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Early Miocene stratigraphy of Central West Anatolia, Turkey: implications for the tectonic evolution of the Eastern Aegean area†

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Small-mammalian faunas enable the discrimination and correlation of uppermost Lower Miocene lacustrine sedimentary units in central western Anatolia. On the basis of sequential stratigraphic relationships, early Early Miocene and latest Early Miocene relative ages are suggested for the older lacustrine mass-flow deposits and younger paper shale units, respectively, which are devoid of age-diagnostic fossils.

In central western Anatolia, the sequential differences between the uppermost Lower Miocene successions delineate a deformation zone of NE–SW-trending fault blocks separated by vertical faults. This deformation zone, inherited from Late Oligocene tectonics, underwent an early Early Miocene sinistral transtension leading to pull-aparts that were emplaced by granitoids. Limited extension caused the late Early Miocene repetitive up- and down-wards motions of the fault blocks, with variable magnitudes. This led to contrasting subsidence histories in the relevant basinal system. During the latest Early Miocene, fault blocks coalesced into a regional body characterized by uniform slow subsidence and non-extensional deformation facies. The general trend of the above tectonic events can be explained by lateral slab segmentation and progressive asthenospheric wedging, in response to NE-directed and decelerated palaeosubduction in the Aegean.

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1. INTRODUCTION

The Aegean region is a world-wide known Late Cenozoic extensional continental region. Special emphasis has been given to latest Oligocene–Early Miocene post-orogenic extension, the overall style and history of which is attributed to five different models: (1) westward escape of the Anatolian Block along its boundary structures, the dextral North Anatolian and sinistral East Anatolian fault systems since the late Serravalian (~12 Ma) (*tectonic escape model*; Şengör *et al*. 1985). (2) southwestward roll-back of the Aegean-Cyprian subduction zone (e.g. Armijo *et al*. 1996) between the northward descending African Plate in the south and the overriding Anatolian Plate in the north and consequent back-arc extension across a thick crust behind the Aegean Arc (*back-arc spreading*

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†It is with great sorrow that we record that Orhan Kaya passed away whilst the revised version of this paper was being prepared. The editors would like to express their sympathy to Tanju Kaya (wife of the senior author) and acknowledge her help in getting this final version completed.
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model) (e.g. Le Pichon and Angelier 1979; Jackson and McKenzie 1988; Meulenkamp *et al*. 1988, 1994; Avigad *et al.* 1997; Jolivet *et al.* 1998; Thomson *et al.* 1998; Okay and Satır 2000 and references therein). This model involves the Late Oligocene—Early Miocene 'palaeosubduction' (Papazachos 1976; Shanov *et al*. 1992) defined by the 'Pindos thrust fault' hinge (Mercier *et al*. 1989), which was originally situated further to the south (Figure 1A). It also predicts, to the north of the palaeosubduction hinge (i) latest Oligocene south-dipping (Lister *et al*. 1984) or Early Miocene north-dipping (Buick 1991) low-angle faults, (ii) transpression defined by conjugate NNE–SSW-trending (dominant) and NW–SE-trending strike-slip faults (Boronkay and Doutsos 1994) and (iii) easterly-trending rift zones, probably older than 15 Ma (Armijo *et al*. 1996). (3) Late orogenic spreading and thinning of crust overthickened (*gravitational collapse model*) during latest Paleogene collision between the

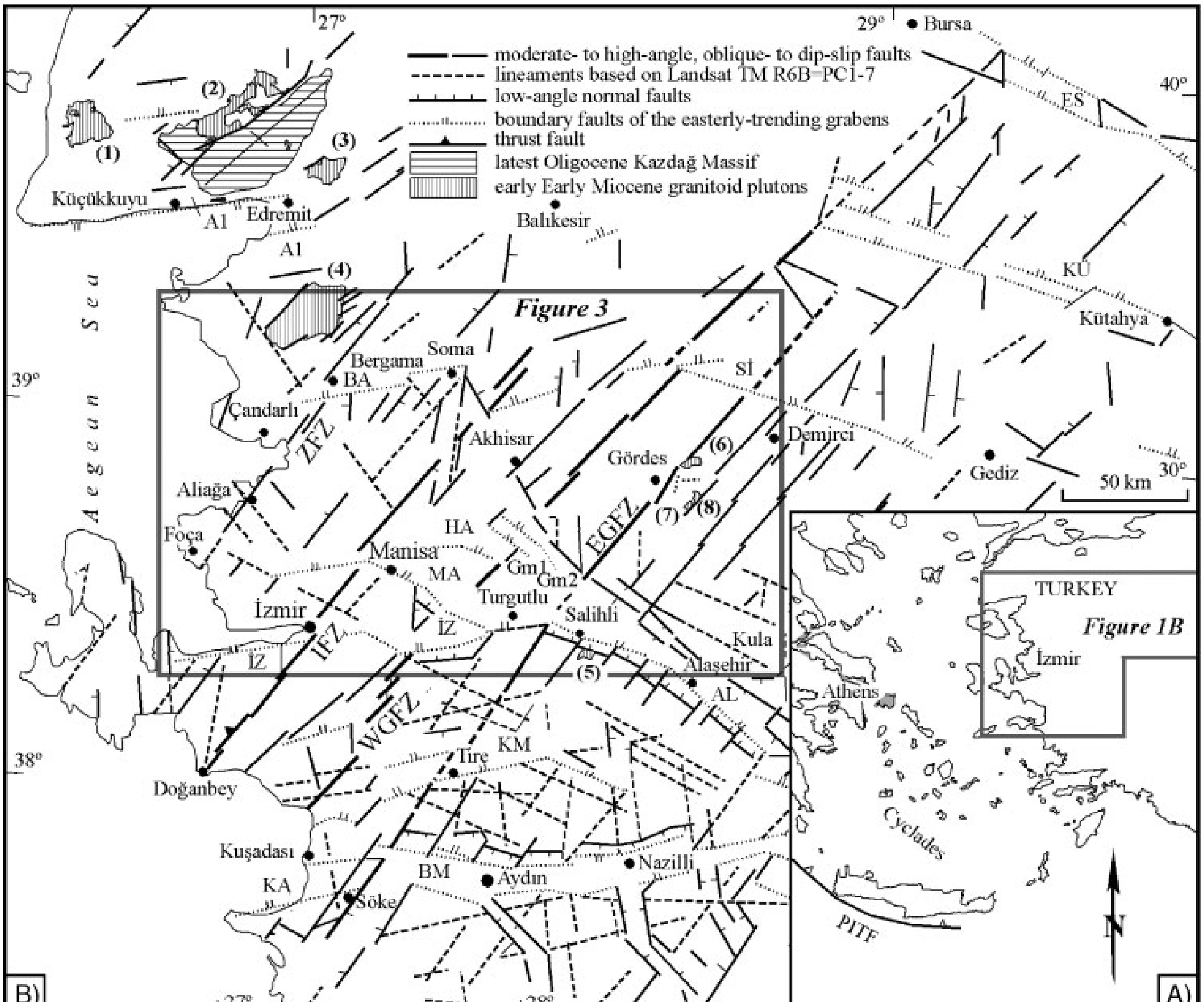

Figure 1. Schematic Late Cenozoic fracture and lineament map of Central West Anatolia, western Turkey (A), showing the dominance of the NE–SW trends (B) AL: Alaşehir half Graben; BC: Bakırçay Graben; BM: Büyük Menderes Graben; GM1, GM2: Göl Marmara half grabens; HA: Halitpaşa half graben; KA: Kuşadası half graben; KM: Küçük Menderes Graben; KÜ: Kütahya half graben; İZ: İzmir half graben; MA: Manisa half graben; SI: Simav half graben; GE: Gediz half graben system that comprises İZ, AL, MA, HA, GM1 and GM2. Late Oligocene–Early Miocene intrusives: (1) Kestanbol pluton; (2) Evciler pluton; (3) Eybek pluton; (5) Salihli pluton; (6) Günlüce pluton; (7) Gördes pegmatite district; (8) Kuyucakpınar pluton. PITF: Pindos Thrust Fault (Mercier *et al*. 1989); ZFZ: Zeytindağ Fault Zone; İFZ: İzmir Fault Zone; WGFZ: Western Gördes Fault Zone; EGFZ: Eastern Gördes Fault Zone. Gördes Fault Zone comprises WGFZ and EGFZ.

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Sakarya Continent in the north and the Anatolian–Tauride Platform in the south across the İzmir-Ankara Neotethyan Suture (Seyitoğlu and Scott 1991, 1992; Seyitoğlu *et al.* 1992). The collapse model predicts that the northerly- and easterly-trending 'graben-horst' systems in central western Anatolia commenced to develop simultaneously by the Late Oligocene–Early Miocene and continued since then (e.g. Seyitoğlu *et al.* 2002). (4) Combination of above models—the extension in western Anatolia is expressed in two distinct structural styles as Early–Middle Miocene core-complex formation (orogenic collapse) and Plio–Quaternary modern graben formation (westward escape of the Anatolian Block), separated by an interval of N–S crustal shortening during late Serravalian–late Early Pliocene times (*Episodic*, *two-stage graben model*) (Koçyiğit *et al.* 1999; Bozkurt 2000, 2003, 2004; Yılmaz *et al.* 2000; Bozkurt and Sözbilir 2004; Purvis and Robertson 2004, 2005a, b; Beccaletto and Steiner 2005; Bozkurt and Rojay 2005; Erkül *et al.* 2005a, b; Rojay *et al.* 2005). (5) Differential rates of convergence between northeastward-directed subduction of the African Plate relative to the hanging-wall Anatolian Plate—rapid southwestward movement of Greece relative to Anatolia determines the extension in the Aegean and Western Anatolia (Doglioni *et al.* 2002; Tokcaer *et al.* 2005). The readers are referred to Bozkurt (2001a) and Bozkurt and Mittwede (2005) for further reading.

Because most of the region is under sea, better understanding of the tectono-sedimentary development of the Central West Anatolian basinal system may provide new constraints for the latest Oligocene–Early Miocene extension, at least, in the Eastern Aegean region. In Central West Anatolia, the Late Cenozoic faults can be grouped under two general trends (Figure 1B): a northerly-trend of NE–SW-, N–S- and NW–SE-striking faults, and an easterly-trend of WNW–ESE-, E–W- and ENE–WSW-striking faults. Models for the Miocene tectonic evolution of Central West Anatolia and that of north-trending basins fall into five different groups: (1) Northerly-trending faults are inherited structures developed during the Paleogene collisional tectonics as a result of north–south compression and shortening across the Neotethys; they are named as '*palaeotectonic Tibet-type cross-grabens*' (Şengör *et al.* 1985; Şengör 1987; Görür *et al.* 1995), then reactivated and gave rise to a similarly-trending basinal system during Early to Middle Miocene N–S compression; they have been superimposed (cut and displaced) by east–west-trending graben-bounding faults ('neotectonic Aegean-type cross-grabens: *replacement structures*') during modern N–S crustal extension since the Late Miocene (Kaya 1982). According to this model, the compressional tectonics is replaced by extensional tectonics during Late Miocene (?Tortonian) (Şengör 1982, 1987; Şengör *et al.* 1985; Savaşçın and Güleç 1990). Yılmaz *et al.* (2000) argued that the age of the northerly-trending faults and related basinal systems is Early Miocene and episodically to be superimposed on the older northerly-trending faults. (2) North-trending basins and east–west-trending grabens developed simultaneously since the latest Oligocene–Early Miocene times during N–S crustal extension, and during late orogenic collapse immediately after latest Paleogene collision along the İzmir-Ankara Neotethyan Suture (e.g. Seyitoğlu and Scott 1991, 1992; Seyitoğlu 1997). (3) NE-trending basins are slowly subsiding intermontane low-lands filled-up with fluvial sediments eroded from intervening uplands (İnci 1988a, b, 2002). (4) The E–W-trending grabens and NE-trending basins developed simultaneously during the Early Miocene where the basin-bounding structures of the NE-trending basins are '*Aegean-type cross-grabens*' and the bounding faults, '*rotational accommodation faults*', which accommodate differential stretching in the hanging-wall of a north-dipping Gediz Detachment (low-angle normal) fault responsible for the exhumation of the Menderes Massif. This model argues that the NE–SW-trending accommodation faults might have followed pre-existing weakness planes and that older *Tibet-type* cross-faults might have existed but did not localize any sedimentation (Bozkurt 2003). (5) The last model suggests that Gediz Detachment is characterized by kilometre-scale corrugations where troughs correspond to NE-trending basins, passively filled-up with fluvial sediments eroded from intervening uplands that correspond to the culminations. The readers are referred to Bozkurt (2003) and Purvis *et al.* (2005a,b) for further reading.

In previous work, the Early to Middle Miocene ages applied to the lacustrine deposits in Central West Anatolia were based primarily on chronologically wide-ranging palaeobotanic data and assumptive correlations with radiometrically dated volcanic rocks. Within this context, the major NE–SW-trending faults, as the most persistent and oldest structures, are known to be broadly Early Miocene synsedimentary sutures (Kaya 1981). This study aims (i) to introduce a stratigraphic classification for the Lower Miocene deposits on the basis of small-mammalian

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evidence, (ii) to delineate a late Early Miocene deformation zone of NE–SW-trending vertical faults, using stratigraphic correlations, (iii) to apply the analogue models of transtensional faulting to the early Early Miocene granitoid plutons to define the structural background of the deformation zone and (iv) to correlate the deformation zone with the known fault pattern in the South Aegean, in favour of a regional model. O. Kaya did the field work, and is responsible for the text. E. Ünay identified the fossils. F. Göktaş supplied local field data. G. Saraç and O. Kaya surveyed for biostratigraphically prospective samples.

2. STRATIGRAPHY

Generalized lithological successions, short-ranged chronological classification and major facies categories of the Lower Miocene sedimentary units, as the implications of this study, are given in Figure 2. The major pre-Miocene basement entities in Western Anatolia include (i) the Menderes Massif consisting of Proterozoic to Mesozoic high- to low-grade crystalline rocks (e.g. Şengör *et al.* 1984; Bozkurt and Park 1994, 1997, 1999; Candan *et al*. 1997; Bozkurt and Oberhänsli 2001; Erdoğan and Güngör 2004; Koralay *et al*. 2004; Seyitoğlu *et al.* 2004; Bozkurt *et al*. 2006; Şengün *et al*. 2006); (ii) the Ovacık Group (Kaya 1990; Kaya *et al.* 2004) consisting of Upper Cretaceous to Lower Palaeocene assemblage of turbidites, olistostromes and megabreccias and ophiolite-related clasts. It is represented by blocks and/or olistoliths of ophiolites (serpentinitized ultramafic tectonites, mafic volcanic rocks and red-green radiolarite) and mountain-forming Mesozoic grey-red recrystallized limestones within a sheared turbiditic matrix (Kaya *et al.* 2004). This unit can be correlated with the Bornova Flysch Zone (Erdoğan 1990; Okay and Siyako 1993; Okay *et al*. 1996); (iii) the Karakaya Complex (e.g. Bingöl 1978; Beccaletto and Jenny 2004; Okay and Altıner 2004; Okay and Göncüoğlu 2004; Pickett and Robertson 2004) comprising primarily ultramafic rocks, Triassic ophiolite and platform-related low-grade metamorphic rocks and a latest Triassic assemblage of turbidites, olistostromes and megabreccias, and (iv) the Kazdağ Massif consisting primarily of mid-Hercynian high-grade metamorphic rocks with a latest Oligocene metamorphic overprint (Okay and Satır 2000; Duru *et al.* 2004).

2.1. Küçükköy Formation

The Formation is composed of dark grey shale and thin interbeds of fine-grained sandstone. It overlies the pre-Miocene basement unconformably with a poorly-sorted conglomerate and pebbly coarse sandstone; the conglomerate is characterized by sporadic occurrence of boulder fragments, all of which are derived from the underlying basement rocks.

2.2. Yeniköy Conglomerate Formation

This conglomerate unit conformably overlies the İkizbaşlı Formation (Figure 4C) and consists mainly of greyish coloured, massive to thick-bedded, poorly- to moderately-sorted, consolidated clast-dominated pebble conglomerate. The clasts are usually pebble-sized and derived from the underlying pre-Miocene rocks. Pebbly sandstone and mudstone also occur as interlayers in different stratigraphic horizons. The lowest parts of the Formation are composed of poorly sorted and consolidated boulder conglomerate with angular to rounded variably sized (up to large cobble size) rock fragments within a fine-grained matrix. The thickness and distribution of this lowest lithology depend on the palaeotopography.

2.3. Samur Group

The Samur Group is composed of a condensed volcano-sedimentary succession with different lithologies in small amounts with a limited areal extent. The lowest lithology disconformably overlies the Yeniköy Conglomerate and is represented by a whitish rhyolitic ash-fall tuff (Tekedere Tuff). The succession continues conformably with

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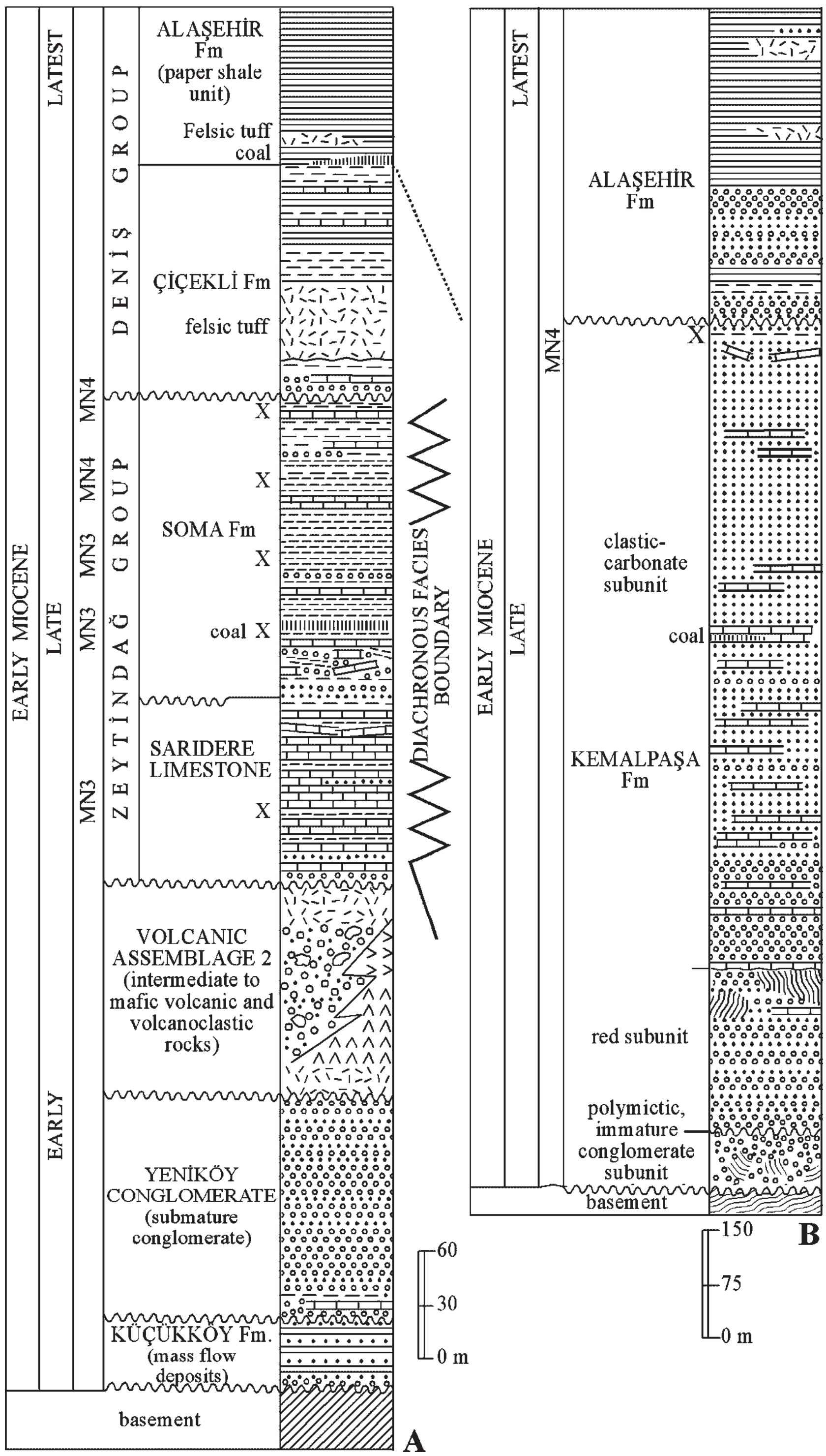

Figure 2. Early Miocene representative lithological succession in Central West Anatolia. (A) Modified after Nebert (1978) and Kaya (1981); (B) this study. X-locations of new mammalian evidence.

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volcanogenic sandstone and tuff alternation with mafic volcanic rock fragments of variable size, up to a few tens of metres (Kurallı Formation). Rhyodacitic lava flows (Güzelhisar rhyodacite) (about 260 m thick) form the other conspicuous lithology within the Samur Group. In addition to dominant rhyodacite flows, this unit also contains latite andesite, andesite and dacite. Basaltic lava flows (Sarıyer basalt) (about 170 m thick) form the second volcanic horizon in the group. They are commonly altered in almost all exposures and are characterized by vesicular to scoriaceous lower and upper boundaries. The topmost lithology in the Samur Group is represented by volcanoclastic rocks composed mainly of felsic lithic to crystal tuff and volcanogenic sandstone with rare limy mudstone intercalations. They rest disconformably above the Sarıyer basalt.

2.4. Zeytindağ Group

The Zeytindağ Group replaces the 'Zeytindağ formation' of Kaya (1981) and consists of two distinct lithologic associations: a lower limestone unit, Sarıdere Limestone, succeeded by the Soma Formation (Figure 2). The following sections summarize the basic characteristics of these units.

2.4.1. Sarıdere Limestone

The Sarıdere Limestone replaces the 'Sarıdere member of the Zeytindağ formation' of Kaya (1982). In the Zeytindağ area (Figure 3, area C), the Sarıdere Limestone consists of light-grey, medium-bedded, microcrystalline limestone and intercalations of yellowish-grey clayey limestone, limy mudrock and light-grey, variably limy, texturally submature conglomerate and sandstone. At the base, the unit is locally defined by a red mudrock-white nodular limestone horizon, which is referred to as the red subunit (Figure 4C). The Sarıdere Limestone rests unconformably on the Miocene Yeniköy Formation boulder conglomerates and the basement rocks.

In the Bozalan area (Figure 3, area E; Figure 4E), small-mammalian fauna recovered from the middle parts of the Sarıdere Limestone (051656°E/428455°N) includes *Cricetodon kasapligili*, *Cricetodon* sp., *Megacricetodon* sp., *Sayimys* sp., Cricetidae (*Democricetodon* ?), Gliridae, Sciuridae, Insectivora and Lagomorpha, which are indicative of a late Early Miocene (MN3) age. In this particular locality, the Sarıdere Limestone rests unconformably on the basement rocks.

The lithologic characteristics and contact-relationships of the Sarıdere Limestone vary from one locality to another; it is also given different names. For example, in the Bornova (Sabuncubeli) area (Figure 3, area F; Figure 4F), the unit unconformably overlies the basement rocks and is represented by the basal red subunit, which interfingers with fanglomerates. In the Gördes area, the Sarıdere Limestone can be correlated with the 'Hamit formation' (Ünay and Göktaş 2000) that conformably overlies the Yeniköy Formation conglomerates (Figure 3, area H; Figure 4H).

In the Soma area the Sarıdere Limestone corresponds to a *ca*. 26 m-thick limestone unit (Figure 3, area D; Figure 4D), which was not differentiated in the previous work. The unit (054724°E/432876°N) consists of a laterally wedging thin clastic horizon at the base, and overlying light brown-grey, medium to thick-bedded and microcrystalline limestone (Figure 4D). Both the basal clastic rocks and the limestones display unconformable contact relationships with the basement rocks.

2.4.2. Soma Formation

The name 'Soma Formation' (Nebert 1978) replaces the 'Şakran member of the Zeytindağ formation' of Kaya (1981). The bulk of the Soma Formation is characterized by a yellowish-grey weathering, bluish-grey, well indurated, diffusely thin- to medium-bedded limy mudrock sequence. It is overlain by a light brown and white, medium- to thick-bedded limestone and clayey limestone sequence. The clastic basal part of the formation is locally 12 m thick and rests on the basement (470450°E/279965°N). It consists, in ascending order, of greenish-grey, poorly to moderately indurated fanglomerate, muddy sandstone, sandy mudrock and at the top about 70 cm of yellowish to brownish-grey, partly silicified limestone. In Harta, southeast of Soma, the basal coal-bearing part of the 'Soma Formation' yielded *Cricetodon kasapligili*, *Eumyarion* cf. *intercentralis, Aliveria* sp., *Democricetodon* sp., *Galerix*

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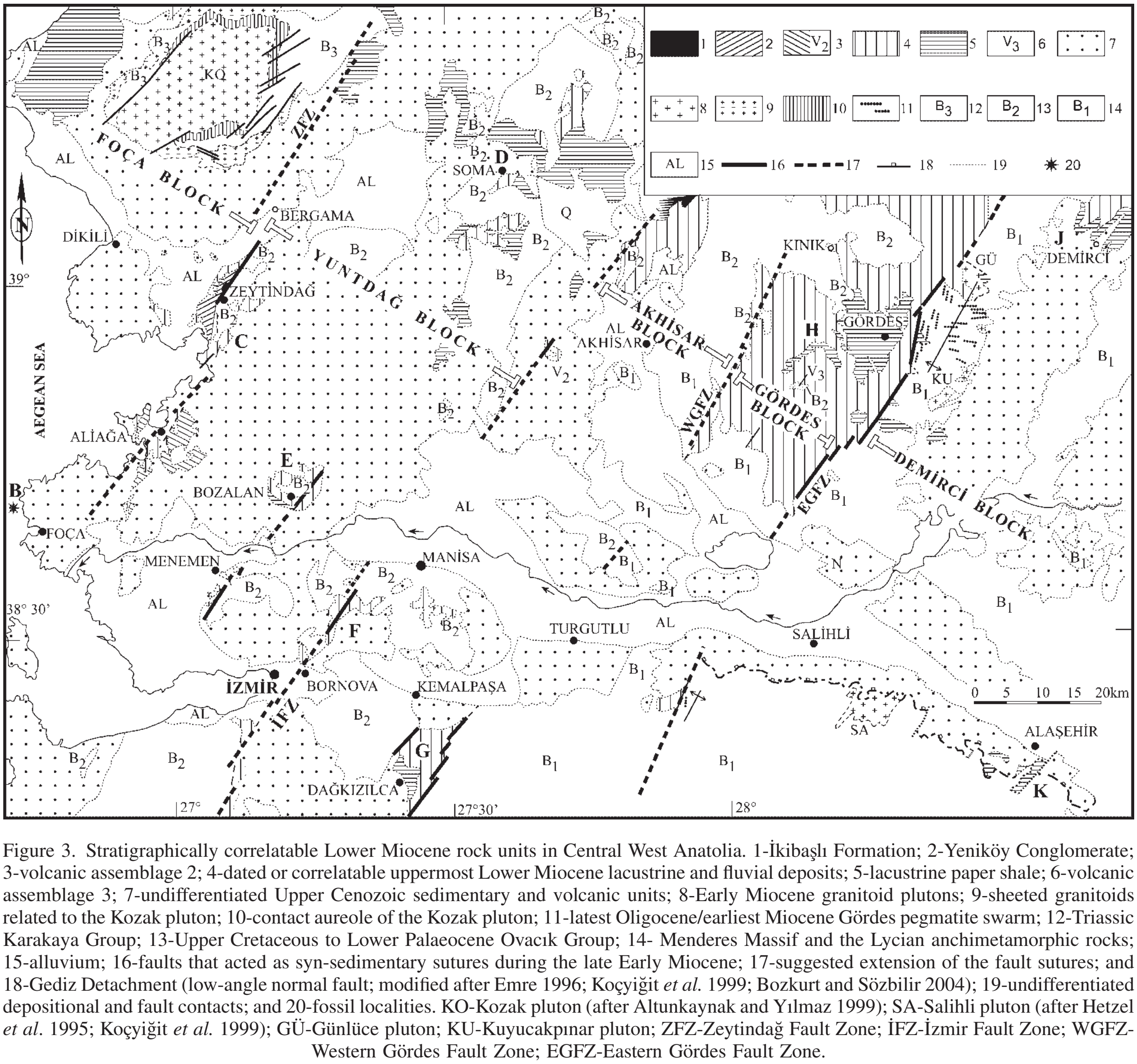

Figure 3. Stratigraphically correlatable Lower Miocene rock units in Central West Anatolia. 1-İkibaşlı Formation; 2-Yeniköy Conglomerate; 3-volcanic assemblage 2; 4-dated or correlatable uppermost Lower Miocene lacustrine and fluvial deposits; 5-lacustrine paper shale; 6-volcanic assemblage 3; 7-undifferentiated Upper Cenozoic sedimentary and volcanic units; 8-Early Miocene granitoid plutons; 9-sheeted granitoids related to the Kozak pluton; 10-contact aureole of the Kozak pluton; 11-latest Oligocene/earliest Miocene Gördes pegmatite swarm; 12-Triassic Karakaya Group; 13-Upper Cretaceous to Lower Palaeocene Ovacık Group; 14- Menderes Massif and the Lycian anchimetamorphic rocks; 15-alluvium; 16-faults that acted as syn-sedimentary sutures during the late Early Miocene; 17-suggested extension of the fault sutures; and 18-Gediz Detachment (low-angle normal fault; modified after Emre 1996; Koçyiğit *et al.* 1999; Bozkurt and Sözbilir 2004); 19-undifferentiated depositional and fault contacts; and 20-fossil localities. KO-Kozak pluton (after Altunkaynak and Yılmaz 1999); SA-Salihli pluton (after Hetzel *et al*. 1995; Koçyiğit *et al.* 1999); GÜ-Günlüce pluton; KU-Kuyucakpınar pluton; ZFZ-Zeytindağ Fault Zone; İFZ-İzmir Fault Zone; WGFZ-Western Gördes Fault Zone; EGFZ-Eastern Gördes Fault Zone.

sp., *Enginia* sp., *Sayimys* sp., Gliridae and Lagomorpha, indicating a late Early Miocene age (MN3) (Göktaş and Ünay 2000).

In the Zeytindağ area, the contact between the Soma Formation (Şakran member in Figure 4C) and the Sarıdere limestone is not well exposed. However, the basal part of the Soma Formation is represented by a mixed succession of mudrocks, lithic and volcanogenic sandstones, and white limestone and coal lenses up to 10 cm in thickness (Figure 4C); the lithologic association is indicative of an abrupt environmental change.

In the Bozalan area, the lowermost part of the formation is composed of folded and cleaved intrabasinal limestone, channel-filling fine-grained lithic conglomerate, coaly mudrock (up to 1 m thick) and several centimetre-thick coal layers (Figure 4E). Tensional fibrous calcite veins, up to 8 cm in width, are common in the limestones; they are thought to be the result of hydraulic fracturing. The limy mudrock in the middle part of the formation (052167°E/428198°N) contains *Cricetodon* sp., *Eumyarion* sp., *Galerix* sp., *Glirulus* sp.,

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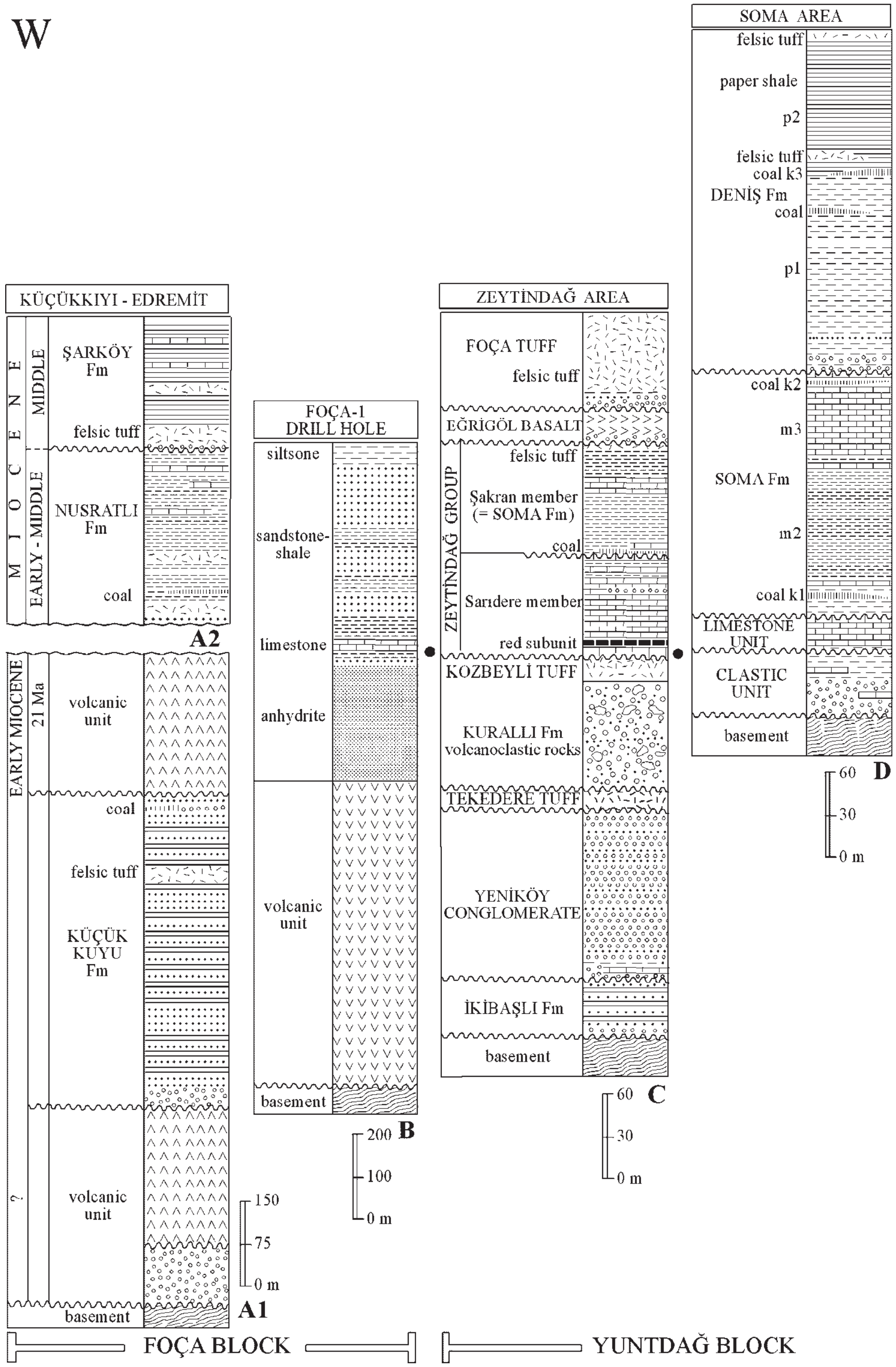

Figure 4. Correlation of the Lower Miocene and probable Upper Oligocene stratigraphic units with reference to the base of the Sarıdere Limestone of the Zeytindağ Group. See Figure 1 for the areas A1, A2, and Figure 2 for the areas B–K. (A1) Küçükkuyu area (Kaya 1982); (A2) Edremit area, İnci (1984); (B) Foça 1 drill-hole (Turgut 1988); (C) Kaya (1979, 1981); (D) modified after Nebert (1978); (E–G) this study; (H) modified after Göktaş (1999); (J) this study.

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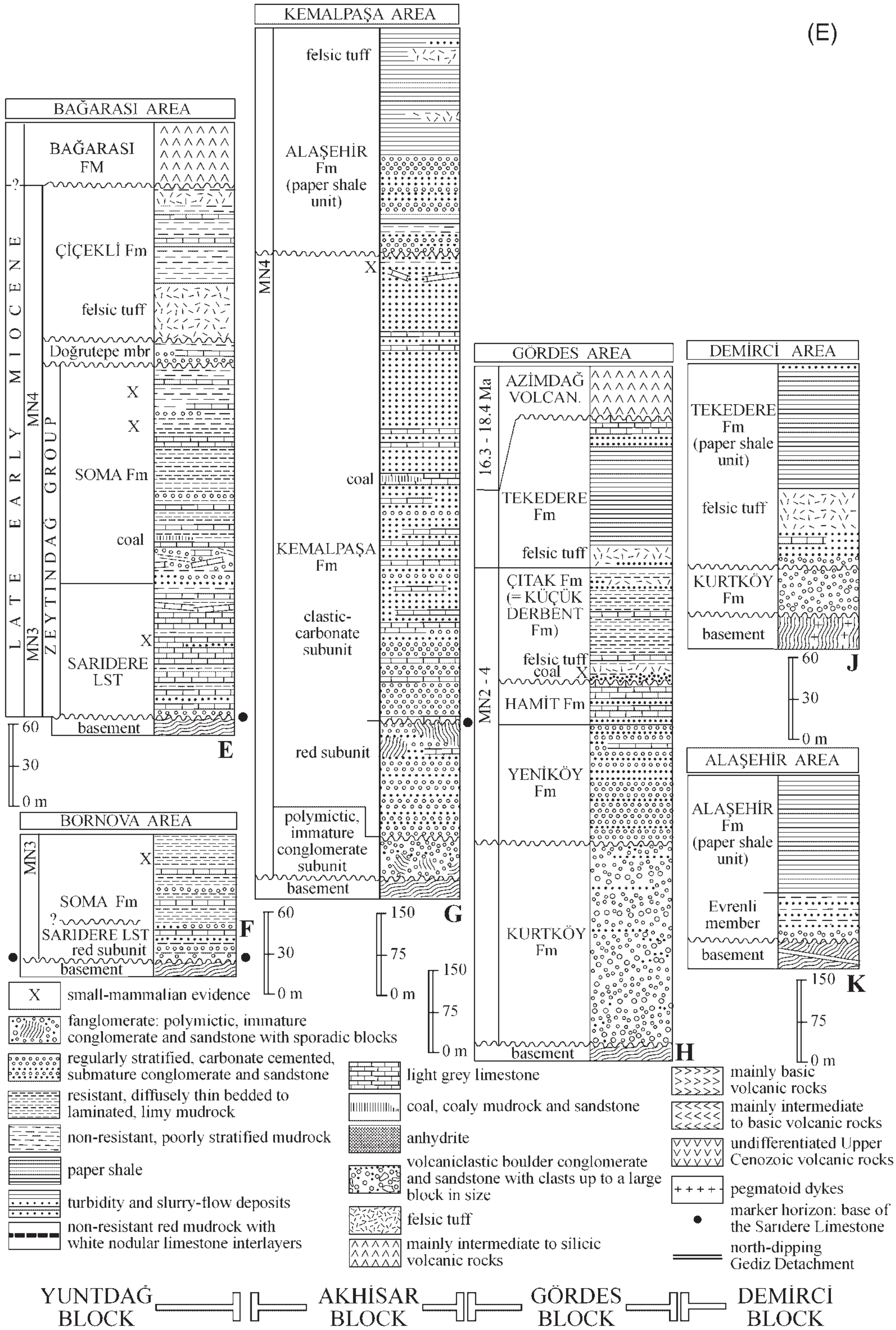

Figure 4. (*Continued*)

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Megacricetodon sp., *Tamias* sp. and Lagomorpha. The uppermost non-resistant mudrock interval (051974°E/428241°N) contains *Cricetodon* sp., *Eumyarion* sp., *Glirudinus* sp., *Democricetodon* sp. and Castoridae. This faunal assemblage suggests a late Early Miocene (MN4) age.

In the Bornova (Sabuncubeli) area, the limy mudrock (052608°E/426704°N) yields *Eumyarion* sp. I and II, *Cricetodon* sp., *Aliveria* aff. *luteyni* and Talpidae, which indicate a late Early Miocene (MN3) age. The lower contact with the Sarıdere Limestone seems to be an unconformity (Figure 4F).

In the Gördes area, the Soma Formation correlates with 'Çıtak formation' (Göktaş 1999) and 'Küçükderbent formation' (Ünay and Göktaş 2000) (Figure 4H). The economically potential coal layer at the base of the 'Küçükderbent formation' (028755°E/275250°N) yielded 'Kınık 1 fauna' of *Cricetodon* aff. *versteegi*, *Cricetodon* sp., *Debruijnia* sp., *Deperetomys* n. sp., *Eumyarion* sp. I and II, *Galerix* aff. *saratji*, *Karydomys* sp., *Megacricetodon* cf. *primitivus*, *Microdyromys* cf. *koenigswaldi*, '*Spanocricetodon*' sp., *Spermophilinus* aff. *bredai*, Talpidae and Ochotonidae; this assemblage indicates a late Early Miocene age (MN3; Ünay and Göktaş 2000).

In the Tire (Akçaşehir) area (Figure 1), outside the southern limit of Figure 2, the economically potential coal layer in a mudrock succession, that is lithologically equivalent to the Soma Formation, contains *Anomalomys* cf. *minor*, *Cricetodon* sp., *Democricetodon* cf. *doukasi*, Gliridae, Soricidae, Talpidae and Ochotonidae, indicating a late Early Miocene (MN4) age.

2.5. Kemalpaşa Formation

The name Kemalpaşa Formation is applied to a succession characterized by yellowish-grey to reddish lithic conglomerate and sandstone, minor mudrock and disrupted limestone (Figure 3, area G), and is the approximate time equivalent of the Zeytindağ Group. The formation comprises three subunits (Figure 4G): The lower subunit consists of primarily greyish, poorly indurated and stratified, fanglomerate, polymictic conglomerate and sandstone. The clasts, up to tens of metres in size, are derived from the basement Ovacık Group. The middle subunit is primarily reddish-brown, and consists of variably calcareous conglomerate, sandstone and mudrock. Near the top, the subunit contains carbonate blocks, up to several tens of metres in size, derived from the Ovacık Group. The upper subunit is made up of reddish to yellowish-grey, medium- to thick-bedded, fine- to medium-grained limy conglomerate, sandstone, mudrock and limestone. The clasts are mostly derived from the metamorphic rocks of the Menderes Massif. The limestones, with the exception of an intrabasinal slab of red limestone at the base of the upper subunit, are light grey to brown-grey, thin- to medium-bedded, microcrystalline to algal-biostromal, and form a horizon up to 17 m thick. They are, in places, bituminous, and contain sporadic thin coal interlayers. Except for the lowermost ones, the limestones in the upper part of the upper subunit are intrabasinal slabs (hundreds of metres in lateral extent) and less commonly intrabasinal blocks (tens of metres in size). At the very top of the upper subunit (053985°E/424405°N), a greenish-grey mudrock horizon (Figure 4G) contains *Aliveria* sp., *Anomalomys* cf. *aliveriensis*, *Cricetodon* sp., *Democricetodon* sp., *Eumyarion* sp., *Galerix* sp., *Megacricetodon* cf. *collongensis*, *Microdyromys* sp., Erinaceidae and Lagomorpha, which indicate a late Early Miocene (MN4) age.

The Kemalpaşa Formation overlies the Ovacık Group, the metamorphic rocks of the Menderes Massif and a northerly-trending fault system that forms the contact between the basement entities. The lower subunit is an alluvial-fan deposit. The middle and upper subunits, which are separated by a short-term hiatus, are characterized by fining/thinning-upward cycles of conglomerate and sandstone. The sporadic presence of red pigment-free interlayers in the middle subunit suggests that the red beds are related to weathering of an iron ore system in the Menderes Massif. In the upper subunit, upward increasing frequency of limestone indicates a lacustrine coastal alluvial-fan system.

2.6. Deniş Group

The Deniş Group replaces the 'Deniş schichten' of Nebert (1978). It is composed of two distinct lithologic associations: (i) a lower stratigraphically disordered mudrock succession (Çiçekli Formation), and (ii) an upper bitumen-bearing paper shales ('Alaşehir Formation' of İztan and Yazman 1990).

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2.6.1. *Çiçekli Formation*

The name Çiçekli Formation replaces the 'Çiçekli unit of the Geren Formation' of Kaya (1981). In the Bozalan type-area, the formation can be divided into three subunits. The lower subunit, the Doğrutepe Member (Figure 4E), is made up of yellowish-grey, medium- to thick-bedded, moderately to well-indurated, texturally submature conglomerate and sandstone at the bottom, and an overlying succession of algal limestone and brownish-grey, non-resistant, poorly stratified mudrock. The middle subunit consists of stratified felsic tuff with acidic volcanic clasts. The upper subunit is composed of a varicoloured, non-resistant mudrock with sporadic limestone, felsic tuff and volcaniclastic sandstone horizons. The lower and middle subunits of the Çiçekli Formation rest unconformably above, and contain clasts (up to block size) derived from, the Soma Formation and the basement rocks.

In the Soma area, the Çiçekli Formation corresponds to the 'Sand-clay unit (p1)' of the 'Deniş Formation' (Nebert 1978) and rests unconformably on the Soma Formation and the basement rocks (Figure 4D).

2.6.2. *Alaşehir Formation*

The Alaşehir Formation is typified by a bituminous paper shale succession. However, the bituminous paper shale to laminated and/or structureless mudrock ratio, has local incorporation of sandstone, conglomerate and limestone interlayers which are highly variable from one area to another.

In the Alaşehir area, the formation contains sporadic sandstone and olistostromal intercalations. The basal clastic succession (Evrenli Member; Figure 4K) lies unconformably on the metamorphic rocks of the Menderes Massif, and contains, at the base, detritus of metamorphic and ophiolite-related rocks. The paper shale unit bears geochemical evidence for deposition in a saline and anoxic environment; hydrogen index values between 469 and 764 mgHC/gTOC and an early maturity within the temperature range 429–440°C, as a whole, indicating a good petroleum source rock potential (Yazman and İztan 1995).

In the Soma area, the Alaşehir Formation correlates with the 'tuff-marl (Papierschiefer), p2' unit of the 'Deniş Formation' of Nebert (1978) (Figure 4D). There, it lies conformably on the 'p1' unit of the 'Deniş Formation' equivalent to the Çiçekli Formation of the Bozalan area (Figure 4E).

In the Gördes and Demirci areas (Figure 3, areas H and J), the Alaşehir Formation corresponds lithologically to the 'Tekedere Formation' (Ünay and Göktaş 2000). In these regions, the Alaşehir Formation commences with a clastic-carbonate-felsic tuff succession unconformably above the basement rocks and older Miocene units, and grades upwards into the paper shale (Figure 4H, J).

In the Kemalpaşa area, the Alaşehir Formation, which rests unconformably on the Kemalpaşa Formation, comprises, at the base, a thick succession of reddish-grey and light green-grey, moderately indurated conglomerate, laminated sandstone and mudrock. This succession grades upwards into paper shales that contain sporadic thin intercalations of sandstone and felsic tuff, and upwards alternates with volcaniclastic sandstone, lithic conglomerate and thicker felsic tuff (Figure 4G).

In the Bergama area, the formation contains sporadic sandstone and felsic tuff intercalations, and rests unconformably on the basement. The fish remains in the shales suggest a late Early Miocene age (Rückert-Ülkümen 2000). In the Edremit area, the heterogeneous basal part of the 'Şarköy formation' (İnci 1984) corresponds to the Alaşehir Formation and rests unconformably on the Miocene strata equivalent to the Soma Formation.

2.7. *Granitoids*

Most of the fault-bounded blocks are also characterized by many Early Miocene calc-alkaline granitoid bodies, such as the Eybek, Evciler, Kestanbol, Kozak, Salihli and Kuyucakpınar plutons (Table 1). Most of these plutons are oriented in NW–SW direction and display typical rhomb-shape geometries with length-to-width ratios of 2.1–4.0. They display either intrusive or fault contacts with surrounding rocks (Figure 5), suggesting that they were emplaced within a NE–SW-trending sinistral shear-dominated deformation zone of vertical faults. Similarly, the Demirci Block in the area between the Gördes and Demirci basins immediately east of the Eastern Gördes Fault Zone (EGFZ), forms a unique locality where the metamorphic rocks of the Menderes Massif are dissected and cut

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Table 1. Age and kinematic aspects of felsic plutons

Plutons (cooling ages)	Intrusive boundaries, suggested by shear planes	Rhomb-shape	ls/ws	lm/wm	lm/wm (map view)
Eybek 22.9 ± 0.6 Ma (1)	NE–SW: Y; NNE–SSW: R; N–S: R'; WNW–ESE: X; Y, *R* = 20°, 30°; Y, *R'* = 35–42°	symmetric asymmetric	2.8	2.3	
Evciler ~21.0 Ma (2)	NE–SW: Y; NNE–SSW: R; N–S: R'; WNW–ESE: X; Y, *R* = 23°, 30°; Y, *R'* = 50°, 52°, 54°; *Φ* = 17°	symmetric	4.0 av.	3.5	3.3
Kestanbol 21.0 ± 1.6 Ma (3)	NE–SW: Y; NNE–SSW: R'; ENE–WSW: P; Y, *R'* = 43°	symmetric ? (not informative)	2.1 ?		
Kozak 20.3 ± 0.8 Ma (4)	NE–SW: Y; NNE–SSW: R; N–S: R'; Y, *R* = 32°; Y, *R'* = 55°	symmetric asymmetric	3.2 2.3		
Salihli 19.5 ± 1.4 Ma (5)	NE–SW: Y; NNE–SSW: R'; WNW–ESE: X; Y, *R'* = 55°	symmetric	2.9		
Kuyucakpınar 18 ± 0.2 Ma (6)	NE–SW: Y; NNW–SSE: R'; Y, *R'* = 70°; *Φ* = 17°	symmetric		2.7	2.2

Analogous experimental models from Basile and Brun (1999). (1) Birkle and Satır (1995); (2) Genç (1998), Okay and Satır (2000), Yılmaz and Karacık (2001), Yücel-Öztürk *et al.* (2005); (3) Bingöl *et al.* (1982); Karacık and Yılmaz (1998); (4) Altunkaynak and Yılmaz (1999), Yılmaz *et al*. (2000); (5) Hetzel *et al*. (1995); (6) this study. ls, length of pull-apart structure along strike; ws, width perpendicular to strike; lm, longest diagonal of the pull-apart structure; wm, with perpendicular to lm.

by NNE–SSW-trending syn-tectonic pegmatite dyke swarms (Ayan 1973) of 24.2 ± 0.8 to 21.1 ± 1.1 Ma old (Seyitoğlu *et al*. 1994). The petrographic and chemical characteristics of these bodies lie outside the scope of this paper and the readers are referred to the references summarized in Table 1.

3. STRUCTURAL ELEMENTS

Structures shaping the Western Anatolia region can be grouped into three categories: (1) NE–SW-trending major fault zones and their bounding blocks. They comprise numerous short, parallel to sub-parallel high-angle oblique-slip fault segments with an almost straight outcrop pattern; they juxtapose basement rocks with Lower Miocene sediments and display a clear sinistral strike-slip component of motion with a relatively minor normal component (Yılmaz *et al.* 2000; Genç *et al.* 2001; Bozkurt 2003; Bozkurt and Sözbilir 2006). (2) The second structure is an E–W-trending presently low-angle normal fault (Gediz Detachment) along the southern margin of

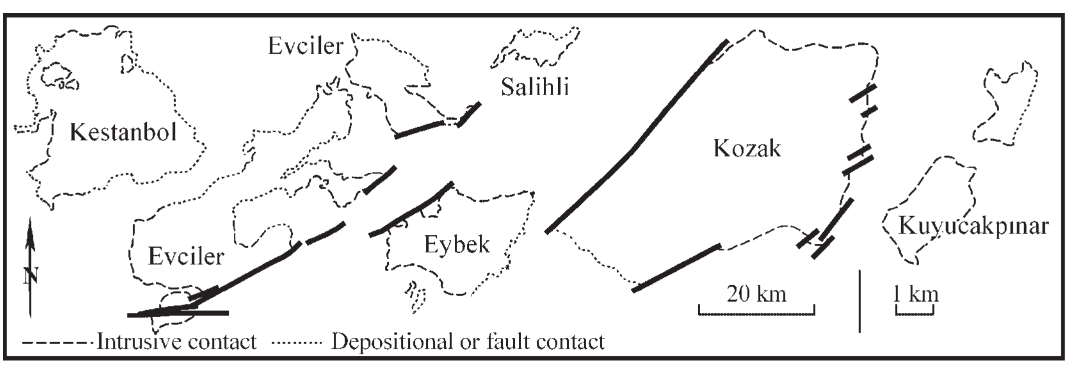

Figure 5. Shape of the latest Oligocene to Early Miocene plutons (see Figures 1 and 2 for locations).

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the Gediz Graben. This major breakway fault controlled the exhumation of the Menderes Massif in which the footwall metamorphic rocks were progressively mylonitized, exhumed and intruded by syn-deformational granitoids (Turgutlu and Salihli granodiorites: Salihli granodiorite yielded Ar^{39}–Ar^{40} amphibole isochron and biotite plateau cooling ages of 19.5 ± 1.4 Ma and 12.2 ± 0.4 Ma, respectively) during a top-to-the N–NNE-directed shearing, while Miocene continental clastics were being deposited in the hanging-wall (e.g. Hetzel *et al.* 1995; Emre 1996; Koçyiğit *et al.* 1999; Bozkurt 2001b; Gessner *et al.* 2001; Lips *et al.* 2001; Sözbilir 2001, 2002; Seyitoğlu *et al.* 2002; Işık *et al.* 2003, 2004; Bozkurt and Sözbilir 2004). (3) E–W-trending high-angle normal faults that form the bounding structures of the Gediz Graben. They cut and displace both the NE-trending fault zones and the Gediz Detachment; they also juxtapose Plio-Quaternary graben-fill with Miocene sediments and the basement metamorphic rocks.

The NE-trending fault zones and the fault blocks in-between form the main focus of the present paper. The fault zones, from west to east, are the Zeytindağ Fault Zone (ZFZ), İzmir Fault Zone (IFZ), Western Gördes Fault Zone (WGFZ) and EGFZ, and the fault-bound blocks are the Foça Block, Yuntdağ Block, Akhisar Block, Gördes Block and the Demirci Block, respectively (Figures 1 and 3). Fault blocks prevail further east of the Demirci Block (Kaya 1982). The Foça Block is floored by the Karakaya Complex and patchily by the Kazdağ Massif, the Yuntdağ Block by the Ovacık Group, the Akhisar and Gördes blocks by the Ovacık Group and the structurally underlying Menderes Massif rocks, and the Demirci Block by the Menderes Massif rocks and small klippes of the Ovacık Group. The characteristic of the fault zones will be described in the following sections.

3.1. *Zeytindağ Fault Zone (ZFZ)*

The Zetindağ Fault Zone forms the contact between the Foça and Yuntdağ blocks and juxtaposes the İkibaşlı Formation in the Foça Block with the basement rocks of the Yuntdağ Block (area C in Figure 3). The Yeniköy Conglomerate unconformably overlies the 'İkibaşlı Formation' (Figure 4C) and overlaps onto the basement rocks of the Yuntdağ Block across the ZFZ. The Sarıdere Limestone, which overlies the above units in the Foça Block, is a widely onlapping succession on the basement rocks across the ZFZ.

3.2. *İzmir Fault Zone (İFZ)*

The İFZ forms the boundary between the western facies assemblage of the Kemalpaşa Formation and the Zeytindağ Group exposed on the Akhisar and Yuntdağ blocks, respectively. In the Bornova area, it forms the margin-bounding fault of the Zeytindağ Group basin against the basement rocks (Figure 3). Similarly, to the south of İzmir, for the large part outside of the map area (Figure 1), the İFZ acted as a margin-bounding fault of the basin in which the western facies assemblage of the Kemalpaşa Formation was deposited. By the post-Early Miocene time, the southern segment of the İFZ was reactivated and overprinted by an east-vergent thrust fault (Cumalı thrust fault of Eşder 1990) (Figure 1).

3.3. *Western Gördes Fault Zone (WGFZ)*

The WGFZ which separates the Akhisar and Gördes blocks (Figures 3 and 8) acted as a margin-bounding fault during the deposition of the Kemalpaşa Formation. The fining/thinning-upward sequence in the Formation can be ascribed to southeastward 'back-stepping' (cf. Heward 1978) of the relay-pattern faults in the WGFZ. The disruption of the limestones in the Kemalpaşa Formation might have been attributed to syn-sedimentary gravitational displacement, as a result of episodes of back-stepping within the fault zone.

3.4. *Eastern Gördes Fault Zone (EGFZ)*

The EGFZ separates the Gördes and Demirci blocks (Figure 3) and forms the major margin-bounding structure of the late Early Miocene basinal system in the west; it is overlain by the uppermost Lower Miocene Alaşehir Formation (Figure 4K).

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The EGFZ and WGFZ are interpreted to form segments of a lithospheric-scale, transcurrent and diffuse regional fault zone, namely the Gördes Fault Zone (GFZ). The GFZ is delineated by: (i) seismic velocity patterns (de Jonge 1995; Papazachos *et al*. 1995; de Boorder *et al*. 1998), (ii) the regional trend of the Moho (Riazkov 1982), (iii) large-scale magnetic anomalies (Şalk 1994), (iv) earthquake locations (Çakır 1997), (v) integrated seismic energy release (Bath 1982), (vi) crustal deformations (Foulger and Hodgkinson 1993) and (vii) heat flow extremes (İlkışık 1995). The GFZ formed during the early Late Oligocene as a sinistral oblique-slip fault. By the latest Pleistocene time, the same fault reactivated and a switch occurred to a dextral sense of shear.

4. DISCUSSION

4.1. Stratigraphy

The Foça, Yuntdağ, Gördes (Figure 3) and the southern part of the Demirci (outside the southern limit of the Figure 3) blocks accommodate the Zeytindağ Group in almost uniform lithofacies. The Sarıdere Limestone and its lithological correlatives, such as the 'Hamit formation' acts as a Lower Miocene stratigraphic and facies marker in the Gördes area (Figure 4). The Sarıdere Limestone is late Early Miocene (MN3) in age.

The Küçükkuyu and İkibaşlı formations are interpreted as lacustrine mass-flow deposits of pre-late Early Miocene age, and are mostly exposed in the the Foça Block. However, they are also exposed widely to the east of the Demirci Block, outside the map area shown in Figure 3. The anhydrite unit in the Foça drill core (Figure 4B) may be related to a marine ingression. Laminar-scale gypsum occurs in the mass-flow deposits in the east.

The Soma Formation in the coastal areas and the 'Çıtak formation' and the 'Küçükderbent formation' in the Gördes area are coeval and lithologically identical rock units (Figure 4). The exposures of this unit are not limited to the Soma Basin, as it extends southward, to the Tire (Akçaşehir) area (Figure 1). In these regions, the lower and upper parts of the Soma Formation are defined by the late Early Miocene MN3 and MN4 zones. In the Foça, Yuntdağ and Gördes blocks the Soma Formation rests, over short distances, either conformably on the Sarıdere limestone, or unconformably on the basement rocks. The boundary between the Sarıdere Limestone and Soma Formation is characterized by the following features: (i) large-scale synsedimentary folding, (ii) stratal disruption, (iii) channel fillings containing intrabasinal blocks, (iv) coal occurrences at or near the base of the Soma Formation (locally of economic potential as in Soma and Gördes) and (v) an abrupt change from carbonate to clastic facies. Erosional removal of the Sarıdere Limestone just before the deposition of the Soma Formation indicates coeval movements with an opposite sense in the fault blocks. In conclusion, the boundary between the Sarıdere Limestone and Soma Formation represents a rapid change in tectonic framework, and also in climate, to more humid conditions.

The Kemalpaşa Formation represents a lateral alluvial fan to coastal alluvial-fan facies of a late Early Miocene lake, developed on the Akhisar Block; its type succession occurs in the southeastern part of the block. The basal red subunit of the Sarıdere Limestone can be correlated with the reddish middle subunit of the Kemalpaşa Formation. The coal occurrence at the base of the Soma Formation is similar to a thick coal interlayer within a limestone horizon in the middle part of the Kemalpaşa Formation. In the north of the Akhisar Block, exposures of the reddish middle subunit with finer-grained clastic rocks dominate. In the western margin of the fault-block, the formation is represented primarily by its upper subunit where increased sandstone/conglomerate ratio and thick mudrock intercalations are characteristic. These lithologic characteristics suggest that the Kemalpaşa Formation grades laterally into the Soma Formation.

There were no previous age determinations for the Sarıdere Limestone until this work; we document here small-mammalian evidence that indicates a late Early Miocene age (MN3). Early Miocene to Middle Miocene (Kleinsorge 1941) and Middle Miocene (Nebert 1978; Akgün *et al*. 1986) ages are assigned to the 'Soma Formation' on the grounds of palaeobotanic evidence. A 20–19 to 15–14 Ma time span (Seyitoğlu *et al*. 1994) and a Middle Miocene age (Akgün and Akyol 1987) were proposed, based on sporomorphs, for the basal coal layer of the 'Çıtak formation'. Similarly, a sporomorph Early–Middle Miocene age was assigned to the 'Nusratlı Formation',

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equivalent to the Soma Formation (İnci 1984, 2002). The 'Kınık 2 fauna of the Küçükderbent Formation' in the presence of *Steneofiber* cf. *eseri* may reflect an MN2 zone and can be explained by biotope difference (Ünay and Göktaş 2000). The above dated units in the previous works are now considered stratigraphically equivalent and the age of the Soma Formation is late Early Miocene (MN3–MN4).

The age of the Alaşehir Formation is, based on the following stratigraphic relations, considered to be latest Early Miocene. In the Kemalpaşa area, the Alaşehir Formation unconformably overlies the Kemalpaşa Formation, the uppermost part is established as MN4 (Figure 4G). In the Gördes area, it is cut by a 18.4–16.3 Ma volcanic assemblage culminating in age at about 17.5 Ma (Seyitoğlu *et al*. 1994; Seyitoğlu 1997). The Alaşehir Formation overlies unconformably a mosaic of the older Miocene sedimentary and volcanic successions in the Foça, Yuntdağ, Akhisar and Gördes blocks, and overlaps onto the basement rocks of the Foça and Demirci blocks. In the Soma area, the Çiçekli Formation rests unconformably on the Soma Formation and is in conformable contact relationships with the overlying Alaşehir Formation. Thus, the Çiçekli Formation seems to have levelled-off depressions preceding the deposition of the Alaşehir Formation. The variable but continuous bitumen content of the paper shale unit involves a uniform depth and subsidence rate. This indicates regional coalescence of the NE–SW-trending major fault blocks into one entity. On the other hand, the age of the Alaşehir Formation is, based on sporomorph associations, Middle to Late Miocene age (Yazman and İztan 1995). The age of the paper shale succession of the Deniş Formation (equivalent to the Alaşehir Formation in the Soma area) is Middle Miocene (Nebert 1978) and late Middle Miocene age (Akgün 1993), on the evidence of molluscan fossils and sporomorphs, respectively. In the Edremit area, the Formation yields Middle Miocene sporomorph assemblages (İnci 1984). The Demirci Formation in the Demirci Basin was suggested to be Middle Miocene in age (Yılmaz *et al*. 2000). In the Gördes area, the unit is older than 15–14 Ma, on the basis of sporomorph data (Seyitoğlu *et al.* 1994). In this study, a latest Early Miocene age is therefore proposed for the Alaşehir Formation.

The Lower Miocene sedimentary and volcanic units are bounded by erosional unconformities differing in each fault block in stratigraphic setting and magnitude (Figure 4). This is attributed to reactivation of and reversals of movement along the boundary faults between the fault blocks. Two implications derived from the repetitive up-and-down motions of the fault blocks are that (i) the boundary faults are vertical and (ii) the relevant deformation zone is of an almost constant width, that is in a quite limited extensional setting. It should be emphasized that no indications are found for strike-slip displacement of late Early Miocene age.

Multiple occurrences of felsic tuffs in the uppermost Lower Miocene stratigraphic record are significant. With few exceptions, the tuff units are volumetrically limited, poorly stratified and sorted, upward-fining, fine-grained ash-fall deposits. In parts, they are combined with stratigraphic breaks. Gradation into overlying fine-grained epiclastic deposits is locally recognizable. The felsic tuffs are comparable with 'phreatoplinian' eruptions (e.g. Branney 1991) that are related to interaction between the ascending silicic magma and water-bearing host rock. Volumetrically limited and spatially and temporally distributed occurrence of the felsic tuff units indicates local temporary extension imposed along the vertical faults.

The correlation of Lower Miocene strata in Central West Anatolia (Figure 4) suggests the presence of a single depositional environment in contrast to previous claims that these sediments were deposited in a NE–SW-trending array of independent 'basins', such as Gördes, Demirci, Selendi, Uşak and Güre basins, separated by uplifts (e.g. Seyitoğlu 1997; Yılmaz *et al.* 2001; Bozkurt 2003; Purvis *et al.*, 2005a,b). The stratigraphic and palaeontologic data presented in this paper therefore does not support the presence of independent basins. We propose that the northerly-trending fractures (Figure 1) in Central West Anatolia are conjugated pairs reactivated (Kaya 1982) or formed (Yılmaz *et al*. 2000) under an Early Miocene N–S compressional stress field reflecting pure shear kinematics. A model invoking an early wrenching and a late vertical block-faulting under limited extension is an alternative explanation.

The model that the E–W-trending Gediz Graben and NE–SW-trending basins developed simultaneously depends on the presence of 'Lower to Middle Miocene' sediments in the graben and basins (Seyitoğlu and Scott 1996; Seyitoğlu 1997). However, the small-mammalian faunas at four separate localities in the Gediz Graben suggest a Pliocene age for these sediments. One of these localities is the unique reference for the widely used Aragonian (middle Burdigalian–middle Serravalian) sporomorph age documented by Seyitoğlu and Scott (1996). There, the

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coal fragments that yielded a Miocene age are clearly reworked (e.g. Sarıca 2000; Yılmaz *et al*. 2000), and the supporting matrix contains *Apademus* sp., *Mimomys* sp., *Tibericola* sp., Lagurini indet., Spalacidae and Talpidae which is consistent with a latest Villanian–Early Biharian time interval. This new data recall urgent revision in the established stratigraphy of the Gediz Graben and widely accepted models of graben formation in Western Anatolia.

4.2. *Origin of NE-trending faults: regional implications*

Two alternative models were proposed for the latest Mesozoic to Cenozoic plate tectonics in the Aegean: (i) the first model involves two separate convergence phases with north-dipping palaeosubduction beneath the North Aegean region (e.g. Papazachos 1976; Fytikas *et al*. 1984; Shanov *et al*. 1992), and subsequent Middle Miocene (13 Ma) to Recent Aegean Arc development (Le Pichon and Angelier 1979); (ii) the second model requires a single phase of convergence along the Aegean Arc that commenced at 40–26 Ma, and involves slab penetration to depths of at least 600 km and slab detachment in the Northern Aegean at a depth of about 200 km (Spakman *et al*. 1988). We favour the first two-stage convergence model on the basis of the following arguments.

The Late Oligocene to Early Miocene stage of convergence between the Eurasian upper plate and the African lower plate is NE- to NNE-directed (Altherr *et al*. 1982; Mazzoli and Helman 1994) and decelerated in time (Dercourt *et al*. 1986). The hinge of the palaeosubduction might have been the 'Pindos Thrust Front', which was originally located further south (Mercier *et al*. 1989) (Figure 6). During early Late Oligocene time, under intraplate decoupling consequent to the deceleration, the increasing thickness of the African continental lower plate from

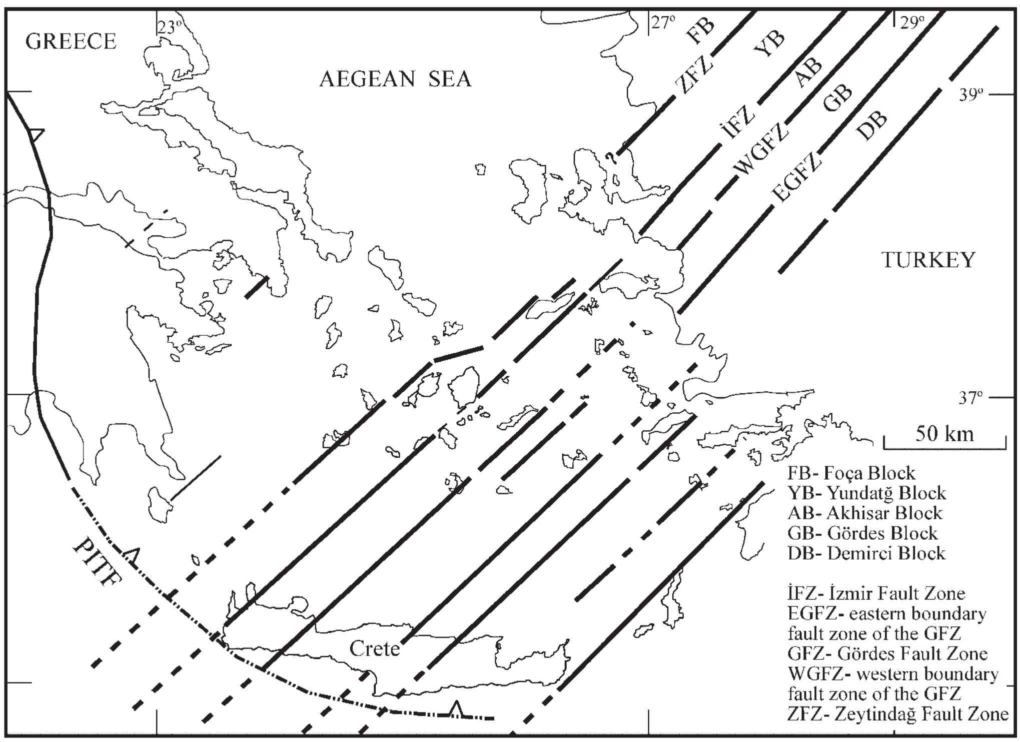

Figure 6. Suggested latest Oligocene lateral segmentation of the palaeoslab. PIFT- present day trace of the Late Eocene–Oligocene to Early Miocene Pindos Thrust Front (Mercier *et al*. 1989), approximate palaeosubduction hinge. Fault system in Southern Aegean Sea after Pavlakis (1993) and Morris and Anderson (1996).

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west to east (Nur and Ben-Avraham 1978) would have given rise to sinistral oblique-slip tearing, that is lateral slab segmentation. The NE–SW-trending fault blocks in West Anatolia form the expression of the lateral slab segmentation on land. Broadly NE–SW-trending vertical faults in the Southern Aegean Sea and Crete (Mascle and Martin 1990; Pavlakis 1993), which are related to a pre-existing transcurrent system (Kokkalas and Doutsos 2001), can be correlated with the boundary faults in West Anatolia and support the lateral slab segmentation.

The tectonic pattern can be interpreted as the result of interaction between lateral segmentation, 'northeastward global asthenospheric motion relative to the lithosphere' in the Eastern Mediterrenean (Doglioni *et al.* 1999) and SW-directed asthenospheric 'corner flows' (Dvorkin *et al.* 1993). Global NE-directed asthenosphere motion is substantiated by (i) the low subduction angle (Figure 7), (ii) the higher structural and morphological elevation of the upper plate, as revealed by Miocene sedimentary successions persistently of continental facies, (iii) large volumes of batholithic intrusions and (iv) the known dominance of calc-alkaline volcanic suites. The SW-directed asthenospheric corner flow system may be expressed by the distribution of the latest Oligocene to Middle Miocene volcanic terranes in West Anatolia. The interaction between the broadly southeastward younging of the NE–SW-trending vertical faults (Kaya 1979) and SW-directed corner flows might have resulted in the known general southward migration of magmatic centres in Western Turkey.

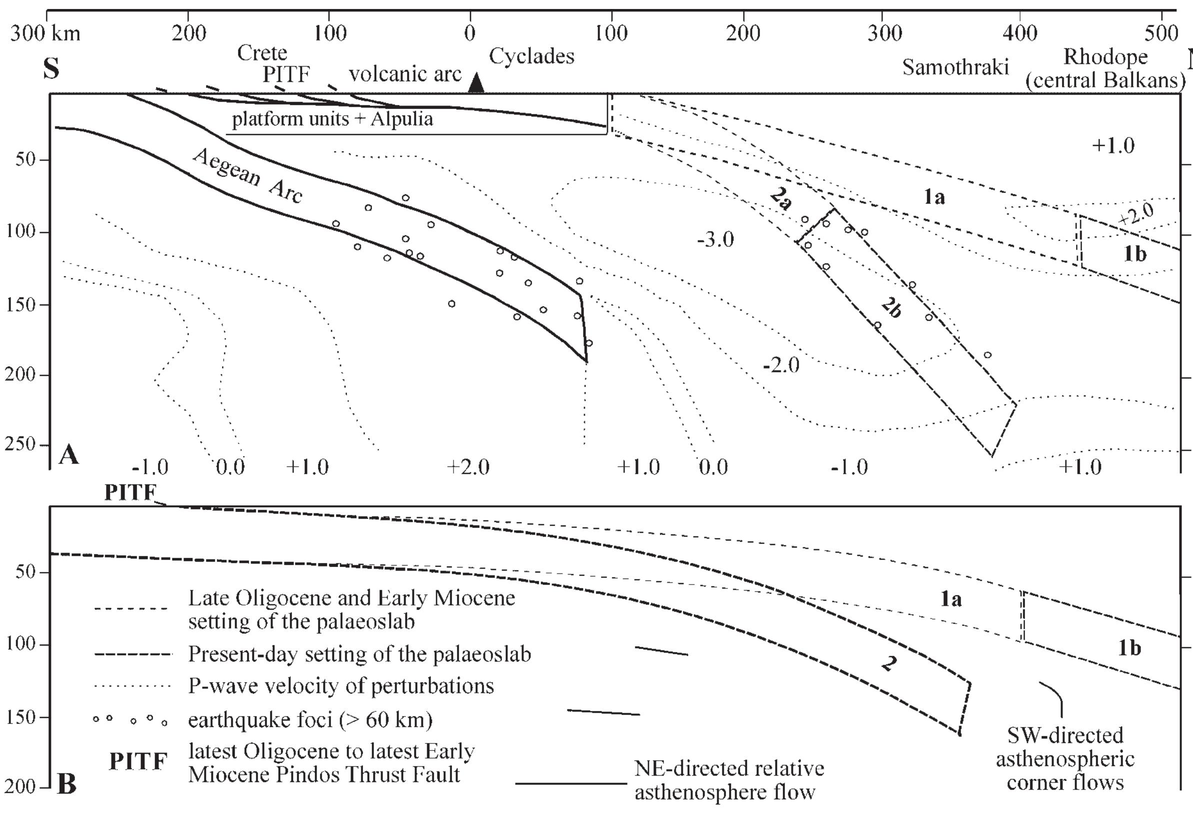

Figure 7. (A) N–S vertical section of the deep structure in the Aegean Sea. Compilation from the P-wave velocity/tomographic panels of de Jonge (1995), which are based on Dercourt *et al.* (1986) reconstructions. Earthquake data and the palaeoslab fragment in the North Aegean from Papazachos (1976) and Shanov *et al.* (1992). (B) Suggested Early Miocene asthenospheric controls on the palaeoslab, which led to the eventual detachment of the palaeoslab.

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4.3. *Gediz Detachment*

We suggest that the north-dipping Gediz Detachment (low-angle fault) (Figure 1) was originally part of a Paleogene (Hetzel *et al*. 1995) major shear plane. The syn-extensional Salihli granodiorite (19.5 ± 1.4 Ma), experienced first progressive ductile, then brittle deformation in the immediate footwall of the detachment on the low-angle fault zone at 13.1 ± 0.2 to 12.2 ± 0.4 Ma (Hetzel *et al*. 1995; Işık *et al.* 2004). The early extensional reactivation of the Gediz Detachment at the cooling stage of the granodiorite involved the northward brittle gravitational displacement of the uppermost Lower Miocene paper shale unit (Alaşehir Formation) resting on the Menderes Massif along the Gediz Detachment in the hanging wall. This piece of evidence suggests that the arrival of the Menderes Massif at the surface is a pre-latest Early Miocene event, supporting the suggestion by Bozkurt and Satır (2000).

4.4. *Granitoids*

The geometry of early Early Miocene granitoids and their contact relationships is consistent with kinematic models of pull-apart spaces (Basile and Brun 1999) in a NE–SW-trending sinistral shear zone (Figure 5, Table 1). The length-to-width ratios of the pull-apart spaces (2.1–4.0) are approximately within the standard range of 2.4–4.3 (cf. Aydın and Nur 1982) and 2.2–3.8 (Basile and Brun 1999). WNW–ESE- and ENE–WSW-trending, inherited transverse intrusive boundaries have the attitude as the P and X shears in an earlier transpressive sinistral shear field, respectively. The occurrence NNE–SSW-trending syn-tectonic pegmatitic dyke swarm to the east of the Western Gördes Fault Zone supports the model proposed in the present text.

Of course we do not rule out the possibility of an alternative explanation of overthickened crust for the origin of latest Oligocene–early Early Miocene magmatic (plutonic and volcanic) activity in western Turkey (e.g. Şengör and Kidd 1979; Yılmaz *et al*. 2000). We speculate that transtensional deformation coeval with pluton ascent, mantle-derived components of the plutons (Birkle and Satır 1995; Akal and Helvacı 1999), high temperature metamorphism in association with plutonism in Western Anatolia (Okay and Satır 2000), Late Oligocene–Early Miocene high temperature area in the Central Aegean (Altherr *et al*. 1982), ‘lithospheric positive balance’ in the context of the northeastward relative asthenospheric flow (Dogliani *et al*. 1999), favour an arc magmatism (Okay and Satır 2000) in relation to a low-angle subduction and southwestward roll-back of Aegean-Cyprian subduction zone, along which the African Plate is descending beneath the Anatolian Plate.

4.5. *Tectonic evolution*

The implied succession of the Early to Middle Miocene tectonic events can be summarized as follows (Figure 8).

4.5.1. *Early Early Miocene*

Under sinistral transtension, the inherited NE–SW-trending faults and related left steps led to pull-apart spaces into which plutons were emplaced. Plutons with mantle-derived components (Birkle and Satır 1995; Akal and Helvacı 1999; Yücel-Öztürk *et al.* 2005) and calc-alkaline extrusives with mantle-affected subduction components (Güleç 1991; Aldanmaz *et al*. 2000, 2006) indicate a lithospheric mantle wedge, as generally accepted.

Constraints of rapid subsidence and uplift for the formation of mass-flow units, the Küçükkuyu and İkibaşlı formations, suggest a depositional framework in relation to the early Early Miocene transtension.

4.5.2. *Late Early Miocene*

The increased dip of the laterally segmented palaeoslab promoted replacement of the lithospheric mantle wedge by the asthenosphere that progressed as SW-directed uprising corner flows. However, corner flows were individually aligned by vertical ruptures defining the NE–SW-trending lithospheric-scale fault blocks of the deformation zone. Under limited extension, the upward-and-downward motions of the fault blocks, and different coeval motions along the length and width of the fault blocks can be explained by the thermal control of aligned individual corner flows.

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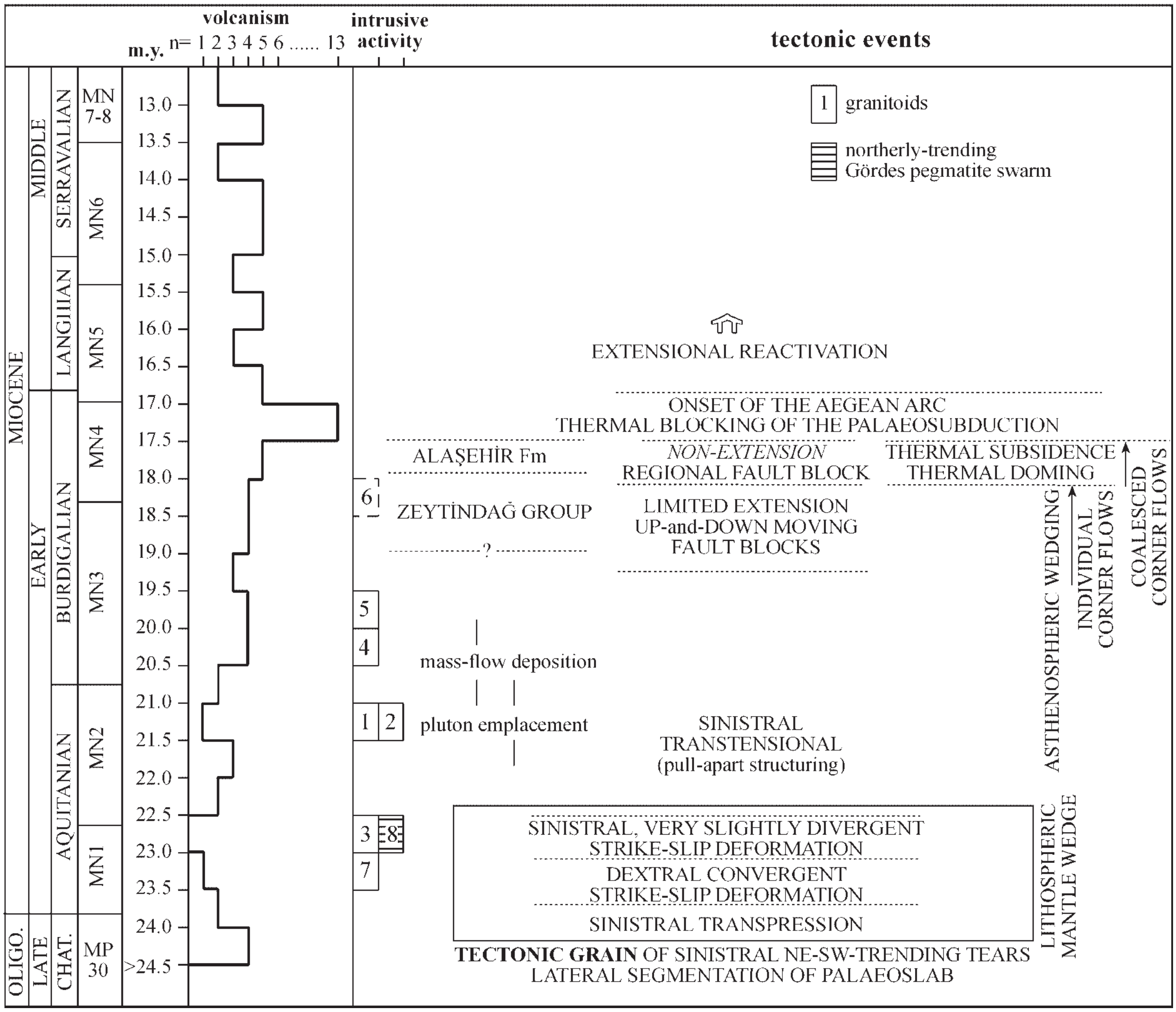

Figure 8. Suggested succession of the Early Miocene tectonic events. 1–6: granitoid plutons (see Table 1); 7: Günlüce pluton (23 ± 0.2 to 21 ± 0.2 Ma). With respect to age, the Kuyucakpınar pluton (6) does not fit to the general model.

The known compositional contrasts in the coeval volcanism (alkaline versus high-K calc-alkaline volcanism) to the end of the Early Miocene, and latitudinal deviations in the distribution of the coeval volcanic centres, in the context of general southward migration, may reflect the control of aligned individual corner flows.

Up-and-down rapid vertical motion, which involves a constant width of the deformation zone, is the primary structural indicator of delamination tectonics (Kay and Kay 1993). The deformation stage is complementary to the delamination model proposed by Aldanmaz *et al*. (2000), as an alternative mechanism for the 'Early–Middle Miocene' volcanism.

4.5.3. Latest Early Miocene

In West Anatolia, the distribution of the paper shale unit (Alaşehir Formation) is wider than the map area shown in Figure 3. The maximum depth to which the unit may have been buried in the past is not known. However, it is a clear fact, that a cover unit with significant thickness, lithologic uniformity and, particularly, with a comparable spatial

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extent never existed. Thermal generation of significant amount of early mature hydrocarbon under Tmax 429–440°C (Yazman and İztan 1995) indicates that the geothermal gradient was high in the basinal system.

The paper shale unit represents a basin of uniform and slow subsidence, accommodated by a regional block comprising the previously existing fault blocks. The uniform tectonic activation of the fault blocks can be related to the homogenization of the corner flows involved in the completed asthenospheric uprise compensating the subduction. The incipient stage of 'crustal doming' of the completed asthenospheric emplacement is shown by the regional unconformity at the base of the paper shale unit. The subsequent stage of 'thermal subsidence' is reflected by the slow and non-extensional downwarp of the basin that entrapped the paper shale unit.

4.5.4. Middle Miocene

Extreme S arrival of asthenosphere wedge is manifested by (i) a high-temperature metamorphic event peaking at 19.8–15.0 Ma (Altherr *et al*. 1982; Wijbrans and McDougall 1988) and (ii) felsic plutons of c. 17–14.0 Ma (Altherr *et al*. 1982) in the Cyclades, with crystallization depths of 5–10 km in the crust (Boronkay and Doutsos 1994) and (iii) onset of alkaline volcanism in Western Anatolia by the Middle Miocene (e.g. Yılmaz 1990; Seyitoğlu *et al*. 1997; Yılmaz *et al.* 2001).

Between 17.5 and 17.0 Ma the culmination of volcanism (Figure 8) supports a maximum in the temperature gradient in the Aegean areas. The completed asthenospheric wedging might have eventually induced the detachment of the palaeoslab (cf. Fytikas *et al*. 1984). The consequent thermal blocking of the palaeosubduction zone should have triggered development of the modern Aegean Arc, by the 'early Middle Miocene' (Mercier *et al*. 1989) (Figure 7).

4.6. Concluding remarks

The major models relevant to Early Miocene tectonics are (i) gravitational collapse of an overthickened continental crust (e.g. Seyitoğlu and Scott, 1991), (ii) easterly-trending rift systems in the back-arc area of the Aegean Arc (Armijo *et al*. 1996) and (iii) roll-back of the subducted African Plate (e.g. Fytikas *et al*. 1984). The Early Miocene deformation zone of NE–SW-trending vertical faults, being in consistency with global asthenospheric flow system, and displaying an early transtension, a late limited extension and an eventual non-extensional facies, is the structural indicator of delamination tectonics, in broad affiliation with the 'roll-back' model. The latest Early Miocene timing for the last stages of the asthenospheric wedging, the crustal doming and thermal subsidence, supports an early Middle Miocene age (Mercier *et al*. 1989), compared to a Middle/Late Miocene age (Le Pichon and Angelier 1979), for the development of the Aegean Arc.

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