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The role of the flexural rotation/rolling hinge model in the tectonic evolution of the Alaşehir graben, western Turkey

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Abstract – The Alaşehir graben is a well-defined prominent extensional structure in western Turkey, generally trending E–W and containing four sedimentary units. At the beginning of graben formation during Early–Middle Miocene times, the first fault system was active and responsible for the accumulation of the first and second sedimentary units. In Pliocene times, a second fault system developed in the hanging wall of the first system and a third sedimentary unit was deposited. The recently active third fault system separates older graben fill and a fourth sedimentary unit. Activity on each fault system caused the rotation and uplift of previous systems, similar to the 'flexural rotation/rolling hinge' model, but our field observations indicate that the rotated first fault system is also active, allowing exhumation of larger amounts of rock units. This paper documents that graben formation in western Turkey is a sequential process. Its different periods are represented by three fault systems and associated sedimentation. Consequently, recent claims using age data from only the second and/or third sedimentary units to determine the timing of graben formation are misleading.

1. Introduction

The Aegean region is a perfect laboratory to examine mechanisms of continental extensional deformation. In this region, prominent E–W-trending grabens are located nearly perpendicular to the east coast of the Aegean Sea. The Alaşehir graben is about 140 km long and 15 km wide (Fig. 1). The major fault systems are located on the southern side of the graben and create an approximately 1300 m topographic difference between the horst and graben floor. The age of the E–W-trending grabens is based on mainly palynological (Seyitoğlu & Scott, 1992, 1996*a*) and isotopic (Hetzel *et al.* 1995) data.

The initiation age of the E–W-trending grabens has been used to test Late Cenozoic regional tectonic models. Seyitoğlu & Scott (1991, 1996*b*) proposed that the cause of latest Oligocene–Early Miocene N–S extension in the Aegean region, particularly in western Turkey, is related to orogenic collapse due to younger triggering events of tectonic escape (Middle Miocene: Şengör, 1982; Şengör, Görür & Şaroğlu, 1985) and back-arc spreading (Middle–Late Miocene or younger: McKenzie, 1978; Le Pichon & Angelier, 1979, 1981; Meulenkamp *et al.* 1988; Meulenkamp, Van der Zwaan & Van Wamel, 1994; Jackson & McKenzie, 1988). However, recent work by Thomson, Stockhert & Brix (1998) suggested an Early Oligocene roll-back process in the Hellenic subduction zone (see also Okay & Satır, 2000). If this age of roll-back is correct, then back-arc spreading and orogenic collapse should be considered equally as a cause of N–S extensional tectonics in the Aegean region, or the orogenic collapse has been balanced by the roll-back process since latest Oligocene–Early Miocene times, as already stated by Dewey (1988) for the Middle Miocene.

Since 1996, answers to the following questions have been sought: (1) Could age data obtained from graben fills be more specific? (2) Is orogenic collapse responsible for the entire history of extensional tectonics from Latest Oligocene–Early Miocene to Quaternary times? (3) Is there a continuous extensional tectonic regime in the region? (4) Do other younger factors (tectonic escape and back-arc spreading) effect the extensional tectonics and could their effect be recognized in the stratigraphic record of grabens? (Seyitoğlu, 1996).

Recently, the third question was addressed by Koçyiğit, Yusufoğlu & Bozkurt (1999) who proposed a short phase of N–S compression during late Miocene to early Pliocene times in western Turkey, as evidenced by folding of the sedimentary succession in the Alaşehir graben. However, Seyitoğlu (1999) argued that immediately north of the Alaşehir graben, Lower–Middle Miocene sedimentary units are nearly horizontal, and the extensional nature of folding (that is, rollover anticlines and drag folds) in the Alaşehir graben demonstrate that N–S extensional tectonics are not interrupted by a contractional stage

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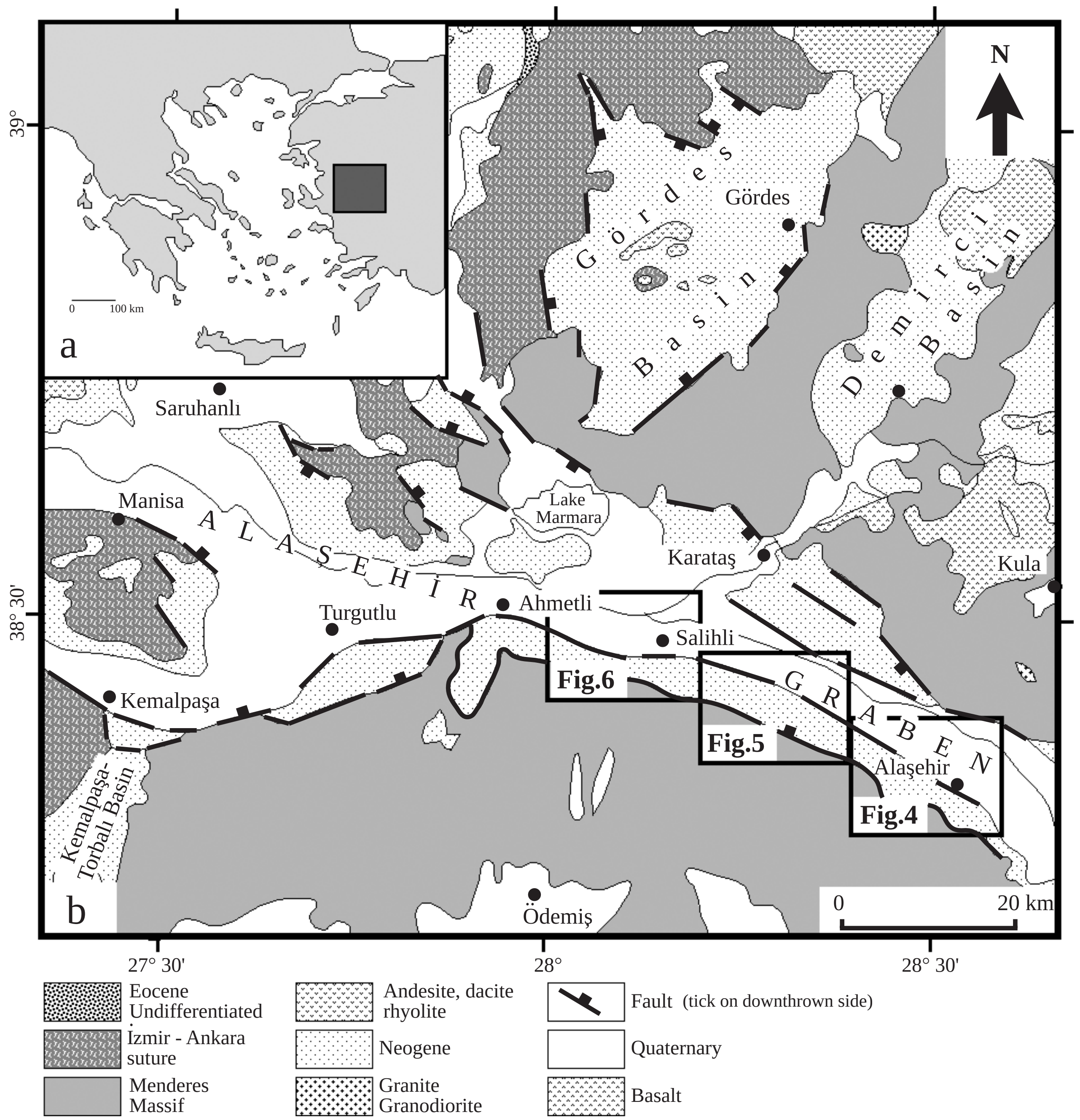

Figure 1. (a) General location of the Alaşehir graben in the Aegean region. (b) Overall structure of the Alaşehir graben and the locations of Figures 4, 5 and 6. Modified from Geological map of Turkey, İzmir Sheet, 1 : 500 000. Fault traces are simplified from Arpat & Bingöl (1969): East of Alaşehir graben; G. Seyitoğlu (unpub. Ph.D. thesis, Univ. Leicester, 1992): Gördes basin and west of Alaşehir graben.

in the interval between Miocene and Pliocene times (Seyitoğlu, Çemen & Tekeli, 2000).

Although isotopic data (Hetzel *et al.* 1995) from synextensional granodiorites demonstrate that N–S extensional tectonic processes had already begun during Early Miocene times, Yılmaz *et al.* (2000) claimed a Late Miocene age for the initiation of these processes. This Late Miocene age preserves Şengör's (1987) idea that N-trending basins developed under a N–S compressional regime during the Early Miocene and later became trapped in the younger E–W-trending graben systems.

The stratigraphic record in the E–W-trending graben and an examination of related fault systems in western Turkey indicate that the tectonic evolution of the Alaşehir graben resembles the flexural rotation/rolling hinge model (Seyitoğlu & Şen, 1998). This model (Buck, 1988; Wernicke & Axen, 1988) suggests that initial high-angle faults rotate to a shallower dip angle because of isostatic rebound. A new fault system

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develops in the hanging wall of the first one because the flattened fault system can no longer accommodate extension. This implies that the rotated fault system becomes inactive and the original throw on the pre-rotational initial fault remains constant after rotation. The faults and associated sediments typically young towards the graben (Buck, 1988; Wernicke & Axen, 1988; Manning & Bartley, 1994; Axen & Bartley, 1997). In this paper, the tectonic development of the E–W-trending Alaşehir graben will be presented and its similarities to, and differences from, the flexural rotation/rolling hinge model will be discussed.

2. Generalized stratigraphy of the Alaşehir graben

The stratigraphy of the prominent E–W-trending Alaşehir graben is briefly introduced here. Details concerning age data and recent related debates (Yılmaz *et al.* 2000; Bozkurt, 2000; Sarıca, 2000) will be discussed in a separate paper giving magnetostratigraphic results from the graben fill (Şen & Seyitoğlu, unpub. data). The graben fill is composed of four sedimentary units. The first sedimentary unit, the Alaşehir Formation (İztan & Yazman, 1990) is the lowermost part of the graben fill (Fig. 2). The formation unconformably overlies the metamorphic basement south of the town of Alaşehir (Fig. 1) and its base is comprised of very angular boulder conglomerates containing schists, metagranites, porphyritic gneisses and mylonitic augen gneisses. The formation continues with alternating yellowish sandstone and mudstone. The overall sedimentary sequence of the lower part of the Alaşehir Formation exhibits a fining-upwards character within a short vertical distance of nearly 50 m. Intervals of 1.5 m thick, very angular boulder conglomerate are common in the fine-grained lacustrine sediments. The uppermost part of the formation is composed of dominantly organic-rich, very well-lithified, laminated mudstone which gradually passes upwards into sandstones with limestone layers and conglomerates (Fig. 3). The Alaşehir Formation is conformably overlain by the Kurşunlu Formation, the second sedimentary unit, which is clearly observed in the valley of Zeytin Çayı to the east of the village of Çaltılık (Fig. 4). Magnetostratigraphic work demonstrates that the transition from the first to the second sedimentary unit occurred around 15.5 Ma (Şen & Seyitoğlu, unpub. data), which is in close agreement with the Eskihisar sporomorph association (20–14 Ma) obtained from the first (Ediger, Batı & Yazman, 1996) and second (Seyitoğlu & Scott, 1996*a*) sedimentary units.

The second sedimentary unit, the Kursunlu Formation, has a dominant red colour (Seyitoğlu & Scott, 1996*a*). Its lowermost part is a dark red angular conglomerate typically seen southeast of Çaltılık (Figs 3, 4). Upper levels, however, are composed of alternating light red- and grey-coloured conglomerate and sandstone, as seen southeast of Göbekli (Fig. 5).

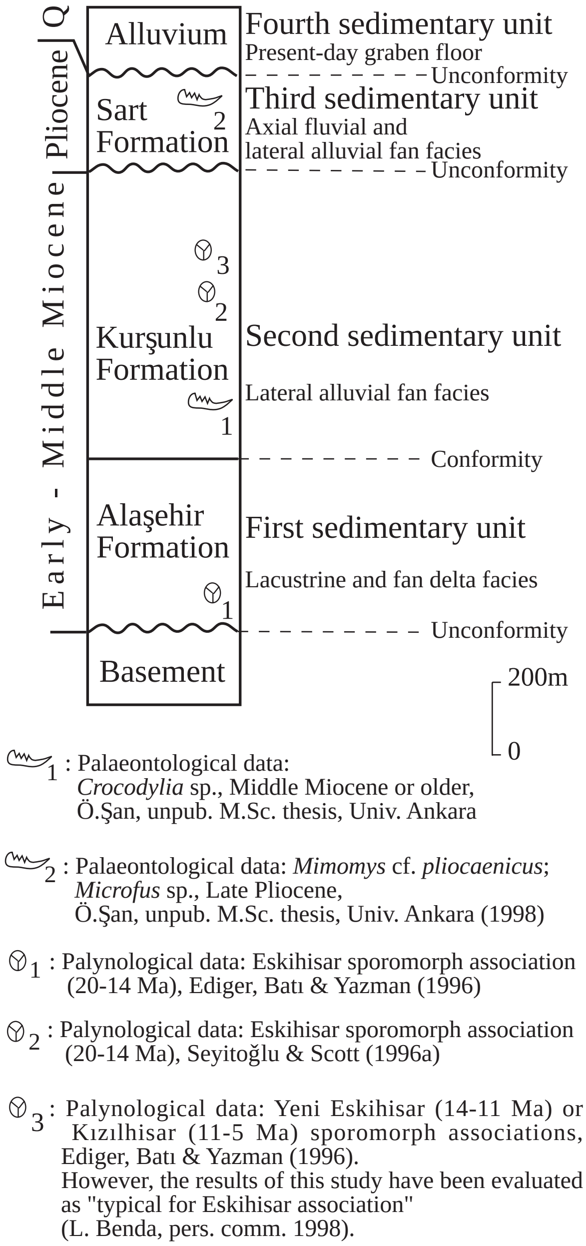

Figure 2. Generalized stratigraphy of the Alaşehir graben. Facies determinations from Cohen *et al.* (1995).

The Lower–Middle Miocene first and second sedimentary units are unconformably overlain by the third sedimentary unit, the Sart Formation, which consists of light yellow semi-lithified conglomerates and sandstones (Seyitoğlu & Scott, 1996a) of Pliocene age. The fourth sedimentary unit comprises recent alluvium deposits (Fig. 2).

3. Fault systems in the Alaşehir graben

Geological maps of the Alaşehir graben (Figs 4, 5, 6) demonstrate that the fault systems in the southern part of the graben can be divided into three categories. The first system is the N-facing, currently low-angle

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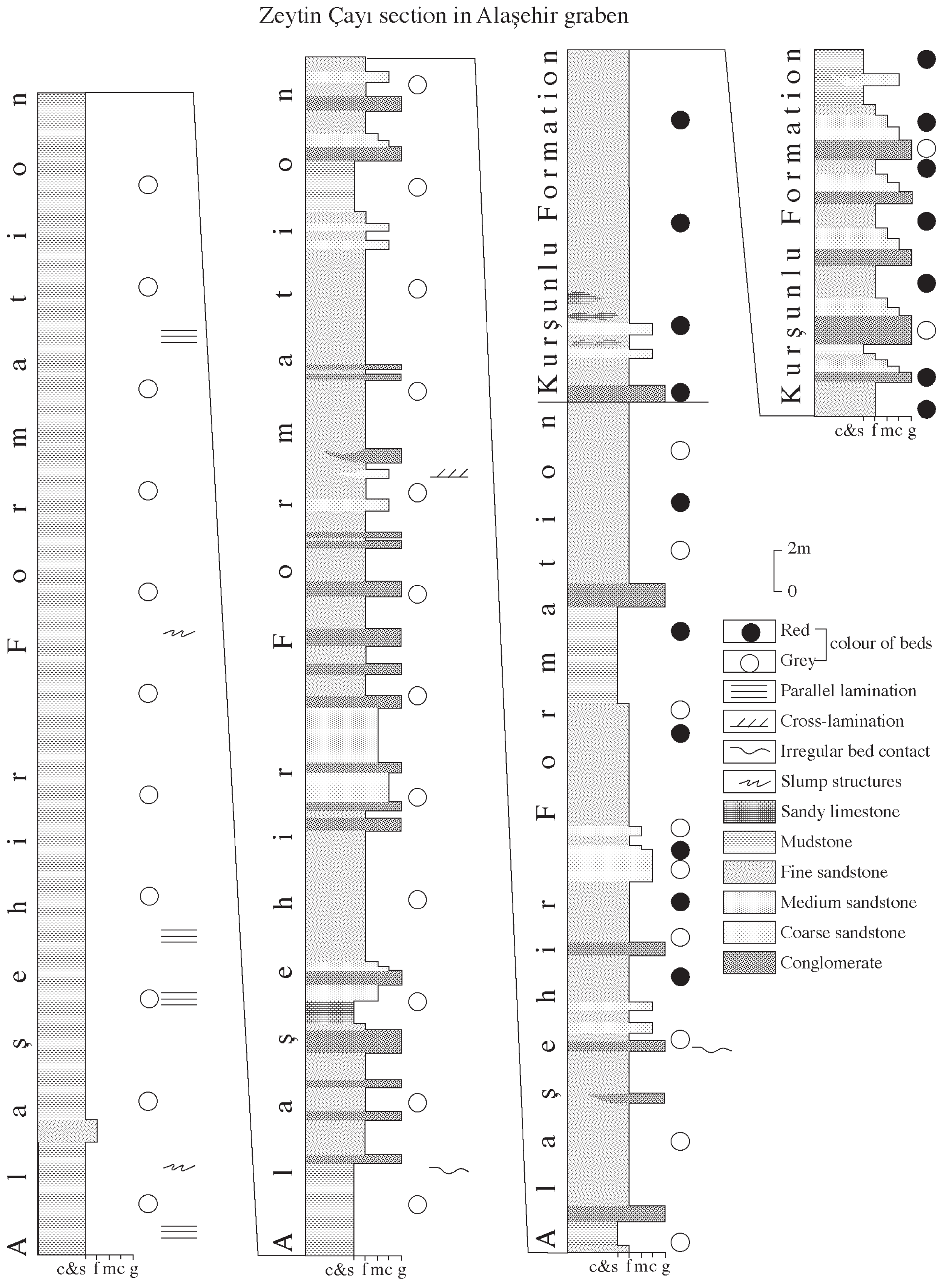

Figure 3. Measured stratigraphic log between Alaşehir and Kurşunlu Formations. See Figures 4 and 8 for location. c&s – clay and silt, f – fine sand, m – medium sand, c – coarse sand, g – gravel.

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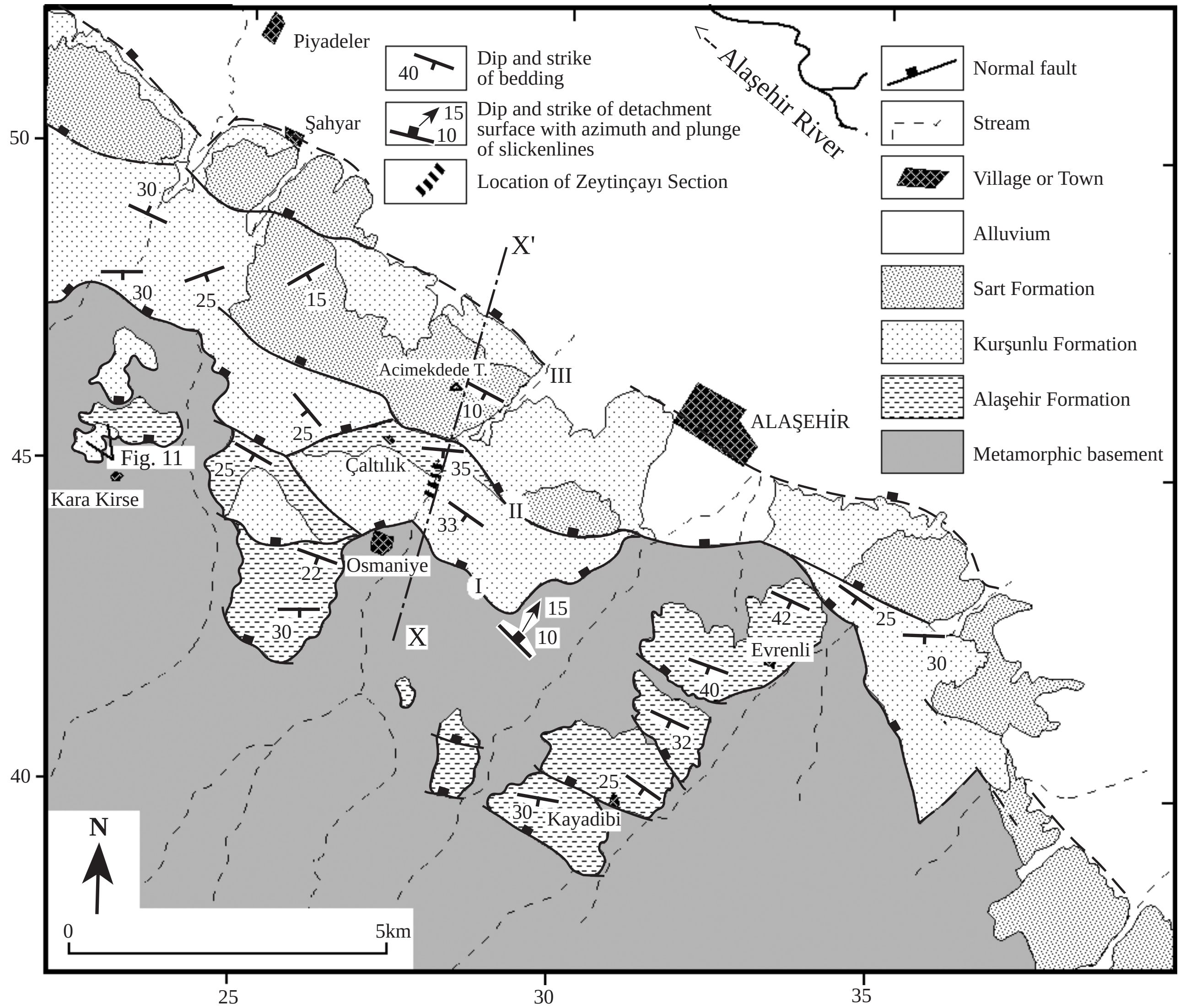

Figure 4. Geological map of the Piyadeler–Alaşehir area in the Alaşehir graben. I – First fault system, II – Second fault system, III – Third fault system. See Figure 8 for X–X' cross-section. Grid coordinates are also shown. Figures 4, 5 and 6 are modified and simplified from M. Yazman, unpub. TPAO rep. no. 2670 (1989); Cohen *et al.* (1995); Seyitoğlu & Scott, (1996*a*) and Emre (1996).

normal fault/detachment (Emre, 1992; Hetzel *et al.* 1995) generally dipping 10°–20° N. The fault plane contains slickenline lineations trending NNE (Fig. 7a). This fault displays cataclasites (breccia, microbreccia, cataclasite) which show foliation defined by surfaces of discrete shearing. Cataclasites are generally brownish-green in colour and consist of angular to subrounded clasts of rock, minerals and fine-grained matrix. The first fault system limits the first and second sedimentary units (Alaşehir and Kurşunlu formations) which are deposited in the hanging wall (Fig. 2).

The second fault system controls the third sedimentary unit, the Sart Formation (Fig. 2) and is composed of N-dipping relatively steep faults, generally striking N 75 W and dipping 45–50 NE; their normal sense of movement has produced drag folds (Seyitoğlu, Çemen & Tekeli, 2000). The second fault system is located in the hanging wall of the low-angle normal fault, and it can be continuously followed for 25–30 km between Salihli and Alaşehir (Figs 4, 5, 6). However, shorter segments of the second fault system, nearly 5 km in length, are found to the south of Alaşehir and southwest of Salihli (Figs 4, 6).

The third fault system is an active fault that separates the Neogene units and Quaternary alluvium. The Alaşehir earthquake of 28 March 1969 (Eyidoğan & Jackson, 1985) is associated with this system and created 30–36 km of surface break downthrown to the northeast. The strikes of the surface ruptures are reported as N 85 W and N 50 W. Displacement on the surface measured about 20 cm (Arpat & Bingöl, 1969; Eyidoğan & Jackson, 1985).

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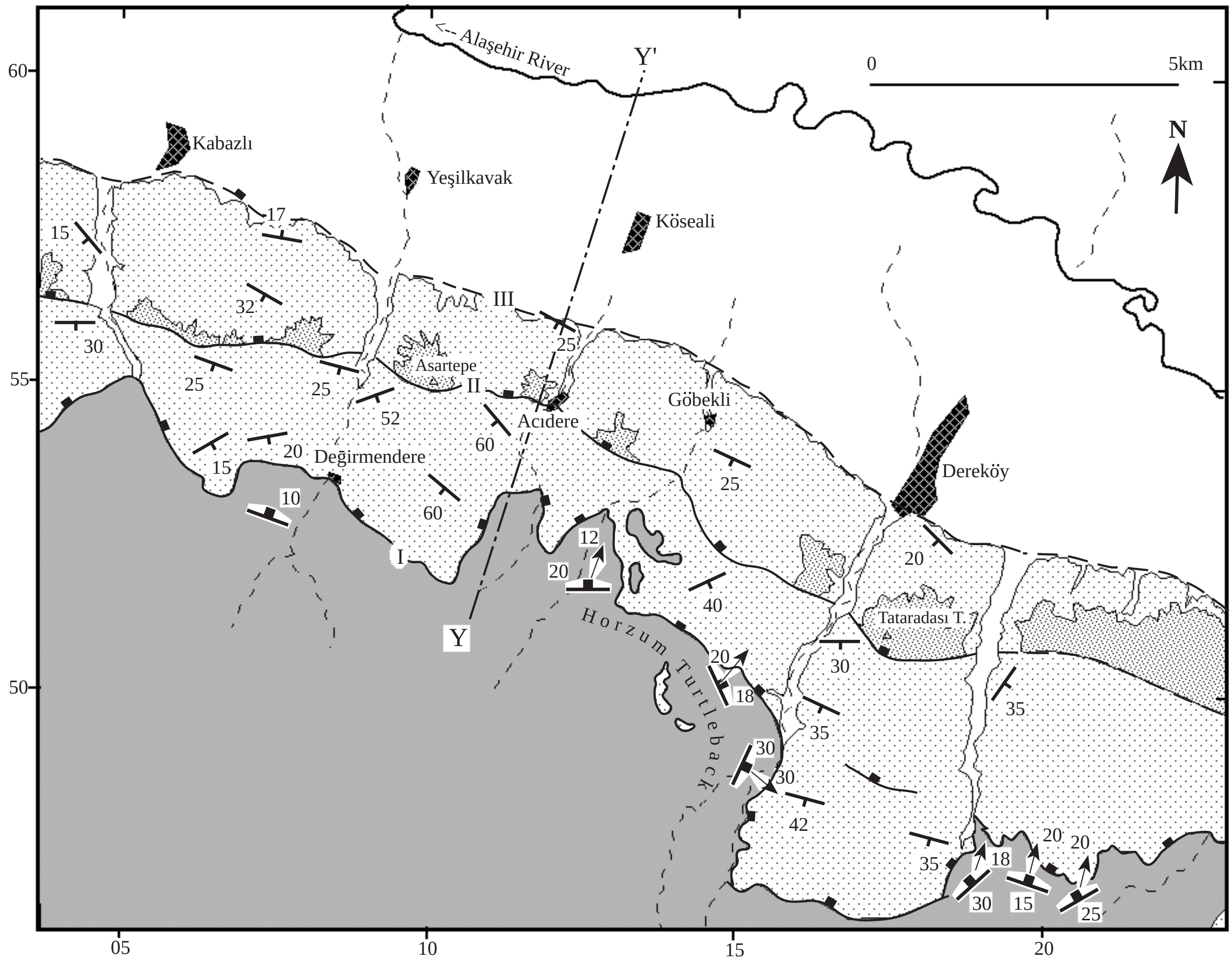

Figure 5. Geological map of the Dereköy–Kabazlı area in the Alaşehir graben. See Figure 8 for Y–Y' cross-section. Key as in Figure 4.

The fault systems are younger basinward (Dart *et al.* 1995) and developed in the hanging wall of the older faults (Fig. 8). This systematic behaviour of the fault systems is very clear between Çamurhamamı (Fig. 6) and the Horzum Turtleback (Fig. 5) (Çemen, Tekeli & Seyitoğlu, 2000), where the detachment surface can be continuously traced. Further to the east, this detachment surface is fragmented by high-angle younger normal faults (Fig. 7b) and disappears to the east of Alaşehir (Fig. 4).

4. Tectono-sedimentary development of the Alaşehir graben

Observations from the lower part of the Alaşehir Formation, the first sedimentary unit (see Section 2), have been interpreted to indicate that during Early Miocene times, the first fault system was a steeply dipping normal fault (30°–60°: Jackson, 1987) with a surface break/scarp. This fault system has produced footwall-derived very angular boulder conglomerates (alluvial fans) which are interpreted to have flowed into a standing lacustrine environment, close to the fault-bounded margin of the half graben (see facies map of Cohen *et al.* 1995, figs 5, 12; cf. Leeder & Gawthorpe, 1987; Gawthorpe & Leeder, 2000). If a low-angle normal fault existed at the beginning of graben formation (supradetachment basin: Friedmann & Burbank, 1995, fig. 4a), as suggested by Hetzel *et al.* (1995) and Emre (1996) for the Alaşehir graben, we would expect to find the lacustrine depocentre of the Alaşehir Formation far away from the low-angle normal fault. However, very fine-grained sandstones and mudstones of the Alaşehir Formation are located near the present low-angle normal fault that separates Neogene sediments and metamorphic basement. These data support the existence of a steep normal fault at the beginning of graben formation.

Figures 9a and 10a show three- and two-dimensional cartoons depicting conditions at the beginning of graben formation, which started in the Early Miocene with steeply dipping normal faults. The first system is composed of fault segments that are probably separated by relay ramps (cf. Gawthorpe & Hurst, 1993), explaining why lacustrine facies of the Alaşehir Formation do not crop out continuously along the

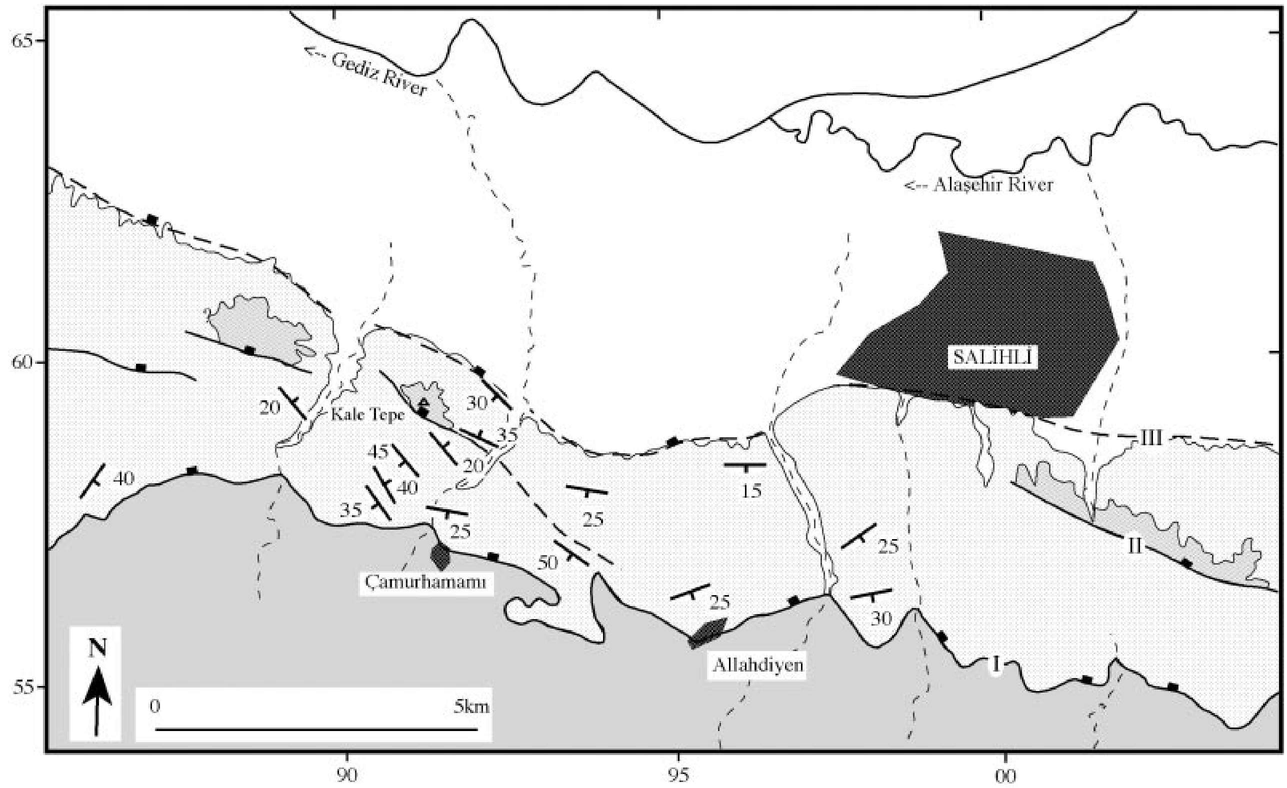

Figure 6. Geological map of Kaletepe–Salihli area in the Alaşehir graben. Key as in Figure 4.

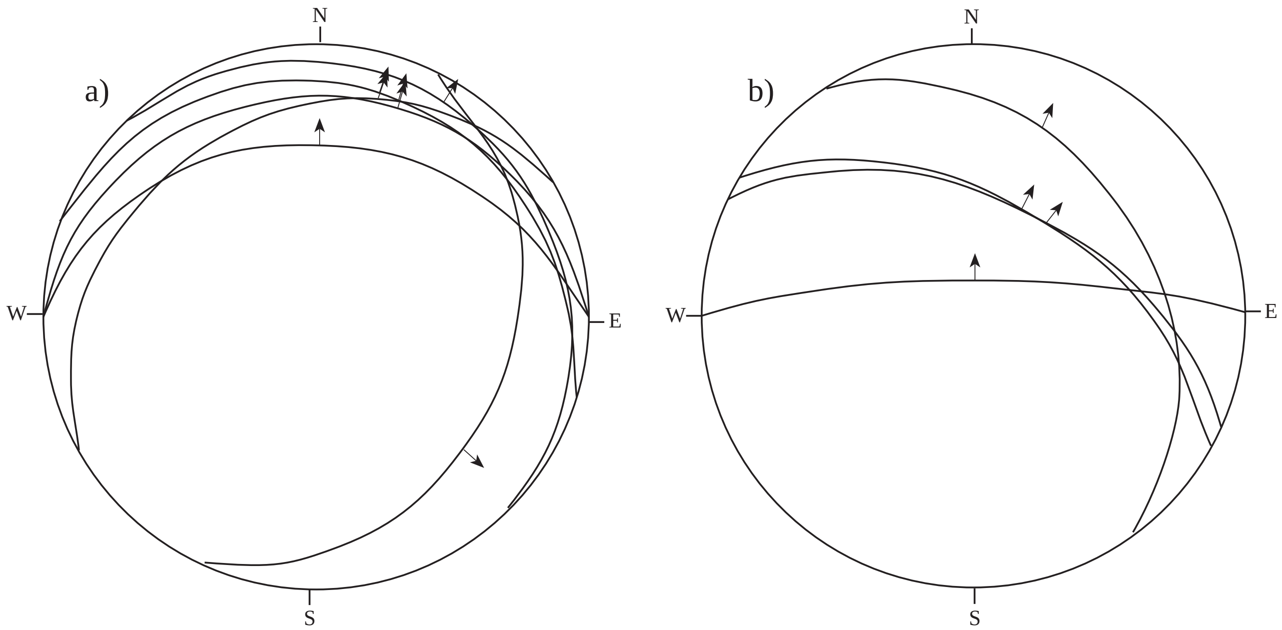

Figure 7. Lower hemisphere equal area projections of fault surfaces with striations. (a) First fault system (detachment fault) data mainly from Değirmendere and south of Dereköy. See Figure 5 for location. (b) Young faults south of Alaşehir around Kayadibi. See Figure 4 for location.

graben. The overall structure creates a hanging wall depocentre, where maximum subsidence occurred in the hanging wall of the E–W-trending first fault system, resulting in dominantly lacustrine sedimentation. This interpretation is also supported by the gravity data (Akçığ, 1988; Ateş, Kearey & Tufan, 1999), and E–W-trending seismic lines made available by TPAO (Turkish Petroleum Co.) in the Alaşehir graben (M. Yazman, pers. comm. 1999) that indicate an intrabasinal high between Salihli and Alaşehir (Fig. 1)

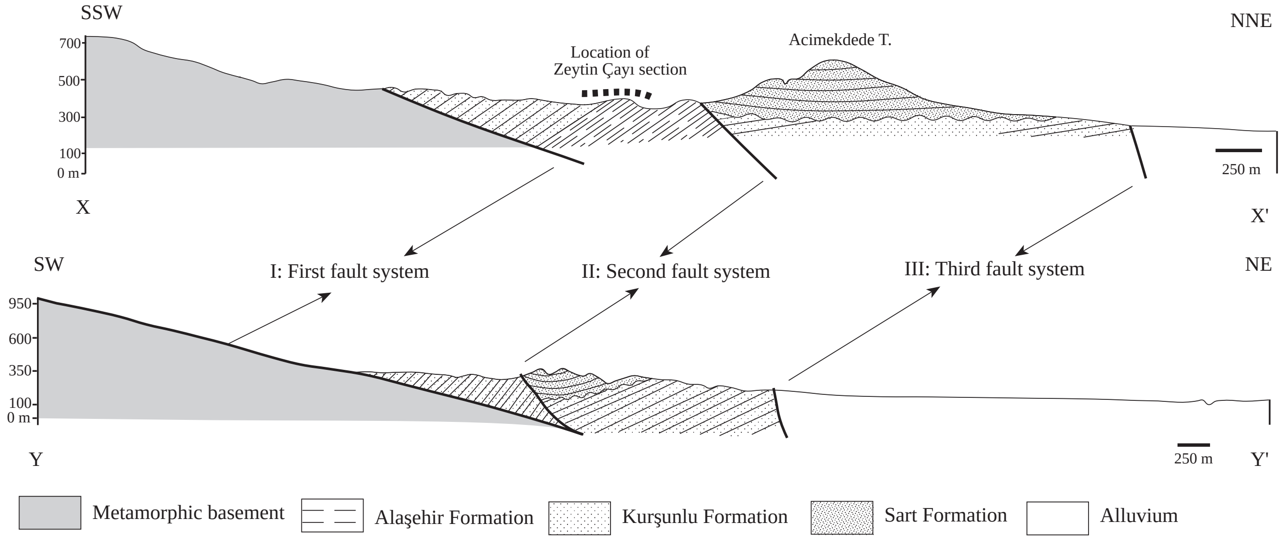

Figure 8. Cross-sections of the Alaşehir graben. See Figure 4 for location of cross-section X–X' and Figure 5 for location of cross-section Y–Y'.

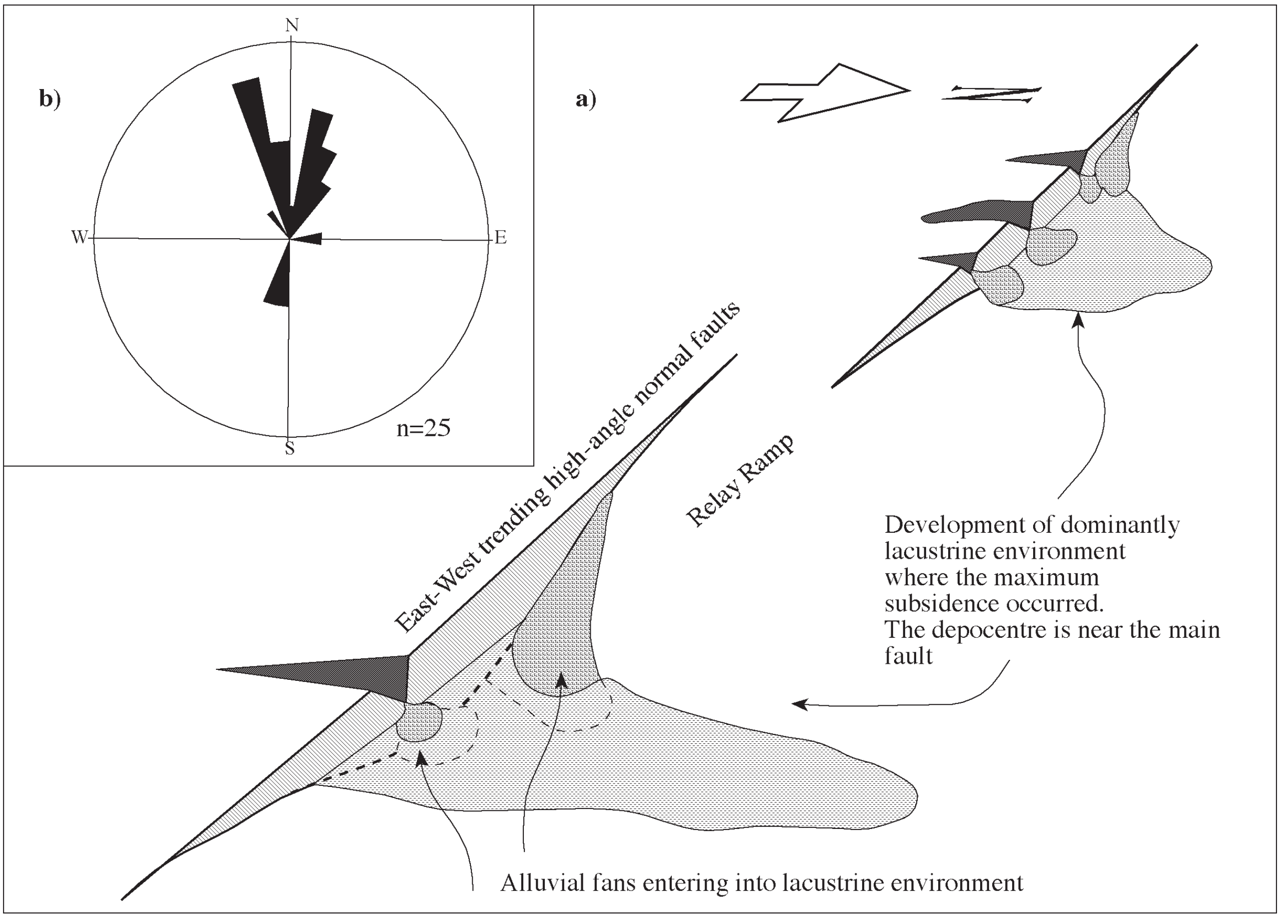

Figure 9. (a) Three-dimensional cartoon showing the palaeo-environments at the beginning of graben formation during Early Miocene times. See also Cohen *et al.* (1995). Relay ramp is thought to be located between Alaşehir and Salihli, according to gravity maps (Akçiğ, 1988; Ateş, Kearey & Tufan, 1999). (b) Palaeocurrent directions at the base of the Alaşehir Formation (n=25). The long axis measurements of boulder conglomerates have been undertaken where approximately three-dimensional visualization is available in the 90°road-cut on Alaşehir–Evrenli road.

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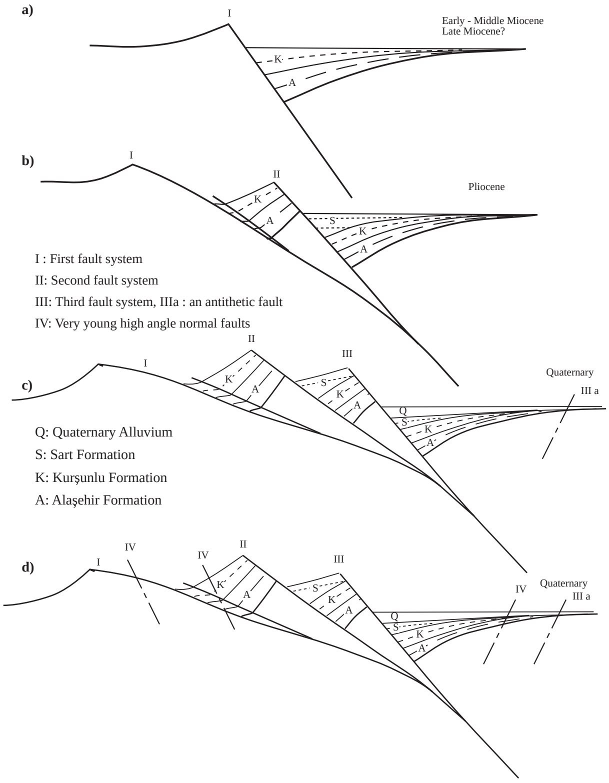

Figure 10. Cartoons illustrating evolution of the Alaşehir graben from Early Miocene to Quaternary times (not to scale). Stages 'a', 'b' and 'c' represent the full explanation of the tectonic development of the graben between Çamurhamamı and Horzum Turtleback, whereas stage 'd' is required to explain the current situation south of Alaşehir. Faults become nearly horizontal at 10 km depth (Eyidoğan & Jackson, 1985).

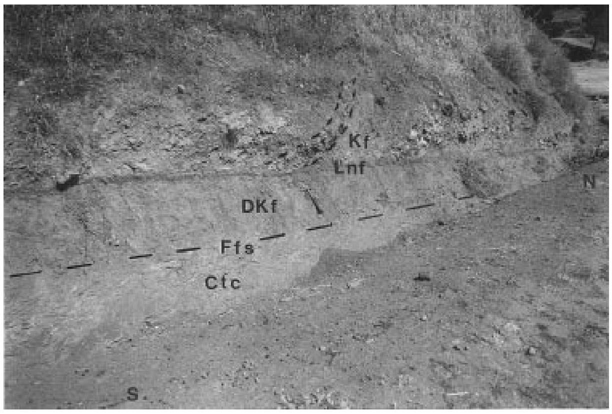

Figure 11. Photo of low-angle fault (Lnf) that cuts the Kurşunlu Formation, second sedimentary unit of the Alaşehir graben. Ctc – Cataclastic rocks of first fault system; Ffs – First fault system (detachment fault); DKf – Highly brittlely deformed Kurşunlu Formation; Lnf – Low-angle normal fault (N 40 W, 15 NE); Kf – Kurşunlu Formation; note that beds of the formation dip towards low-angle normal fault and show drag folding (N 72 W, 55 SW and N 35 W, 15 SW) indicating the normal sense of shear on Lnf. N – North; S – South. See Figure 4 for location. Length of hammer 33 cm.

Information regarding the syntectonic development of the Alaşehir and Kurşunlu formations was presented by Cohen *et al.* (1995). Additional palaeocurrent measurements (Fig. 9b) from the base of the Alaşehir Formation north of Evrenli village (Fig. 4) demonstrate that the boulder conglomerates were mainly transported from the south–southeast and south–southwest. In the Alaşehir Formation west of Çaltılık (Fig. 4), dominantly mudstone units become thicker towards the N 75 W, 42 NE-oriented syn-sedimentary fault. Moreover, there is a southward-tilted (because of the younger faults, see below) cataclastic zone between the metamorphic basement and Alaşehir Formation, approximately 1 km south of Kayadibi (Fig. 4). These observations contradict the argument of Yılmaz *et al.* (2000) that the Alaşehir Formation is controlled by a N-trending fault and belongs to a N–S-trending basin.

The Kurşunlu Formation, the second sedimentary unit (Seyitoğlu & Scott, 1996*a*), is interpreted to have accumulated as lateral alluvial fans (Cohen *et al.* 1995) that show fan delta characteristics where these alluvial fans entered the lacustrine environment (Fig. 9a). To the north of Osmaniye (Fig. 4), individual beds of the Kurşunlu Formation become thicker towards the first fault system. The deep-cutting, N-trending valleys and associated hills in the Acıdere and Değirmendere area (Fig. 5) provide a chance to observe a cross-sectional view of the steeply dipping Kurşunlu Formation. The dip angle is high (up to 60°) at the lower stratigraphic levels, whereas at the upper levels the dip becomes shallower (15°) towards the south, indicating syntectonic accumulation.

The second fault system is interpreted to have become established in the hanging wall of the first fault system as a result of continued extension (Fig. 10b). In the meantime, the high-angle first fault system was rotated, becoming a low-angle fault system. The palaeohorizontal surfaces such as lacustrine limestone layers and planar laminations (cf. Sharp *et al.* 2000) in the Alaşehir Formation indicate southward rotation of up to 35° about horizontal axes. Tilting and uplifting of the Alaşehir and Kurşunlu formations occurred while the Sart Formation was deposited in front of the newly active second fault system during Pliocene times. The Sart Formation, the third sedimentary unit, is interpreted as an axial fluvial and lateral alluvial fan facies (Cohen *et al.* 1995).

Cohen *et al.* (1995, fig. 5a) illustrated the existence of a low-angle (13°) fault between the basement and the second sedimentary unit to the north of Kara Kirse (Fig. 4). They interpreted this as evidence of rotation of the faults in the area. However, in the same location, it is observed that this low-angle normal fault (N 40 W, 10–20 NE) cuts the second sedimentary unit

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(Fig. 11) and lies parallel to, and approximately 1 m above, the detachment fault (first fault system). This observation demonstrates that the rotated fault system was also active during uplift (Fig. 10c). Recent $^{40}Ar/^{39}Ar$ dating (7 ± 1 Ma) of the first fault system probably corresponds to this activity (Lips *et al.* 2001). These data contradict the flexural rotation/rolling hinge model (Buck, 1988; Wernicke & Axen, 1988) that suggests inactive rotated low-angle initial fault.

The recently active (Alaşehir earthquake of 28 March 1969) third fault system is located between Quaternary alluvium and the Neogene graben fill. It is interpreted to have caused the final uplift of the earlier graben fill (Fig. 10c). The triple fault systems and associated sedimentary units become younger in one direction (towards the north). This is one of the characteristics of the flexural rotation/rolling hinge model. However, the youngest high-angle normal faults fragment and rotate the first fault system as observed south of Alaşehir (Figs 4, 7b, 10d), which is similar to the Yerington district, Nevada, USA (Proffett, 1977). In this last stage at the eastern edge of the Alaşehir graben, young faults are not completely restricted to the hanging wall of third fault system. This situation does not fit the flexural rotation/rolling hinge model (Fig. 10d).

5. Discussion and conclusions

The model presented in this paper cannot explain the complete exhumation history of the Menderes massif, which must have been exhumed before the Miocene by an unknown mechanism, as indicated by the presence of mylonitic boulders at the base of the Alaşehir Formation. However, the model presented here better explains the tilted sediments (up to 60° towards the south) of the Alaşehir and Kurşunlu formations than an initial low-angle normal fault model (Hetzel *et al.* 1995; Emre, 1996). A triple fault system can also be recognized in the Büyük Menderes graben, similar to that of the Alaşehir graben, and creates a mirror image dipping towards the south. It can be speculated that the Büyük Menderes graben has had a tectono-sedimentary development similar to that of the Alaşehir graben.

At the beginning of Alaşehir graben formation during Early Miocene times, the first fault system was active and responsible for the accumulation of the first and second sedimentary units. This accumulation continued into the Middle Miocene, and possibly into Late Miocene times. The second fault system (Pliocene) developed in the hanging wall of the first system and controlled the geometry and facies distribution of the third sedimentary unit. The recently active third fault system separates older graben fill and Quaternary alluvium. Each fault system causes rotation of the previous systems, resulting in the present-day low-angle dip of the first graben boundary fault. This sequential development of the fault systems and related sedimentary units in the Alaşehir graben implies that 'the hanging wall field test' of the rolling hinges model (Axen & Bartley, 1997) has been passed. The formation of the graben is a sequential process. Its different periods are represented by three fault systems and associated sedimentation. Consequently, supradetachment vs. rift basins differentiation (Sözbilir & Emre, 1996) and the term 'neotectonic graben formation' (Bozkurt, 2000) have no meaning in western Turkey, and the use of the age data from only the second and/or third sedimentary units to determine the timing of graben formation (Yılmaz, 1998; Hakyemez, Erkal & Göktaş, 1999, Yılmaz *et al.* 2000; Bozkurt, 2000) is also misleading.

This study contributes to the flexural rotation/rolling hinge model by demonstrating the reactivation of rotated fault systems allowing exhumation of a greater volume of rock units than that exhumed by the initial throw of the first fault system.

Another important result of this study is to provide valuable data on the discussion of the development of N-trending and E–W-trending basins in western Turkey. Although concomitant development of these two differently trending basins has been pointed out using isotopic and palynological data (Seyitoğlu, Scott & Rundle, 1992; Seyitoğlu & Scott, 1994; 1996a,b; Seyitoğlu, 1997), the cross-graben model of Şengör (1987) and Yılmaz (1998) influences the evaluation of the hydrocarbon potential of the Alaşehir graben (Yazman *et al.* 1998; Yılmaz *et al.* 2000); this model suggested that N–S structures host the first sedimentary unit, and superimposed younger E–W-trending structures control the second sedimentary unit. However, this paper and the sedimentary work of Cohen *et al.* (1995) demonstrate that these two sedimentary units accumulated continuously under the control of the E–W-trending first fault system of the Alaşehir and Büyük Menderes grabens.

6. Addendum in review stage

In the review stage of this paper, a paper by Gessner *et al.* (2001), suggesting an active bivergent rolling hinge detachment system in western Turkey, was published without acknowledging Seyitoğlu & Sen (1998) which previously applied the rolling hinge model to the grabens using hanging wall data. Apatite fission-track thermochronology studies of Gessner *et al.* (2001) demonstrated that high-angle faults rotated into shallower orientations and low-angle origin of detachments is unlikely in western Turkey. These findings are in close agreement with the model presented in this paper (Fig. 10). It should be emphasized that graben formation in western Turkey is a sequential process and the rapid cooling following 5 Ma documented by Gessner *et al.* (2001) corresponds with the generation of the second fault system and related accumulation of the third sedimentary unit, and consequent uplifting of the previous fault system described in this paper. This should not be interpreted as an initiation of the graben formation.

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