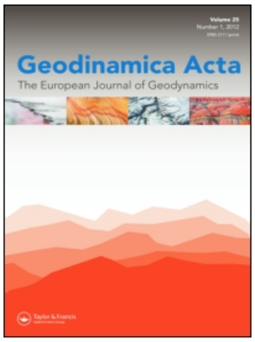

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Abstract

The Küçük Menderes Graben (KMG) is part of the horst-graben system of southwestern Anatolia (Turkey), bounded by the Bozdağ horst in the north and the Aydın horst in the south. The Plio-Quaternary evolution of the KMG has been evaluated using the nature of the Miocene-Quaternary fill sediments and palaeostress analysis of slip data measured in different parts of the graben.

The graben is composed of five subbasins—the Kiraz, Ödemiş, Bayındır, Dağkızılca-Torbalı and Selçuk—that are connected to each other through narrow Quaternary troughs. The Dağkızılca, Kiraz and Selçuk basins bear Miocene and younger sequences whereas the other subbasins are largely filled by Quaternary sediments. The maximum thickness of the Quaternary fill reaches about 270 m in the Ödemiş and Bayındır subbasins.

The calculated slip results indicate multidirectional extension, three successive deformational periods, and possible counterclockwise rotation in the KMG during the post-Miocene period. The first phase was a strike-slip regime under N-S compression, followed by a second phase of deformation which resulted in ENE-WSW extension with strike-slip components. The final phase of deformation was NE-SW extension which constituted the final evolution of the KMG.

The graben gained its present morphological configuration via the onset of E-W-trending, high-angle normal faulting imposed on the regionwide synformal structure during the Plio-Quaternary. The KMG evolved as a result of rifting during the Plio-Quaternary which followed Late Miocene unroofing of the Menderes Massif and the evolution of the Büyük Menderes and Gediz grabens.

Keywords: Neotectonics; Slip data; Palaeostress; Küçük Menderes Graben; Menderes Massif; Southwestern Anatolia

1. Introduction

The western Anatolian and Aegean grabens are some of the most important neotectonic structures in Anatolia (Turkey). The neotectonic evolution of these grabens has been discussed extensively and various geodynamic evolutionary models for the system proposed (e.g., summarized in Bozkurt [1]). The models include: (1) a *tectonic escape* model proposes a rifting event since late Serravalian (12 Ma) (e.g. [2]); (2) a *roll-back* model ("back-arc spreading model") proposes a rifting event from 60 Ma to 5 Ma (e.g. [3, 4]); (3) an *orogenic collapse* model ("gravitational collapse of the overthickened crust") since the latest Oligocene to Early Miocene (~18 Ma) (e.g. [5-8]); (4) a *bilateral extensional symmetric orogenic collapse* model (e.g. [9]); (5) a *two-stage episodic* model ("two-stage graben model") (e.g. [10]); (6) a *two-stage episodic model with late Serravalian-late Early Pliocene intervening compressional period* (e.g. [11-14]), (7) a *bivergent rolling-hinge detachment system* [15] and (8) a *velocity differences between overriding plates (Aegean and Anatolian plates) on the African plate* model [16]. Moreover, a combination of models operating sepa-

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rately during different geologic periods seems to be a possible explanation for the extensional history of the western Anatolian graben system. The readers are referred to recent literature about the age, origin and evolution of extensional tectonics in southwest Turkey ([17-26] and references therein).

Palaeomagnetic data (e.g. [27, 28]), GPS plus SLR velocity vectors relative to fixed Eurasia [29-32] and analogue models (e.g. [33]) address a counterclockwise rotation in the Aegean and western Anatolian plates that are overriding the African Plate. This rotation, on the other hand, is interpreted as block rotation as well (e.g. [34]). However, support for counterclockwise rotation via slip-data analysis is not well documented for western Anatolia, except for the southwestern part [35-37].

In order to refine our present understanding of the extensional history of the central part of western Anatolia—the Küçük Menderes Graben (KMG)—the structural framework of the KMG, its Plio-Quaternary evolution, and the results of palaeostress analysis from slip-data are set forth herein.

2. Tectonic setting

The graben is bounded by the Bozdağ horst in the north that separates the Gediz Graben (GG) from the KMG, and by the Aydın horst in the south that separates the Büyük Menderes Graben (BMG) from the KMG (Fig. 1). The KMG is one of the least-known grabens in so far as its basin-fill sediments, age and geometry are concerned.

The E-W-trending KMG, 80-km long and 3-10 km wide, developed over pre-Miocene basement rocks comprising metamorphic rocks of the Menderes Massif and the Upper Cretaceous-Palaeocene Bornova wildflysch; it is filled with Miocene-Quaternary continental deposits (Figs. 1, 2).

2.1. Metamorphic rocks of the Menderes Massif

The Menderes metamorphic complex consists of a Precambrian core (550 Ma zircon ages: e.g. [38-41]) and a cover sequence of Palaeozoic to Lower Tertiary metamorphic rocks (e.g. [42]). These rocks were metamorphosed during the Eocene, coeval with major Alpine collision in Anatolia (e.g. [43-47]). The Menderes metamorphic rocks can be stratigraphically differentiated into three groups: namely, augen gneisses closely associated with metagabbros; metaclastics and marble/calc-schists; and metagranites [48]. The intrusion age of the metagranites (augen gneisses) dated as 570 Ma to 520 Ma (mean 550 Ma; Pb-Pb and U-Pb single zircon ages) [38, 44, 49]. Stratigraphically, the upper parts of the sequence—where metaclastics/calc-schists/marbles dominate—have been radiometrically dated as 526 Ma on zircons [39] and palaeontologically dated as Late Devonian–Late Permian (between 374 Ma to 248 Ma) [50, 51]. The enveloping marbles, which constitute the uppermost sequence of the Menderes Massif, have been palaeontologically dated as Late Triassic–Late Cretaceous (between 231 Ma to 65 Ma) [52-56]. Accretion of the metamorphics produced a thick accreted metamorphic complex (over 4 km), with various undated ophiolitic slices. Readers are referred to recent literature about the Menderes Massif for further reading (e.g. [57]).

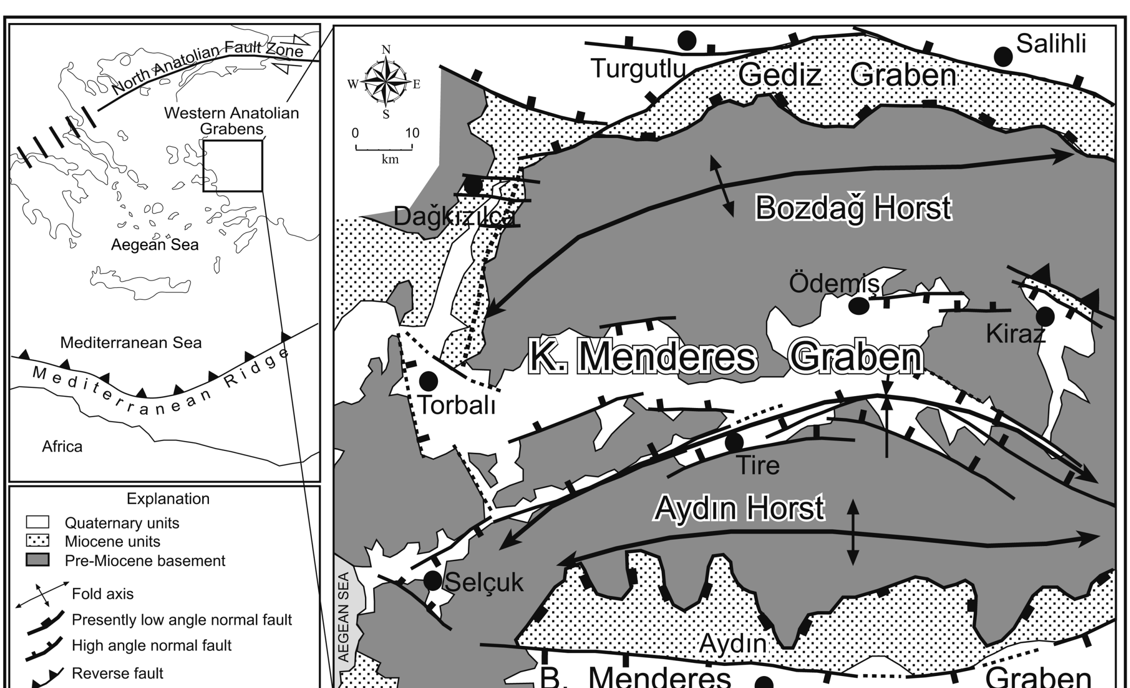

Fig. 1 Tectonic setting of the KMG within the central Menderes terrain (modified after Gessner *et al.* [76] and in light of our field observations done in 2001).

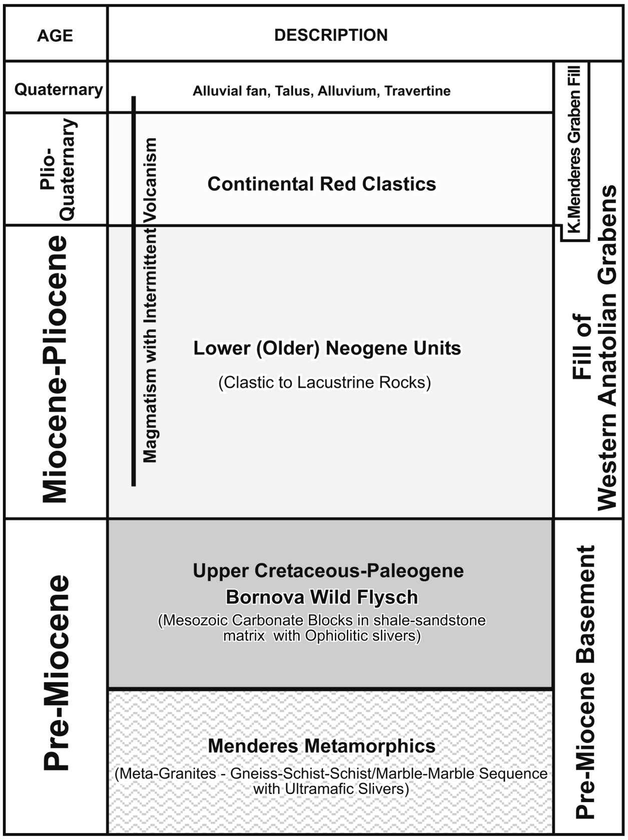

Fig. 2 Generalized tectonostratigraphic columnar section of the KMG.

2.2. Upper Cretaceous-Palaeocene Bornova wildflysch

The accretionary complex atop the Menderes metamorphic rocks is composed mainly of two parts, namely, stratified and dismembered-chaotic sequences with sheared ophiolitic blocks. The Bornova wildflysch, with a thickness of over 110 meters, comprises a slate/sandstone/conglomerate sequence with dolomitized carbonate interbeds, dolomitized carbonate and ophiolitic blocks. The sequence is of Campanian-Palaeocene age [58].

2.3. Granitoids

On the basis of field observations and radiometric dating, granitoids to the south of Salihli-Turgutlu (north of Ödemiş-Kiraz) most probably intruded after metamorphism. The radiometric dating carried out on these granitoids have yielded an intrusion age of about 20 Ma (Ar^{40}/Ar^{39} amphibole isochron age) and a cooling age of about 12 Ma (Ar^{40}/Ar^{39} biotite isochron age) [59].

The Miocene-Quaternary graben fill will be discussed separately in the following section.

3. Major characteristics of the Küçük Menderes Graben

The area investigated in this study corresponds to the drainage basin of the Küçük Menderes River that flows westward and enters the Aegean Sea west of Selçuk (Fig. 3). The flood plain of the river has an average elevation of 50 m amsl. The northern and southern boundaries of the flood plain have irregular trends, in contrast to the GG and BMG that have almost linear or curvilinear trends (Fig. 1). Due to this irregularity, the basin seems to be segmented into several subbasins. In order to elucidate the reason for this segmentation, various characteristics of the graben have been studied. The foliation patterns of the basement rocks, the nature of Miocene-Quaternary fill of the graben, and the evaluation of available borehole data are the main elements analysed here.

3.1. Foliation

Rocks older than Miocene are defined as basement rocks and are shown as a single unit on the geological map (Fig. 3). However, in cross-sections perpendicular to the axis of the graben, various lithologies within these basement rocks are differentiated (Fig. 4).

One of the most prominent characteristics of the basement rocks is the pattern of the foliation that suggests a non-plunging and asymmetrical synform with a hinge line passing through Beydağı in the east, to far northeast of Selçuk in the west (Fig. 3). A total of 1474 foliation planes were measured within the area and contour diagrams prepared for the northern and southern limbs; these indicate that the modal limb dips are N78°E/49°S and N85°E/36°N, respectively.

One of the distinguishing characteristics of the synform axis is its location within the graben. Although some parts of the hinge line are buried beneath the Quaternary deposits, its most probable location is closer to the southern margin and parallels the axis of the graben (Fig. 3). This situation suggests a control exerted by palaeotectonic structures on the development of the graben. Another feature of the axis is that it cannot be traced to the northeast of Selçuk and east of Beydağı. Foliations around Selçuk and Beydağı reveal a consistent direction towards the south suggesting its continuation in that direction. These, in turn, may be indicators of NNW-SSE-striking palaeofaults that terminate the axis northeast of Selçuk and east of Beydağı (Fig. 3).

3.2. Miocene-Quaternary units

The Miocene-Quaternary sequences are composed of five distinct rock units mapped, from bottom to top, as Miocene-Pliocene continental deposits, Pliocene fluvial clastics, Plio(?)-Quaternary elevated fluvial clastics, Quaternary alluvial fans and Quaternary alluvium (Fig. 3).

Miocene-Pliocene continental deposits are widespread to the north of Torbalı and west of Selçuk. Other limited exposures crop out to the northeast of Kiraz, and east and west of Tire. The outcrops around Torbalı and Selçuk collectively form a belt having similar lithological characteristics.

The sequence to the north of Torbalı (Dağkızılca sector) is represented by a lower fluvial and an upper lacustrine intervals that are unconformably overlain by Pliocene clas-

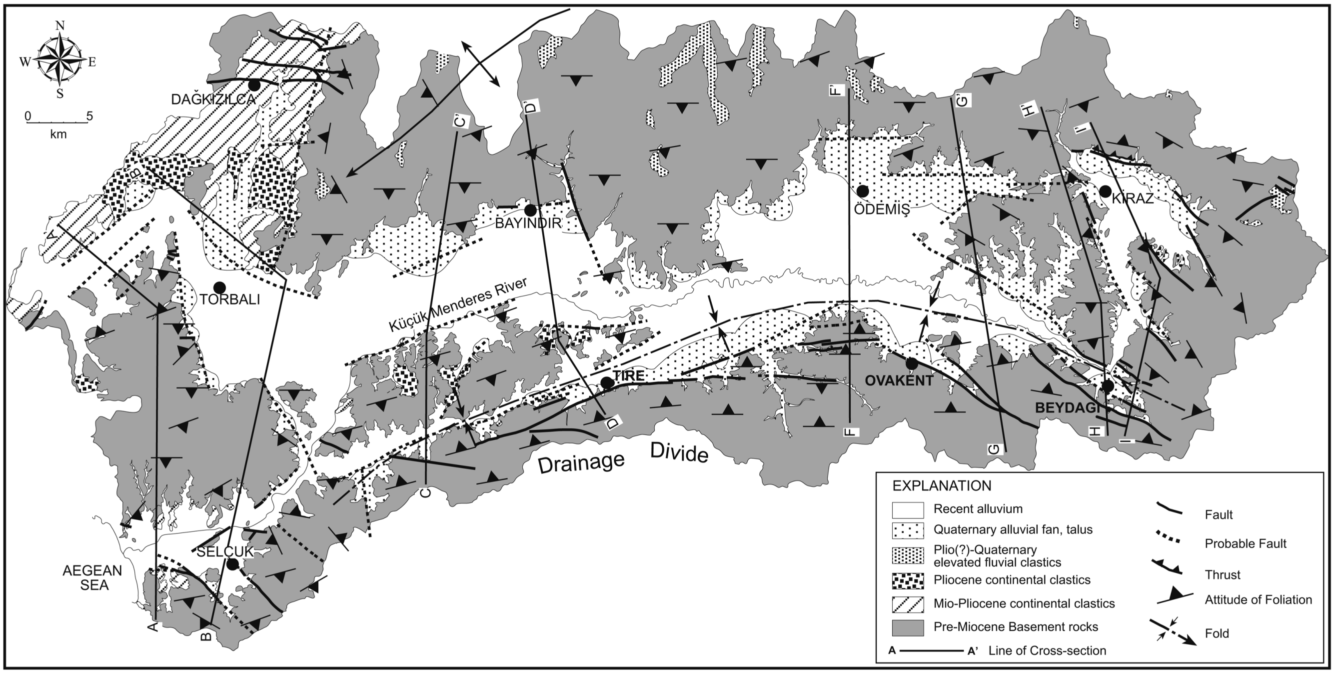

Fig. 3 Simplified geological map of the KMG showing the positions of geological cross-sections.

tics. The fluvial deposits comprise pinkish to brown, thick-bedded conglomerates and sandstones with organics-rich beds, whereas the lacustrine section comprises white to cream-coloured, thin- to medium-bedded limestones intercalated with silty-sandy limestones. The most striking feature of the Torbalı sequence is steeply tilting beds with dips ranging from 10° to 60°S.

The Miocene sequence around Selçuk comprises dominantly fluvial and lacustrine sediments. A fining-upward sandstone-conglomerate sequence with marls and clayey limestones at the top is over 200 m thick in Selçuk subbasin. The sequence, similar to the Dağkızılca-Torbalı sequence, is tilted up to 48°, with well-developed syn-sedimentary normal faults.

Miocene-Pliocene sequences at three other localities within the graben are relatively less-well exposed. One outcrop is present to the west of Tire over a limited area that hosts some lignite deposits. This outcrop is interpreted as a deposit within a karstic depression [60], a feature commonly observed in the karstic landscape of the region [61].

The second sequence is located about 10 km east of Tire. The thickness of the sequence is about 90 m, with medium- to thick-bedded, well-cemented sandstones and conglomerates bearing boulders of gneiss. The sequence is steeply inclined (47°-63°) towards the north, and cannot be traced in the graben due to limited exposures at the surface (Fig. 3). However, surveys carried out on boreholes provided by the State Hydraulic Affairs of Turkey (DSİ) reveal that there is also no continuation of these clastics in the subsurface. Therefore, the sequence is interpreted as an ancient alluvial fan deposit.

The last Miocene-Pliocene sequence is observed to the north of Kiraz as a belt 300-700-m wide and 7-8-km long that parallels the margin of the Kiraz subbasin. The sequence is composed of grey to yellow and brown, medium- to thick-bedded mudstone-sandstone-conglomerate alternations. The sequence is steeply tilted (40° to 85°) towards the northeast.

Pliocene continental clastics are concentrated mainly in three areas within the graben. These are: (1) Torbalı-Dağkızılca, (2) Kiraz, and (3) northwest of Tire. The sequences in all three areas are characterized by red, semi-consolidated fluvial clastics. They show no sign of deformation as indicated by their gentle or horizontal attitudes, and unconformably overlie Mio-Pliocene sequences. They are exposed as alluvial fans located on the downthrown blocks of neotectonic faults. A Pliocene age is assigned on the basis of stratigraphic relationships.

Elevated Plio(?)-Quaternary fluvial sediments are observed along the Bozdağ horst (northern part of the graben) near the hydrological divide between the Küçük Menderes and Gediz drainage basins. These sediments are partly exposed within the Küçük Menderes drainage basin and extensively in the Gediz drainage basin. These sediments are systematically deposited along present stream channels with almost N-S orientations (Fig. 3).

Quaternary deposits cover a large area, particularly in the central part and at the margins of the graben; they are exposed as alluvium, alluvial fans and intercalated talus deposits. Alluvial deposits constitute a flat graben floor from Torbalı to south of Ödemiş. Alluvial fans are confined to the margins of the graben and are associated with neotectonic faults. The largest fans, with thicknesses exceeding 30 m, are observed around Ödemiş, north of Kiraz, east of Tire, west of Bayındır and north of Torbalı.

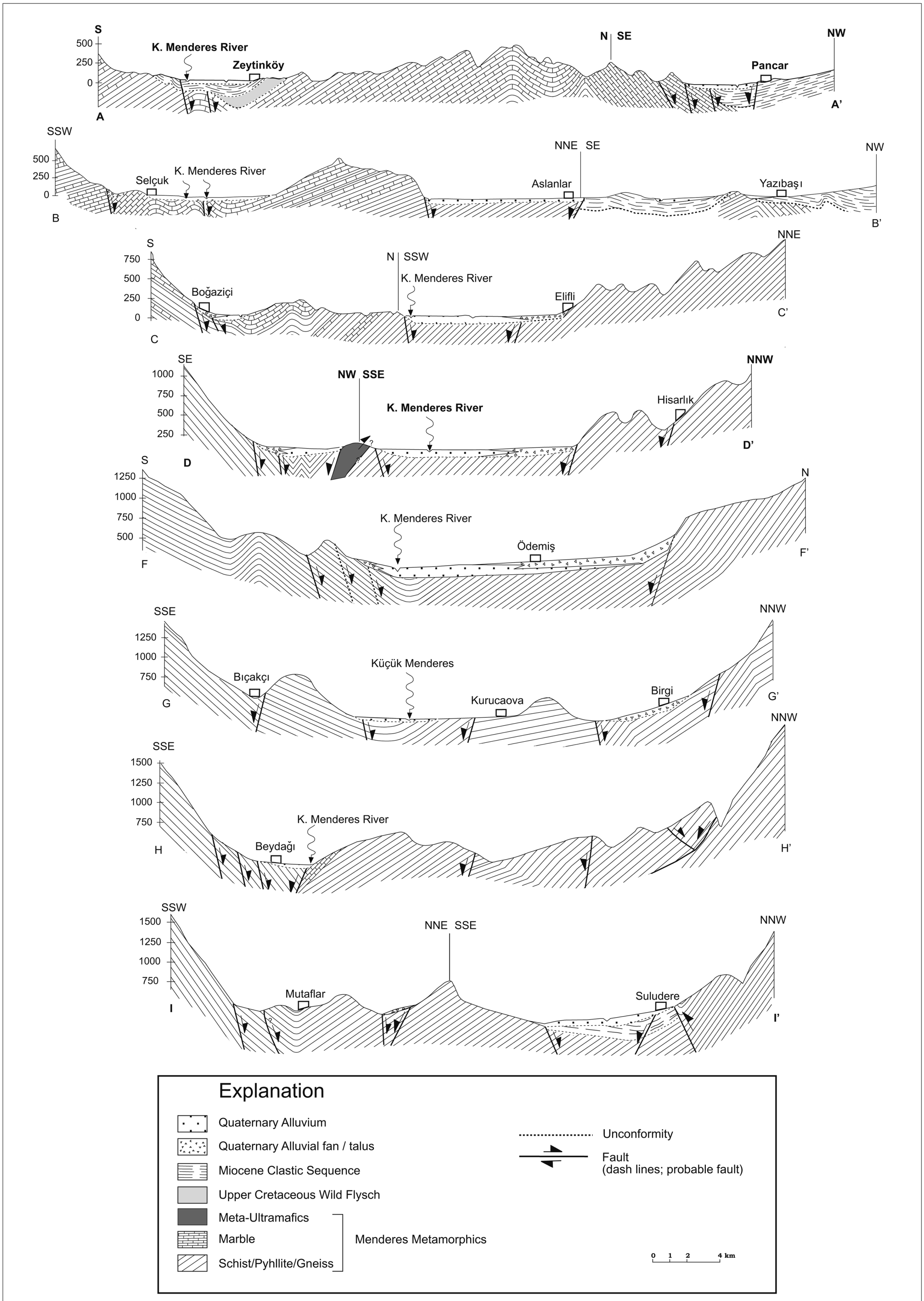

Fig. 4 Series of geological cross-sections showing various sectors of the KMG depicting horst and graben structures overprinted onto the huge synclinal structure (see Fig. 3 for positions of geological cross-sections).

3.3. Stratigraphy from borehole data

A total of 240 borehole logs, provided by DSİ (DSİ report, 1973), were analysed in order to investigate the nature of the basin-fill deposits [62, 63]. These logs were evaluated and the depths of the different rock units documented. Quaternary clastics, Miocene-Pliocene sequences and pre-Miocene basement rocks are differentiated in the logs.

The rock type immediately below the Quaternary deposits was recorded for each borehole and plotted on the map (Fig. 5A). In 211 out of 240 boreholes, pre-Miocene basement rocks were encountered; the other 29 boreholes reveal the presence of Miocene-Pliocene sequences. The spatial distribution of these data indicates that the Miocene-Pliocene sequences are present only in the western parts of the graben (Torbalı and Selçuk sectors). It is important to note that the eastern limit of buried Miocene-Pliocene materials corresponds to an almost N-S line near Torbalı. This line coincides with the eastern margin of the Miocene-Pliocene sequences exposed at the surface (Fig. 3). This situation may indicate the faulted margin of an almost N-S-trending Miocene basin (Dağkızılca-Torbalı subbasin).

The basal elevations of the Quaternary deposits suggest that there are various subbasins within the KMG linked to one another by narrow troughs (Fig. 5B). Elevation gradually decreases, east to west, in the Ödemiş and Bayındır sectors—from 500 m to –200 m. The base elevation at –200 m is evidence for subsidence in the region. The deepest points are observed in the Ödemiş and Bayındır sectors. The overall pattern indicates that there are two elliptical, en-échelon NE-SW-trending subbasins at Ödemiş and Bayındır (Fig. 5B). The Kiraz subbasin, which forms the easternmost part of the KMG, is represented by a NW-SE-trending relatively shallow depression. This subbasin is elevated relative to the Ödemiş and Bayındır subbasins (Fig. 5B). Coinciding with the Aegean coast, the southwesternmost edge of the graben, the Selçuk subbasin, can be traced eastward to NE of Selçuk to Tire through a 30-km-long narrow trough. This trough, which runs almost parallel to the Bayındır and Ödemiş depressions, may be a fault valley (Fig. 5B).

A thickness map for the Quaternary deposits was produced by subtracting the depth of the deposits in boreholes from the topographic elevation (Fig. 5C). Accordingly, the thickness of the Quaternary deposits varies from 0 to 270 m. The most striking feature on this map is a wide graben floor around Ödemiş that contains the thickest Quaternary deposits (around 270 m). The second deepest part is situated to the south of Bayındır, but shallows over short distances. Quaternary fill deposits occur elsewhere in the graben with average thicknesses of 50-60 m.

4. Faults and slip data

4.1. Faults

The faults shown in the geological map (Fig. 3) are post-Miocene age, characterized either by the presence of fresh fault scarps or associated with recent alluvial fans, travertines and/or talus deposits. Some of the buried faults were detected during the evaluation of borehole data and are shown in the cross-sections (Fig. 4; [64]). The nature of these faults will be discussed below in relation to slip data measured along these faults. Information on the faults in which fault striae have developed are as follows (Table 1):

(1) The most striking and continuous faults are confined to the southern margin of the graben. This margin is fully controlled by faults that extend from Beydağı in the east to northeast of Selçuk in the west. A recent narrow depression between Tire and north of Selçuk developed along these faults. The strike of the faults gradually changes, east to west, from NW-SE to ENE-WNW. Northern blocks of the faults are downthrown.

(2) The northern margin of the graben is discontinuously faulted as indicated by an irregular boundary throughout the margin. Two relatively long faults are observed north of Ödemiş and north of Bayındır (Fig. 3). Strikes of the faults in this margin are almost E-W where southern blocks of the faults are downthrown.

(3) The Kiraz subbasin is fully controlled by faults striking in NW-SE direction. In general, this area is in the form of a graben with a horst developed along its southwestern margin. Along the north and northeastern margin of the basin, a NE-dipping reverse fault is recognized, where Menderes metamorphic rocks have been thrust onto the Miocene-Pliocene sequences.

(4) The western part of the area (the Dağkızılca subbasin) is characterized by E-W-striking faults. The faults here are closely spaced and relatively short. Other probable faults that strike both NNE-SSW and NNW-SSE are suggested to parallel the NNE-SSW-trending Dağkızılca graben margin (Fig. 3). This fault might be a transtensional palaeo-fault controlling the evolution of the Dağkızılca-Torbalı subbasin.

(5) Around Selçuk, faults striking NW-SE are exposed along the southern (Efes fault; [35-37]) and northwestern margins of the Selçuk subbasin.

We were not able to document any N-S- or E-W-trending transtensional faults in the KMG. However, as mentioned above, the sudden termination of the axis of the synform to the northeast of Selçuk and east of Beydağı, and of the Miocene sequences in Dağkızılca-Torbalı subbasin, may be indicators of the presence of NNW-SSE-striking transtensional palaeo-faults in the KMG (Fig. 3).

4.2. Slip data

A total of 174 fault-striae data were collected from 16 areas with over 40 faults, each having at least 4 fault plane striations (Fig. 6; Table 1). The slip data was then grouped into four different sectors within the graben. Eight measurement stations with 44 measurements are located on the southern margin from northeast of Selçuk to Beydağı, four stations with 68 measurements around Selçuk, three stations with 51 measurements around Dağkızılca and, finally, one

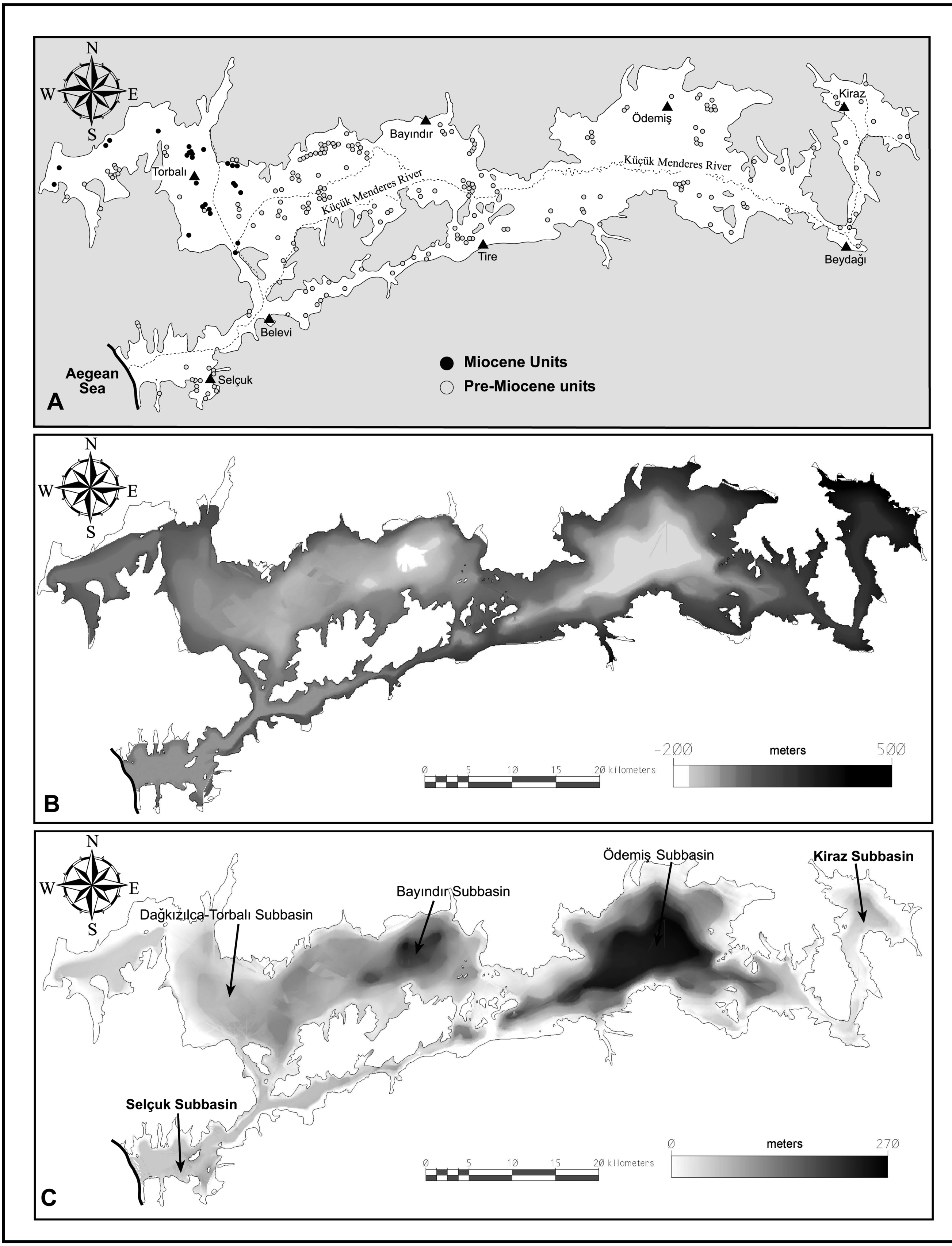

Fig. 5 Maps showing **(a)** distribution of DSI boreholes in pre-Miocene and Miocene units; **(b)** basal elevation of Quaternary deposits within the KMG; **(c)** Quaternary fill thickness.

Table 1
Information on faults where slickenlines were measured.

ID of slip data station	Location	Attitude of fault plane	Nature of fault	Number of slip data	Field observations
1	N4218730 E0604160 N of Beydag	WNW–ESE striking, S-dipping.	normal faulting (NF) with left-lateral strike-slip component	11	Southern margin fault between pre-Miocene rocks and Qal; southern block downthrown.
2	N4217210 E0601400 W of Beydag	E–W striking, N-dipping.	NF with right-lateral strike-slip component	4	Southern margin fault between pre-Miocene rocks and Qal; northern block downthrown.
3	N4217990 E0593300 E of Ovakent	E–W striking, S-dipping	NF with left-lateral strike-slip component	5	Southern margin fault between pre-Miocene rocks and Qal; southern block downthrown.
4	N4217270 E0592000 E of Ovakent	NW–SE striking, N dipping	normal faulting	5	Southern margin fault between pre-Miocene rocks and Qal; northern block downthrown.
5	N4217900 E0573350 E of Tire	ENE–WSW striking, S-dipping antithetic faults	NF with left-lateral strike-slip component	4	Southern margin fault developed on Miocene clastics; southern block downthrown. Main fault strikes ENE-WSW and dips towards N; northern block downthrown.
6	N4220500 E0562350 NW of Tire	WNW-ESE striking, S dipping	NF with left-lateral strike-slip component	4	Southern margin fault between pre-Miocene rocks and Qal; southern block downthrown.
7	N4212170 E0560670 SW of Tire	ENE–WSW striking, N-dipping	NF with right-lateral strike-slip component	4	Southern margin fault between pre-Miocene rocks and Qal; northern block downthrown.
8	N4209810 E0545940 ENE of Belevi	WNW–ESE to ENE–WSW striking, S-dipping	NF with left-lateral strike-slip component	7	Southern margin fault between pre-Miocene rocks and Qal; southern block downthrown.
9	N4203310 E0533600 NE of Selçuk	E–W striking, vertical to N-dipping	7 of the data left-lateral strike-slip fault, 2 of the data NF with strike-slip component	9	Between pre-Miocene rocks and Qal; northern block downthrown.
10 (Efes fault)	N4198490 E0529200 SW of Selçuk	NW–SE striking, N-dipping	NF and NF with left-lateral strike-slip component	18	Between pre-Miocene rocks and Qal; northern block downthrown; NF overprints onto left-lateral strike-slip faulting.
11	N4203870 E0523310 NW of Selçuk	(a) NW–SE striking, N-dipping (b) ENE–WSW striking, S-dipping	NF with left-lateral strike-slip component. N block downthrown NF with right-lateral strike-slip component S block downthrown	16	Developed within Miocene clastics; conjugate set of faulting.
12	N4203600 E0523100 NW of Selçuk	NW–SE striking, S-dipping	NF with right-lateral strike-slip component and right-lateral strike-slip faulting with normal dip-slip component	25	Developed within Miocene clastics.
13	N4238100 E0539000 SE of Dagkizilca	NW–SE striking, N-dipping	NF with left-lateral strike-slip component	4	Developed within Miocene clastics; southern block downthrown.
14	N4244580 E0536080 NE of Dagkizilca	NW–SE to E–W striking, S-dipping	NF with left-lateral strike-slip component	9	Developed within Miocene clastics; northern block downthrown
15	N4245300 E0538600 NE of Dagkizilca	NW–SE striking, S-dipping	NF with right-lateral strike-slip component to right-lateral strike-slip fault with normal component	38	Developed within Miocene clastics; normal faulting with strike-slip component is the final motion; southern block downthrown.
16	N4232300 E0556150 N of Bayindir	ENE–WSW striking, S-dipping	NF with right-lateral strike-slip component.	11	The only slip data from the northern margin of the graben; southern block downthrown

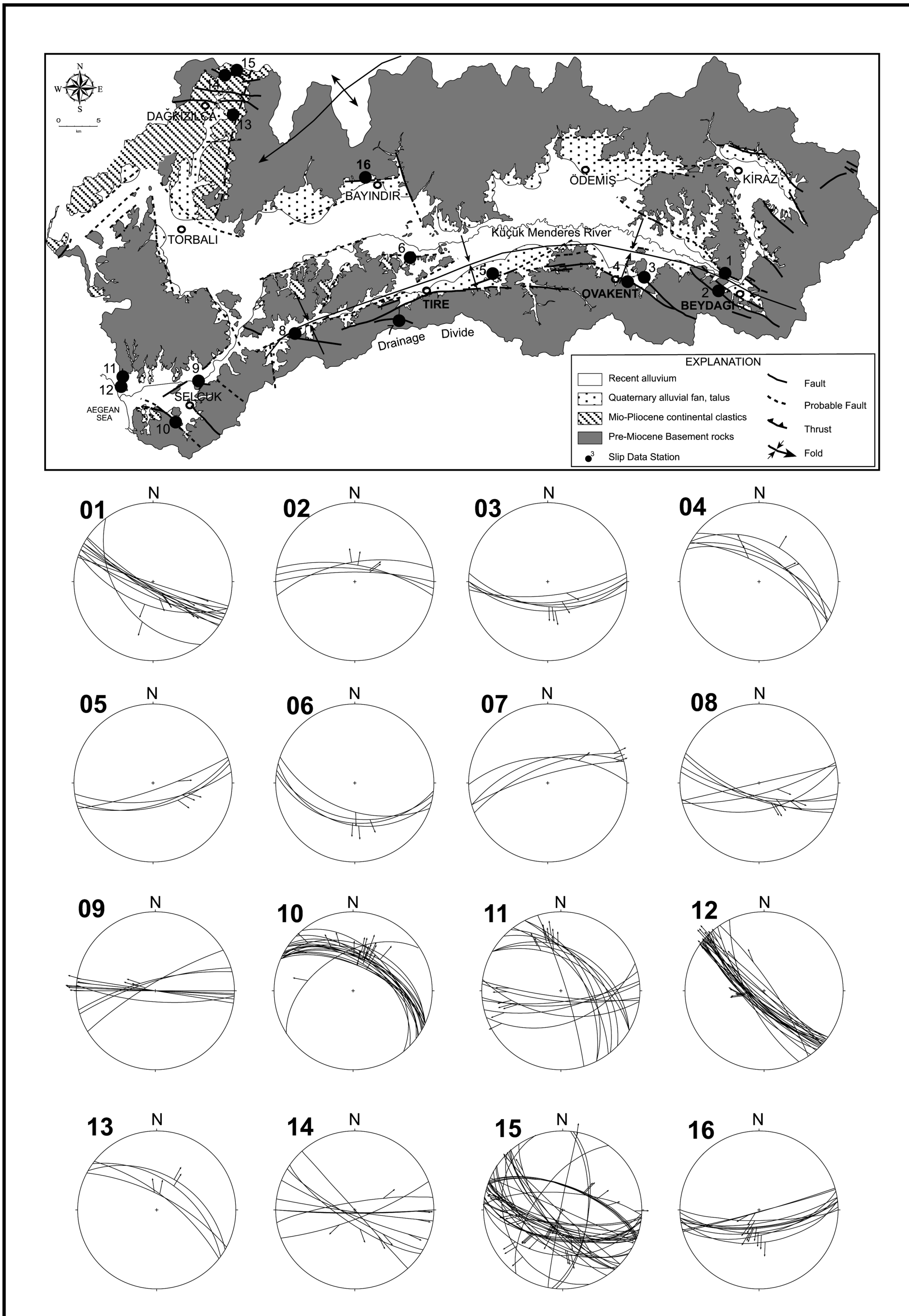

Fig. 6 Stereographic plots of measured faults and slickensides. Sites of tectonic analyses (stations) on faults are shown as black dots on the map.

station with 11 measurements from north of Bayındır (Table 1, Fig. 3). Stations 5, 11, 12, 13, 14, and 15 are from faults developed on Miocene clastics, and the rest of the stations are from fault planes developed on pre-Miocene rocks that controlled the deposition of Quaternary deposits (Fig. 3).

The Angelier inversion method is used in slip-plane calculations [64, 65]. Considering the distribution of the data within the graben and the geological characteristics of the mapped terrain, the data were differentiated into three sets. Each set was processed separately. The set areas are: (i) the Dağkızılca area (nos. 13, 14, 15); (ii) Selçuk area (nos. 9, 10, 11, 12); and (iii) the rest of the graben (nos. 1, 2, 3, 4, 5, 6, 7, 8, 16).

Deformation in the Dağkızılca area (Table 2) was initially activated in a compressional period (a sinistral oblique-slip with normal components), and the phase later operated in multidirectional extension that may have created E-W-trending extensional faults. Multidirectional extension is from ENE-WSW to NW-SE, whereas NNE-SSW extension was observed in the other areas of the KMG as well. Depending on the overprinting of the fault-plane lineations, NW-SE extension with slight compression in multidirectional extension overprints sinistral oblique-slip faulting. Almost 60° of counterclockwise rotation for the principal stress direction has been observed for this subbasin.

Table 2
Results of slip-lineation data for the Dağkızılca area.

	σ_1	σ_2	σ_3	ϕ
1	85º/017º	30º/146º	40º/236º	0.352
2	48º/343º	41º/180º	80º/083º	0.494
3	77º/177º	50º/288º	12º/019º	0.478
4	76º/048º	14º/240º	30º/150º	0.057

Results of analysis for the Selçuk area (Table 3) indicate N-S-directed sinistral strike-slip compressional deformation that is rotated into an oblique-slip phase and finally to NE-SW extension. The last deformational phase (extensional phase) dominates and shapes the area. A probable counterclockwise rotation of 60° for the extension may be proposed.

Table 3
Results of slip-lineation data for the Selçuk area.

	σ_1	σ_2	σ_3	ϕ
1	50º/318º	36º/169º	16º/067º	0.251
2	80º/353º	78º/219º	90º/085º	0.441
3	16º/354º	74º/178º	10º/084º	0.627
4	79º/197º	00º/107º	11º/017º	0.667

Slip analysis for the rest of the graben (Table 4) yields similar results to the solutions for the previous two regions. First, almost N-S-directed strike-slip compressional deformation affected the region; during a later stage, NNE-SSW extension dominated and reactivated pre-existing fractures. In the final stage, almost E-W-trending normal faults shaped the subbasins as a result of NNE-SSW to NW-SE extension. The results of slip-data analysis reveal that the southern margin faults—from Beydağı in the east to Selçuk in the west—are high-angle normal faults with right-lateral components.

Table 4
Results of slip-lineation data for other areas of the KMG.

	σ_1	σ_2	σ_3	ϕ
1	75º/074º	12º/289º	80º/197º	0.241
2	64º/094º	21º/236º	14º/331º	0.432
3	21º/338º	68º/176º	60º/070º	0.626

In summary, the common results of calculations depict three basic deformational phases for fault kinematics in the KMG (Fig. 7):

1. A N-S compressional period indicated by strike-slip faulting (followed by multidirectional extension from ENE-WSW to NE-SW (see 2 and 3);

2. ENE-WSW extension indicated by normal faulting with strike-slip component;

3. NE-SW extension indicated by normal faulting.

Based upon the principal (σ_1) and minimum (σ_3) stress directions, a counterclockwise rotation for principal stress direction is observed—from N-S compression to NE-SW extension (Fig. 7).

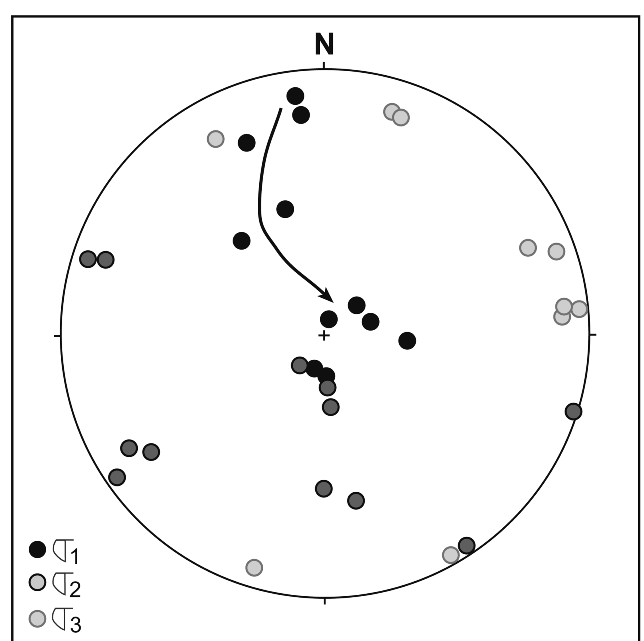

Fig. 7 Stereographic plots of fault slip data for the KMG. Note the migration of principal stress direction (confirmed by the most confident minimum stress direction) from N-S compression to NE-SW extension.

5. Discussion

5.1. Geometry and segmentation

Geometry of the KMG greatly differs from its two neighbouring grabens—the GG to the north and the BMG to the south. Both the topographic configuration and the Quaternary fill suggest that the KMG is not a single depression but, rather, is composed of several subbasins initially disconnected from each other, but later connected. The distribution and thickness of Quaternary deposits indicate five separate subbasins: the Kiraz, Ödemiş, Bayındır, Dağkızılca-Torbalı and Selçuk subbasins.

The Ödemiş subbasin is the best-developed basin in the graben as illustrated by the accumulation of thick Quaternary deposits. The thickness of recent deposits is about 270 m; the subbasin has a wide, flat floor elongated in NE-SW (Fig. 5C). This basin, however, pinches out along its southeastern tip around Tire. Therefore, the Ödemiş subbasin is also an isolated basin. The lack of Miocene-Pliocene basin-fill deposits and numerous outcrops of basement rocks along its eastern and western margins are the best evidence for this conclusion (Fig. 5A).

The Bayındır subbasin is the second largest basin within the KMG. This basin has characteristics similar to the Ödemiş subbasin as far as geometry and basin-fill deposits are considered. The western margin of this subbasin displays a transitional zone to the Dağkızılca-Torbalı subbasin as indicated by gradual variation in thickness of the Quaternary deposits (Fig. 5C).

The Dağkızılca-Torbalı subbasin is distinct from the others in terms of fill. This basin is characterized by the presence of Miocene-Pliocene, Pliocene and Quaternary deposits. The unconformity between the first two sequences is clear from field data. The unconformity between the last two sequences, on the other hand, can be inferred from outcrop patterns and lithological characteristics, as in the Selçuk and Kiraz subbasins. The base of the Miocene-Pliocene sequences was not reached in the boreholes. Therefore, the thickness of this basin cannot be estimated. The Torbalı section of the subbasin is exposed in the shape of an inverted "V" facing south, and is the southern extension of the Dağkızılca subbasin. The Quaternary section of the basin is comprises a thin cover where connected to the Bayındır subbasin in southeast. A low barrier along its western margin separates the subbasin from other Quaternary basins outside the area to the west.

The Selçuk subbasin comprises Miocene-Pliocene sequences, indicating that it is one of the oldest subbasins within the graben. Lithological characteristics of the sequence in this basin differ from those of the Dağkızılca-Torbalı subbasin. Furthermore, there is no field evidence for a connection between these two basins. Therefore, it is assumed that these two basins formed separately but at the same time. The narrow corridor that connects the Selçuk subbasin to the Bayındır and Ödemiş subbasins formed during the last stage, as indicated by the presence of only Quaternary deposits within the corridor.

The present orientation of the Kiraz subbasin, in contrast to all other subbasins, is NW-SE. The northern margin of the basin involves Miocene-Pliocene sequences which are lacking along all other margins of the basin. There are several Pliocene red clastic sequences along its margins, whereas the central part of the basin is filled with Quaternary deposits. The basin is connected via a narrow channel to the Ödemiş subbasin with almost no intervening sedimentary fill. Therefore, like the Selçuk subbasin, the Kiraz subbasin is an isolated depression.

5.2. Basin fill

The basin-fill sediments of the KMG indicate an important difference from the GG and BMG in so far as the thick Miocene-Pliocene sequences that are characteristic features of other two grabens are missing in the KMG. Miocene-Pliocene sequences in the KMG are mostly confined to the Selçuk and Dağkızılca-Torbalı subbasins that form the western parts of the graben. Other Miocene-Pliocene sequences observed within the graben (NE of Kiraz, east and west of Tire) are only local exposures and were not detected in boreholes. Therefore, the rest of the graben (central and eastern parts) is younger than other two grabens, as previously noted [66, 67].

5.3. Control of palaeotectonic structures

The main folds in the region likely developed under conditions of N-S compression during post-Eocene—pre-Miocene period (palaeotectonic period) [15]. The synforms were the possible depositional sites whereas the antiforms were the horsts (Aydın and Bozdağ Horsts). The overthickened and uplifted terrain was isostatically balanced through the evolution of high-angle normal faults by forming subbasins, as in Dağkızılca-Torbalı and Selçuk depressions. During the Plio-Quaternary, the KMG acquired its present graben structure and some of the subbasins were elevated (e.g., the Dağkızılca and Kiraz subbasins), and some were interconnected.

The spatial relationship between the major synform and the major high-angle normal faults near the southern margin is quite distinctive (Fig. 3), indicating that palaeotectonic structures played a role in the development of neotectonic structures.

Although it is accepted here that palaeostructures such as the Küçük Menderes synform have influenced the neotectonic evolution of the KMG, Gessner *et al.* [15] proposed that the synform developed during western Anatolian extension (bivergent rolling-hinge detachment system).

5.4. Slip results

Comparison of the slip results with documented extensional phases in the region clearly shows that the N-S compressional period (reflected by strike-slip faulting in Küçük Menderes terrain) should be time equivalent to the intervening compressional period in the region [11, 36, 37]. This compression may have been related to local block rotations—resulting from deformation along block margins of faults—or might be a region-wide intervening compressional period as proposed by Koçyiğit *et al.* [11]. However, the existence of both compressive and tensile striae on the same fault planes indicates a phase instead of a pulse.

The compressional period, dated as Early Quaternary, followed region-wide extension [36, 37]. However, the Late Serravalian-late Early Pliocene is presumed to be the time of N-S compression in the region [11]; this is *not* in agreement with the results of previous researchers [36, 37]. To conclude, the Early Quaternary compressional period is also not in agreement with our results.

Syn-sedimentary normal faulting recorded during the Miocene in the Selçuk subbasin has a WNW-ESE trend. This normal faulting was followed by compressional strike-slip faulting in the post-Late Miocene. The strike-slip faulting—clearly dated as post-Miocene in age—has had no control on the Quaternary configuration. However, overprinted extensional faulting has had a direct control on the spatial distribution of the Pliocene red clastics and Quaternary deposits. Therefore, the compressional period must have been post-Late Miocene—pre-Pliocene on the basis of the spatial distribution of the sedimentary units.

The multidirectional extensional period (ENE-WSW extension reflected by normal faulting with a minor strike-slip component, and NE-SW extension reflected by normal faulting) may have been a continuous process. Therefore, instead of calling it a "phase", it might be better to say a "migration of principal stress" in the region during the last extensional period.

Based upon the orientation of the principal stresses acting in the region, a possible counterclockwise rotation is proposed. However, this proposed rotational movement requires justification through geomagnetic measurements. The proposed 30° counterclockwise rotation may restore "NE-SW"-striking grabens (so-called "N-S" grabens) to almost E-W-trending grabens [27, 28]. If this is the case, there is a continuing extensional process giving rise to the development of grabens. The change in the orientation of the grabens presently from "NE-SW" to "E-W" may be a result of regional rotation of the "Aegean and Anatolian plates" as a result of counterclockwise rotational extrusion of the "Aegean plate" onto the African plate along the Mediterranean ridge.

5.5. Evolution of the basin

The KMG basically differs from the GG and BMG in two respects. First, it is not a single depression but, rather, it composed of several subbasins. Most of these basins are not connected to each other except through narrow troughs formed during the latest Quaternary period. Second, spatial distribution of the basin-fill deposits drastically varies in each subbasin suggesting different time intervals for the evolution of these subbasins. The most recent configuration is under the control of E-W-striking normal faults that tend to connect the subbasins.

In a simplified tentative model (Fig. 8) (after Erinç [67]), unroofing occurred on exhumed ductile crust [33, 34] along an overprinted extensional shear structure (detachment surface on a pre-existing northward-thrusting shear structure) during pre-7 ± 1 Ma (pre-Late Miocene) [68]—top-to-the N-NNE in the north and top-to-the S-SSW in the south [13, 47, 69-75]. Unroofing on a "low-angle normal fault" ended with the evolution of the GG and BMG during Miocene to Pliocene time (e.g. [6, 14, 15, 73-76]). Transtensional faults possibly controlled the Miocene to pre-Pliocene configuration of the grabens and bisected the grabens as a result of progressive rotation. The uplifted "Menderes core horst" was isostatically balanced with the evolution of the KMG in the centre, and gave rise to the evolution of the Bozdağ horst to the north and the Aydın horst to the south of the KMG during Plio-Quaternary time [66, 67]. The KMG, GG and BMG have continued to deepen since then.

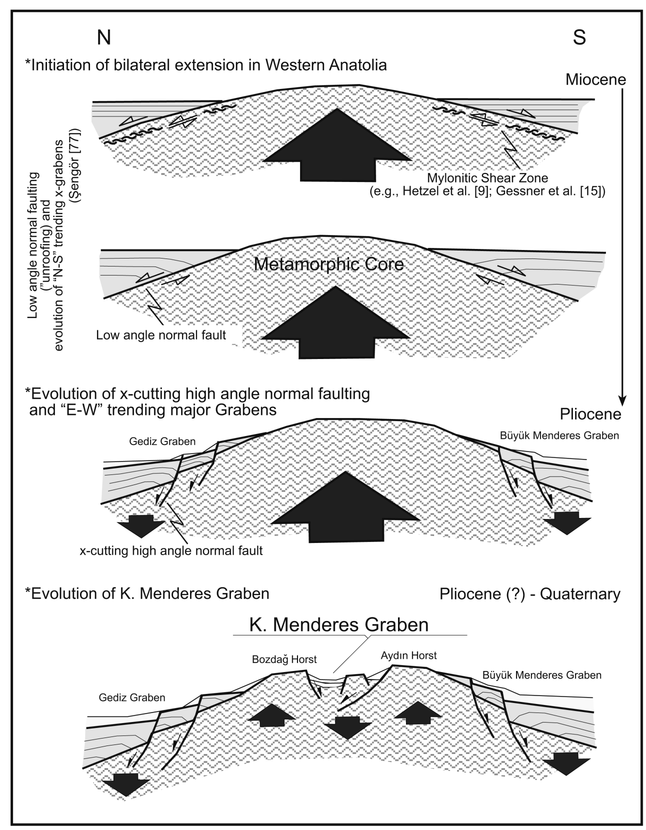

Fig. 8 Schematic tentative cross-sections showing the Miocene to Quaternary evolution of the KMG (modified from Erinç [66]). Note the continuing extension since Miocene.

6. Conclusions

The KMG evolved mainly during Pliocene-Quaternary time. Therefore, the KMG is much younger than the GG and BMG. The KMG comprises several subbasins (rather than a single depression) that are not connected to each other or are only partially connected through Quaternary troughs. These five subbasins are the Kiraz, Ödemiş, Bayındır, Dağkızılca-Torbalı and Selçuk subbasins.

Miocene-Pliocene sequences are mainly observed within the western subbasins (Dağkızılca-Torbalı and Selçuk) except for the Kiraz subbasin. However, the Miocene-Pliocene sequences are present locally in the other basins. All of the basins are dominantly characterized by Quaternary deposits, especially by extensive, thick alluvial fans.

The recent morphological configuration was gained by the onset of almost E-W-trending normal faults onto an undulating palaeotectonic synformal structure.

The results of calculated slip data reflect one compressional period and multidirectional extensional periods (three successive deformational phases), and a possible counter-clockwise rotation in the KMG for the post-Miocene period. The phases are: (i) N-S compression indicated by strike-slip faulting; (ii) ENE-WSW extension with strike-slip components; and (iii) NE-SW extensional regimes that have been operating in the region since that time.

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