimentary succession is early Miocene in age in the sedimentary basins of the Northern Menderes massif and in the Alasehir and Büyük Menderes grabens. These data suggest that the basins may have formed simultaneously in the early Miocene due to the north-directed Cenozoic extension in western Anatolia (see the proposed tectonic model).

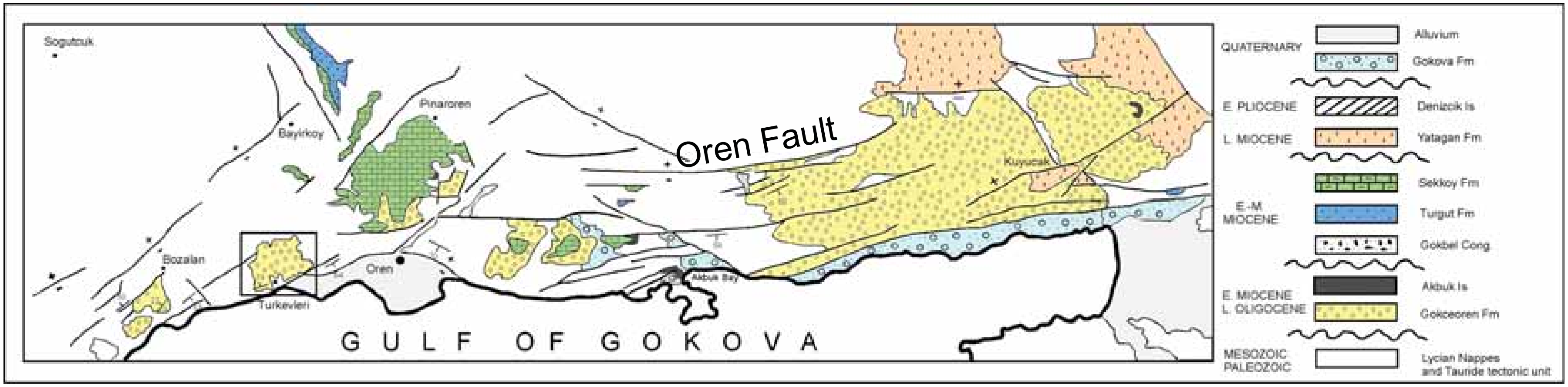
THE SOUTHWEST ANATOLIAN SHEAR ZONE

The Western Anatolia extended terrane is bounded by an ENE- to northeast-trending fault zone to the south and southeast (Figs. 2 and 9). The fault zone contains mostly normal faults in the vicinity of the Gulf of Gokova. However, its movement is mostly oblique slip from the vicinity of Tavas toward Lake Acigöl (Fig. 10), where it makes a northward bend and possibly joins the Eskisehir fault zone north of the city of Afyon. We name this fault zone, which is composed of many normal to oblique-slip fault segments, the Southwest Anatolian shear zone.

The Southwest Anatolian shear zone separates the highly extended Western Anatolia extended terrane to the north and the northwest from the Lycian nappes and the Tauride units to the south and the southeast. It consists of the Datça, Kale-Tavas, and Acigöl segments. The Datça segment is located to the south of the Gulf of Gökova and shows mostly normal slip (see Fig. 12 later in this chapter) in the seismic profiles of Kurt et al. (1999). It extends landward along the eastern end of the Gulf of Gökova and joins the Kale fault zone to south of the town of Kale (Fig. 9). The Kale-Tavas segment trends northeasterly and bounds the Kale-Tavas basin to the southeast. The Acigöl segment is located to the southeast of the Denizli basin (Figs. 9 and 10). The Southwest Anatolian shear zone plays an important role in the extensional tectonics of western Anatolia. Its origin and tectonic significance are discussed later in this article.

There are several sedimentary basins adjacent to the Southwest Anatolian shear zone. From southwest to northeast, these basins are the Ören, Yatagan, Kale-Tavas, and Denizli basins (Figs. 9). In the Ören and Yatagan basins, the basinal sediments unconformably overlie slightly metamorphosed successions of the dominantly carbonate rocks of the western Taurides (Fig. 11). Yılmaz et al. (2000) report that the formation of the Ören and Yatagan basins was apparently controlled by a fault system displaying major dip-slip and a subordinate dextral strike-slip component. The basin fill in the two basins is similar and consists of a lower unit composed predominantly of coarse conglomerates grading upward to sandstones and an upper unit of shale-marl-dominated fine clastics (Yılmaz et al., 2000).

Figure 10. (A) A general view of the Acigöl segment of the Southwest Anatolian shear zone showing well-developed oblique-slip slickenlines. (B) Close-up view of the slickenlines that pitch 50° northwest within the fault plane (N50°E, 85°NW).



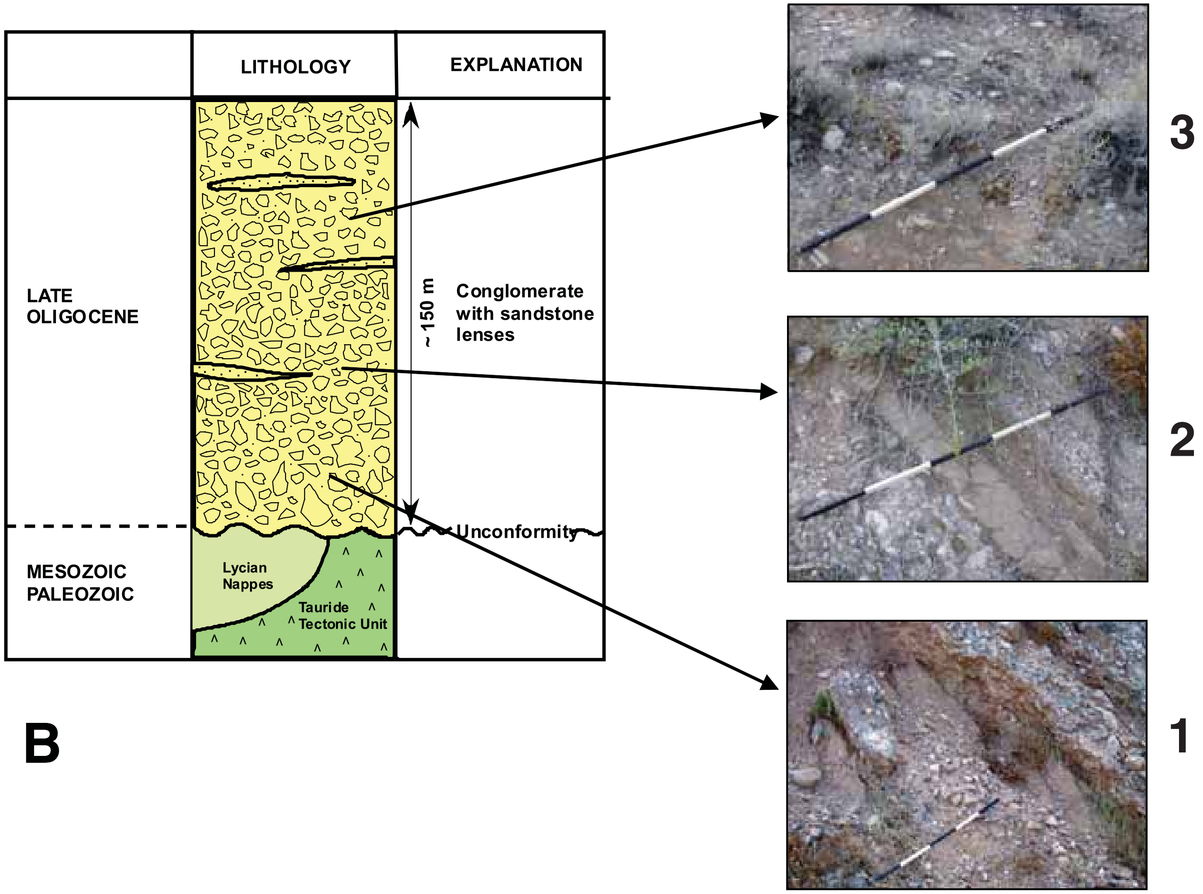


Figure 11. (A) Geologic map of the Gökova region (after Gürer and Yılmaz, 2002) showing the Oligocene sediments unconformably overlying slightly metamorphosed successions of the dominantly carbonate rocks of the western Taurides. (B) Columnar section of the Gokceoren conglomerate in the Ören basin in the vicinity of Turkevleri village. (1) Outcrop view of the lower part of the section. (2) Outcrop view of the middle part of the section. (3) Outcrop view of the upper part of the section.

Exposed along the northern margin of Gulf of Gökova in the vicinity of the town of Ören is ~150-m-thick cobble to boulder conglomerate composed mostly of limestone, marble, and phyllite clasts (Fig. 11). The conglomerate unconformably overlies the Lycian nappes along the northern margin of the Gulf of Gökova. This discontinuously exposed conglomerate unit (Fig. 11) is termed the Gokceoren formation and is assigned a late Oligocene age by Gürer and Yılmaz (2002). The conglomerate is generally poorly sorted and contains clasts up to 1 m in diameter in its basal part (Fig. 11). The clast size decreases upward, where it contains sandstone lenses. The conglomerate has been interpreted as a submarine alluvial fan deposit (Ozerdem et al., 2002). The northern boundary of the conglomerate is a down to the south normal fault system that may have been responsible for the unit's deposition (Fig. 11). This fault probably provided the highland for the formation of the conglomerate.

A seismic reflection profile across the Gökova basin (Kurt et al., 1999) shows the presence of a major down to the north fault along the southern margin of the Gulf of Gökova (Fig. 12). The fault was named the Datça fault by Seyitoğlu et al. (2004). It has a large rollover anticline and associated antithetic faults that control the deposition in the Gulf of Gökova. The fault system that controlled the deposition of the conglomerates of the late Oligocene Gokceoren formation strikes parallel to subparallel to the Datça fault. We interpret this fault system as the antithetic fault of the Datça fault, which is part of the Southwest Anatolian shear zone (Figs. 9, 11, and 12). If this interpretation is correct, the Datça fault was initiated in the late Oligocene, because its antithetic is late Oligocene in age. Therefore, we suggest that the basins of the Southern Menderes massif (i.e., Gökova, Ören-Yatagan, and Kale-Tavas) formed by extension adjacent to a major normal oblique slip fault zone, the Southwest Anatolian shear zone. We also suggest that this fault zone is a primary breakaway that formed during the north-directed late Oligocene extension (e.g., Seyitoğlu et al., 2004).

The Kale-Tavas basin, which trends east-west to northeast-southwest, is the largest of the Cenozoic basins adjacent to the Southwest Anatolian shear zone. The basal sedimentary units of the Kale-Tavas basin are the time equivalents of the basal sedimentary units of the Ören and Yatagan basins. The southeast side of the basin is bounded by a northeast-southwest-trending normal fault that is part of the shear zone (Fig. 9). The fault controls the accumulation of the basin fill and is a normal fault formed along the northern side of a southward-thrusting (Lycian nappe front) tectonic wedge (Yılmaz et al., 2000). The basin fill starts with Oligo-Miocene (Akgun and Sözbilir, 2001) debris flow and fluvial deposits containing red continental clastics derived from fault-induced structural highs to the south. The Oligo-Miocene units unconformably rest on the Lycian nappes. The basin fill continues with lagoonal and shallow marine clastics and limestone lenses. The marine units are unconformably overlain by the middle–late Miocene continental clastics, which are capped by the Pliocene lacustrine limestones (Yılmaz et al., 2000).

PROPOSED MODEL OF CENOZOIC EXTENSION IN WESTERN ANATOLIA

We suggest a testable 3D model for the Cenozoic extensional tectonics evolution of the Western Anatolia extended terrane (Figs. 13 and 14). The regional Alpine contraction, which produced the Izmir-Ankara suture zone in west Anatolia, may have ceased in the Eocene (Şengör et al., 1984; Okay, 2001; Figs. 13A and 14A). Our model suggests that the Cenozoic extension in the terrane is the product of a continuous north-directed extension. The extension has not been interrupted since its initiation and continues today, as is evidenced by GPS measurements (McClusky et al., 2000) and earthquake activity in the region detected by normal fault first motion studies (e.g., Taymaz et al., 1991). However, the extensional deformation in the region can be divided into three stages. Each stage may have been triggered by different mechanisms.

The first stage occurred in the late Oligocene, when extension was probably initiated along an extensional simple shear zone, the Southwest Anatolian shear zone, in the southern part of the Western Anatolia extended terrane (Figs. 1A and B and 12B), as evidenced by the presence of the Ören, Yatagan, and Kale-Tavas extensional sedimentary basins containing late Oligocene conglomerate. Seyitoğlu and Scott (1996) suggested that the late Oligocene extension may have been initiated by an orogenic collapse of thermally weakened crust of the Izmir-Ankara suture zone. The extension was probably initiated in a similar manner to that of the simple shear–rolling hinge models (e.g., Wernicke, 1985; Wernicke et al., 1988; Axen and Bartley, 1997).

The Southwest Anatolian shear zone extends from the south side of the Gökova Gulf to the southeastern margin of the Denizli basin (Figs. 9, 13, and 14). The seismic reflection profiles in the Gulf of Gökova (Kurt et al., 1999) clearly show a listric normal fault and an associated rollover structure (Fig. 12). The Ören basin (Figs. 9 and 11) formed on the hangingwall of this simple shear zone (Figs. 9, 13B, and 14B) as an extensional basin. The basin contains an Oligocene conglomerate unit called the Gokceoren formation (Yılmaz et al., 2000; Gürer and Yılmaz, 2002), suggesting that the shear zone formed in the late Oligocene. The first stage of our proposed extension model (Fig. 14B) might have been originated by the processes of orogenic collapse in the late Oligocene.

The Kale-Tava basin is also an extensional basin located adjacent to the Southwest Anatolian shear zone, which has a substantial strike-slip component (Fig. 14B) as it progrades east-northeastward and controls the southwestern margin of this basin (Figs. 9 and 14). Extension across the shear zone and associated erosion and tectonic unroofing caused the high-grade metamorphic rocks of the Menderes massif to be brought to the surface by the early Miocene (Figs. 13B and 14B).

Three lines of evidence for the existence of erosion and extensional unroofing in the late Oligocene–early Miocene are: (1) fission track ages indicate that metamorphic rocks of the Menderes massif were close to the surface in the early Miocene

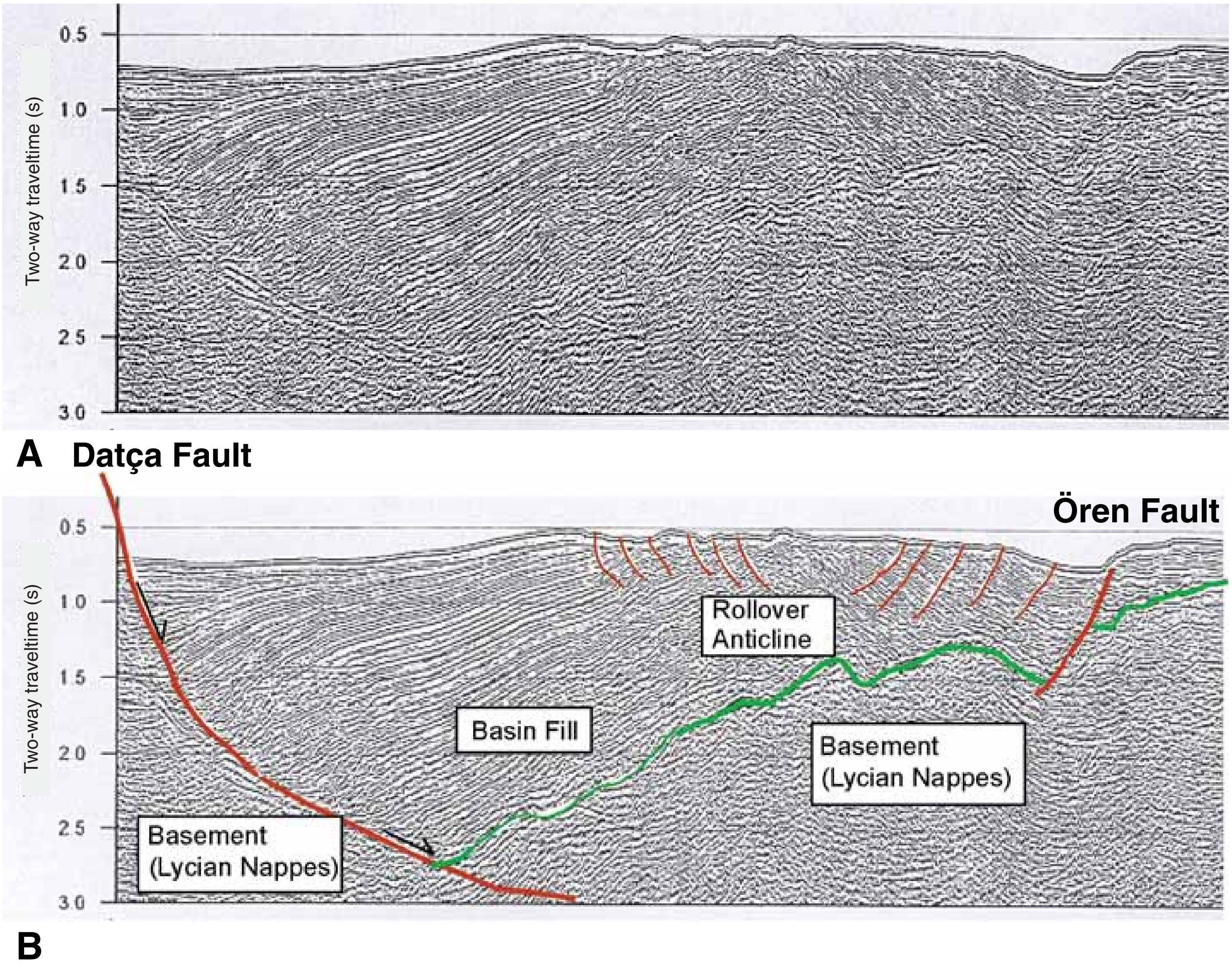


Figure 12. Uninterpreted (A) and interpreted (B) seismic reflection profiles from the Gulf of Gökova showing a well-developed rollover anticline within the basin fill and basement (Kurt et al., 1999). The approximate location of the line is shown in Figure 8.

(ca. 20 Ma) (Gessner et al., 2001b), (2) pervasive top to the north extensional shear sense indicators are well exposed throughout the high-grade metamorphic rocks of the Menderes massif (Figs. 2 and 5), and (3) the sedimentary basins that were formed in the early Miocene (i.e., the north-trending basins of the Northern Menderes massif and the Alasehir and Büyük Menderes graben) contain only high-grade metamorphic rocks of the Menderes massif in their lower Miocene conglomerate units.

The Oligocene Gokceoren conglomerate of the Ören and Yatagan basins is composed of Mesozoic recrystallized platform carbonate and underlying phyllitic low-grade metamorphic rocks (Fig. 11; Yılmaz et al., 2000; Ozerdem et al., 2002). The Oligocene conglomerates of the Kale-Tavas basin contain predominantly ophiolitic material derived from the uppermost tectonic slice in the Lycian nappe pile (Yılmaz et al., 2000), which was overlying the Menderes massif in the Eocene (Şengör et al., 1984). The Miocene sedimentary succession in the Ören, Yatagan, and Kale-Tavas basins, however, contains high-grade metamorphic rock fragments of the Menderes massif (Sözbilir et al., 2000). This sedimentary record indicates that extension in the Western Anatolia extended terrane started in the Oligocene, when the Lycian nappes were covering the Menderes massif. The rocks in the upper structural levels of the nappe pile (i.e., ophiolitic, recrystallized carbonates and low-grade phyllitic metamorphic rocks) provided clasts in the Oligocene. However, the high-grade metamorphic rocks were at the surface in the

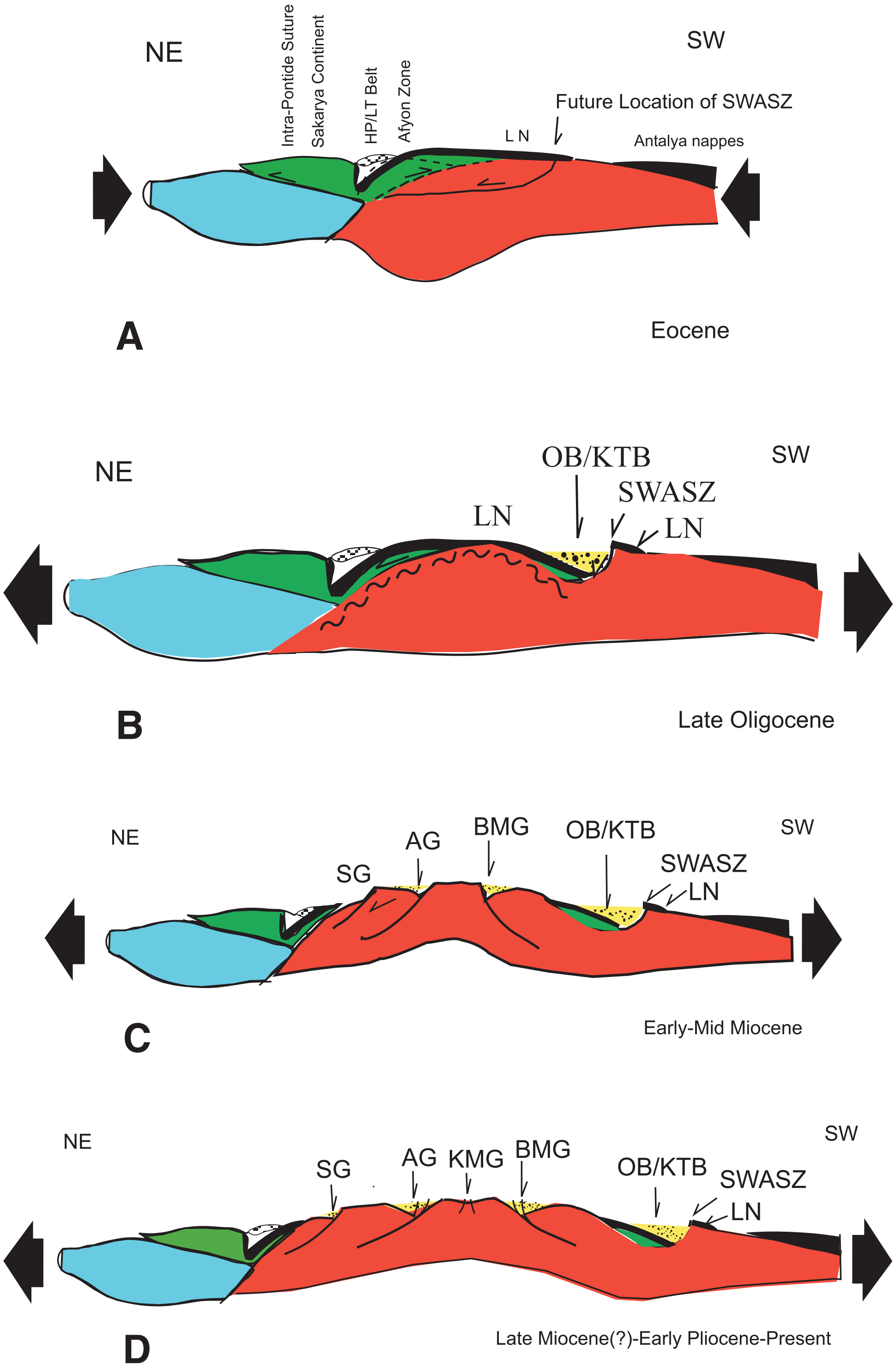


Figure 13. Schematic cross-sections showing proposed extensional model of the Cenozoic extensional evolution of the WAET (slightly modified from Seyitoğlu et al., 2004). The cross-sections are schematic illustration of (A) Eocene; (B) Late Oligocene; (C) Early to Mid-Miocene; and (D) Late Miocene-Pliocene to present. Abbreviations: AG—Alasehir graben; BMG—Büyük Menderes graben; KMG—Kucuk Menderes graben; KTB—Kale-Tavas basin; LN—Lycian nappes; OB—Ören basin; SG—Simav graben; SWASZ—Southwest Anatolian shear zone.

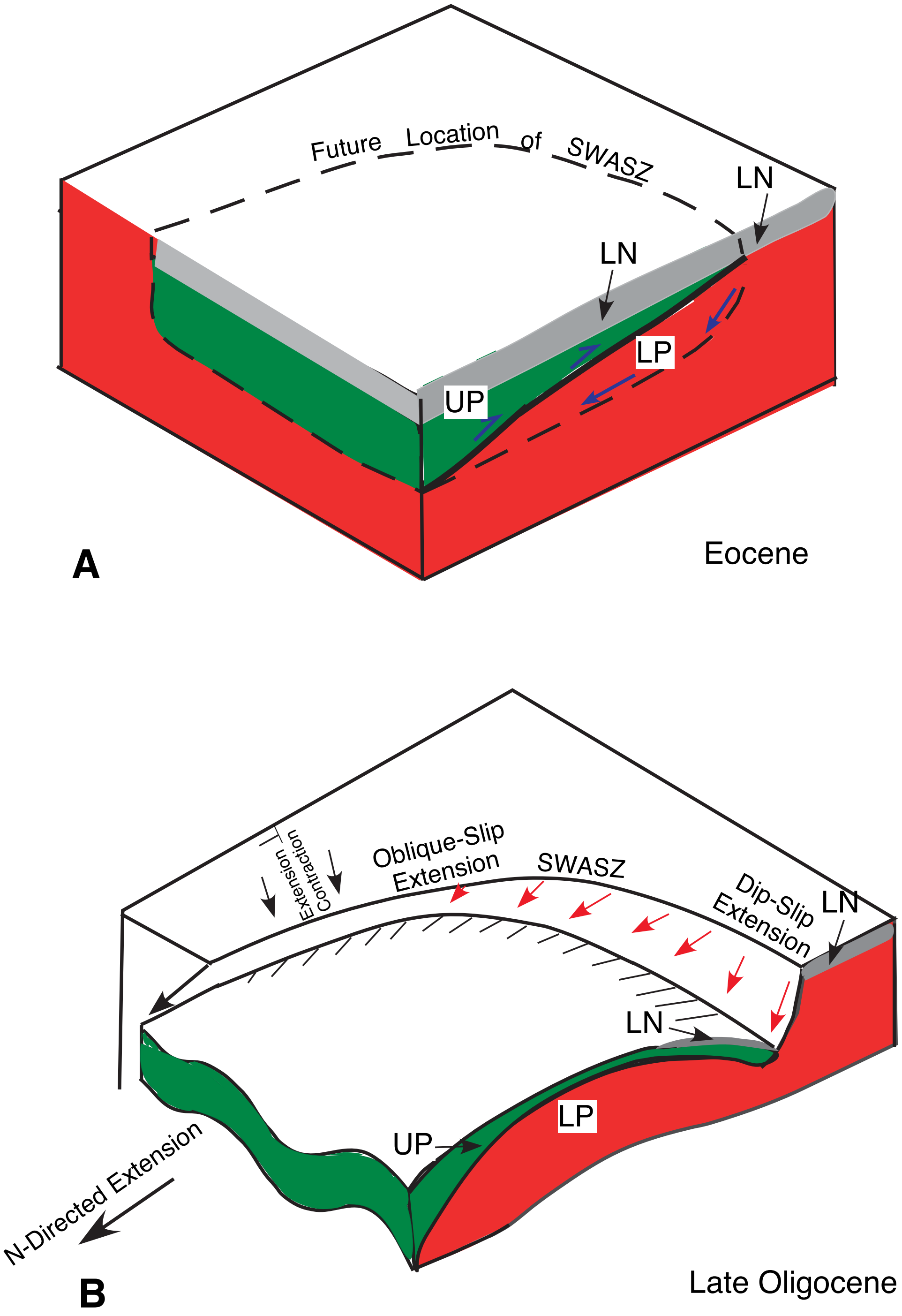


Figure 14. 3-D cartons emphasizing the role of the Southwest Anatolian shear zone (SWASZ) in the structural evolution of the Western Anatolia extended terrane in (A) the Eocene, (B) the late Oligocene, (C) the early–middle Miocene, and (D) the late Miocene or the Pliocene to the present. They do not include the Simav detachment area. The 3-D cartons are not drawn to scale and do not indicate the amount of extension in each stage. Abbreviations: AG—Alasehir graben; BMG—Büyük Menderes graben; OB/KTB—Ören and Kale-Tavas basins; LN—Lycian nappes; KMG—Kucuk Menderes graben; LP—lower plate; SG—Simav graben; SWASZ—Southwest Anatolian shear zone; UP—upper plate.

Miocene and provided clasts for the conglomerates in the sedimentary basins (Figs. 13C and 14C).

The second stage of our proposed extension model (Fig. 14C) was probably triggered by the subduction roll-back processes started in the early Miocene. Continued extension produced the Alasehir and Büyük Menderes detachment surfaces (Figs. 13C and 14C). The original dip angle of the Alaşehir detachment surface is controversial. The detachment surface may have formed with a steep dip in the early Miocene but rotated to its present low angle as the extension continued (Seyitoğlu et al., 2000, 2002). Alternatively, the Alasehir detachment may have originally been initiated as a low-angle detachment fault (Purvis and Robertson, 2004).

The Simav detachment must have formed in the hanging-

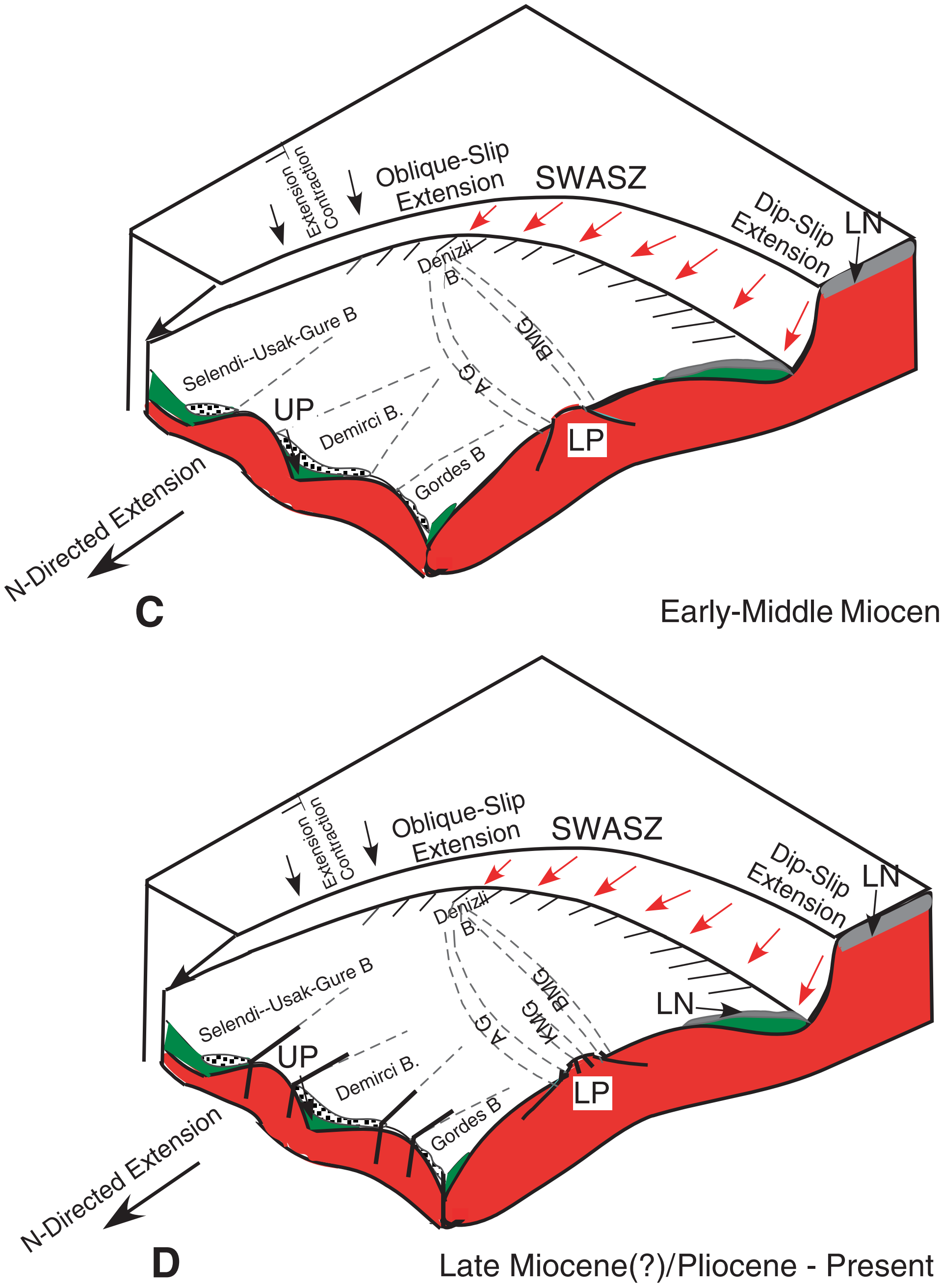


Figure 14. *Continued*

wall of the Alasehir detachment. The down to the south normal faults along the northern margin the Alasehir detachment brought to the surface the footwall of the Simav detachment, which contains extension-parallel antiformal and synformal folds with a wide range of scale. The axial traces of all folds are parallel to the N10°E to N30°E mylonitic stretching lineations. Considering that mylonitic lineations form parallel to the direction of extension, these folds suggest compression perpendicular to extension. Large-scale antiforms and synforms are also observable along the unpublished TPAO east-west seismic reflection profiles in the sedimentary succession of the Alasehir graben.

The large antiforms and synforms that formed in the lower plate of the Southwest Anatolian shear zone (Fig. 14B) provided the initial configuration in the early Miocene for the north-trending sedimentary basins of the northern Menderes massif (i.e., the Demirci, Gördes, and Usak-Selendi basins). However, the northeast-trending faults that control the eastern and western margins of these basins may have been formed as accommodation faults (Şengör, 1987) due to differential stretching, because they have a substantial strike-slip component.

Purvis and Robertson (2004) proposed that the early Miocene extension is related to the subduction roll-back of the Aegean subduction zone. The roll-back may still be an effective mechanism of extension in western Anatolia.

The third stage of extension in western Anatolia started in the late Miocene ca. 5 Ma (Catlos and Çemen, 2005), coinciding with the formation of the North Anatolian strike-slip fault zone (Barka, 1997). This third stage produced continuous extension along the Simav, Alasehir, and Büyük Menderes detachments and oblique slip movement along the Southwest Anatolian shear zone (Figs. 13D and 14D). This extension was probably also responsible for the formation of the Kucuk Menderes graben and the second and third orders of the normal faults (Seyitoğlu et al., 2000) along the Alasehir graben.

The North Anatolian fault zone influenced the structural development of western Anatolia within the last 5 m.y. and accommodated the tectonic escape (Şengör, 1979; Sengör and Yılmaz, 1981) or lateral extrusion of the Turkey plate westward (Çemen et al., 1993, 1999). The lateral extrusion may have been responsible for the third stage of the proposed extension model (Fig. 14D) together with subduction rollback of the Aegean subduction zone.

DISCUSSION

This article summarizes the metamorphic history, geochronology, structural geology, and development of the sedimentary basins in the Western Anatolia extended terrane and presents a 3-D extensional model for the region that fits the available data (Fig. 14). This model can be tested by the following:

1. Carrying out a quantitative study of the rocks in the Oligocene and Miocene basins of the terrane in terms of their tectonic and sedimentation history, including detailed observations of the lithologies of conglomerates. One critical required constraint is the timing of the appearance of high-grade metamorphic clasts in the conglomerates of the Oligocene to Miocene sedimentary successions in the Ören, Yatagan, and Kale-Tavas basins.
2. Conducting combined thermobarometric and geochronologic studies, such as in situ dating of monazite located in the garnet-bearing assemblages used to generate *P-T* conditions. Currently, the peak metamorphic conditions reported for rocks of the Menderes massif cannot be ascribed with confidence to specific tectonometamorphic events. In situ ion microprobe or electron microprobe dating of monazite and chemical correlation of those dates with silicate compositions and *P-T* conditions would provide insight into the nature of the complicated deformation events affecting the Menderes massif.
3. Conducting a petrologic and geochronologic study of the volcanic rocks well exposed throughout the Western Anatolia extended terrane. If there is a well-defined southward younging direction in the volcanic rocks of the terrane, the timing and the role of subduction roll-back in the Cenozoic extension in western Anatolia can be better understood.

In this article, we have not addressed the issue of the percentage and amount of extension in the Western Anatolia extended terrane because no comprehensive geological study has addressed this issue. In western Anatolia, this problem cannot be solved without a valid reconstruction of the Eocene Alpine contractional tectonics and a better understanding of the timing and the process of transition from Alpine contraction to extension.

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