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ORIGINAL PAPER

Complex basin evolution in the Gökova Gulf region: implications on the Late Cenozoic tectonics of southwest Turkey

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Abstract Southwestern Turkey experienced a transition from crustal shortening to extension during Late Cenozoic, and evidence of this was recorded in four distinct basin types in the Muğla–Gökova Gulf region. During the Oligocene–Early Miocene, the upper slices of the southerly moving Lycian Nappes turned into north-dipping normal faults due to the acceleration of gravity. The Kale–Tavas Basin developed as a piggyback basin along the fault plane on hanging wall blocks of these normal faults. During Middle Miocene, a shift had occurred from local extension to N–S compression/transpression, during which sediments in the Eskihisar–Tınaz Basins were deposited in pull-apart regions of the Menderes Massif cover units, where nappe slices were already eroded. During the Late Miocene–Pliocene, a hiatus occurred from previous compressional/transpressional tectonism along intermountain basins and Yatağan Basin fills were deposited on Menderes Massif, Lycian Nappes, and on top of Oligo–Miocene sediments. Plio-Quaternary marked the activation of N–S extension and the development of the E–W-trending Muğla–Gökova Grabens, co-genetic equivalents of which are common throughout western Anatolia. Thus, the tectonic evolution of the western Anotolia during late Cenozoic was shifting from compressional to extensional with a relaxation period, suggesting a non-uniform evolution.

Keywords Western Anatolia · Piggyback basin · Nappe emplacement · Intermountain basin · Compression · Extension · Transpression · Neotectonic

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Introduction

Western Anatolia has recently undergone rapid extension (Taymaz et al. 1991). But, there is still no consensus on the ongoing debates about the prevailing extension in western Anatolia. One of the main problems in the area is to differentiate the older compressional systems and current N–S extension (Yılmaz et al. 2000).

In western Anatolia, several Late Cenozoic structural basins are filled with terrestrial clastics and volcanic rocks. These basins are different in orientation, geometry, and the nature of infills. Mainly two sets of extensional basins are present: E-trending and N-trending grabens (Fig. 1a, b). E-trending grabens, with their intervening horsts and related normal faults, are almost the most prominent features of western Anatolia. Other, less evident, structural elements of western Anatolia are the N-trending basins and their intervening uplands (Yılmaz et al. 2000; Bozkurt 2003).

In recent years, three major problems have been associated with the geology of the graben regions and the

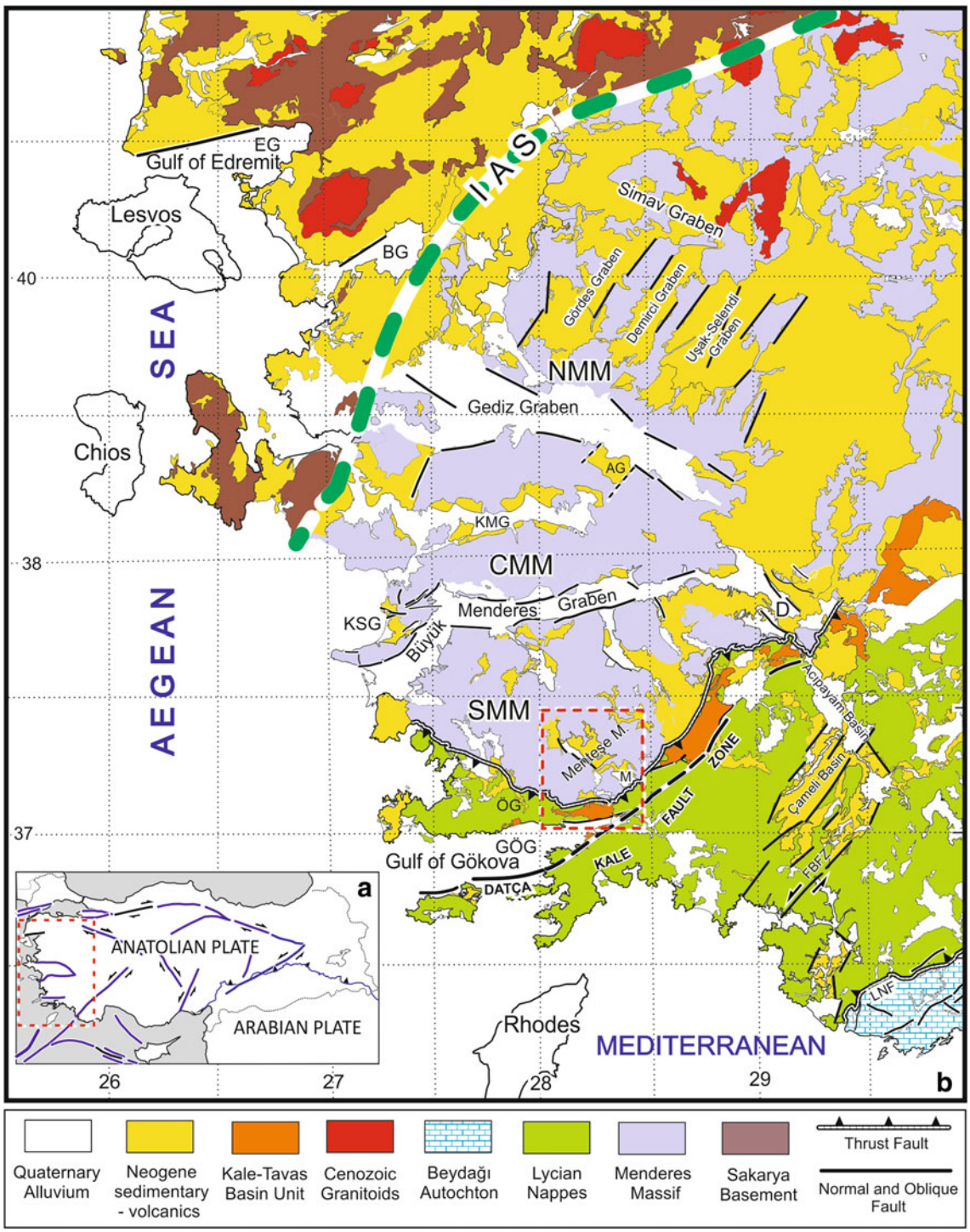

Fig. 1 **a** Tectonic map of Turkey showing major tectonic structures. **b** Geological map of the western Anatolia. IAS: İzmir–Ankara Suture, LNF: Lycian Nappe front, EG: Edremit Graben, KMG:Küçük Menders Graben, BG: Bakırçay Graben; Küçük Menderes Graben, KSG: Kuşadası-Söke Graben, ÖG: Ören Graben, AG: Alaşehir Graben; GÖG: Gökova Graben, NMM: Northern Menderes Massif, CMM: Central Menderes Massif, SMM: Southern Menderes Massif, DKFZ: Datça–Kale Fault Zone, FBFZ: Fethiye-Burdur Fault Zone; D and M are cities of Denizli and Muğla, respectively. Modified from Mineral Research and Exploration Institute of Turkey (2002)

related structures: (1) What are origins of the extension? Mainly, five groups of different models have been proposed to answer this question: (a) southward rollback of the African slab or the back-arc spreading model (McKenzie 1978; LePichon and Angelier 1979; Jackson and McKenzie 1988; Kissel and Laj 1988; Meulenkamp et al. 1988;

Thomson et al. 1998; Avigad et al. 1997; Jolivet et al. 1998; van Hinsbergen et al. 2005, 2008; Jolivet and Brunn 2010; Agostini et al. 2010), (b) the post-orogenic collapse model (Dewey 1988; Seyitoğlu and Scott 1991; McClusky et al. 2000), (c) the tectonic escape model (Dewey and Şengör 1979; Şengör 1987), (d) with a post-orogenic collapse combined with slab retreat (Gautier et al. 1999; Jolivet 2001), and (e) the two-stage extension model (orogenic collapse/rollback and tectonic escape) (Koçyiğit et al. 1999; Westaway 2003; Bozkurt 2000, 2001, 2003, 2004; Yılmaz et al. 2000; Cihan et al. 2003; Purvis and Robertson 2004, 2005; Bozkurt and Rojay 2005); (2) What are origins of the N-trending basins? The origin of the N-trending basins has also been a subject of controversy for years and has generally been proposed to one of four different models: (a) the basins are "palaeotectonic Tibet-type cross-grabens" developed under N–S contraction. They later replaced by "neotectonic Aegean-type cross-grabens" under the following N–S extensional regime (Şengör 1987). (b) the basins in western Anatolia develop coevally during the post-orogenic collapse of the anomalously thickened orogenic crust, since the latest Oligocene–Early Miocene times (Seyitoğlu and Scott 1991). (c) N-trending basins are not related with extension, but are slowly subsiding low lands of intermontane depocenters (İnci 1998). (d) the basins are deposited in a supra-detachment basin formed on the detachment faults (Seyitoğlu et al. 2004; Ersoy et al. 2011; Sözbilir et al. 2011); (3) Is the extension in the region continuous? (a) According to some authors, extensional forces continuously operated from the Late Oligocene to Quaternary times (Seyitoğlu and Scott 1991; Seyitoğlu et al. 2002; Işık et al. 2003). (b) Some other authors proposed a multi-stage extensional history with two different suggestions. The first group of scientist suggested that Late Oligocene–Early Miocene extension cannot be responsible for the entire history of extensional tectonics and that continental extension in the region is not a continuous event (Purvis and Robertson 2004, 2005; Bozkurt and Sözbilir 2004; Bozkurt and Rojay 2005). However, according to this extensional model, in western Anatolia, the direction of extension has always been N–S. The second group proposed prolonged extensional evolution or multiple episodes of extension (Koçyiğit et al. 1999; Yılmaz et al. 2000; Yılmaz and Karacık 2001; Genç et al. 2001; Gürer and Yılmaz 2002; Ring et al. 2003; Gürer et al. 2001a, b, 2002, 2003, 2004, 2006; Koçyiğit 2005; Kaymakçı 2006; Gürbüz et al. 2012; Özburan and Gürer 2012; İşcan et al. 2013).

The origin of crustal extension and evolution, and even discussion of these matters, is inevitably speculative. On the other hand, hypotheses related to the continuity of the extension can be examined by detailed geological studies in the graben regions.

The Gökova region, with its structural basins, is different in age and orientation and forms the southernmost part of the western Anatolian extensional province. Units of two key tectonic systems are juxtaposed: the compressional Lycian Nappes and the extensional core complex Menderes Massif (MM) rocks. Therefore, a study of the structural basins developed in the both systems of the Gökova region leads to a better understanding of the transformation from a compressional system to ongoing extension. Four different types of Neogene–Quaternary extensional types are recognized and sedimentation in extensional basins of complex origins occurred. They are: (1) piggyback basin, (2) pull-apart basins along oblique strike-slip faults, (3) intermontane basin filling topographic lows, and (4) graben basins (Görür et al. 1995; Yılmaz et al. 2000).

The basins of the Gökova Gulf region are continental except the Kale–Tavas Basin, which is a continental–marine basin (Fig. 2a) (Hakyemez 1989; Görür et al. 1995; Yılmaz et al. 2000; Sözbilir 2005). Three different types are proposed for the Kale–Tavas Basin: (1) as a molasse basin (Şengör and Yılmaz 1981; Koçyiğit 1984; Akgün and Sözbilir 2001; Sözbilir 2005), which developed between the Lycian Nappes and MM, and is related to the collision of the Sakarya and Tauride-Anatolide continents; (2) as the first N–S extensional basin related to the ongoing extension (Seyitoğlu et al. 2004; Sözbilir 2005; ten Veen et al. 2009); and (3) as a piggyback basin on the Lycian Nappes during their emplacements on Tauride Platform (Görür et al. 1995; Yılmaz et al. 2000; Sözbilir 2002; Gürer and Yılmaz 2002; Alçiçek and ten Veen 2008).

The Yatağan Basin is a N-trending basin. Previously, it was considered either a supra-detachment (Seyitoğlu et al. 2004; Çemen et al. 2006; Alçiçek and ten Veen 2008), or a pull-apart-like basin (Görür et al. 1995; Yılmaz et al. 2000; Gürer and Yılmaz 2002). The Gökova Basin is considered either a rift (Görür et al. 1995) or a graben (Yılmaz et al. 2000) connected with the ongoing N–S extension in the Aegean region.

The detailed study of the thick sequence of fluvial, lacustrine, and marine sediments, and the analysis of related structures between the west and east Menteşe Mountains presented in this paper, allow us to revise the timing and style of faulting that controls sedimentation in the Muğla and Gökova Gulf region. The results of our field study, combined with the results of published data including tectonics, stratigraphy, and sedimentology, are synthesized. Their findings on exhumation of the MM, and on the prevailing western Anatolian extension, are discussed.

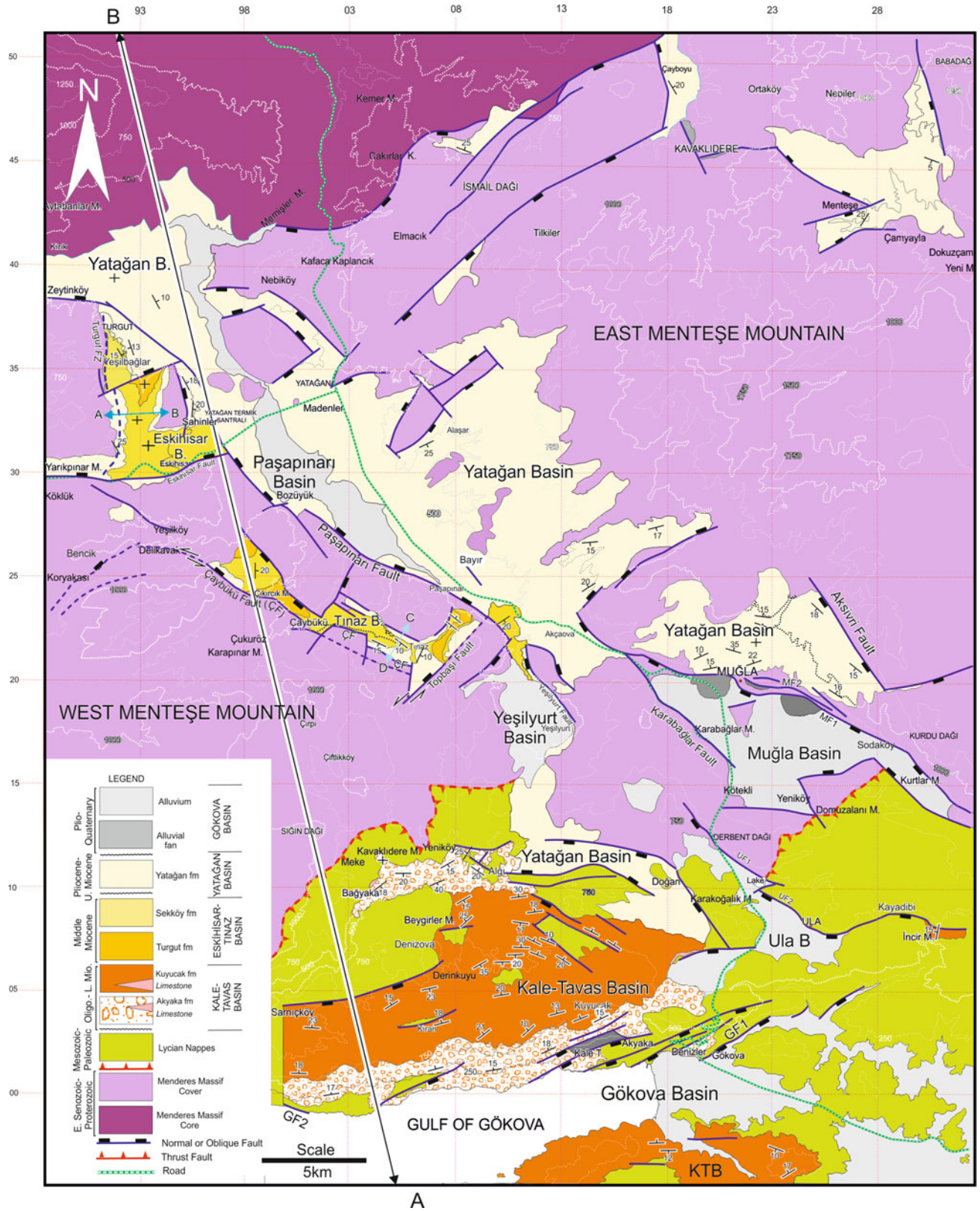

Fig. 2 **a** Geological map of the Muğla and Gökova Gulf region. PF: Paşapınarı Fault, MF1, MF2: Muğla Fault; GF1, GF2; Gökova Fault, KTB: Kale–Tavas Basin, EB: Eskihisar Basin, TB: Tınaz Basin, YAB: Yatağan Basin, PB: Paşapınarı Basin, YB: Yeşilyurt Basin, MB: Muğla Basin, UB: Ula Basin, GB: Gökova Basin. **b** Cross-section from **a**, **b**

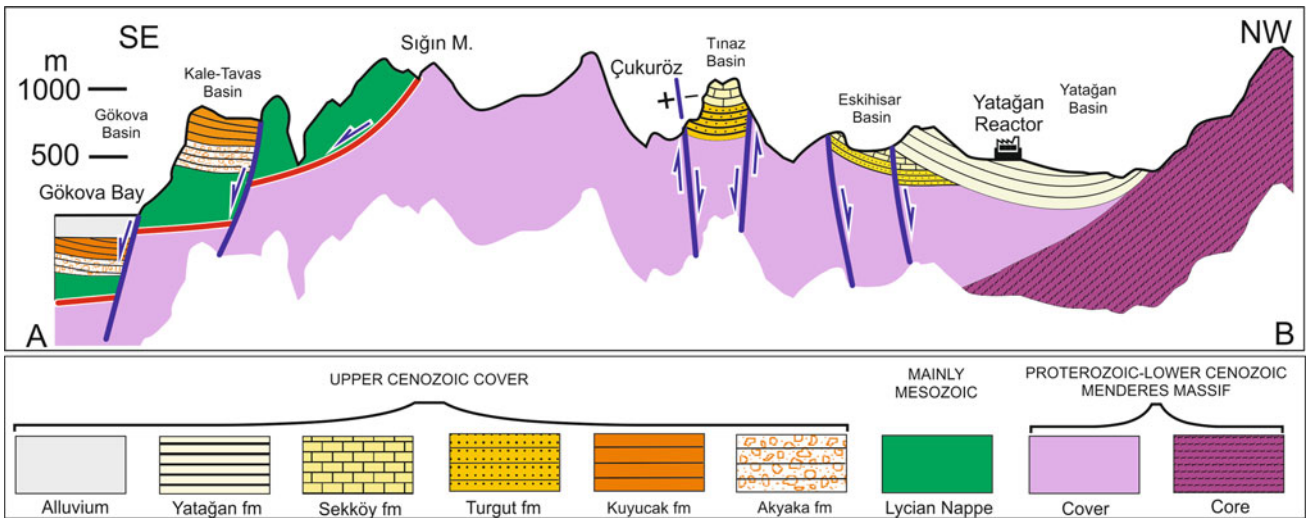

Fig. 2 continued

Geological setting

Three major rock groups are identified in the Muğla and Gökova regions: (1) Proterozoic–Lower Cenozoic MM, (2) Lycian Nappes, and (3) Lower Cenozoic sedimentary cover (Figs. 2b, 3).

The basement primarily consists of autochthonous MM and the allocthonous Lycian Nappes in southwestern Anatolia (Fig. 1b). The MM is formed during the Proterozoic–Early Cenozoic as a result of multiple deformation and metamorphism in western Anatolia. The MM is exposed in a large tectonic window bringing out deep structures to the Earth's surface. The MM is divided into northern, central, and southern submassifs by E–W-trending grabens (Fig. 1b). The MM is typically divided into two tectono-metamorphic units: an augen gneiss core and an overlying metasedimentary cover imbricated by Late Alpine compressional deformation (Schuiling 1962; de Graciansky 1966; Dürr 1975; Sengör et al. 1984; Satır and Friedrichsen 1986). This basic subdivision has been shown to be incorrect (e.g., Bozkurt et al. 1993; Gessner et al. 2001). Some authors recently described the MM as a pile of nappes (Dora et al. 1995; Ring et al. 1999; Gessner et al. 2001). It is surrounded by thrust slices. The MM is tectonically overlain by the nappes of the İzmir–Ankara Suture Zone (Şengör and Yılmaz 1981) on its northern side, by the Afyon Zone on its eastern border (Şengör et al. 1984), and by the Lycian Nappes (Brunn et al. 1970; de Graciansky 1972; Poisson 1977; Collins and Robertson 1998, 1999, 2003) on its southern side. The Lycian Nappes is composed of carbonate and detrital sedimentary units, and mélange of ophiolitic thrust slices (Bernoulli et al. 1974; Şengör and Yılmaz 1981), and overlies MM over a thrust plane (Brunn et al. 1970). Several mechanisms for the exhumation and/or uplift of the MM have been proposed.

Because the detailed descriptions of the MM and Lycian Nappe rocks are beyond the scope of this paper, we have concentrated our efforts on Late Cenozoic cover and its relationship with deformation. In Muğla and Gökova regions, four basin types were identified based on the distinct orientations (NE–SW, E–W, and N–S) and the age of formation from the Oligocene to Quaternary.

The Kale–Tavas Basin

The Kale–Tavas Basin trends E–W in the north and south of the Gökova Gulf, and NE–SW between the Gökova Gulf and Denizli (Figs. 1b, 2a). It is approximately 200 km long and 10–25 km wide and is situated 600–700 m (to the north of Gökova) and 900–1,100 m (around Kale) above the sea level. The Kale–Tavas basin is uniquely identified on the Lycian Nappe units. It unconformably overlies the marble in the north of the Gökova Gulf, and ophiolites in the south of Gökova Gulf and in the east, around Acıpayam, Denizli, and Burdur. The continuity of the Kale–Tavas Basin sequence can be found in the west, in Cycladic archipelago and in Greece. It corresponds to the Molasse unit described by Papanikolaou (1984).

The infill of the Kale–Tavas Basin is grouped under two formations: the Akyaka and Kuyucak formations. The Akyaka formation outcrops in two strips situated in the north and in the south (Fig. 2a). The southern strip is located to the north of Gökova Gulf, whereas the northern strip is situated around Bağyaka and Kavaklıdere villages. At the base, the sequence in the southern strip comprises gray and beige well-supported, thick-bedded conglomerates (Fig. 4a). The clasts derived from the marble are medium to well-rounded and matrix-supported. The clast

imbrication indicates an approximate southeast to northwest palaeocurrent direction. A fining-upward profile is defined by coarse conglomerates that are graded progressively with fine-grained conglomerates, sandstones, and mudstones. In the upper levels, these clastic rocks are interbedded with marine limestones. The sequence in the northern strip comprises gray-beige colored, medium-thick, and well-bedded conglomerates. The clasts, similar to those in the southern strip, are medium to well-rounded, matrix-supported, and are derived from marble. The clast imbrication indicates an approximate north to south palaeocurrent direction. Like the southern strip, the sequence passes upwards and consists of alternating gray-beige siltstone and sandstone. Around the Kavaklıdere Village, the sequence starts directly on the basement with fossiliferous micrites and has no clasts. In both strips, the thickness of the sequence reaches up to 350 m.

The Kuyucak formation outcrops in the north and in the south of the Gökova Gulf (Fig. 2a). In the north, the Kuyucak formation is transitional with the underlying Akyaka formation. At the base, the formation comprises red-brown fluviatile conglomerate and sandstone. Most of the clasts are derived from marble and quartzite, with small clasts of ophiolite and schist (10–15 %). The ophiolite component is responsible for the red color of the formation. Toward the top, the fluviatile conglomerate also includes intercalations of brown-beige sandstone lenses with cross-bedding and mudstone. Some slump structures, syn-sedimentary normal faulting, and channel fill structures (Fig. 4b) are also observed. The upper part of the sequence is represented by

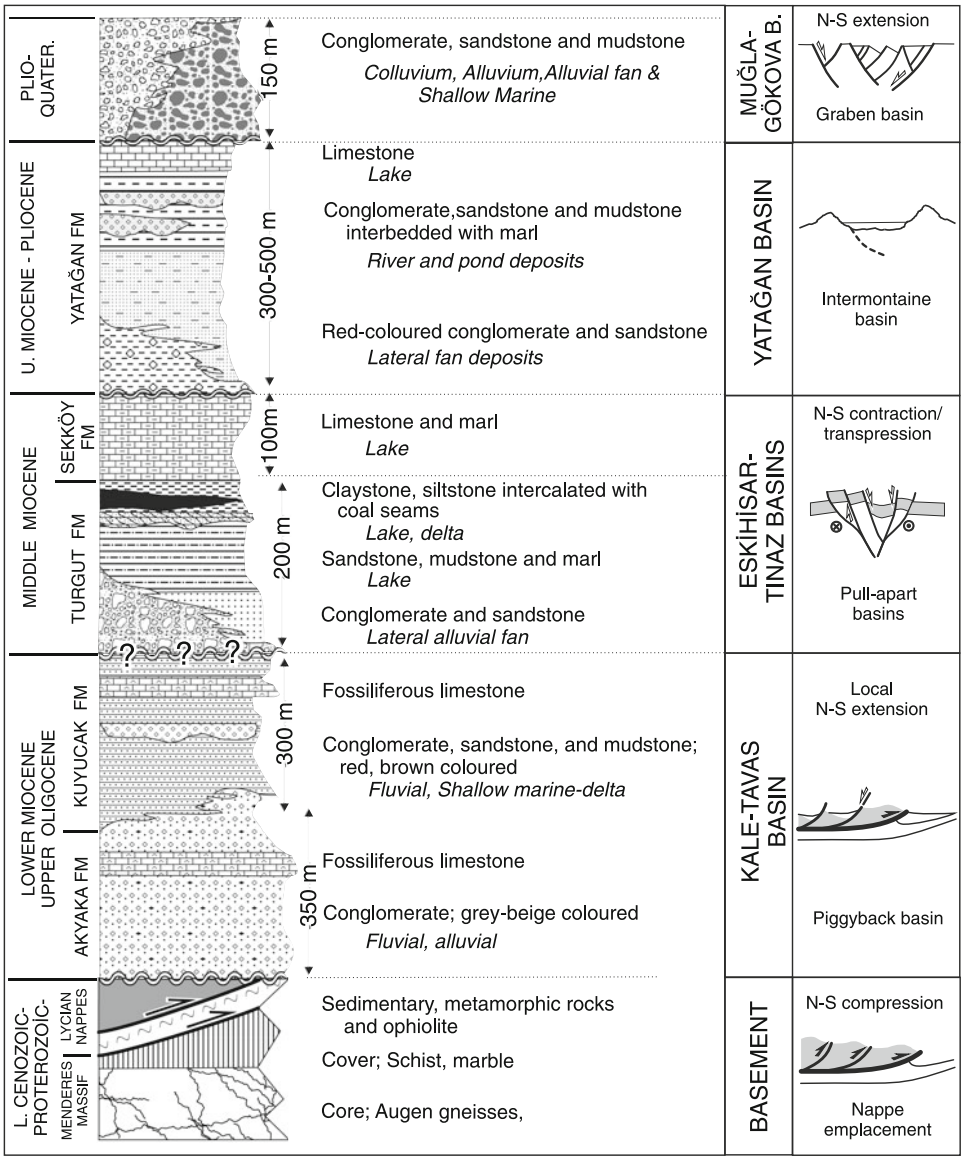

Fig. 3 Generalized stratigraphic columnar section of the study area

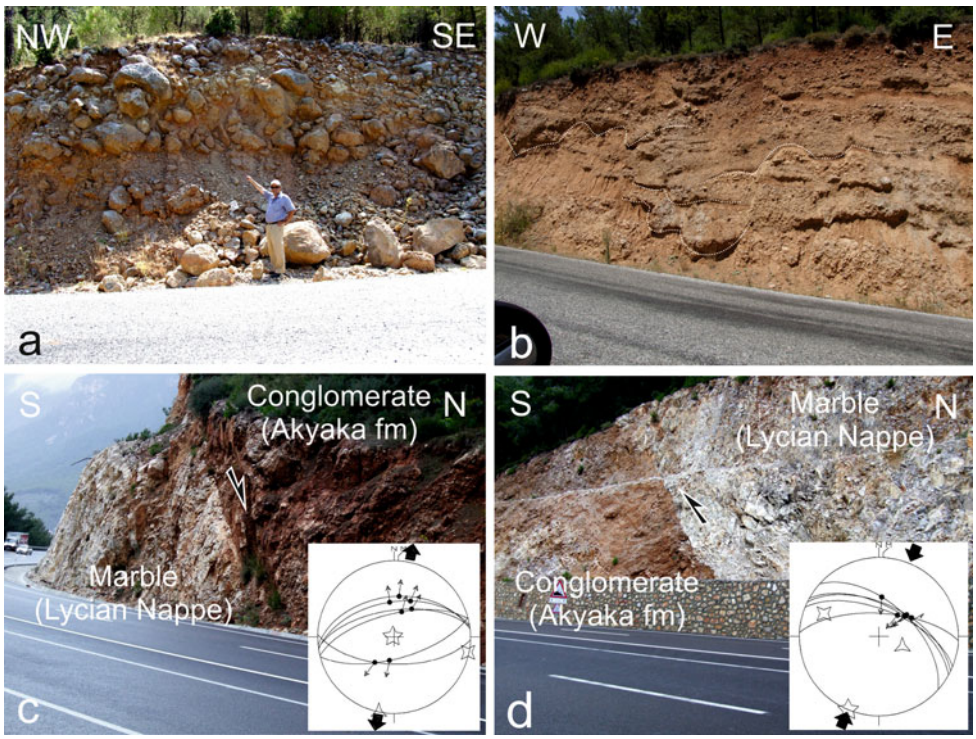

Fig. 4 Field photographs representing basin fill facies and structures of Kale–Tavas Basin. **a** View internally chaotic, well-rounded and subspherical mainly marble boulders in the Akyaka formation (35S 4101028N/611715E). **b** Channel structures in the Kuyucak formation (35S 4103519N/607670E). **c** E–W trending, 70 N dipping normal fault between the Lycian Nappes and the Akyaka formation and the kinematic analysis of the fault (35S 4102420N/620267E). **d** The reverse fault which displaced the marble of the Lycian Nappes on the Akyaka formation and the kinematic analysis of the reverse fault. Trend and dip of the fault; E–W, 70N (35S 4102717N/619744E)

fossiliferous marine limestone and marl intercalation, which pinches out toward north. At the south of the Gökova Gulf, the Kuyucak formation overlies unconformably the Lycian Nappe units. The lowermost section of the Kuyucak formation comprises beige-brown basal conglomerate and its upper sections include intercalations of beige-brown sandstones and mudstones. The thickness of the sequence is 350 m in the south and 250 m in the north.

To the northeast, outside of the study area, the Akyaka and Kuyucak formations crop out along the Datça–Kale Fault Zone (DKFZ) (Fig. 1b). In the south of Kale area, the sequence at the base comprises a red-brown, thick, laterally extensive, fluviatile conglomerates and massive sandstones, together with overlying turbidites and reefal limestones (Hakyemez 1989; Görür et al. 1995; Yılmaz et al. 2000). Around the town of Kale, it contains reefal limestones, onlappe turbidites. Shallow marine sediments are the Oligocene–Early Miocene (Becker-Platen 1970; Hakyemez 1989) and Aquitanian–Burdigalian (Hakyemez 1989; Görür et al. 1995; Akgün and Sözbilir 2001). In Ören, to the west of the Gökova Gulf, dated coal containing units on the Akyaka formation are the Lower–Middle Oligocene (Akgün and Kayseri 2008).

The north-dipping DKFZ is the main structural element that controlled the development of the Kale–Tavas Basin. Its western part is the DKFZ situated to the north of the Gökova Gulf. One of the most characteristic faults outcrops in Sakar Geçidi along the Muğla-Marmaris road. The fault has an E–W trend and 60°N dip; the Akyaka formation forms the hanging wall, whereas the marbles of the Lycian Nappes form the footwall (Fig. 4c). The kinematic analysis indicates a N–S-directed extension (Fig. 4c). In addition to the normal faults, which were responsible for the development of the basin, there are reverse faults between the basement rocks and the basin sequence. As shown in Fig. 4d, the Lycian Nappe marble is displaced on the Akyaka formation with a reverse fault. This fault has an E–W trend and 70°N dip; the kinematic analysis shows a N–S-directed compression (Fig. 4d).

Some folds occur as a series of anticlines and synclines with approximately parallel axes. The folds mainly trend NE–SW and E–W, and they are large, open, NE–SW-plunging, and have gentle to moderately dipping limbs. The origin of the mapped folds can be explained by a NW–SE compression that occurred after the deposition of the Akyaka and Kuyucak formations. Therefore, we propose a Middle Miocene–Pliocene age for the folds. The NE–SW-trending mappable folds have been also reported from the northeast of the Denizli region (Sözbilir 2005). To the east, however, the Acıpayam Basin deposits are nearly horizontal (Alçiçek and ten Veen 2008). This implies different structural history for the different parts of the basin.

Interpretation

Southward emplacement of the Lycian Nappes may have started during the Late Cretaceous in western Anatolia

(Şengör and Yılmaz 1981; Yılmaz et al. 2000). During the Oligocene, the emplacement geometry of the upper part of the Lycian Nappes showed a local reversal from thrust fault to a north-dipping normal fault regime (DKFZ). The DKFZ probably developed where the fault geometry was a structural high, and the Kale–Tavas Basin started its evolution as a piggyback when the Lycian Nappes rolled back along the normal fault plane.

Stratigraphy/sedimentology indicates that the basin geometry was controlled by tectonic regime; the basin fill and bed thicknesses thicken from north to south and displays wedge-shape geometry, and additionally, the basin axis extends east–northeast. All these observations suggest that the geometry and evolution of the Kale–Tavas Basin must have been controlled by the DKFZ which juxtaposes the basin at south (Fig. 1b).

The provenance of the sediments varies. Coarse clasts of marble of the Akyaka formation in the Kale–Tavas basin derive mostly from a structural high to the south (out of study area) and partly from the north. As a result, initial Oligocene clastic sediment in the adjacent Kale–Tavas Basin was rich in marble-related material which declined as the marble unit eroded, exposing mainly Mesozoic ophiolite rocks beneath. While conglomerates in Kale–Tavas stratigraphy show abundant poorly sorted coarse clastics and indicate structurally active periods, sandstones, mudstones, marls, and limestones indicate quiescent periods. This context indicates the existence of a previously important relief that rapidly eroded. Near the base, conglomerate clasts are poorly sorted and matrix-supported. In the upper section, sorting improves and clast support predominates. The lower part of the of the Kale–Tavas Basin succession is interpreted as high-energy mass-flow deposits, which are typical of the proximal parts of alluvial fan complexes.

No clastic source material of MM is observed in the basin fill, suggesting that the Lycian Nappes dominated the Oligocene–Early Miocene topography and that its areal coverage was much larger than its present outcrop. Lack of MM detritus in the sediments also suggests that the uplift and exhumation of the MM, located to the north of study area, had not started during the opening of the Kale–Tavas Basin in the Oligocene–Early Miocene. Our view is also supported by the apatite fission-track measurements taken from rocks on both sides of the Lycian Nappes/MM contact (Gessner et al. 2001; Ring et al. 2003; Rimmele 2003). The measurements suggest that the MM rocks were very close to the surface, though not exposed in the Late Oligocene–Early Miocene. Thermochronological data reveal that the Late Cretaceous–Tertiary nappe pile of the Anatolide belt of western Turkey displays a two-stage cooling history (Ring et al. 2003). In the southern submassif (Çine), relatively rapid cooling in Late Oligocene and Early Miocene times may have been related to top-to-the-S extensional reactivation of the basal thrust of the overlying Lycian nappes. The second phase of cooling in the Anatolide belt is related to Pliocene to recent extension, resulting in the formation of the Central Menderes metamorphic core complex in the inner part of the Anatolide belt (Ring et al. 2003). Moreover, the apatite fission-track ages also decrease toward the south in the southern MM between 25 and 15 Ma, which is interpreted as being related to the upward bending of the main breakaway fault (Seyitoğlu et al. 2004)

Observations supporting our hypothesis that the DKFZ is a normal boundary fault are as follows: (1) provenance of the Kale–Tavas Basin infills is solely the Lycian Nappes; (2) Basin infills wedge out to the north; (3) clast imbrications point to south–southeast in the north and north–northwest in the south; and (4) facies change northward from coarse fluviatile to shallow marine clastics and fossiliferous carbonate (fluviatile-turbidites onlapping reefal carbonates) in the Kale region.

Filling of the basin terminated in the Early–Middle Miocene, as it has been proposed (Sözbilir 2005), by the folding of the Early Miocene strata by a probable regional pulse of compression/transpression in the Kale–Tavas Basin. The basin was unconformably overlain by nearly horizontal Upper Miocene–Pliocene Yatağan basin deposits.

Structural onshore data set, concerning the Kale–Tavas Basin, is also available outside the study area, around the town of Kale (Fig. 1b), where a NE-trending normal fault juxtaposes the southeastern margin of the Kale–Tavas Basin against Lycian Nappes (Yılmaz et al. 2000). Shallow, offshore seismic data taken in the Gökova Gulf also support this hypothesis as it clearly shows the existence of a normal fault (the Datça Fault) (Kurt et al. 1999; Uluğ et al. 2005). This fault was previously described as an E–W-trending, north-dipping, listric fault, which was active during Late Miocene–Pliocene and was thought to be responsible for opening of the Gökova Graben (Kurt et al. 1999). This normal fault was thought to be reactivated thrust (Yılmaz et al. 2000). Seyitoğlu et al. (2004) reviewed and interpreted the available data and suggested that the Datça and the Kale Faults (named as Datça–Kale Main Breakaway Fault) are the same fault which joins along the Gökova Gulf. Thus, the total length of this fault is approximately 200 km. Our observations also suggest that both the Datça and Kale Faults are the same faults.

Eskihisar and Tınaz Basins

Terrestrial Eskihisar and Tınaz Basins are located at the NW of the study area (Fig. 2a). The Eskihisar basin is an

L-shaped, orthogonal basin, whose long axis (N–S) is 10 km and short axis is 5 km long. The Tınaz basin, located to the south of the Eskihisar Basin, is an unevenly branched chevron basin. While its longer branch that trends NW–SE is 13 km long and 3 km wide, its shorter branch trends NE–SW and 4 km long and 2 km wide (Fig. 2a). The contact between the basement MM rocks and basin infill is either an unconformity or tectonic.

The Eskihisar and Tınaz basins consist of two major units: the clastic-dominant Turgut formation and the overlying marl and limestone-dominant Sekköy formation. In the Eskihisar Basin, the Turgut formation at the base comprises a gray, massive to poorly bedded, poorly sorted, coarse conglomerate, with moderately rounded clasts derived from the underlying marble, quartzite, gneiss, and schist. The lower parts are relatively poorly sorted and texturally immature. To the west of the Turgut district, and adjacent to the Turgut Fault Zone, the unit mainly consists of coarse-grained clastic facies (Fig. 3). The sequence shows a fining-upward profile, passing from coarse clastics into medium-to-fine, well-bedded, brown-to-gray sandstones that are interbedded with mudstones and are incised by channelized conglomerates. The upper clastic unit is more extensive and texturally mature. The sandstones are mainly thin (10–30 cm) and laterally continuous (20–30 m). The clastic succession also includes a number of lignite beds, suggesting a shallow lacustrine depositional environment. Fossils recovered from the limestone are a Middle Astaracian (Middle Miocene, 14 Ma) (Atalay 1980).

The Tınaz Basin, which is mainly a marble-derived conglomerate within the lower clastic unit of the Turgut formation, becomes coarser toward the Çaybükü Fault. The formation is made up of brown and poorly sorted alluvial conglomerate at its base, passing upwards into grayish-brown sandstone and mudstone. The lower 20 m of the formation is comprised of matrix-supported conglomerates with sandstone interlayers. Conglomerate clasts include marble, gneiss, schist, and quartzite. The conglomerate and sandstone alternation is overlain by a mudstone-dominant succession with intercalations of sandstone and siltstone.

In both the Eskihisar and Tınaz Basins, the Sekköy formation rests conformably on the Turgut formation. It consists of white, thin- to medium-bedded, micritic, lacustrine cream-colored marl, limestone, and tuff alternation. The unit thickens slightly toward the east and north in the Eskihisar and Tınaz Basins, respectively. Mammalian fossils found in the Sekköy formation are Upper Astaracian (Middle Miocene, 13 Ma) (Atalay 1980).

The Eskihisar and Tınaz Basins were L-shaped, inward-draining lacustrine basins. The Eskihisar basin is bounded in the west and south by the Turgut and Eskihisar faults which are approximately perpendicular to each other (Fig. 2a). The Turgut Fault is a N–S-striking boundary fault that is approximately 1 km wide and 10 km long. It is located in the area between Eskihisar in the south and Turgut in the north. The Turgut Fault Zone, in several places, lay down the Eskihisar basin sediments in contact with the MM rocks (Fig. 6a). The fault plane kinematic analysis indicates a N–S-directed compression (Fig. 5a). The presence of the Upper Miocene–Pliocene sediment cover on the fault trace suggests that the fault activity ended in the Late Miocene–Pliocene. The stratigraphic constraints lead us to infer that the Turgut Fault was active during the Middle Miocene. The southern boundary fault of the basin, called here the Eskihisar Fault, delimits MM rocks to the south and the Sekköy formation to the north. The Eskihisar fault, which cut across the Yatağan formation, is thought to be enhanced reactivation of a preexisting fault (Fig. 2a). The basin in fill is deformed by several normal faulting, reverse faulting, and compressional folding (Fig. 5b–d).

Tınaz basin is bounded by the Çaybükü Fault N50 W, 70–80°NE (Figs. 2a, 6b). It marks the structural contact between the MM and the Turgut, Sekköy, and Yatağan formations. This fault is mapped as three discrete traces extending for about 15 km between Delikavak in the west and the Tınaz district in the east. The N45°E trending Topbaşı Fault defines a linear, NE-trending topographic high and includes fault planes dipping at an average of 65°NW, with rakes of 60–70°SW. This fault that cuts the Turgut, Sekköy, and Yatağan formations must be a younger fault developed after the opening of the basin (Fig. 2a).

Interpretation

The time for the development of the N–NW-trending Eskihisar and Tınaz basins coincided with the ultimate erosion of the Lycian Nappes and the exposure of the “cover” units of the MM. The Eskihisar and Tınaz basins were most likely structural depressions on the “cover” units of the MM. The basement for the Eskihisar basin may also includes the Lycian Nappes (Görür et al. 1995), and the northern limit of the nappes may extend to the towns Muğla and Yatağan. However, close examination of sediment clasts reveals that all of the detritus shares a common origin of “cover” metamorphic rocks range of the MM and the Lycian Nappes could not have been a provenance for the sediment load in the Eskihisar basin. Thus, the northern limit of the nappes must have been located further south of Muğla. This also means that the “cover” units of the MM must have been exhumed by erosion as undulating in the Middle Miocene. The NE and NW orientation of structural depressions may be the direct result of E–W extension, accompanied by N–S compression. Thus, the evolution of

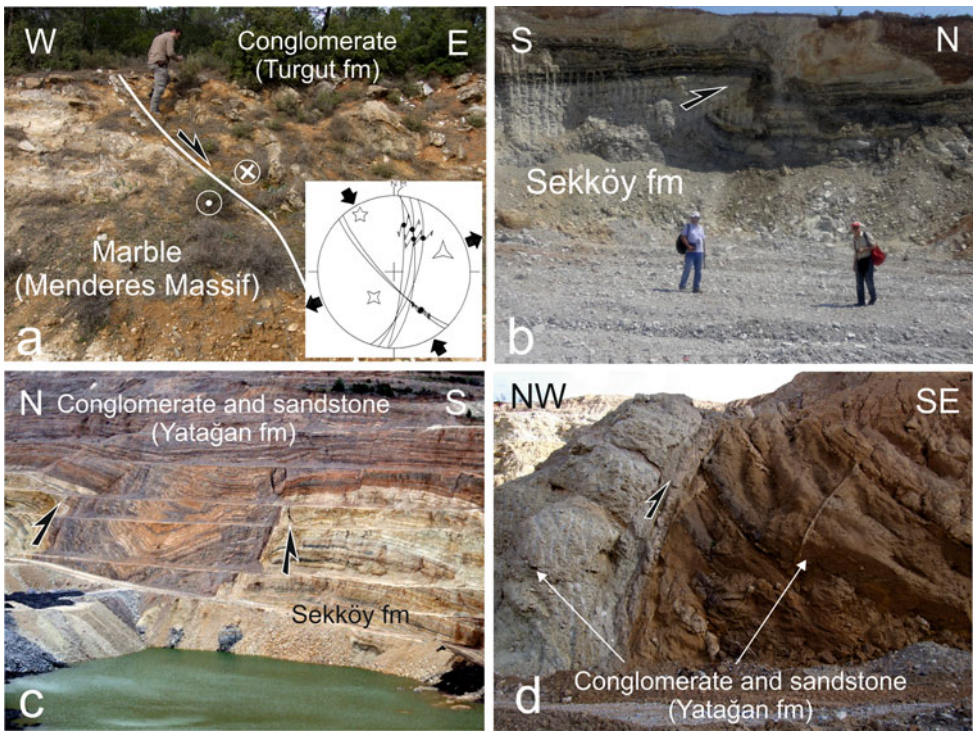

Fig. 5 Field photographs representing basin fill facies and structures of Eskihisar and Tınaz Basins. **a** The fault plane of the Turgut Fault Zone delimiting the Eskihisar formation from the west and the kinematic analysis of the fault (35S 4129657N/592066E). **b** Thrust fault in Turgut formation in north of Eskihisar (35S 4135802/593422). **c** Snyclinal structure developed between two high-angle, E–W reverse faults, Tınaz Coal Mine (35S 4121395N/607818E). **d** The reverse fault trending N70E, 75NW in the Yatağan formation, Tınaz Coal Mine (35S 606117 N/4121810E)

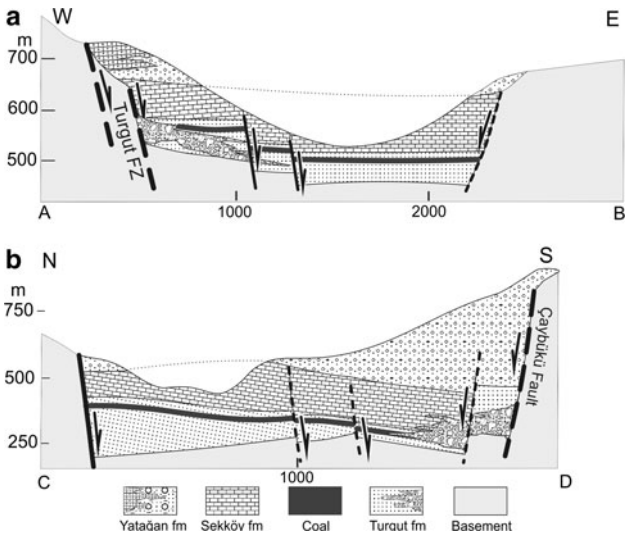

Fig. 6 Interpretation of E–W geological cross-section along the Eskihisar Basin (**a**), N–S geological cross-section along the Tınaz Basin (**b**)

the NE- and NW-trending chevron geometry was likely controlled by oblique-slip normal faults in the Muğla–Gökova region. The probable cause of this deformation was the collision of the Sakarya and Torid-Anatolid continents. The syn-tectonic infill started with coarse detrital clastics, and by Middle Miocene, was aggraded into coal-bearing continental clastic and carbonates (i.e., the Turgut and Sekköy formations). The Eskihisar and Tınaz Basins were completely filled with fluvial, alluvial fan, and lacustrine deposits by the end of the Late Middle Miocene, when tectonic subsidence apparently ceased.

The Turgut and Çaybükü faults are responsible for sediment accumulation in the Middle Miocene basins. Along the basin margins, coarse clastics were deposited and sourced from the fault-elevated blocks. Away from the basin margins, the conglomerates grade into fine clastics and then into lacustrine siltstone and marl, deposited along the centers of the basins. This also supports that the Turgut Fault Zone and Çaybükü Fault Zone are boundary faults (Fig. 2a). These faults were subsequently overprinted and displaced by the NE- or NW-trending normal faults that are associated with the development of the Plio-Quaternary basins (e.g., Muğla Basin).

To the north of the studied area, in the Gediz and Büyük Menderes Graben regions, there are several N-trending basins on the Menderes Massif which dates back to the Lower–Middle Miocene. However, in the Muğla region, the first terrestrial sequence on the Menderes Massif dates back to the Middle Miocene (The Eskihisar and Tınaz Basins). This age differences should be related to the differentiated exhumation of the Menderes Massif basement in the Early Miocene to the north and the Middle Miocene to the south.

Yatağan Basin

The terrestrial Yatağan Basin is located between the town of Yatağan and the Gökova Gulf, extending NW–SE, and

is 30 km long and 10 km wide with poorly defined boundaries and geometry. The basement for the basin is MM to the north and the Lycian Nappes to the south. The basin fill, the Yatağan formation (Atalay 1980; Yılmaz et al. 2000), is randomly exposed at different parts of the study area. The basin fill comprises of Upper Miocene to Pliocene continental clastics over an unconformable or tectonic contact with the underlying different basement.

The basin infill is made up of a brown, poorly sorted, thick-bedded alluvial conglomerate at its base, which passes upward into grayish-brown sandstone and mudstone. The succession ends with light-gray, white clayey limestone intercalations at the top. The conglomerates are characterized predominantly by marble, gneiss, and schist clasts, which range from boulder to granule in size. Many conglomerates are lenticular and 10–100 cm thick. They are upward fining with interbedded sandstones in the upper portions. Sedimentary layers in most of the deposits are characterized by tabular cross-bedding and pebble imbrications. To the north of Muğla, measurements from imbricated conglomerates yield a paleocurrent direction from NE to SW, whereas, around Yatağan, measurements from clast imbrications give a NW to SE paleocurrent direction. At different levels in the sequence, there are limestone and marl lenses, tuff intercalations, and travertine. The tuff is thinly bedded and rhyo-dacitic in nature. The thickness of the sequence is 300–500 m, and the red beds yield a mammalian fauna that ranges from the Middle Astracian to the Turolian in the Muğla region (Atalay 1980).

No clearly observable major fault system exists in the study area and farther to the west in the Milas-Ören region (Gürer and Yılmaz 2002). The boundary fault of the Yatağan Basin is the Aksivri Fault, situated to the north of Muğla. It is a 50 m wide and 5 km long, NW-striking normal fault along the Yatağan formation where the MM is tectonically juxtaposed. Various sized, local faults delimit the basin deposits, which are also identified (Fig. 2a, b). For example, to the south of the Tınaz Basin, two faults controlled the deposition of the Tınaz and Yatağan Basin fill. They are the Çaybükü Fault (ÇF), which is situated at the southwest of the basin, and the Topbaşı Fault (TF), which is situated at the southeast of the basin (Fig. 2a).

Interpretation

After this N–S compression ceased, a severe process of erosion began. It produced a regional erosional topography during the Late Miocene–Pliocene. The general NW–SE trend of the Yatağan Basin indicates that the depression formed during the Middle Miocene was preserved and a fluvial network developed. The Late Miocene–Pliocene was a period of severe erosion, causing the denudation of the gneissic core units of the MM to the north. During this period, important deformation did not occur in the region; this is clearly demonstrated by the region's wide, nearly horizontal position of Middle Miocene–Pliocene strata. However, in the Turgut, Sekköy, and Yatağan formations, there are some E–W-trending reverse faults relevant to the compression (Fig. 5b–d). The clastics of the Yatağan formation deposited in fluvial, alluvial fan, and lacustrine environments formed as a result of the intense karstification and erosion in the region. Thick travertine deposition ($\sim$100 m) occurred closer to the reactivated Middle Miocene faults. Neither a boundary fault zone, which controlled the development of this basin, nor depositional features indicating structural control, are present. The basin is interpreted as an intermountain basin that developed without any important tectonic control.

Plio-Quaternary basins

Plio-Quaternary deposits constitute large alluvial fans, and Late Quaternary alluvium is related to the rivers and marine deposits of the current Gulf of Gökova. Deposits were studied in five different Plio-Quaternary basins with different orientation and geometries. From the north to the south, these are the Paşapınarı, Muğla, Yeşilyurt, Ula, and Gökova basins (Fig. 2a). When Muğla is chosen as a reference point, the altitudes of the basins decrease to the north and the south. At the north of the Muğla Basin, the Paşapınarı Basin is situated 300–400 m above sea level. The Muğla Basin is located at 650–700 m and the Gökova Basin is located at $-$850 m altitude. The thickness of the deposits of the basins situated to the south of Muğla increase from the north to the south. The thicknesses of the deposits are 50–70 m in the Muğla Basin, 100 m in the Ula Basin, and 150 m in the Gökova Basin (Unpublished borehole data; Çağlar and Duvarcı 2001).

The youngest basins in the study area were filled with cobble-pebbles, pebbly sands, sands, and clays of the alluvial, colluvial, and alluvial fan deposits. For the most part, the infill of the Muğla and Gökova Basins has extensive outcrops. The Muğla Basin is a 12 km long and $\sim$6 km wide depression that is filled with Plio-Quaternary deposits. This NW-trending rhomboidal basin is controlled by normal faults; marble in the MM and the Yatağan formation form the footwall, and colluvial and alluvial fan deposits form the hanging wall of the boundary faults of the basin. The alluvial fans are extensive along the northern basin. The largest fan is located nearby the city of Muğla. This fan, approximately 1 km long, extends to the toe of the mountain front. The basal, texturally immature, clastic intervals of the individual alluvial fans are interpreted as

high-energy debris-flow deposits, probably reflecting the presence of steep slopes created by the Late Pliocene–Quaternary faulting. In contrast, higher depositional units within the fans are dominated by more texturally mature, better-sorted, well-imbricated conglomerates.

Within the large alluvial fans, vertical successions are exposed in perpendicular stream sections or highway edges. For example, to the west of Muğla, the basal 20 m of the succession is composed of unsorted breccias with large blocks (~2 m) of locally derived marble, set in an unsorted matrix of sand and silt. The bedding locally shows evidence of multiple depositional and scouring events, leaving only remnants of successive depositional phases. The upper part of this unit is composed of breccias and conglomerates, which are more sheet-like and pass upwards into ca. 50 m of (texturally) more mature, normally graded, clast-supported conglomerates with well-developed erosive bases into individual depositional units.

The Gökova Basin is the southernmost graben of western Anatolia. It is 150 km long and widens westward from 5 to more than 30 km (Figs. 1b, 2a). A major part of the graben is offshore, forming the Gulf of Gökova. The northern margin is bounded by a linear mountain front, which rises steeply to more than 900 m. The southern margin of the graben is topographically less steep and marked by many bays and small offshore islands (Yılmaz et al. 2000). The northern margin of the Gökova Basin, the east- and northeast-trending faults cut the north-to-south-trending graben bounding faults and the rock groups of the pre-Quaternary basins.

The Gökova Gulf deposits are composed of terrestrial and marine sediments. Detailed 3.5 kHz, single channel air gun seismic reflection profiles of the northeastern continental shelf of the Gökova Gulf is shaped by deltaic sequences that are separated by discontinuities (Uluğ et al. 2005).

Structural and kinematic features of the Plio-Quaternary Basin faults

The study area, the Plio-Quaternary Basins, is half-grabens opened and controlled by high-angle normal faults. These faults are large (2–10 km) and lies between the Muğla and the Gökova Gulf. They cause the region to subside from the north (Muğla) to the south (Gökova Gulf) in a step-like pattern. Also, these normal faults have become recently active, based on the observation of fresh fault planes and unconsolidated fault talus that is vegetation-free. Slip lineations from all fault sets of extensional faults suggest that they are predominantly dip-slip normal faults with minor strike-slip components, rarely exceeding 25° deviation from pure dip slip. Five of the clearly observable faults within the slip data are defined below. They are the: (a) Paşapınarı Fault, (b) Yeşilyurt, (c) Muğla Fault, (d) Ula Fault, and (e) Gökova Fault (GF1 and GF2).

Fault kinematic analyses using data from striated fault planes of high-angle normal faults were performed to determine the kinematic framework of faulting. Approximately 76 fault-slip data were collected from ten different sites (Table 1; Fig. 7a, b). In two of these locations, overprinting relationships were noted and two striations on the same fault plane were observed. The data set was processed using the direct inversion method (INVD) Angelier (1990). During the inversion process, field-based separations were applied. Using the fault-slip data, 12 stress configurations were constructed. Among these, seven yielded an approximately NE–SW direction of extension and five yielded a NW–SE extension (Fig. 7a, b).

Most of the main faults of the basin are located in the area from Muğla to Gökova. Some of the characteristics of these faults are showed in Fig. 8. The main faults are described below.

The topography and elongate geologic outcrop patterns to the west and east Menteşe Mountain adjacent to the Paşapınarı Basin are closely controlled by NW-trending Paşapınarı fault. The Paşapınarı Fault, which dips 70–85° at the surface, delineates the eastern flank of bedrock exposure in the West Menteşe Mountains (Fig. 2a). The fault strikes N20°W at its northern end, curving abruptly to a strike of N45°W to the south. It juxtaposes the Yatağan formation and alluvium with a metamorphic basement. The fault bounds the present valley floor and runs along the base of the topographic escarpment on the western side of modern valley. Although there is faulting along the whole length of the valley edge, the fault zone is en echelon in character. The segmentation of the faults is on a scale of 5–10 km. The major fault segments display triangular facets and locally preserved slickensided fault planes that show the Paşapınarı Fault as an oblique-slip, normal fault, dipping at an average of 75°N, with minor, right strike-slip offset.

The Yeşilyurt Basin is an N–S trending, ellipsoidal basin. Its only boundary fault is the N25°W-trending Yeşilyurt Fault, which is located to the east of the basin. There are no clearly observable slickensides on the fault planes.

The Muğla Fault (MF) delimits the northern margin of the Muğla Basin (Fig. 2a). This is an important morphological feature, which controls the opening of the Muğla Graben. The MF is composed of two parallel fault segments MF1 and MF2. MF1 is linear throughout much of the western Muğla area, striking N75°W until it makes a sharp 20° bend, changing strike to due north in the east of Muğla. The MF2 is parallel to MF1 and approximately 6 km long. MF2 was developed in limestone from the

Table 1 Results of stress tensor determinations with the new direct inversion method (Angelier 1994)

Site	Fault	UTM coordinates (zone 35S)		$\sigma 1$		$\sigma 2$		$\sigma 3$		ϕ (stress ratio)	N (number of faults per site)
		E	N	Trend	Plunge	Trend	Plunge	Trend	Plunge		
1	MF1_a	623108	4119653	035	70	286	07	194	19	0.155	5
2	MF2_a										
	Phase 1	622923	4120027	347	72	087	03	178	18	0.404	8
	Phase 2			034	65	220	25	129	02	0.287	4
3	MF2_b	624879	4119402	325	75	100	10	192	10	0.250	5
4	KF	620213	4117405	248	68	053	21	145	05	0.237	5
5	UF1	624245	4109532	033	66	151	12	246	20	0.188	7
6	YF	593153	4135260	200	71	100	04	009	18	0.244	7
7	PF	605720	4125349	163	71	311	16	44	10	0.236	5
8	GF1	622530	4103230	329	71	123	18	216	08	0.243	6
9	GF2	600649	4099219	023	70	264	10	171	17	0.288	7
10	MF1_b										
	Phase 1	624738	4119461	046	77	283	07	192	10	0.615	6
	Phase 2			262	17	099	72	353	05	0.472	5
	Phase 3			036	79	294	02	204	11	0.295	6

cover units of the MM. The Quaternary alluvial fan deposits are situated to the western part of the fault. The morphology of the alluvial fans was strongly influenced by recently active, normal faulting. Large fault scarps, which are up to several hundred meters high, were generated that border the north of Muğla Graben.

Along both segments, the fault zone has steep dips (75–85°SW) (Fig. 8a). The hanging wall consists of Quaternary alluvial fan deposits, and the footwall consists of the Yatağan Basin fill and cover of MM. On the fault axis, we measured two differently oriented striation sets on the same slip surface of the MF1 (Fig. 8b), of a N80°W strike and 76°SW dips. The younger set is represented by slip lines with rakes of 10–15°NW that overprint the older striation set and have an average rake of 80°SE. The two observed slickenside lineations, each with different plunges and slip senses on the same fault plane, suggest that the strike-slip surface was overprinted by dip–slip movement. The fault is characterized by a highly brecciated zone (Fig. 8c).

High mountainous areas to the northeast of Muğla that represent the footwalls of large fault lineaments are dominated by precipitous fault scarps and are floored by extensive loose scree. Numerous fault planes are present, mainly within Mesozoic carbonate rocks, which located along a road north of Muğla. These fault planes have well-developed slickensides.

The northern and southern margins of the Ula Graben (Fig. 2a) have different morpho-tectonic characteristics due to the nature of the faults along these margins. The northern margin faults are well-developed, with considerable vertical movement on high-angle normal faults. Linear fault scarps and triangular facets are morphological manifestations of the high-angle normal faults. This fault is mapped as two discrete fault traces, UF1 and UF2, extending for about 17 km between İncirli in the east and the Haliller district in the west. The UF1 trends N45°W, dips 80°SW, and is 5 km long. The footwall rocks are made up of the limestones of the basement, while the hanging wall is comprised of the Plio-Quaternary deposits. The fault surface at the sediment–bedrock interface is slightly curved and scored by abundant slickenlines and grooves. Several well-exposed fault planes strike approximately NW–SE, with an average 60–80°SW dip, and a rake of slip lines averaging 70–80° (Fig. 8d). The UF2 is an arc-shaped fault, trending N45°W to the west, E–W in the center, and N70°E to the east.

Numerous NE–SW normal faults dominate the modern-day topography in the Gökova Graben. The northern and southern margins of the basin have different morpho-tectonic characteristics due to the nature of the faults along these margins. NE-trending normal faults are confined mostly to the northern margin, which is defined by south-dipping, high-angle (70–85°) normal faults. All of these high-angle normal faults, bordering the northern side of the Gökova Gulf, are grouped together under the generic name of the Gökova Fault (GF1 and GF2). The east- and northeast-trending fault scarps cross-cut the previous NW–SE-trending fault traces. The southern margin faults are observed as short and discontinuous fault segments. An irregular basin boundary in the south is the main evidence of this fault segmentation.

Kinematic data were gathered from the fault scarps of the two faults, named GF1 (north of Gökova town) and GF2 (northwest of Gökova Gulf). GF1 is approximately

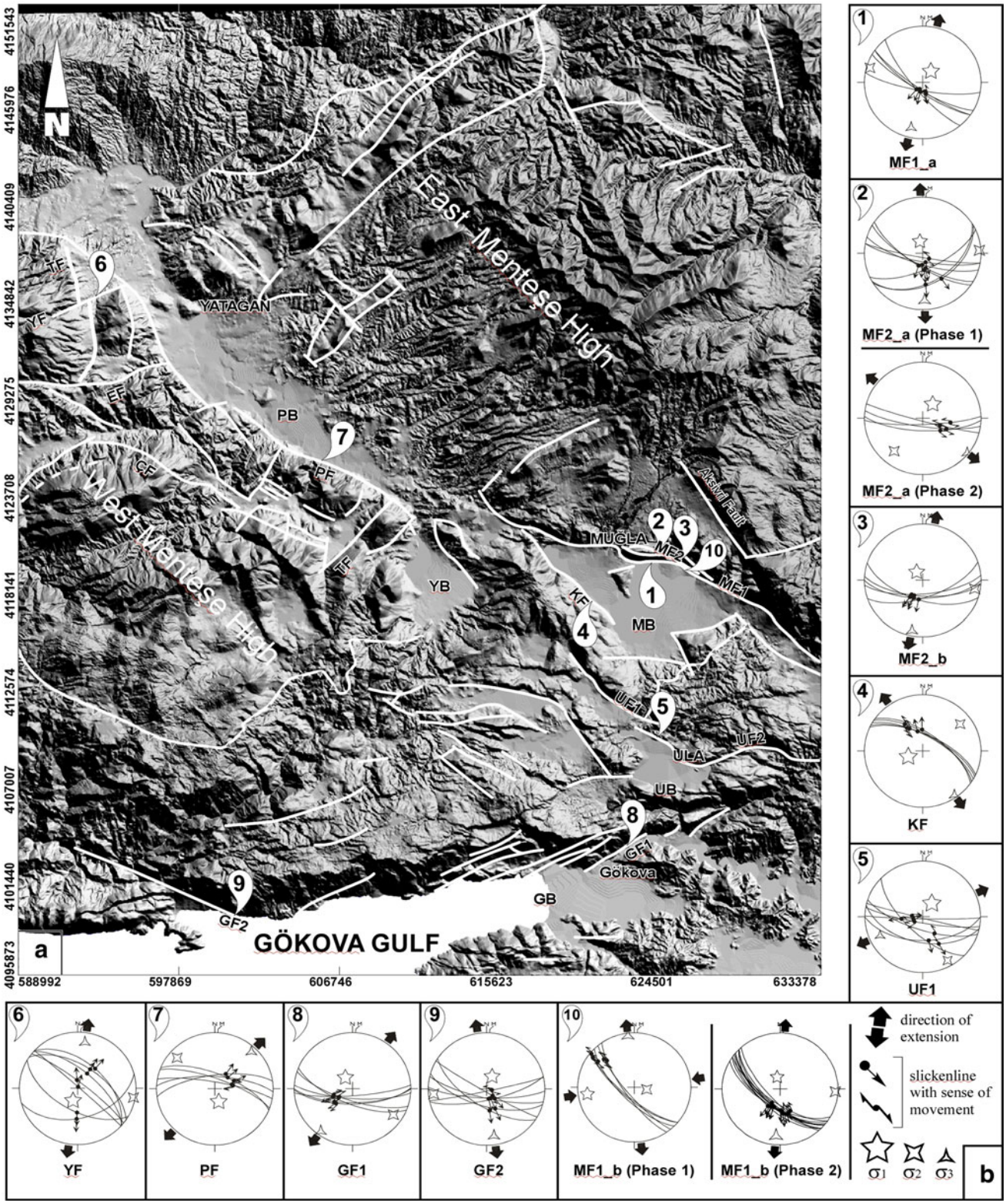

Fig. 7 **a** Raised relief image of the Muğla and Gökova region produced from 1 arc second (∼30 m) DTED2 (Digital Terrain Elevation Data Level 2); the termination of major structures in the region are indicated. **b** Lower hemisphere, equal area projection of principal stress axes constructed from fault-slip data using direct inversion method (Angelier 1994). YF; Yeşilbağlar Fault, PF; Paşapınarı Fault, MF1, MF2; Muğla Fault; UF1, UF2; KF; Karabağlar Fault, Ula Fault, GF1, GF2; Gökova Fault

5 km long and was developed between the limestones of the Lycian Nappes and the alluvium (Fig. 2a). The fault trends N45°E and dips 75°SE (Fig. 8e). Footwall rocks of the GF1 consist of the limestone from the Lycian Nappes. The GF2 trends N50°W, dips 75°SW, and was developed in the same lithologies (Fig. 8f).

The Gökova Gulf has been subjected to high-magnitude, hazardous earthquakes in its history and especially in the twentieth century. Two different hazardous earthquakes occurred in 141 AC in the Gulf region. In 1493, the town of Bodrum was totally destroyed (Luttrell 1999). Other hazardous earthquakes in the region have been known to have occurred in 174, 1851, 1863, and 1869. In the twentieth century, two different high-magnitude earthquakes on April 23, 1993 (with $M = 6.4$ toward İstanköy) and on May 23, 1941 (near Ula-Gökova) indicate a continuing earthquake risk in the region. At present, a hazardous earthquake risk still continues for settlements on the Turkish mainland (including Milas, Bodrum, and Gökova) and for those (like İstanköy) on the Greek islands (Aktar et al. 2006). Most of the seismic activity, however, is concentrated along the northern branch of Gökova Fault Zone, and it is controlled by an E–W-trending normal fault system. Intense earthquake activity occurred in Gulf of Gökova in 2004 and in 2005. Source mechanism solutions and rupture histories for ten earthquakes with magnitudes of $M\text{w} \geq 5.0$ and shallow focal depths ($h < 20$ km), which occurred in the region between 1986 and 2005, are used to investigate the geometry of faulting in the region (Yolsal and Taymaz 2005, 2007, 2010). The kinematics of the deformation is controlled by normal faults with small strike-slip components, trending E–W, NE–SW, and NW–SE in direction. Earthquake source mechanism solutions indicate that normal fault mechanisms with a strike-slip component have been observed on the E–W-oriented graben and normal fault systems in the Gulf of Gökova, which confirms that the extension is in a north–south direction. This

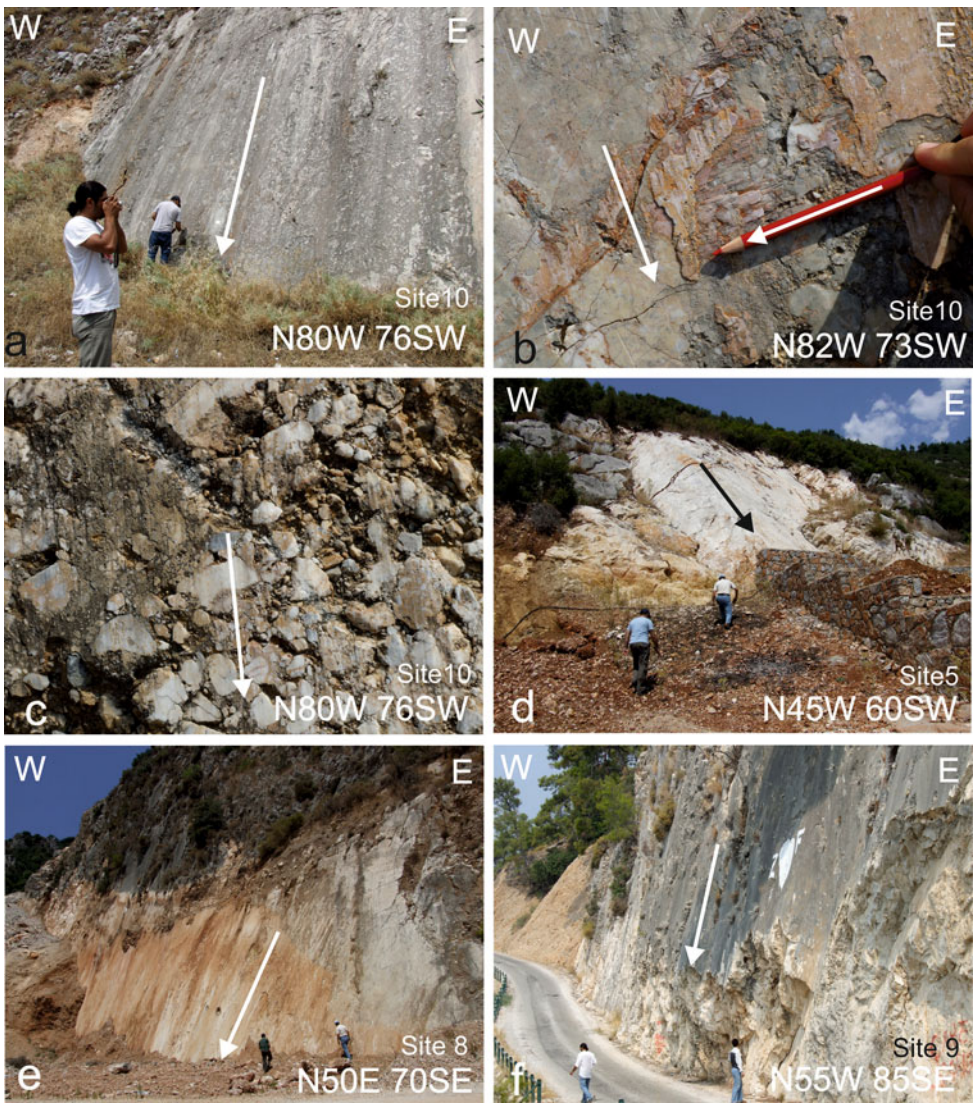

Fig. 8 Field photographs of Plio-Quaternary faults. **a** Field view of NW-striking MF1 (North of Düğerek district) (35S 4102345N/621891E). **b** Detail of slip surface within MF1, showing two different slickensides. Superimposed slickensides with older strike-slip motion and younger dip-slip normal motion (35S 4102340N/621903E). **c** Close-up view of brecciated marble with well-defined slip surfaces. Slickensides indicate normal-slip motion (Fig. 6a). (35S 4102340N/621903E).**d** Well-developed fault plane of Ula Fault with a nearly dip-slip slickenline (35S4111561N/621535E). **e** Fault plane on the GF1 to the northeast of Gökova town (35S 4119334N/624413E). **f** Fault plane on GF2 showing dip-slip movement north of the Gökova Gulf (35S 4119334N/624413E)

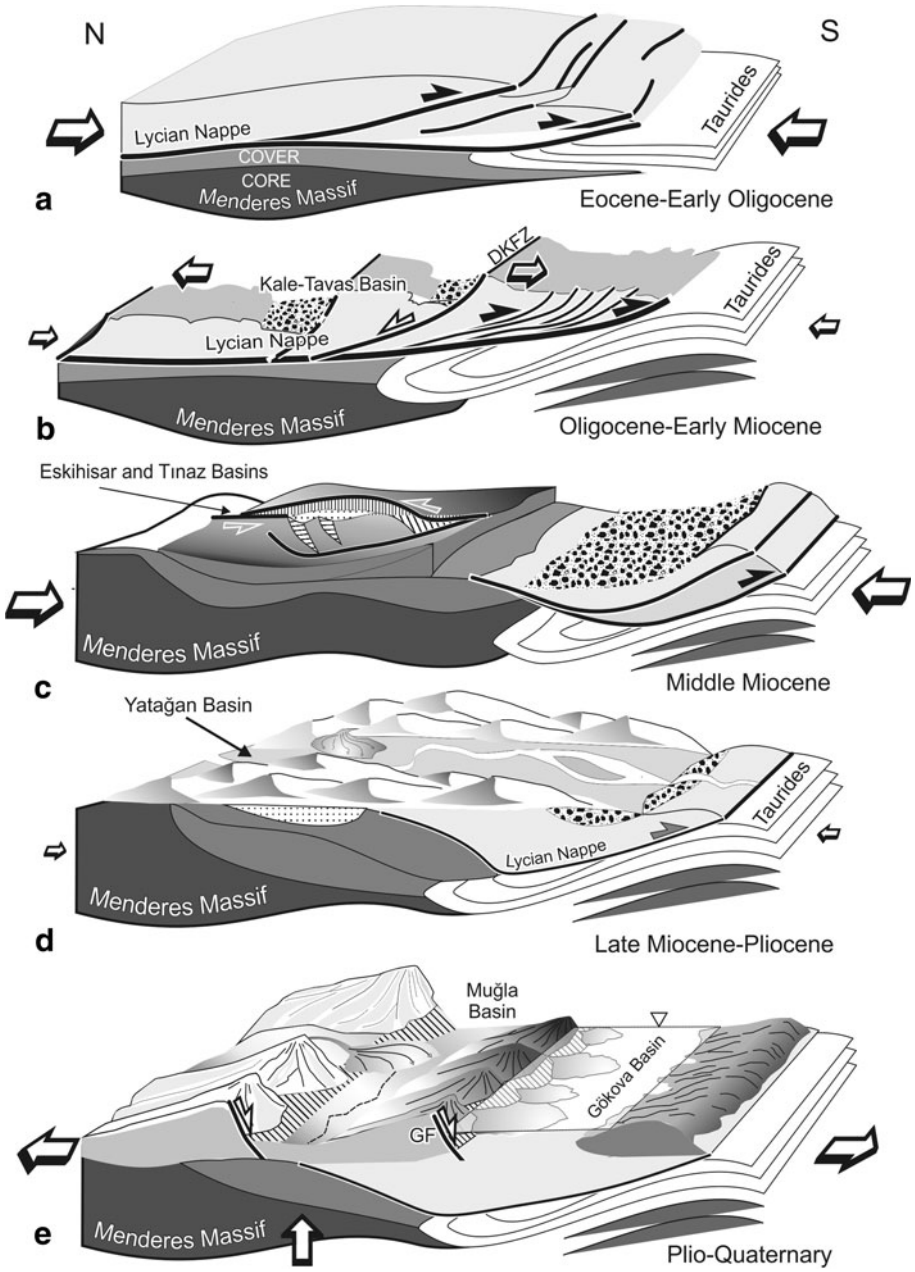

Fig. 9 Schematic block diagrams showing the tectonic evolution of the Muğla and Gökova Gulf region. **a** Eocene–Oligocene: Displacement of the Lycian Nappes by traversing the MM and thrusting on the Taurides. **b** The formation of the Kale–Tavas Basin on the Lycian Nappes as a piggyback basin by the gravity-induced inverted movement of the nappe slices toward the north. DKFZ: Datça–Kale Fault Zone. **c** Middle Miocene: N–S contraction and development of N–NW-trending oblique faults and Eskihisar and Tınaz basins. **d** Late Miocene–Pliocene: Uplift and erosion, and the development of the Yatağan formation on the irregular topography. **e** The development of the high-angle normal faults and formation of the Plio-Quaternary basins, under the N–S extensional system. GF: Gökova Fault

information is in good agreement with the geology and tectonic structure of the region (Yolsal and Taymaz 2010). No clear activities have been observed to the southern part of the gulf, except at its western limit. This may indicate that, in this part of the gulf, the faults are inactive, but in the western end of the Datça Peninsula (between İstanköy and Datça), they are indeed active (Aktar et al. 2006).

Interpretation

In the Muğla and Gökova Gulf region, an important pulse of normal faulting in the Late Pliocene–Quaternary generated large fault scarps. These acted as sources for large Plio-Quaternary alluvial fans, which prograded across active, normal-slip faults. They have accommodated vertical movements of as much as several hundred meters. In the study area, the extensional regime caused the development of the extensive basins in the form of rhomb-shaped, half-grabens controlled primarily by normal faults, and secondarily by karstic features. As a result of the activity of these normal faults, the region between Gökova and Muğla subsided to the sea level.

Following the compressional/transpressional event of the Middle Miocene, the Muğla–Gökova region underwent pervasive, extensional faulting during Plio-Quaternary and

the presents physiographic features of the Muğla and Gökova regions resulted primarily from the Plio-Quaternary extension.

Discussion and conclusion

The Muğla–Gökova region underwent several phases of Late Cenozoic faulting, resulting in a dense network of faults of variable orientations. Geological mapping of the region reveals the presence of four groups of structural basins, each of different age and orientation. The first group is represented by an E/NE-trending basin (the Kale–Tavas Basin) that is filled with the Oligocene–Lower Miocene shallow marine–terrestrial deposits. The second NE- and NW-trending structural depressions (the Eskihisar and Tınaz Basins) are filled with Middle Miocene continental deposits. The third group is NW- and SE-trending basin, with the Upper Miocene–Pliocene infill (Yatağan Basin). The fourth one cross-cuts the first three and is represented by the E–W-trending Gökova Basin, which is filled with Quaternary continental and marine deposits. The formation of the basins occurred in different structural settings and resulted from different, successive tectonic regimes. Figure 9 shows a synthesis that reconstructs the evolution of the basins in the Muğla–Gökova region from their origin to present day, in light of stratigraphic and tectonic data.

The region underwent a N–S compression during the Late Cretaceous to Early Cenozoic (Fig. 9a–c). The northern branch of the Neo-Tethys Ocean closed in Eocene times as a result of the collision between the Sakarya zone in the north, and the Tauride-Anatolide Platform in the south (Şengör and Yılmaz 1981). Nappe slices related to the closure of the Neo-Tethys Ocean migrated southward, traversing the Tauride-Anatolide platform (De Graciansky et al. 1967; Koçyiğit 1977; Hayward 1984; Şengör 1982). The late post-collisional, intra-continental convergence continued in southwestern Anatolia until Middle Pliocene, as is implied by the final emplacement of the Lycian Nappes in the region (Koçyiğit 1977; Poisson 1977; Yılmaz et al. 2000). In the Oligocene–Early Miocene, the uppermost slice of the Lycian Nappes recorded a top-to-the-north displacement and continued subsidence, as a result of thrust-loading, allowing the development of a thrust-sheet-top basin behind the front of the deformation (Fig. 9b). The Kale–Tavas Basin is a syn-tectonic sedimentary basin that developed simultaneously with the thrust activity during Oligocene–Early Miocene. Tectonic control of the sedimentary processes, recorded in the rapid deepening and consecutive infilling of the Kale–Tavas Basin, is a strong argument for interpreting it as a typical piggyback basin developed above the low-dipping normal fault plane.

A major problem in the MM concerns the geometry and sense of transport of the nappes. Top-to-the-north movement may be pre-Alpine deformation (Gessner et al. 2001), pre-Eocene (Regnier et al. 2003), Eocene (Rimmele 2003), Late Oligocene–Early Miocene (Bozkurt and Park 1997; Seyitoğlu et al. 2004; Bozkurt 2004, 2006; Alçiçek and ten Veen 2008). A northward continuum of deformation responsible for top-to-the-N shearing associated with the MM (Paleocene–Eocene) and its progressive cooling (Late Eocene), north-verging folding, thrusting, imbrication of "core" and "cover" series, and N–S to NE–SW intense stretching associated with the Menderes HP metamorphism and its exhumation (Rimmele et al. 2003). Both the top-to-the-north to top-to-the-northeast movements are probably related to the northward backthrusting of the Lycian Nappes, reactivating the contact between the Menderes Massif and the Lycian Nappes as a top-to-the-NE shear zone that allowed exhumation of the Lycian high-pressure rocks (Rimmele et al. 2003). In addition, north–northeast movement on the southern Menderes massif is attributed to northward thrusting (Ring et al. 1999; Whitney and Bozkurt 2002). Seyitoğlu et al. (2004) suggest that all these top-to-the-NNE directions are related to the major shear zone of the Datça–Kale Main Breakaway Fault. However, there are some submissions, based on kinematic studies (Regnier et al. 2003), stating that there was no top-N shearing Early Cenozoic in Aegean region and its environs.

The present study supports the assumption that the development of the Kale–Tavas Basin is syn-tectonic and related to the inverted movement (i.e., the Datça–Kale Fault Zone) in the Lycian nappes (Kurt et al. 1999; Yılmaz et al. 2000; Gürer and Yılmaz 2002). Therefore, this inverted movement in the Lycian Nappes should be coeval with the age of the Kale–Tavas Basin, that is, Oligocene–Early Miocene. The provenance of the infill of the Kale–Tavas Basin represents ophiolites and limestones from the Lycian Nappes. No lithologies from the MM have been found in the basin fill (i.e., the Akyaka and Kuyucak formations). The occurrence of erosional products derived from the Lycian Nappes in the Oligocene–Early Miocene implies that the latter was cropping out over a much larger area than it does today. This suggests that, during the same period, the MM was still buried under the nappes, but was close to the surface.

Another clue indicating the uplift of the MM is related to the DKFZ. Seyitoğlu et al. (2004) hypothesized that this fault determines the southernmost boundary of the western Anatolian extensional system as a detachment. Our observations, however, suggest that it is probable that an unexposed segment was not located in the Gökova Gulf, and that the DKFZ was not a detachment fault. We think that the location of its unexposed segment is located to the north of Datça Peninsula, rather than Gökova Gulf, because the infill

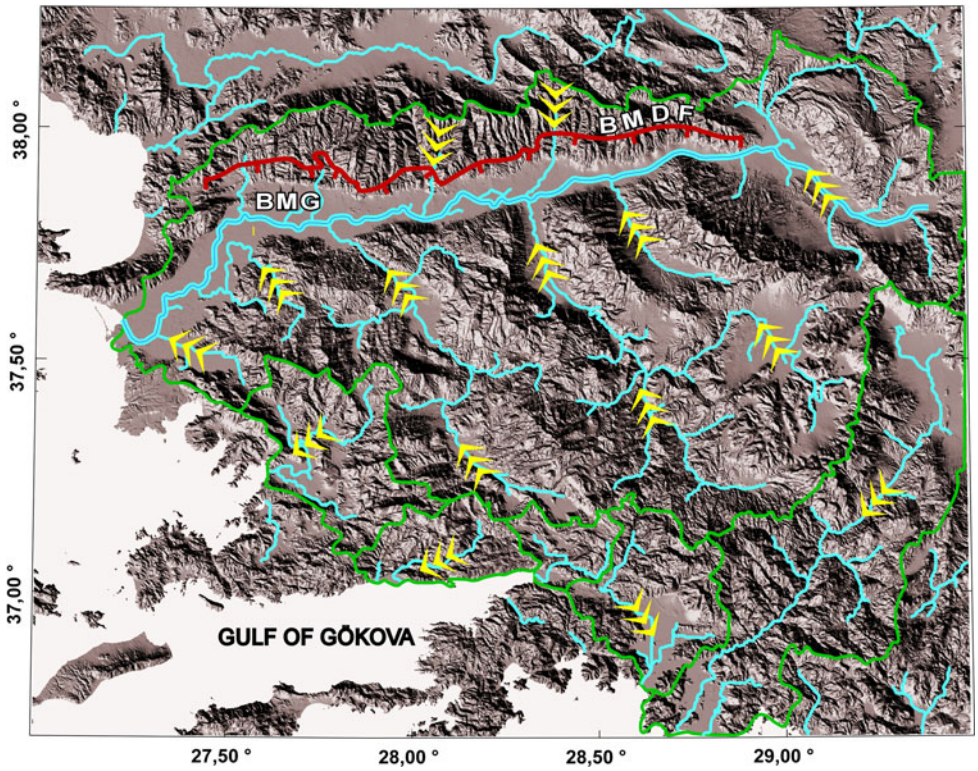

Fig. 10 Drainage pattern in southwest Anatolia. All major streams originating from Gökova Gulf flow northwards to join Büyük Menderes River

of the Kale–Tavas Basin can be traced to the north of Datça Peninsula (Figs. 1, 2a). We also believe that the DKFZ is a normal listric fault (as shown in Kurt et al. 1999, Fig. 12) that is related to the Lycian Nappe emplacement, rather than a boundary fault of the Gökova Graben (Kurt et al. 1999) or a detachment fault (Seyitoğlu et al. 2004). The following observations suggest that the DKFZ was not a boundary fault of the Gökova Graben because: (a) it uniquely bounds the Oligocene–Early Miocene deposits of the Kale–Tavas Basin (Yılmaz et al. 2000; Gürer & Yılmaz 2002, in this study) (Fig. 2a) and is therefore considered here to be the boundary fault of this older piggyback basin; and (b) no earthquake data are present. In short, it is a seismologically inactive fault open to the recent gulf. Other observations suggest that the DKFZ was not a detachment extensional main fault. First, evidence of secondary synthetic and antithetic faults crossing or adjoining the "detachment" fault (Lister and Davis 1989) in the Gökova region is absent in seismic sections or in earthquake studies. Second, it is a seismologically inactive fault (Aktar et al. 2006). Third, contrary to our expectation, the detachment faulting juxtaposes an unmetamorphosed hanging wall against medium- to high-grade metamorphic footwalls in metamorphic core complexes, and the DKFZ never juxtaposes the MM core complex rocks against any basin infill, either in onshore (Fig. 1) or in offshore studies. For example, the Datça Fault shown in seismic sections in Kurt et al. (1999) is situated only within Lycian Nappes. Instead, the DKFZ is confined to the Lycian Nappes units. Fourth, the region between the Büyük Menderes Graben and the Gökova Gulf was tilted northwards toward the Büyük Menderes Detachment Fault. The major streams to the north of the Gökova Gulf do not flow into the sea, but instead flow to join the Büyük Menderes River to the north (Fig. 10). If the DKFZ was a detachment fault, we should expect a southward regional tilting toward the DKFZ. Similarly, we expect the streams to flow southward to join the gulf.

The presence of open folds in the Kale–Tavas Basin deposits is the result of a regional pulse of compression/transpression in the Middle Miocene. The probable cause of this deformation was the collision of the Anatolide and Arabian plates in eastern Turkey (Şengör et al. 1985). In the Middle Miocene, continuing erosion and movement of the Lycian Nappes (once again southwards), under the N–S compressional/transpressional regime, first caused erosion-related exhumation of the MM in the north. By this time, the pull-apart Eskihisar and Tınaz basins, with fluvial-lacustrine fills, were opened (Fig. 9c).

Between Middle Miocene and Pliocene, no important tectonic events were recorded in the region, suggesting a tectonic quiescence period (Fig. 9d). The important event recorded during this period was the erosion of the uplifted cover units of the MM, which caused the denudation of its gneissic core. The irregular topography created during this period caused the formation of an approximately NW–SE-trending fluviatile-lacustrine intermountain basin (i.e., the Yatağan Basin).

The N–S extensional tectonic activity started at the end of the Pliocene and still continues (Fig. 9e). It is characterized in the study area by the activity of normal faults cutting through all previous units. It is also marked by the coeval deposition of coarse sediments. A recent morphological appearance was formed by the onset of almost high-angle normal faults onto an undulating paleotectonic structure during the Plio-Quaternary. This tectonic activity was responsible for the development of Plio-Quaternary, half-graben-type basins (including the Paşapınarı, Muğla, Yeşilyurt, Ula, and Gökova basins), which are co-genetic with the E-trending Gediz and Büyük Menderes Grabens, located central part of the Western Anatolia. This tectonic activity is related to the active N–S extension in the Aegean region that includes western Anatolia.

Chatzaras et al. (2011) have obtained new structural data from Amargos Island located to the west of Gulf of Gökova. Two important results from that study are parallel with our results. First, the dominant compressional deformation, which possibly occurred in the Oligo–Miocene, produced a series of imbricate NW-directed thrust faults. Second, the area was affected by transpressional deformation in the Middle/Late Miocene, during which the principal NE–SW orientation, while a pure, extensive stress regime (back-arc-related) seems to have been established in the late Miocene times.

In the eastern Mediterranean, the South Aegean subduction zone has experienced a complex history of subduction systems (e.g., Faccenna et al. 2006; Le Pichon and Kreemer 2010; Ring et al. 2010; Capitanio et al. 2010). The main plate tectonic elements of the eastern Mediterranean region are the South Aegean and Cyprus arcs, along which the African plate plunges beneath the Aegean Sea and the Anatolian block in a northerly direction. Ongoing subduction plays a major role in affecting the boundary conditions acting on the deforming African lithosphere (Le Pichon and Angelier 1981; Meijer and Wortel 1997; Faccenna et al. 2006). Several researchers have thought that the rollback mechanism plays an important role on the N–S extension in the Aegean region. However, there is no consensus on the initiation age of subduction rollback process and the claims range from Late Eocene–Oligocene (Jolivet and Brunn 2010; Jolivet et al. 2010), Late Oligocene–Early Miocene (Bonev and Beccaletto 2007; Faccenna et al. 2003), Early–Middle Miocene (LePichon and Kreemer 2010; van Hinsbergen et al. 2010a, b; Altunkaynak and Dilek 2006; ten Veen and Postma 1999; Zachariasse et al. 2011), Late Serravalian (Mercier 1981; Mercier et al. 1989; Jackson and McKenzie 1988; Meulenkamp et al. 1988, 1994; Kissel et al. 2003) to Early Pliocene (Boronkay and Doutsos 1994). According to the data we acquired from the Gökova region, the influence of the rollback mechanism on the extension in the region began in the Late Pliocene. Pre–Late Miocene faults and basins were related to the N–S compressional phase.

According to the geological history of the Gökova region, based on the synthesis of the data presented in this paper and previous works, we discuss how our results relate to the hypothesis regarding the origin and evolution of the extensional tectonics in western Anatolia. Our data showed that the switch from the older compressional tectonic regime (i.e., emplacement of the Lycian Nappes) to the prevailing N–S extension in the region occurred after a period of tectonic quiescence in the Middle–Early Pliocene. This means that the extension in the region started in the Plio-Pleistocene interval in the favor of the results of Sarıca (2000), Gürer et al. (2009). According to the age of this switch, the possible driving forces of the active extension in the region are related to the two main Anatolian plate boundary events that define the present-day stress field, and their commencement fits well with: (1) the southward rollback of the subducting oceanic slab under the South Aegean Arc, which can be seen as being responsible for the core complex development in the region; and (2) the southwestward motion of the Anatolian block along its boundary faults.

We conclude that, in southwestern Anatolia, starting from the Late Cenozoic, three basins related to the N–S compressional system, and five basins related to the N–S extensional systems, were subsequently recorded with an intervening period of intermontane basin formation. The transition from the compressional to the extensional system occurred in the Plio-Quaternary. In contrast to the proposed single extensional history, our data point to complete history with successive compressional and extensional situations.

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