NEOTECTONICS OF THE KARAMIK GRABEN-AFYON, ISPARTA ANGLE, SW TURKEY

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NEOTECTONICS OF THE KARAMIK GRABEN-AFYON, ISPARTA ANGLE, SW TURKEY

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

NEOTECTONICS OF THE KARAMIK GRABEN-AFYON-(ISPARTA ANGLE), SW TURKEY

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The Karamık Graben (KG) is 6-17-km-wide, 29-km-long and NNE-SSW-trending active depression located within the Isparta Angle of the Southwestern Turkey extensional neotectonic domain. The KG is bounded by ENE-SSW-trending Karacaören fault zone to the south, the NNE-SSW-trending Koçbeyli-Akkonak fault zone to the east, the WNW-ESE-trending Akşehir fault zone to the north, and the NE-SW to NNE-SSW-trending Devederesi fault zone to the west.

The KG contains two graben infills separated by an angular unconformity: (1) Middle Miocene-Middle Pliocene deformed infill, and (2) the Upper Pliocene-recent non-deformed infill. Some geological structures reveal that the older infill was accumulated under the control of an extensional tectonic regime (phase-I extension). Analysis of NW-SE-trending folds and some strike-slip faults indicate that the older infill deformed by a short-term NE-SW-directed compression. This contractional event is the last record of the paleotectonic period.

Some geological and geophysical evidence indicate that the younger infill has been deposited under the control of an extensional tectonic regime (phase-II extension). Analysis of some slickensides implies that the current tectonic regime is being characterized by a multi-directional extension in predominantly N-S, E-W and NW-SE directions. This multi-directional extension dominates the Plio-Quaternary neotectonic period initiated Late Pliocene.

Total throw amounts accumulated along the margin boundary faults imply that subsidence rates are ~0.15 mm/yr and ~0.21 mm/yr since Late Pliocene. Some of the northern margin-boundary faults of the KG reactivated during the neotectonic period as evidenced by 2002.02.02 Mw = 6.5 Çay earthquake. However, the rest of these faults are still active and they keep their nature of seismic gap.

Key words: Karamık Graben, Isparta Angle, SW Turkey, neotectonics.

ÖZ

KARAMIK GRABENİ'NİN NEOTEKTONİĞİ-AFYON-(ISPARTA AÇISI), GÜNEYBATI TÜRKİYE

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Yüksek Lisans, Jeoloji Mühendisliği Bölümü
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Karamık Grabeni (KG) yaklaşık 6-17 km genişliğinde, 29 km uzunluğunda KKD-GGB-gidişli aktif bir çöküntü alanı olup, güneybatı Türkiye genişlemeli yeni tektonik bölgeyi karakterize eden Isparta Açısı içinde yer alır. Karamık Grabeni güneyden DKD-BGB-gidişli Karacaören fay kuşağı, doğudan KKD-GGB-gidişli Koçbeyli-Akkonak fay kuşağı, kuzeyden BKB-DGD-gidişli Akşehir fay kuşağı, batıdan ise KKD-GGB-gidişli Devederesi fay kuşağı tarafından sınırlanır.

Karamık Grabeni birbirinden açılı uyumsuzlukla ayrılmış iki farklı dolgu içerir: (1) Geç Erken Miyosen-Orta Pliyosen yaşlı ve deforme olmuş dolgu, ve (2) Geç Pliyosen-günümüz yaşlı fakat deforme olmamış dolgu. Bazı jeolojik yapılar yaşlı dolgunun genişleme türü bir tektonik rejimin denetiminde çökelmiş olduğunu (1. genişleme fazı) göstermektedir. Buna karşın KB-GD-gidişli kıvrımlar ve bazı doğrultu atımlı fayların analizleri ise eski dolgunun KD-GB-yönlü kısa dönemli bir sıkışma tarafından deforme edildiğini göstermiştir. Sıkışmalı-daralmalı bu olay eski tektonik dönemin son kaydını oluşturur.

Bazı jeolojik ve jeofizik veriler, genç dolgunun da genişleme türü bir tektonik rejimin (2. genişleme fazı) denetiminde çökelmekte olduğunu belgelemektedir. Fay aynası verilerinin stereografik analizi güncel tektonik rejimin (yeni tektonik rejim) egemen olarak K-G, D-B yönlerinde etkin olduğunu göstermektedir. Geç Pliyosen'de başlamış olan çök yönelimli genişleme türü tektonik rejim yeni tektonik dönemi temsil etmektedir.

Graben kenar fayları boyunca birikmiş olan düşey atım oranları Geç Pliyosenden beri ~0.15 mm/yıl and ~0.21 mm/yıl olarak hesaplanmıştır. Kenar faylarından bazıları Mw = 6.5, 02.02.2002 Çay depreminin de gösterdiği gibi son zamanlarda etkin hale gelmiştir. Buna karşın, geri kalan kenar fayları günümüzde sismik boşluk özelliklerini hala korumaktadır.

Anahtar kelimeler: Karamık Grabeni, Isparta Açısı, GB Türkiye, Yeni Tektonik

To My Family

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CHAPTER 1

INTRODUCTION

1.1. Purpose and Scope

Southwest Turkey is a tectonically very active region that lies within the Alpine-Himalayan mountain belt and one of the world's well-known areas of active Intracontinental extensional deformation. The complex deformational pattern in the region owes its nature to overlapping more than one process (Özacar, 2001). That is to say, escape of Anatolia, subduction-roll back in the vicinity of South Aegean-Cyprus arc and collapse of Western Anatolian Lithosphere and differential plate velocities. The initiation age of the neotectonic regime, deformational phases and origin of the graben-horst system of SW Turkey are still on debate. The present thesis aims to bring some solutions to the above-mentioned problems in the frame of field geological mapping and structural analysis of a relatively local extensional structure, the Karamık Graben, which contains 14 settlements in the size of village and town in the junction of the apex of Isparta Angle located in the lakes district in Southwest Turkey. The study has been performed by means of new field data and observations in the light of stratigraphic, structural, and geophysical data.

1.2. Method of study

In order to achieve the goal mentioned above, a research has been carried out at three stages; (1) office work, (2) field work, and (3) laboratory and office work.

During the office work, first of all, available literature was surveyed and reviewed. Thereafter, available borehole data was picked up from General Directorate of State of Hydrolic Works (DSİ) and General Directorate of Mineral Research & Exploration (MTA) in order to assess the thickness of Plio-Quaternary sedimentary sequence (whole modern graben infill).

During the field work, 1/25000 scale of lithological boundaries, geological structures such as strike/dip of bedding planes, fold axis, fault traces and local fault plane measurements were carried out. Those features were also documented by photography. In addition to this, detailed stratigraphy of the latest paleotectonic and neotectonic infill of the basin (Miocene and Quaternary rocks) were studied in order to distinguish the deformational patterns of paleotectonic and neotectonic periods. For these purposes, the latest paleotectonic and the neotectonic sedimentary sequences were studied and analyzed in terms of measured stratigraphic sections.

Subsequent to the field work, laboratory and office works have been started. At this stage, the structural data such as bedding plane measurements and local fault plane measurements, bedding plane assessments run by computer program, 'Rockware-Rockworks 2002'. Another computer program 'Tector' developed by (Angelier 1989). It provides stereographic plots of fault planes and orientations of stress tensors. It has been used to determine the local stress tensor orientations including operation directions of the stresses at the time of sedimentation and after the sedimentation.

Consequently, this thesis has been prepared by using softwares of Tector, 5.42, Freehand 11 Mx, Rockware-Rockworks 2002, and Microsoft Office 2003 Professional.

1.3. Location and Accessibility

The study area, the Karamık Graben, is located between 4249000-4278000 latitudes and 303000-326000 longitudes (36 S, EDM 1950) in the southern corner of the WNW-ESE-trending Akşehir Graben. It falls into the Afyon K25-c3-c4, L25-b1-b2 topographic base maps and covers an area of more than 400 km^2. The Karamık Graben is a NNE-SSW-trending depression with the maximum relief of approximately 1330 m between the lowest basin floor and the highest peak of the margin-bounding highlands.

The accessibility to the study area is provided by Ankara-Afyon and Konya-Afyon highways running through the study area (Figure 1). There are also some other suborder roads such as asphaltic, stabilized and earthy roads cutting or joining to the main road. By means of these roads, all margins of the graben are accessible.

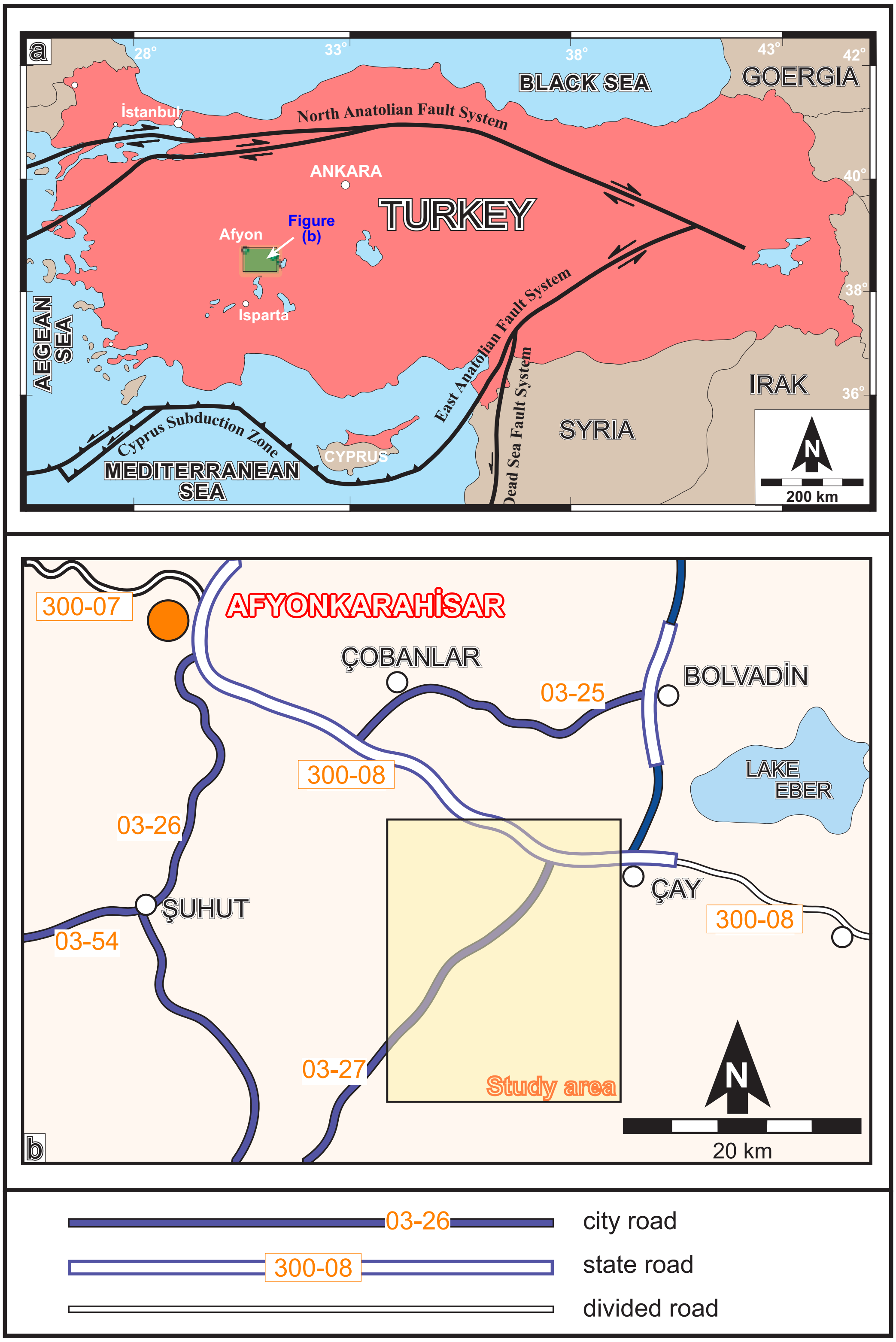


Figure 1. **a)** Map of Turkey. **b)** Location map of the study area and close vicinity.

1.4. Previous studies

Despite the fact that the neotectonic characteristics of the Karamık Graben have been poorly studied, some data about paleotectonic, stratigraphical, sedimentological and paleontological features have been collected to some extend by researchers from all across the world, particularly, since the second half of the 20^{th} century. The contributions to the geology of the vicinity of the Karamık Graben are in Turkish, English, French, and German languages. They are summarized below.

First attempts related to the geology of the vicinity of the Karamık Graben were done by (Bering, 1967). He studied tectonic development of Neogene and Quaternary basins in Western Taurides. According to the researcher, the sedimentation started in the basins around Afyon, Yalvaç, and Konya at the time.of Late Miocene. Thereafter, this sedimentation was accompanied by a volcanic activity. Finally, during the Pliocene, the basin fills were succeeded by fluvio- lacustrine sedimentation

(Keller & Villari, 1972) studied the rhyolithic ignimbrites around Afyon in Central Anatolia by means of field studies and geochemical compositions. The workers have stated that these volcanic rocks are made up of high potassic basalt lavas of trachytic and lathytic domes, rhyolithic ignimbrites composed of leucitic lavas agglomerates to breccias and tuffs. In addition to this, the authors also reported that the volcanic activity had taken place at a time slice of Late Miocene-Early Quaternary.

(Erişen, 1972) studied in Afyon-Heybeli (Kızılkilise) geothermal field located within the Akşehir Graben and in the NW of the Karamık Graben. In addition to the main geological properties of the study area, he has also researched the geochemistry of a series of hot water springs and structural properties of second order grabens (Şuhut and Karamık Grabens) crossed by the Akşehir Graben. Moreover, he tried to explain the relationships between faults, geochemistry and the origin of the springs. According to his study, the springs come out of the surface where the E-W-trending and NE-SW-trending faults intersect each other.

(Atalay, 1973) has investigated the geomorphological properties of the area between Akşehir and Çay located within the Akşehir and the Karamık Grabens. According to the author, the prominent depressions in the study area are tectonic in origin and bounded by normal faults. He named the depression as

Akarçay Basin, which renamed by Koçyiğit et al. (2000) as the Akşehir Graben. The author also reported that the Akarçay Basin is occupied by Quaternary Akşehir, Eber and Karamık lakes oscillating from time to time as indicated by terrace deposits, located at different elevations along lakes coastal areas.

(Atalay, 1974) studied the effects of the tectonic movements on the geomorphology of the Sultan Mountains. In this work, the author summarized the Paleozoic, Mesozoic and Cenozoic general stratigraphic outline of the study area and attempted to explain its Neogene geomorphological development history. In addition, he also classified the post-Oligocene faults shaping the Mountain range into two groups; (a) NW-SE-trending longitudinal faults, which bound the Sultan Mountains to the north and, (b) NNE-SSW-trending transverse normal faults which cut and displace the general trend of the Sultan Mountains.

(Sickenberg et al., 1975) investigated stratigraphy and mammalian fossil content of the Neogene continental deposits in a very broad region.

(Besang et al., 1977) performed some K/Ar radiometric dating studies on samples from the volcanics of Afyon – Sandıklı area and assigned an age of 8 - 14, 75 Ma to them.

(Çuhadar, 1977) studied the Akarçay Basin for hydrogeological purposes. He focused on the basic geological characteristics, age (Late Oligocene-Quaternary), aquifer types, ground water properties, circulation through the ground water of the Akşehir and Sinanpaşa Grabens. In his work, the aquifers are represented by the Plio-Quaternary alluvial fans with the thicknesses over 300 m in places. Besides, he also reported that there are some sulfur and sulfate rich solution seepages along the normal faults covered by the infill of the grabens.

(Koçyiğit, 1980; 1983; 1984a) investigated a very broad area of Lakes district. He mapped the geological structures (faults, folds, unconformities, dykes, etc.) at a scale of 1/25000 and classified the lithological units in the rank of group, formation and member. (Koçyiğit, 1984b) focused his works on the neotectonics of southwestern Turkey, and proposed an initiation age (Late Miocene) for the neotectonic regime in this region.

(Demirkol & Yetiş, 1985) mapped the allochthonous units located in the NW of Sultan Mountains at 1/25000 scale and summarized general geological features. They also tried to explain the origin, emplacement age, and lateral relationships of the allochthonous units with other units. In addition to these, they reported that the Cretaceous ophiolithic units (Hoyran ophiolithes) had emplaced to the study area by the transportation from ENE towards WSW after Middle

Eocene. Moreover, they also suggested that the normal faults cutting across the sedimentary units in the study area, had appeared since Middle Eocene

(Çevikbaş et al., 1988) studied the geology of the Neogene volcanics in the Afyon-Şuhut area. They dealt with the geochemistry of the volcanics and interpreted their composition as alkaline-calcalkaline magmas resulted from partial melting.

(**Boray et al., 1985)** investigated Afyon, Şuhut, south of Çay, Yalvaç and Yarıkkaya areas and reported existence of some N-S-trending folds and reverse faults. They also interpreted both E-W-and NNE-SSW-trending normal faults as reverse faults with the dips of 80° to 85°. Finally, they proposed that the Isparta Angle has been developing under the effect of WSW ward extrusion of Anatolian platelet due to its behavior as a barrier against the moving plate.

(Aydar et al., 1996) studied the development, mineralogical-petrographical and geochemical properties of Afyon stratovolcano. They claimed that the volcanism had occurred in three stages. The first stage is characterized by trachyandesite lava flows, lahars, block, ash flows and ignimbrites; second stage is dominated by trachytic-porphyric lava domes-lava flows that are rich in megasanidine crystals and the final stage is represented by lava flows and dykes produced by small-scale hydrovolcanic activities. The same authors also proposed that the Afyon volcanics had been sourced from partial melting and mantle metasomatism processes.

(Koçyiğit et al., 2000) investigated the Çay-Bolvadin section of the Akşehir Graben. They prepared detailed fault map, studied the stratigraphy and development history of the graben. Moreover, they also determined the earthquake potential of the graben-margin boundary faults. The same authors reported that the graben has been developing episodically, i.e. based on the episodic two-stage extension model of Koçyiğit et al. (1999).

(Doğdu & Bayarı, 2002 a, b) tested hydrothermal waters of Ömer-Gecek and Gazlıgöl geothermal fields. They pointed out that the fresh waters near by the geothermal fields had contaminated because of some leakages from the geothermal aquifers.

(Özden et al., 2002) handled the 2002 February 3 Çay (Afyon) earthquakes. They reported that two faulting events had occurred in the same day. According to the researchers, the first earthquake event took place in the Çay district and south of Maltepe village and also sourced from the WNW-ESE-trending and northward dipping normal faults while the second event occurred near of the west of Kadıköy to the north of Maltepe village and it was originated from the NE-SW-trending and SE-dipping normal fault. They also reported up to 30 cm throw on the hanging wall of the WNW-ESE-trending fault, and up to 10 cm throws on the hanged wall of the NE-SW-trending fault.

(Kalafat et al., 2002) also studied 2002 February 3 Çay (Afyon) earthquakes. They reported two successive earthquakes with Mw= 6.5 and 6.0 in the Çay region and until June, 2002. The focal mechanism solutions of those earthquakes support oblique-slip normal faulting.

(Dirik, 2002) made some geological observations after the 2002 February 3 Çay (Afyon) earthquakes, and reported that the magnitudes of the earthquakes were Mw= 6.1 and Md= 5.3, respectively. He also suggested that the earthquakes had been originated from NE-SW- and NNE-SSW-trending dip slip normal faults. In addition, (Dirik, 2002) also reported some ground ruptures with the trends of N45°E to N80°E paralleling to the strike of fault determined by focal mechanism solutions of the earthquakes.

(Tapırdamaz et al., 2002) are another group of researchers studied the 2002 February 3 Çay (Afyon) earthquakes. They evaluated the aftershocks of the earthquake and tried to estimate the length, width, trend and dip amount of the activated section of the fault. According to them, the activated section of the fault is a 37-km-long, 7-km-wide, E-W to ENE-WSW-trending, and northerly dipping (62°) oblique-slip normal fault, which activated and propagated westward.

(Başokur et al., 2002) investigated the 2002 February 3 Çay (Afyon) earthquakes as well. According to them, the total length of the surface rupture is about 19 km. During the earthquakes, three fault segments in the listric nature reactivated. They are E-W-trending and NNE-SSW-trending surface fault segments and related surface ruptures. They also reported some features, such as artesian wells, sand and mud eruptions, and cracks as evidence of liquefaction caused by earthquakes.

(Ulusay et al., 2002) attempted to manifest the damages caused by 2002 February 3 Çay (Afyon) earthquakes from the geotechnical point of view. They reported that the magnitude of the ground motion is Ms= 6.1 and it occurred in the depth of 11 km. They also suggested that the earthquake was restricted to area of the Maltepe village in the Çay district. Indeed these authors focused their works on the main cause of the damages to the structures, and they concluded that the constructions have not been done based on the earthquake-resistant ground conditions and by using suitable techniques.

(Akal, 2002) studied the Middle Miocene potassic-ultrapostassic Afyon volcanic complex. According to him, the volcanism occurred in three stages. The volcanic products occurred at first stage, are made up of melilite-leucites-rich lavas. Second stage products consist of lamproites. The third and last stage products are represented by phonotephritic domes, dykes and lava flows. He suggested that the potassic-ultrapostassic volcanics were originated from either partial melting of primitive mantle source or an enriched source near a subduction zone and collision-induced processes related to active plate margin.

(**Akan, 2003)** studied in the Afyon Ömer-Gecek geothermal area and reported that the surface waters of the Akarçay Basin have been polluted by the seepage of the contaminated hot waters. They suggested reinjection. These used water should be pumped back into the system to provide the continuous circulation of water.

(Dinç, 2003) studied the 3-D P-wave velocity structure beneath the Sultandağı region (the Çay section of both Karamık and Akşehir Grabens) by using 576-selected after shocks of 2002, February 3-Çay-Afyon earthquakes in the light of local earthquake tomography. In this study, she prepared a number of cross-sections by using local tomographic images along the Karamık Graben, Akşehir Graben, and Sultan Mountains. She also obtained the reliable tomographic images up to 14 km depth and proposed a maximum thickness of 5 km for infill of the Akşehir Graben. In addition, Dinç discussed the existence of a low velocity zone beneath the metamorphic rocks of Sultandağı Mountain and related it with a thrusting at the beginning of neotectonic period of (Boray et al. 1985).

(Emre et al., 2003) studied surface faulting associated with the 2002, February 3 Sultandağı Earthquake of Mw= 6.5 and reported that this earthquake had taken place in the vicinity of Sultandağı-Çay section of the Akşehir Graben. The earthquake caused to life loss of 46 and heavy damage to 622 buildings. They also reported that three major aftershocks had followed the main shock; let the development of totally 26-km-long surface ruptures with a maximum throw amount of up to 21 cm. In addition they classified these surface ruptures in two main groups: (1) E-W-trending normal faults and (2) NE-SW-trending normal faults, indicating a distributed extension such as N-S - NW-SE and NE-SW directions. (Emre et al., 2003) mapped some faults located within the northern portion of the Karamık Graben and defined another structure, namely the Kali sub-graben included within the major Karamık Graben as Kali graben which will be discussed in more detail below.

(Gökten et al., 2003). Studied the February 3, 2002 Çay (Afyon) earthquake mechanism and seismic risk of the region. The authors thought that the major event took place along the southern margin boundary fault of the Akşehir-Afyon Graben. They also reported two differently trending fault sets. One was observed near Maltepe village and Cumhuriyet town with E-W-trends. Maximum subsidence amount was measured as ~25 cm along this segment. Moreover, analysis of geophysical studies point out that the fault geometry probably is listric in character. The other set was observed near west of the Maltepe village and displays NNE-trends. The researchers also claimed that the NNE-trending faults developed as a consequence of the differential subsidence of the Akşehir Graben floor.

(Koçyiğit & Özacar, 2003) studied the episodic development history, margin boundary faults, stratigraphy of the Akşehir Afyon Graben infill, and the ground ruptures of 2000 December 15 Sultandağı and 2002 February 3 Çay earthquakes based on both the field data and focal mechanism solutions of earthquakes. They proved that the current regime in the vicinity of the Isparta Angle is extensional, even if it was reported as contractional by previous authors (Boray et al., 1985; Şaroğlu et al., 1987; Barka et al., 1995).

(Ulusay et al., 2004) studied the two successive 2002, February 3 Çay earthquakes and reported that the activated section of the fault segment is nearly 30-40 km in length, trends NE-SW and a normal fault with minor amount of sinistral strike-slip component in nature. They also reported that the northern section of the NE-SW-trending Karamık Graben had been reactivated during the same earthquake.

(Koçyiğit & Deveci, 2005) presented an abstract dealing with the Akşehir-Simav fault system. They defined a new fault system, namely, the Akşehir-Simav fault system in their presentation. According to them, this fault system, which is located between Karaman in the SE and Sındırgı in the NW, an approximately 500-km-long, 10-30-km-wide zone of deformation characterized by a series of normal faults, governing the present-day tectonic regime to extensional regime in SW Turkey. They pointed out the existence of a long-term seismic gap (Çobanlar-Çukurören seismic gap) in the area between Çobanlar (Afyon) and Çukurköy (Kütahya) regions.

(Akyüz et al., 2006) excavated two trenches, Çay and Maltepe trenches, for the purpose of paleoseismological studies along the Çay and Maltepe fault segments cutting across the northernmost tip of the Karamık Graben. In these trenches, they observed up to 30 cm vertical offset on the Çay segment and 25 cm offset on the Maltepe segment. They also determined the 1150 AD historical earthquakes sourced from the Maltepe segment and the historical earthquakes pre-dating 760 AD from the Çay segment, and finally concluded that both segments have different histories. The researchers claimed that the Maltepe and Çay segments are different segments from each other and have different earthquake histories.

(Koçyiğit & Deveci, 2007) studied the Şuhut Graben which is located ~15 km west of the Karamık Graben and mapped the post-Oligocene structural features such as beddings, folds and faults. According to them, Şuhut Graben is a superimposed basin characterized by two graben infills separated with an intervening angular unconformity. These graben infills are: (1) the deformed volcano-sedimentary sequence of Lower Miocene-Middle Pliocene age, and (2) the younger and Plio-Quaternary undeformed modern graben infill. Same authors also reported that the first basin infill had been deposited under the control of an extensional tectonic regime, but, deformed by the short-term tectonic regime, in which the principal stress was operating in WNW-ESE after the sedimentation of first infill, but, before the sedimentation modern graben infill. Briefly, they suggested the initiation age of the neotectonic regime in the Isparta Angle is Late Pliocene.

(Ergin et al., 2009) studied the aftershocks of the February 3, 2002 earthquakes recorded by a temporary seismic network of 27 vertical component seismometers installed after two days later from the main shocks to monitor aftershock activity. 1069 aftershocks with the magnitudes ranging ML= 0.2 and ML= 3.3 were recorded in a time slice of 5 days. They analyzed the P and S wave's arrival times and the P wave first motion data to obtain high-quality hypocenters and focal mechanisms which revealed fine details of the fault zone. The authors concluded that the 37-km-long part of the fault zone had been ruptured, and the average slip developed on it during the main shock is estimated to be 32 cm. based on the linear distribution of the aftershocks and the epicenter location of the main shock. They also suggested that the rupture had initiated in the east and propagated unilaterally westward. This study reveals the activation of both the WNW–ESE-trending Akşehir fault zone and the NNE-SSW-trending

Devederesi fault zone, which bounds the western margin of the Karamık Graben. They also carried out fault plane solutions of 392 aftershocks to find out type and geometry of the earthquake-induced fault deformation.

1.5. Regional Tectonic Setting

SW Turkey is one of the most well-known extensional areas in the world and has attracted many researchers, in particular since the second half of the 20th century. This is because of the area has a great potential to study all branches of geology, especially tectonics.

The southwestern Turkey extensional neotectonic domain is an area of active intracontinental extensional deformation bounded by the dextral North Anatolian fault system and İnönü-Eskişehir fault system to the north, by the Lake Salt and Central Anatolian fault systems to the east, and by the South Aegean-Cyprus arc (active subduction zone) to the west (Koçyiğit, 2005) (Figure 2). It comprises a series of extension related diagnostic features such as horsts, grabens, normal and/or oblique-slip normal faults, and normal faulting related block rotations.

Isparta Angle is one of localities characterizing the Lakes district sub-neotectonic domain. It is an inverse “V” shaped morphotectonic structure in SW Anatolia (e.g. Koçyiğit & Deveci, 2007). Its northern outline appears in the vicinity of Silifke (Mersin) in the southeast, runs in NW direction across Beyşehir, Akşehir, Çay and Şuhut settlemets of Afyon city, respectively (Figure 2). After city of Afyon, the outer outline of the Isparta Angle bends towards southwest and continuous in the same direction up to Gökova Bay, where it enters into the seawaters of Aegean Sea. However, the inner outline of the Isparta Angle begins near west of Anamur County (Mersin) in the southeast again, and then it runs in NW direction across Alanya and Manavgat, where it rebends and continues in the same direction following the western margin of the Antalya Bay, finally, it enters into the Mediterranean Sea water and disappears. The Isparta Angle is a paleotectonic structure resulted from the deformation of an originally E-W-trending Tauride orogen due to both nappe emplacements and block rotations. However, its age is still controversial (Dumont, 1976; Özgül, 1976; Poisson, 1977; Gutnic et al., 1979; Koçyiğit, 1983; Boray et al., 1985; Kissel et al., 1993; Barka et al., 1995; Piper er al., 2002; Flecker et al., 2005. In the present, the Isparta Angle is shaped and characterized by a number of well-developed graben-horst structures-trending in NE-SW, NW-SE, E-W, and N-S directions. Their sizes range from a few square

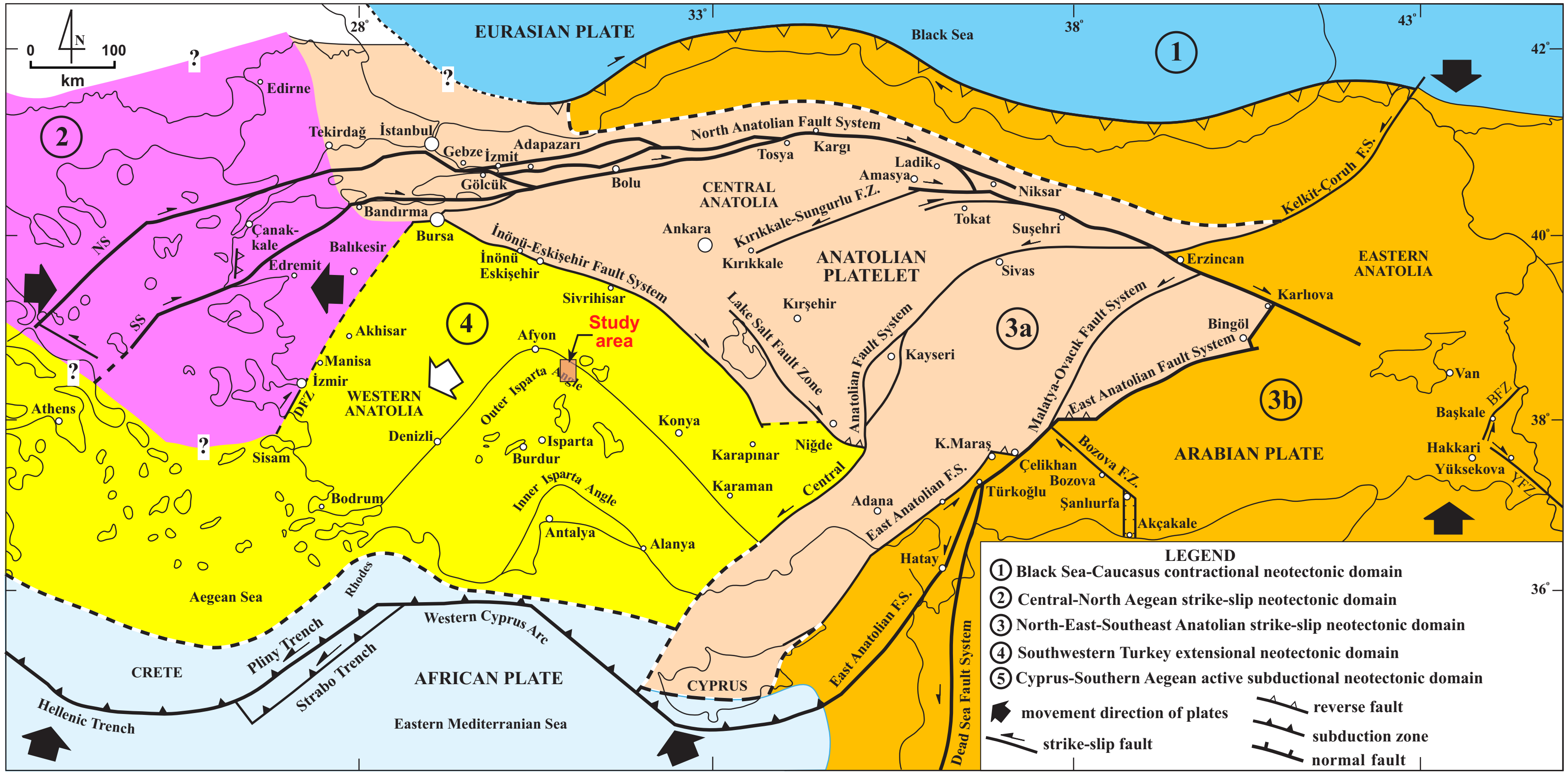


Figure 2. Simplified neotectonic map of Turkey and adjacent areas (Koçyiğit, 2009)

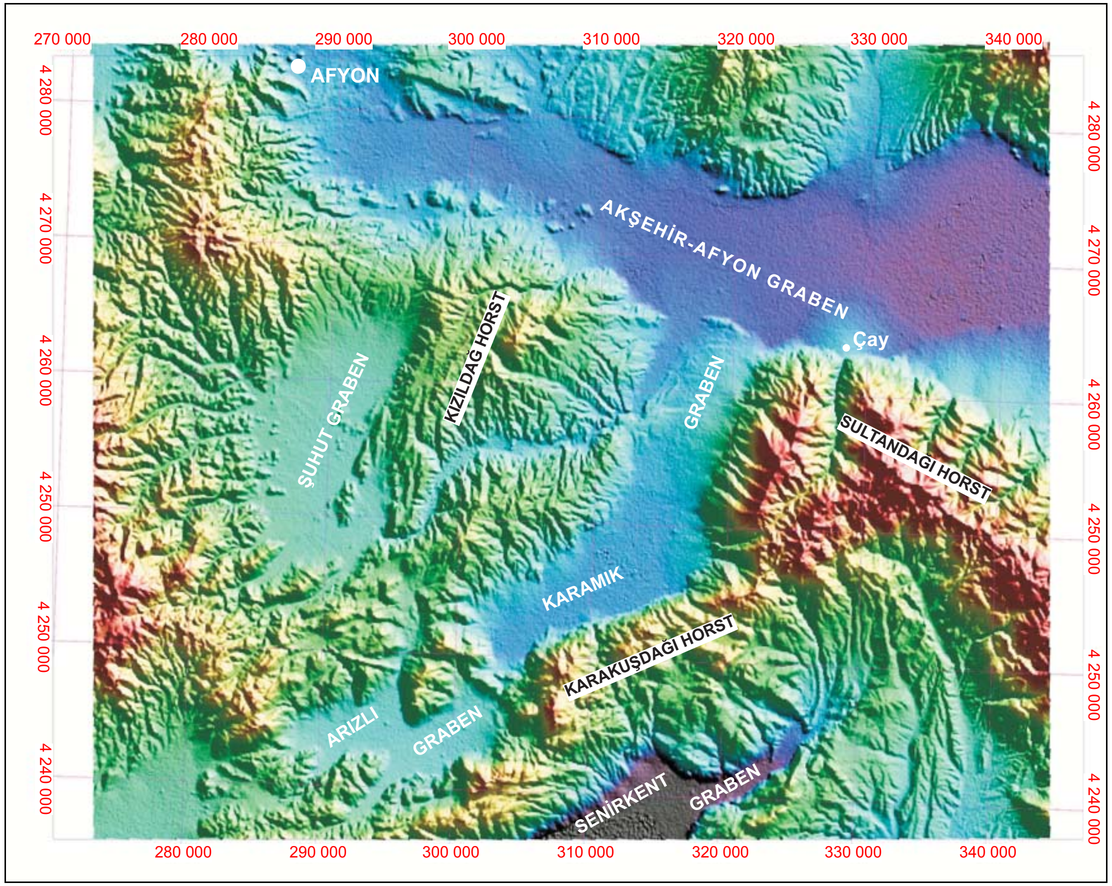


Figure 3. SRTM image of some grabens included in apex of the Isparta Angle (UTM Grid Designation Zone Is 36S, EDM 1950).

kilometers to up to tens of square kilometers. The biggest one is Akşehir Graben. It is a 130-km-long, 4-20-km-wide, and NW-SE-trending depression, bounded by oblique-slip normal faults (Koçyiğit & Özacar, 2003). These grabens are superimposed basins in character as indicated by two graben infills, separated by intervening angular unconformities (e.g. Koçyiğit, 1996). One of these superimposed grabens is Karamık Graben, which was selected as a study area of this thesis (Figures 2 & 3). The Karamık Graben is an approximately 6-17-km wide, 29-km-long and NNE-SSW-trending active depression, located within the Isparta Angle included in the Lakes District. The graben is bounded by the Akşehir Graben to the north, (Figure 2). by the Sultan Mountains to the east, the Hoyran Graben to the south by the Şuhut Graben to the west and intervening horsts such as Kızıldağ, Karakuş, and Sultandağları Horsts (Figure 3). The Karamık Graben has two graben infills separated from one another by an angular unconformity. This view supports the model of episodic two-stage extension interrupted by an intervening short-term phase of contraction (Koçyiğit & Deveci, 2007). The main aim of this study is to explain the neotectonic characteristics of the Karamık Graben including its Miocene-Quaternary stratigraphy, deformation pattern, faults, development history and initiation age of the neotectonic regime in and adjacent to the study area. Mostly original field data obtained based on the field geological mapping have been used to achieve the aim of the thesis.

CHAPTER 2

STRATIGRAPHY

Based on the ages and deformation patterns, the rocks exposing in and adjacent to the study area can be divided into three categories: (1) pre-Miocene rocks, (2) Miocene-Lower Pliocene graben infill (latest paleotectonic units), and (3) Plio-Quaternary graben infill (neotectonic unit) (Figure 4).

2.1. Paleotectonic Units

The older rocks exposing in and adjacent to the study area are classified into two sub-categories (1) Paraautochthonous sedimentary sequence and (2) allochthonous ophiolitic mélange nappe defined by (Koçyiğit, 1984a). The paraautochthonous sedimentary sequence is represented by the Paleozoic, Mesozoic and Paleogene rocks. The Paleozoic units divided into various rock stratigraphic units by (Koçyiğit, 1984a). These older rocks begin with the Middle-Upper Cambrian slightly recrystallized Çaltepe formation. It is conformably overlain by the Upper Cambrian-Upper Ordovician green colored Seydişehir formation. The Upper Devonian Engilli Quartzite conformably overlies the Seydişehir Formation and is unconformably overlain by the Lower-Middle Carboniferous Yalnızağaç Formation composed of quartzite-calcschist-phyllite and recrystallized limestone. Further up in the sequence, the Upper Carboniferous to Upper Permian recrystallized Karahasan Limestone covers conformably the Yalnızağaç Formation. Despite the type sections of most of the units croping out along the north-eastern margin of the Karamık Graben, the diagnostic exposures of the Yalnızağaç and the Karahasan Formations are observed along the northwestern margin of the Karamık Graben. The Paleozoic sequence is overlain unconformably with an angular unconformity by the thick-bedded Mesozoic platform carbonates of Dereçine Formation. The Dereçine Formation occupies almost the entire southern margin of the Karamık Graben. The allochtonous sequence is made up of post-Lutetian Internal Tauride ophiolithic mélange (Metin et al., 1987). It is composed of the mixture of various

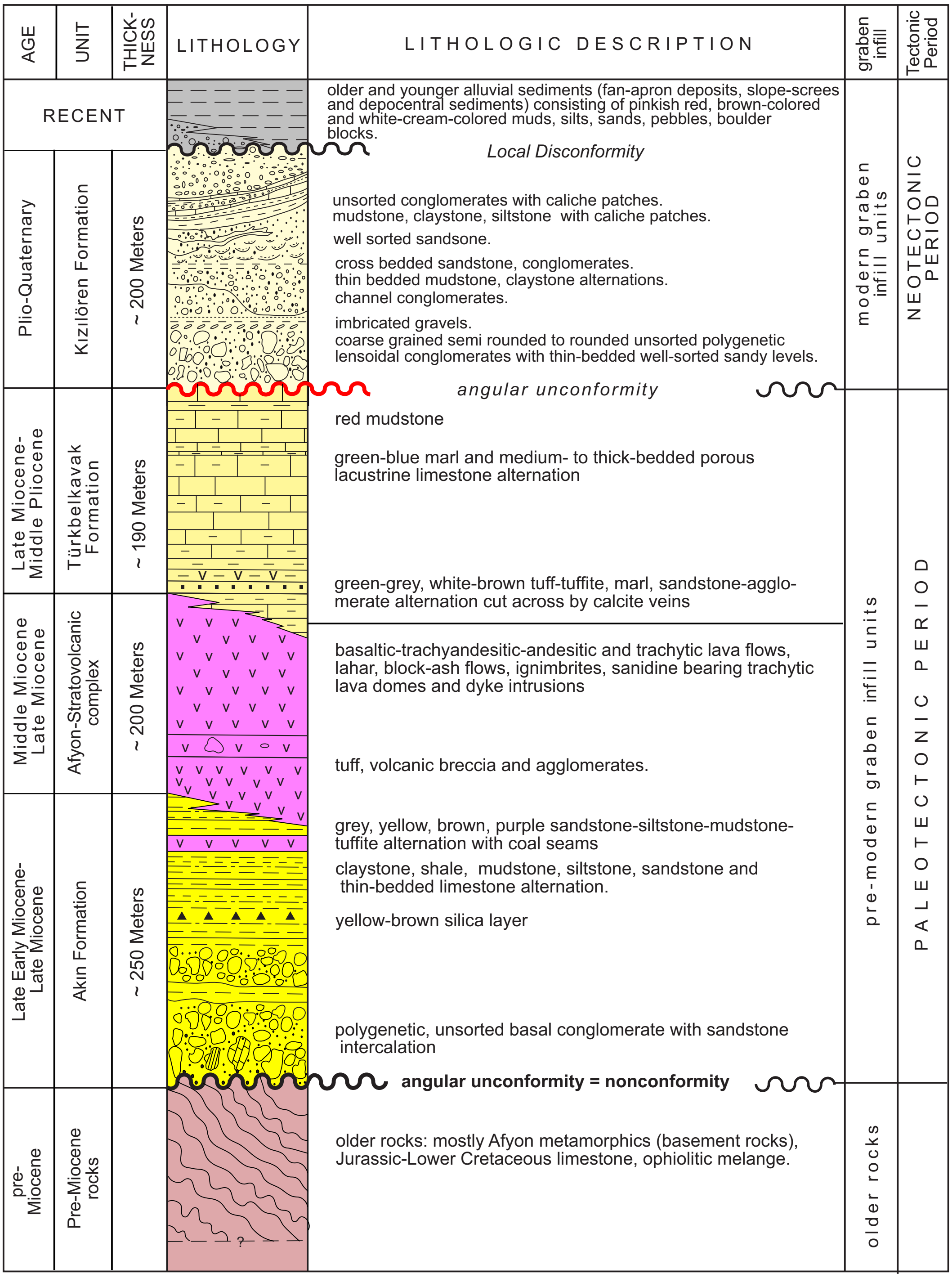


Figure 4. Generalized stratigraphic columnar section of the Karamık Graben.

blocks of different ages and lithofacies in a fine-grained, sheared matrix made up of greywacke, tuff, shale, ophiolithic clastics. The Ophiolithic mélange thrusted on the Lutetian Dereköy formation, which has not been observed within the study area (Koçyiğit, 1984a). The older rocks are also overlain unconformably by three sequences. These are the approximately altogether 640-m-thick Lower Miocene fluvio-lacustrine-sedimentary succession, the Middle-Upper Miocene Afyon strato-volcanic complex and the Upper Miocene-Middle Pliocene fluvio-lacustrine sequence (Figure 4). These three sequences, altogether comprise the latest paleotectonic unit. It will be described in detail as well as neotectonic units so as to make a distinction between the paleotectonic and neotectonic periods in the frame of this work.

Latest paleotectonic unit is subdivided into three rock stratigraphic units in the rank of formations. These are the Akın Formation, the Afyon strato-volcanic complex, and the Türkbelkavak Formation. These youngest paleotectonic units are here also termed to be the older graben infill (Figures 4 & 5).

2.1.1. The Akın Formation (Ta)

This formation was firstly named as the Yeniköy Formation by (Ercan et al., 1978) and subdivided by (Metin et al. 1987) into two members. (Boray et al., 1985) used the term "İsalı Formation" for the same unit. Later, (Koçyiğit & Deveci, 2007) renamed the formation as the Akın Formation by using its measured type sections at its outcrops observed within and around the Şuhut Graben, located in near west of the Karamık Graben (Figure 3). The Akın Formation exposes along the southwestern margin of the Karamık Graben. The lowermost levels of the formation could only be observed ~2 km north of the Kılıçyaka village. It starts with basal conglomerates at the bottom and represents fining upward sequence towards top (Figure 4). It displays well-developed and preserved sequence at its reference locality, near west of Bulanık village (Figures 6 & 7). In general, the Akın Formation is underlain unconformably by the pre-Miocene older rocks, such as the metamorphic rocks (marble, quartzite, calcschist, and micaschist alternation), the ophiolithic mélange, and the Jurassic-Cretaceous marine limestone in the west but outside of the Karamık Graben. The upper horizon of the formation shows both lateral and vertical transitional contact relationships with the Middle-Upper Miocene Afyon strato-volcanic complex and the Upper Miocene-Middle Pliocene Türkbelkavak Formation. The observable part of the unit is mainly made up of very thick-bedded to laminated and thin-bedded light grey, green, red, blue, purple, brown-colored claystone, mudstone, siltstone, marl, sandstone and tuffite alternations (Figures 6 & 7). The thickness of the unit was measured as ~250 m in ~ 2 km NE of Bulanık village (Figures 8 & 9). There are extensive biostratigraphic studies carried out to date the Akın Formation. (Benda, 1971) identified *Pollenites* fallax from the İsalı coal mine and assigned Messinian (Latest Miocene)-Earliest Pliocene age to the Akın Formation. (Boray et al., 1985) identified a great number of pollen fossils from the İsalı coal mine in the vicinity of İsalı village, located in the NW and outside of the present study area. Their fossil assemblage contains *Baculatisporites sp., .Laevigatosporites heardti, İnaperturopollenites dubius (pot. and Ven), İnaperturopollenites hiatus,* Cyperaceae, Graminae, *Triocolpopollenites asper, Triocolporopollenites megaexactus, Tricolporopollenites kruchi,* Artemisia *sp.,* Patella, Dinotherium *sp.* Based on this fossil content, they assigned the Tortonian (Early Late Miocene) age to the same formation. (Metin et al., 1987) identified another pollen assemblage from the same coal mine such as Cingulatisporites *sp., Monocolpopollenites trenquıllus, Laevigatosporites haarditi, İnaperturopollenites dubius, İnaperturpollenites emmaensis, Pityosporites microalatus, Friatriopollenites rurensis, Polyvestibulopollenites verus, Polyporopollenites undulosus, Triocopopollenites asper, Triocolporopollenites cingulum, Reriporomultinites multuporatus and Glyptostrobus europaeus.* Based on this pollen assemblage, he assigned the Middle Miocene-Late Miocene age to the Akın Formation. In addition to this, (Sickenberg et al., 1975 & Saraç, 2003) also determined following fossils in the same sequence exposing near the Koçgazi village (Sandıklı Graben): Shizogalerix *sp.,* Desmanella *sp.,* Desmanodon *sp., Insectivora soricidae, Rodentia sciurinae,* Keramidomys *sp.,* Heterominthis *sp.,* Protallactaga *sp.,* Myominus sp., Megacricetodon sp., Byzantinia cariensis, Pliospalax sp., Amphilagus fontannesi, Alloptox cf. gobiensis, Begertherium grimmi, Anchitherium sp., Triceromeryx sp., Micromeryx flourensianus fauna. According to these fossil assemblages collected from the middle and upper levels of the Akın Formation, the Latest Early Miocene-Middle Miocene age was assigned to the Akın Formation. Consequently, the same age was used for the Akın Formation in the present work.

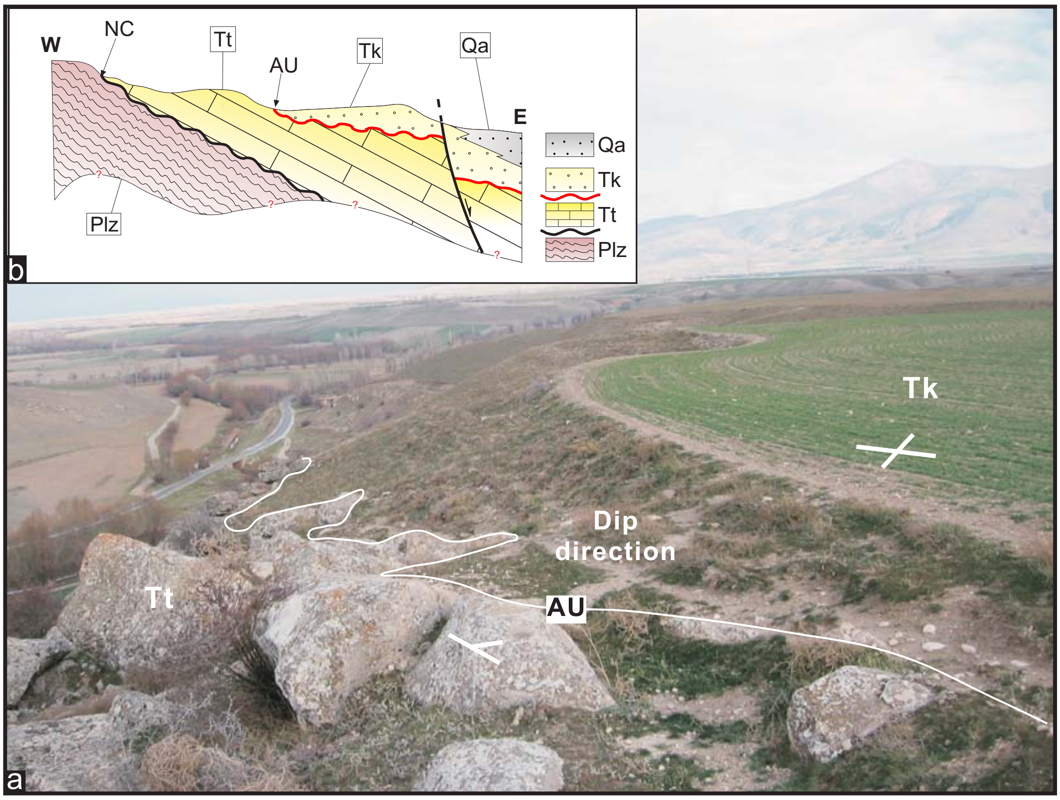


Figure 5 a) General view of the angular unconformity (AU) between deformed/older (Tt) and non-deformed/ younger (Tk) graben infills (~4 km east of the İnli town, view towards northeast) **b)** Sketched geological cross-section depicting various lithofacies and their contact relationships along the unconformity. Plz: Paleozoic basement units, Tt: Upper Miocene-Middle Pliocene Türkbelkavak Formation, Tk: Plio-Quaternary Kızılören Formation, and Qa: Quaternary alluvium, NC: nonconformity, AU: angular unconformity (~3 km ENE of the İnli town, view to NE).

2.1.2. Afyon Strato-volcanic Complex (Tv)

Although the term the “Afyon strato-volcanic complex” has been first used in this study for the volcanics exposing in the SW and outside of the study area, different names were also used for the same volcanics exposing in the study area and close vicinity by other researchers. For instance, (Çevikbaş et al., 1988) and (Aydar et al., 1996) have preferred to use the term “Afyon volcanics”, whereas, (Boray et al., 1985) have suggested the term “İnli volcanics”. (Koçyiğit & Deveci, 2007) used the term “Afyon strato-volcanic complex”. Therefore, term “Afyon strato-volcanic complex” has also been used in the present work.

The reference locality of the Afyon strato-volcanic complex in the study area is İnli town, but it has been well-preserved and well-exposed around the

Şuhut Graben. However, some exposures are also present in the WNW of the Aşağıdevederesi and NW of the Bulanık villages (Appendix-I). The Afyon strato-volcanic complex displays both the vertical and lateral transitional contact relationships with the uppermost levels of the Akın Formation at the bottom and with the lowermost levels of the Türkbelkavak Formation at the top. The Afyon strato-volcanic complex consists of grey, purple, pinkish trachytes, trachyandesite, dacites, andesites, basalts, agglomerates, tuffs, and tuffites (Figures 4, 8 & 10). The measured thickness of the volcanics is about 200 m in ~2 km NE of Bulanık Village (Figure 8). Some radiometric dating studies were performed by (Keller & Villari, 1972; Bessang et al., 1977; Çevikbaş et al., 1988) in the west and outside of the Karamık Graben, e.g., in the vicinity of Şuhut and Sandıklı Grabens (Figure 3). The K/Ar radiometric ages range between 14.75 ± 0.3 Ma to 8.0 ± 0.6 Ma for samples taken from different horizons of the volcanics. (Becker-Platen et al., 1977) reported K/Ar radiometric age of ~12 Ma for volcanics exposing around İnli town. This age corresponds to the Latest Middle Miocene (Serravalian) age according to the Stratigraphic Time Scale of International Stratigraphy Commission ICS, (2008). In addition, these ages can also be compared with the paleontological ages obtained from the fossils included in the sedimentary intercalations of the volcanics cropping out near İnli town. These fossils are *Triogocerus amaltheus and Wegner,* Sus *sp.,* Felis *sp.* (Boray et al., 1985). Consequently, based on the paleontological data, the stratigraphical relationships, and radiometric dates, the Middle-Late Miocene age is assigned to the out crops of the Afyon strato-volcanic complex.

2.1.3. Türkbelkavak Formation

This unit was first named by (Tatlı, 1973) as the Gebeciler Formation. Later on, (Boray et al., 1985) have used the term “Yarımca Formation” for the same succession. However, (Cihan, 2000) renamed the same sequence as the Türkbelkavak Formation based on the International stratigraphic nomenclature. Therefore, the name Türkbelkavak Formation was also preferred in the present work. The Türkbelkavak Formation is well-exposed in the vicinity of Gözsüzlü, Kızıldağ, Aşağıdevederesi villages, and İnli town. However, its reference section occurs in ~ 4 km east of İnli town along the NW margin of the Karamık Graben.

Figure 6. General view of the Akın Formation (~5 km NE of Bulanık village, view to NE).

Figure 7. Close-up view a very thin bedded facies of the Akın Formation (~5 km NE of Bulanık Village, the length of the hammer is 33 cm).

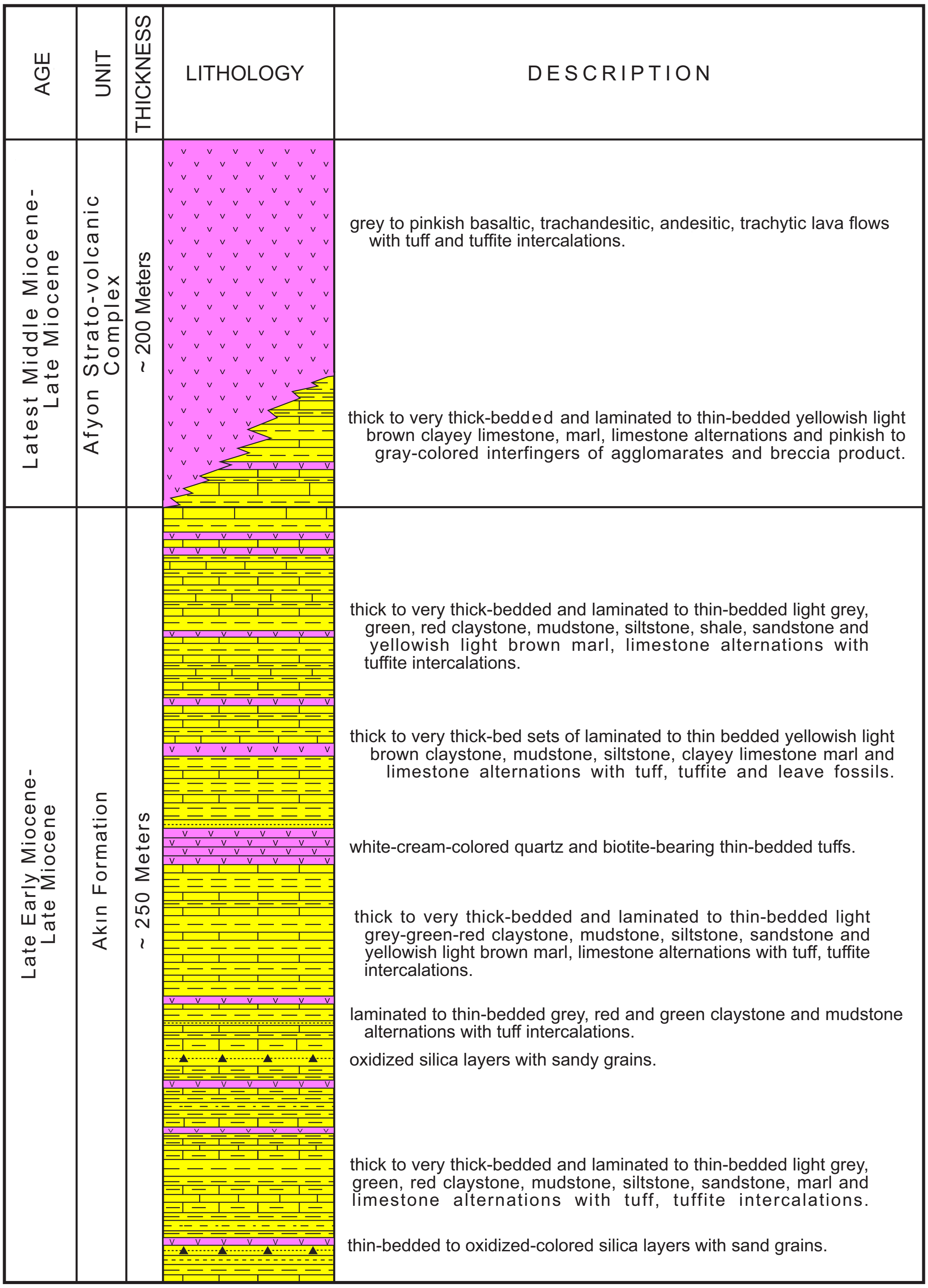


Figure 8. Measured straticgraphic column of the Akın Formation and the Afyon strato-volcanic complex (~2 km NE of Bulanık village).

Figure 9. General view of a part of the measured section site of the Akın Formation (~2 km NE of Bulanık village, view to NW).

The Türkbelkavak Formation displays various contact relationships with the older rocks at the bottom and with the upper parts of the pre-modern graben infill of the Karamık Graben at the top (Figure 11). The Türkbelkavak Formation is directly underlain with a nonconformity by the older metamorphic rocks near Kızıldağ village in the NW and ~4 km E of İnli (Appendix-I). In addition, the Türkbelkavak Formation displays both tectonic contact and erosional contact relationships with the modern graben infill in several places (Appendix-I). Bottom contact of the Türkbelkavak Formation is also observed outside of the Karamık Graben near south of the Işıklar village (Figure 12). At this place, the Türkbelkavak Formation rests with nonconformity on the erosional surface of the pre-Mesozoic metamorphic rocks. It starts with yellow-light brown, medium-to thick-bedded, polygenetic, unsorted basal conglomerate at the bottom. Conglomerate pebbles are mostly made up of schist, marble and volcanic fragments. The basal conglomerates are succeeded by the alternation of medium-to very thick-bedded, white to yellow-colored lacustrine marl, claystone, siltstone, tuff/tuffite, limestone, sandstone, and conglomerate. Topmost part of the type section consists of medium- to very thick-bedded (up to ~2 m) light grey, cream colored, porous limestone and marl alternations (Figure 13). In the NW of the study area near Gözsüzlü and Kızıldağ villages, white to light grey, thin- to medium-bedded claystone, marl and limestone alternation, rich in gastropoda, is well-observed. The limestone-marl alternation is covered by a thin, red package of mudstone, which is rich in mammalian fossils of Middle Pliocene age (Sickenberg et al., 1975; Sarac, 2003; Koçyiğit et al., 2007) (Figure 14) According to the measured stratigraphic columnar sections near Işıklar town, outside of the study area, and SW of İnli town, the thicknesses of the Türkbelkavak Formation are ~ 140 m and ~ 190 m, respectively (Figures 12 & 15). Abundant pollen assemblages were identified by (Metin et al., 1987) within the Türkbelkavak Formation. Some of these are *Candona neglecta, Candona cf.candida,* Ilyocypris *sp.,* Darvinula*? sp.,* Chara*,* Caspiolla *sp., Helix (helix) aff. Pomatia Linne, Zonocypris ef. Membranae (LIVENTIAL), Ilyocypris cf gibba (RAND), Clyrinotus salinus (BRADY).* Based on this fossil assemblage, they have assigned a Late Miocene-Pliocene age to the Türkbelkavak Formation. In addition, (Sickenberg *et al.,* 1975; Saraç, 2003) have also determined a number of mammalian fossils at different horizons of the Türkbelkavak Formation. These are *Turogontherium minus, Mimomys polonicus, Mimomys septimamus, Mimomys occitanus Canis odessanus, Vulpes alopecoides, Stephanorhinus meparhinus*, based on this fossil

Figure 10. Close-up view of the mass flow, agglomerates and cold emplacement of Afyon strato-volcanic complex (~1.5 km of Bulanık village, the length of the hammer is 33 cm)

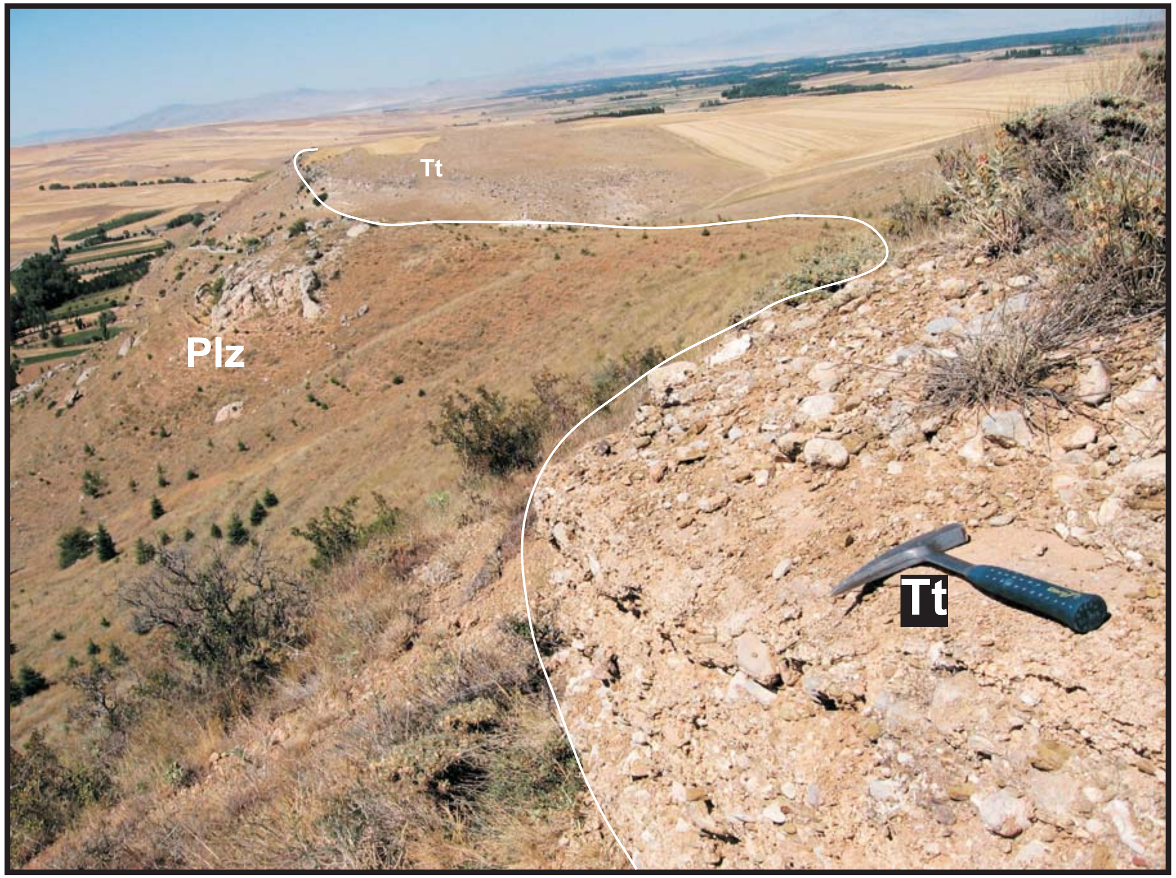


Figure 11. Close-up view of the lowermost facies (basal conglomerates) of the Türkbelkavak Formation (Tt) (~4 km east of the İnli town) (Plz: Paleozoic rocks, the length of the hammer is 33 cm).

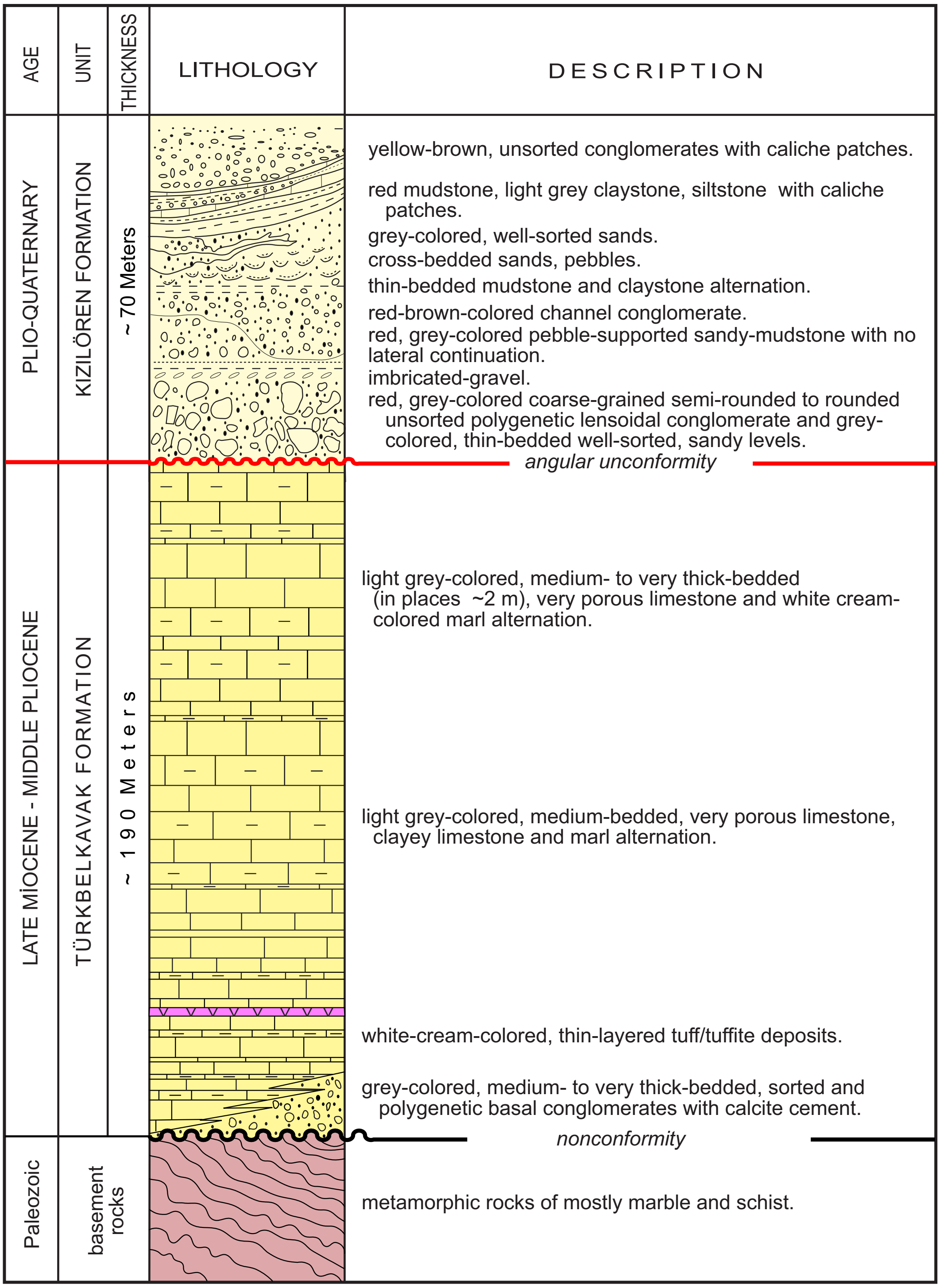


Figure 12. Measured stratigraphic columnar section of the Türkbelkavak Formation (north of Işıklar village located north of Şuhut county).

Figure 13. Close-up view of a very thick-bedded (~190 cm) limestone of the Türkbelkavak Formation (the length of the stick is 120 cm) (near east of the İnli town).

infill units. The size of clasts ranges from mm to ~ 20 cm in while Q3 fans are prominently white to cream-colored. Some of the Q3 fans are assemblage, they have assigned Late Miocene-Middle Pliocene age to the Türkbelkavak Formation.

2.2. Neotectonic Units

The undeformed (nearly flat-lying) rocks and sediments underlain unconformably by the pre-modern graben infill of the Karamık Graben are here termed to be the neotectonic units or modern graben infill. Based on both measured section and borehole data (Çuhadar, 1977), the total thickness of the neotectonic units is about 200 m. They are subdivided into two categories: (1) Plio-Quaternary-Kızılören Formation and, (2) Holocene alluvial deposits. Both of them display vertical and lateral facies changes, and rest with an angular unconformity on the erosional surface of the deformed (folded and faulted) paleotectonic units. The neotectonic units are described in detail below.

2.2.1. Kızılören Formation (Tk)

This unit was first named by (Erişen, 1972) as a member, namely, the Erdemir conglomerate member of the Gebeciler formation without using the columnar section. Therefore, the succession was renamed as the Kızılören Formation with its geographic name of type-locality and measured section by (Gökçe, 1998). The Kızılören Formation is the lower facies of neotectonic unit in the Karamık Graben. Its reference section is well-exposed in ~2 km W of Akkonak (Akharım) town along the western margin of the Karamık Graben (Appendix-I). However, it also occurs along the other localities of western margin of the Karamık Graben, and is terraced by the Devederesi fault zone (Appendix-I). The formation was crossed at ~140 m depth below surface in the boreholes drilled by the General Directorate of State of Hydrolic Works (DSİ) near Koçbeyli town at the eastern margin of the Karamık Graben (Çuhadar, 1977). The Kızılören Formation overlies, with an angular unconformity, the Türkbelkavak Formation. This angular relationship is well-observed along the İnli asphaltic highway road (Figure 5). The sequence of the Kızılören Formation consists of green, grey, red, pinkish, white-colored, semi-rounded to rounded and lensoidal (in some places) polygenetic pebble, sand, silt, clay, mud, marl alternations with caliche patches accumulated in both fluvial to lacustrine environment (Figure 16). In addition to

Figure 14. Uppermost section of the Türkbelkavak Formation, which is rich in mammalian fossils (near south of the Işıklar village located north of the Şuhut county, the length of the stick is 120 cm).

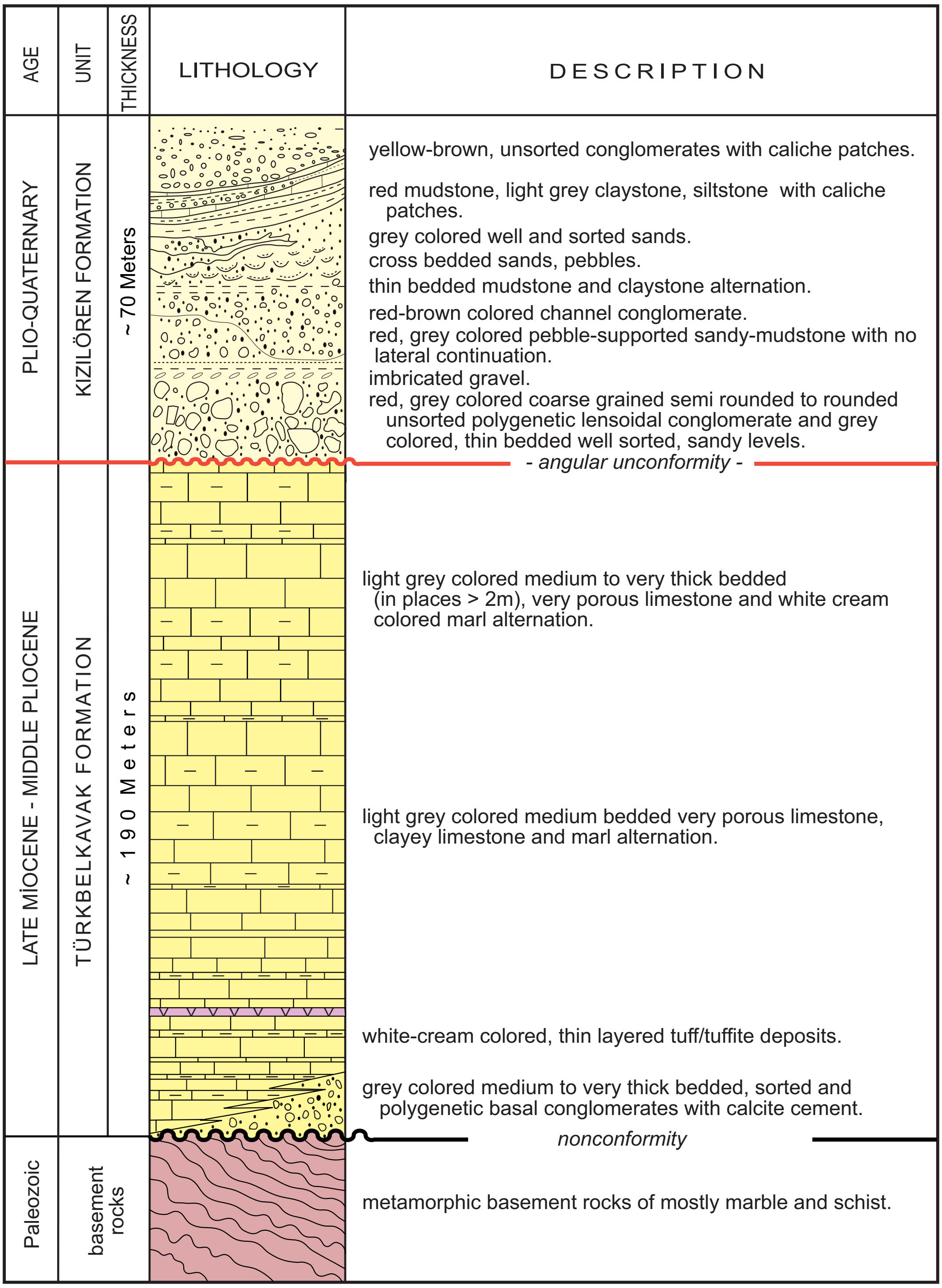


Figure 15. Measured stratigraphic column of the Türkbelkavak and Kızılören Formations (~4 km east of the İnli town).

these, cross beds are very diagnostic in some places (Figure 17). These clasts have been derived mostly from the underlying metamorphic rocks and pre-graben diameter. The thickness of the Kızılören Formation has been measured as ~ 70 m at its reference section near İnli town. Previously, some fossil assemblages have been identified by (Atalay, 1973). These are Dreissensia polymorpha, Dreissensia buldurensis, and Valvate piscinalis. Based on this fossil assemblage, the age of Latest Pliocene-Early Quaternary was assigned to the Kızılören Formation.

2.2.2. Lower Quaternary Units (Q1)

Lower Quaternary deposits are mostly made up of coarse-grained marginal and fine-grained depocentral sediments that cover unconformably the pre-Quaternary rocks and sediments of the Karamık Graben.

Marginal sediments consist of coarse-grained fan-apron, slope-scree, talus cones, and pinkish to red colored older alluvial fan deposits. The observed size of those sediments ranges between a few mm to ~ 3 m in diameter. They exist in a narrow (1-2-km-wide), but in a considerably long (25 km) zone restricted to the fault-bounded southern and northern margins of the Karamık Graben. Lower Quaternary deposits are superimposed by Q2 and Q3 alluvial fans in places (Figure 18). It may be related to reactivated periods of the margin boundary faults or climatic changes. These sediments are very diagnostic with their pinkish to reddish colors in many places.

2.2.3. Lower-Upper Quaternary Units (Q2 and Q3)

Lower-Upper Quaternary deposits (Q2 & Q3 sequence) are composed mostly of coarse-grained marginal and fine-grained depocentral sediments as well as Q1 sequence. Marginal sediments of Q2 (overlying the Q1 sequence) and Q3 (overlying the Q2 and Q1 sequences) alluvial fans occur at the mouth of streams, particularly along the active fault-bounded margins of the Karamık Graben. Q2 sequence is distinct with grey color and large size along both margins of the Karamık Graben. They are likely Lower Quaternary-recent deposits, while Q3 series, which overlie Q2 series, are distinct with their cream to white color and relatively smaller size. Age of Q3 alluvial fans is likely Holocene (Figure 18b). The basic differences between Q2 and Q3 sequences are (1) the initiation age of the Q2 alluvial fans are a bit older than Q3 fans (Figure 18b), (2) Q2 fans are more

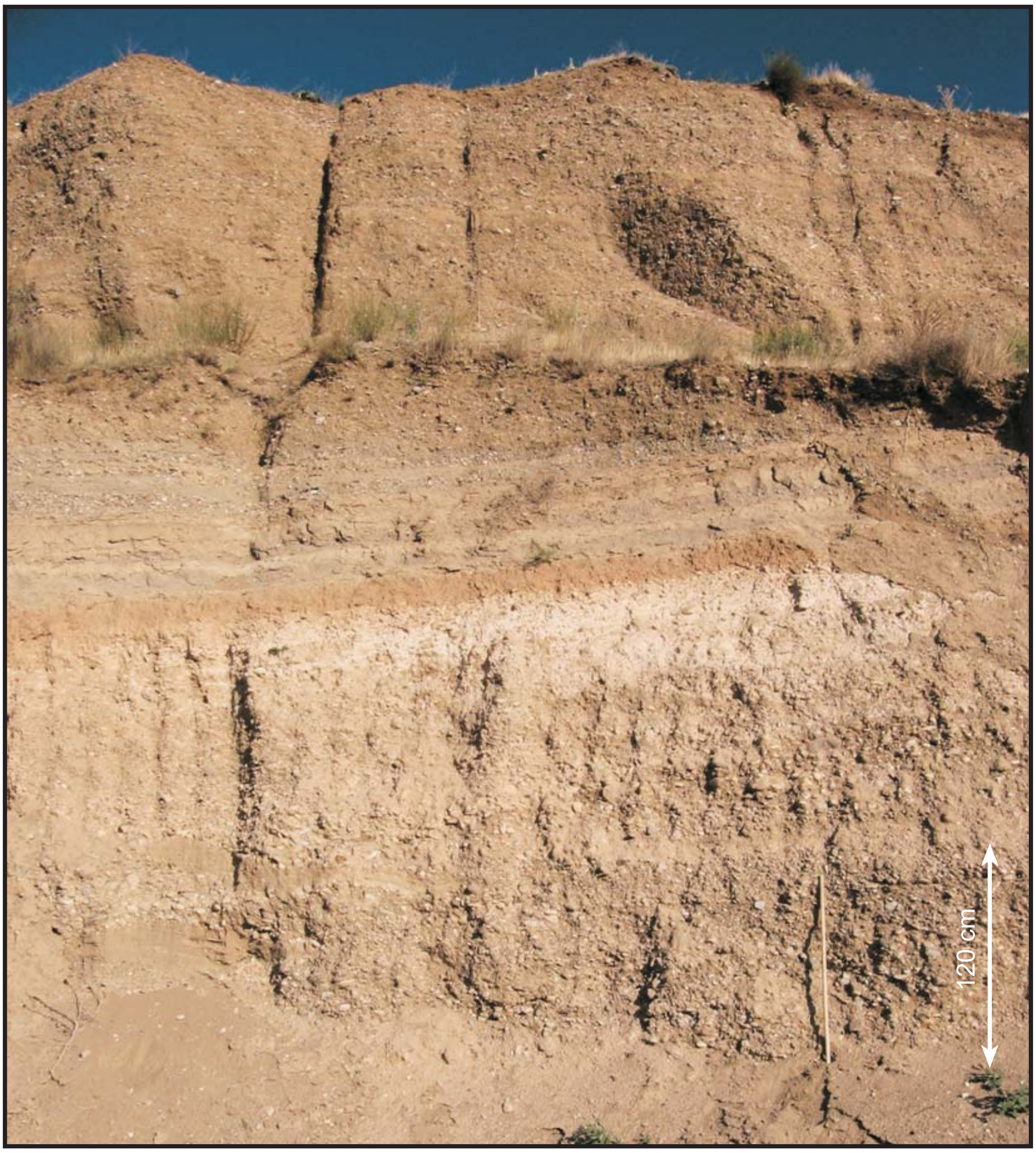


Figure 16. Close-up view of the Kızılören Formation along the western margin of the Karamık Graben (~5 km east of İnli town).

Figure 17. Close-up view of the Kızılören Formation of fluvial origin (~5 km east of the İnli Town, the stick is 120 cm long)

diverse than Q3 fans, (3) Q2 fans are superimposed by Q3 fans (Figure 18b) in some places, and (4) Q2 fans are usually grey-colored and also are not easy to distinguish especially from Q2 sequences in places. Therefore, Q2 & Q3 sequences could not be differentiated from each other.

Q2 and Q3 alluvial fans are made up of coarse-grained marginal and fine-grained depocentral sediments that cover the Q1 alluvial fan series with a local unconformity in places

The marginal facies of Q2 and Q3 are essentially distinct with coarse-grained proximal and medial fan associations consisting of boulder blocks, angular to semi-angular cobbles and pebbles derived directly from the underlying. older rocks. However, the depocentral facies of the Q2 and Q3 series alluvial fans are composed mainly of fine-grained, organic material-rich silt, clay, mud, sand, and lensoidal pebble intercalations, in places. The Q2 and Q3 alluvial fans have been still developing especially within the small-Kali sub-graben, along which the Kali stream flows in the NW corner of the Karamık Graben (Appendix-I).

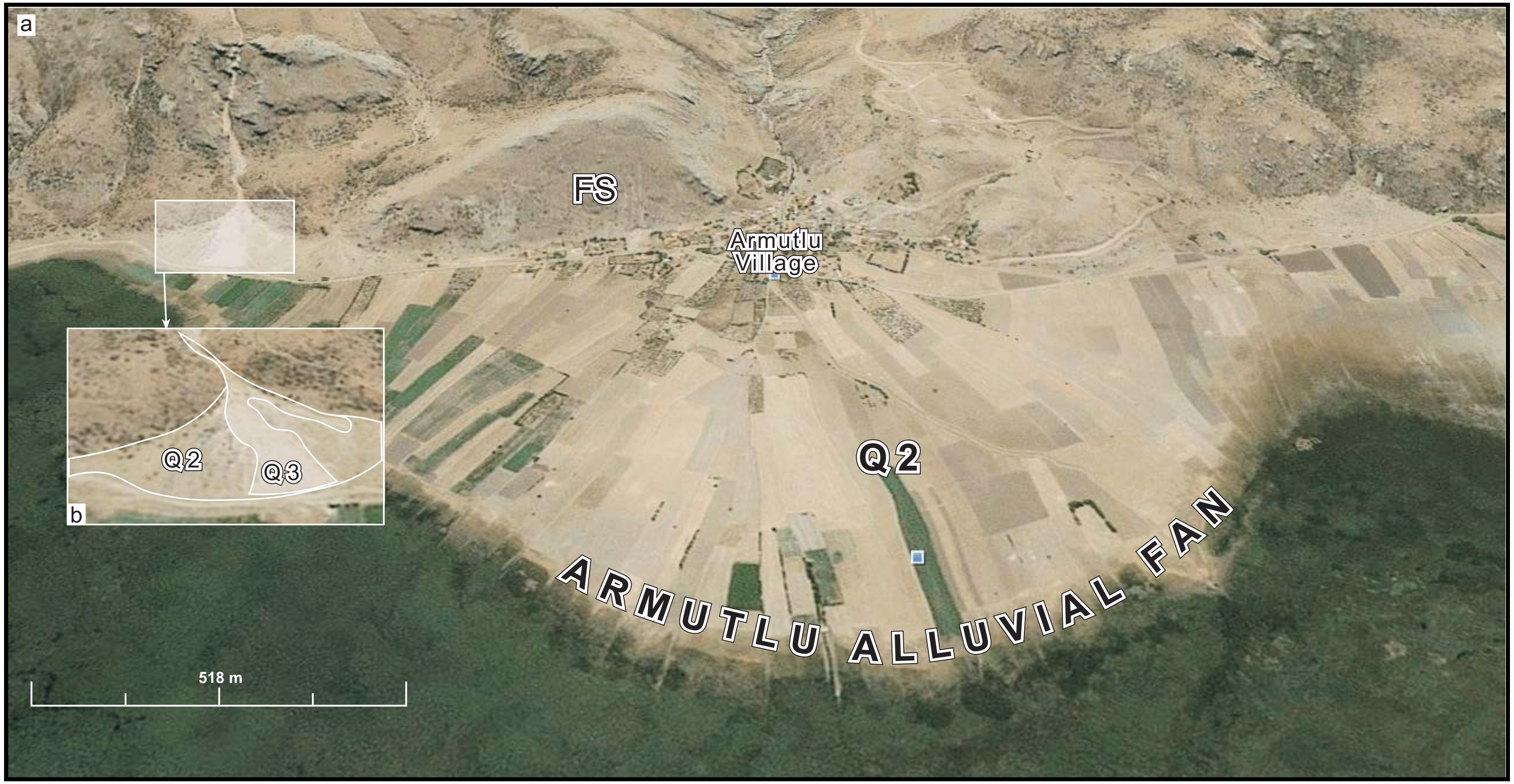


Figure 18. a) General (Google Earth) view of the Armutlu section of the Karacaören Fault zone, and Quaternary older (Q2) & superimposed younger (Q3) alluvial fans (FS: fault scarp). **b)** Close up view of the superimposed relationship between Q2 and Q3 alluvial fans (true to scale, view to SE, looking angle is ~40 with respect to horizontal ground).

CHAPTER 3

STRUCTURAL GEOLOGY

This chapter deals with the definitions and analysis of the geological structures including beds, unconformities, folds, faults observed and examined in the study area. Based on tectonic periods during which they developed, these structures are divided into two categories: (1) Paleotectonic structures, and (2) Neotectonic structures.

The structural properties and deformational patterns of the pre-Miocene rocks are not in the scope of this work. The structures that have reactivated or newly formed in the time slice of Miocene-Quaternary will be described in detail. In addition to this, latest paleotectonic structures, which have deformed the older graben infill and interrupted the first stage development of the Karamık Graben, will also be explained in detail.

The dataset that will be used in structural analysis and interpretations of neotectonic structures were collected in terms of field geological mapping at scale of 1/25,000. During the field work, attitudes of various planar and linear structures such as strike-dip, trend-plunge, rake, and throw amount were measured. Thereafter, the datasets were analyzed by using pole plots and a computer software programme designated as “Tector 2.0”. It allows us to be able to reveal the relationship between faults and principle stress directions.

The program processes the data based on three sub-programs. “Mesure”, “Tensor” and “Diagra” are the computer softwares which give to the user the principle stress directions. The software “Diagra” presents the results of the processed data obtained from the fault planes by using stereographic projection method. During the processing of the slip-plane data, direct inversion method of (Angelier, 1990) has been used.

3.1. Karamık Graben

It is a 4-17-km-wide and 29-km-long active depression included in the Lakes district sub-neotectonic domain of the major southwestern Turkey extensional neotectonic domain (Figures 2, 3 & 19). The Karamık Graben located near the northernmost tip of the Isparta Angle, is also one of the major extensional structures comprising the Isparta Angle included in the southwestern Turkey extensional neotectonic domain. The Karamık Graben is confined between some major extensional structures, namely the Akşehir Graben in the north, and the Karaadilli graben in the west-southwest, Şuhut Graben in the west and Senirkent graben in the south (Figure 3).

3.2. Geological Structures

The structures characterizing the Karamık Graben are of two major categories: (1) structures deforming the pre-modern graben infill or latest paleotectonic structures, and (2) structures controlling sedimentation of modern graben infill or neotectonic structures.

3.2.1. Latest Paleotectonic Structures

Structural analysis of bedding planes and folds clearly show that the pre-modern graben infill displays deformed pattern. The structures, which developed during and at the end of the sedimentation of the pre-modern graben infill units, were analyzed so as to make a clear distinction between the paleotectonic and neotectonic periods.

The structures observed only in the paleotectonic units are subdivided into four sub-categories: (1) beds, (2) unconformities, (3) folds, and (4) faults.

3.2.1.1. Beds

The units of the older-deformed package of the Karamık Graben consist of Lower Miocene-Middle Miocene Akın Formation, the Middle-Upper Miocene Afyon strato-volcanic complex and Upper Miocene-Middle Pliocene Türkbelkavak Formation.

The Akın Formation is characterized by well-bedded lacustrine sediments intercalated with volcanic products. The dip amount of the Akın Formation exceeds 40° in places; it is predominantly around 30°. Thickness of the bedding planes commonly does not exceed several tens of centimeters. They have been well observed along the deeply incised valleys and in places where the sediments are terraced along the western margin of the Karamık Graben by the normal faults.

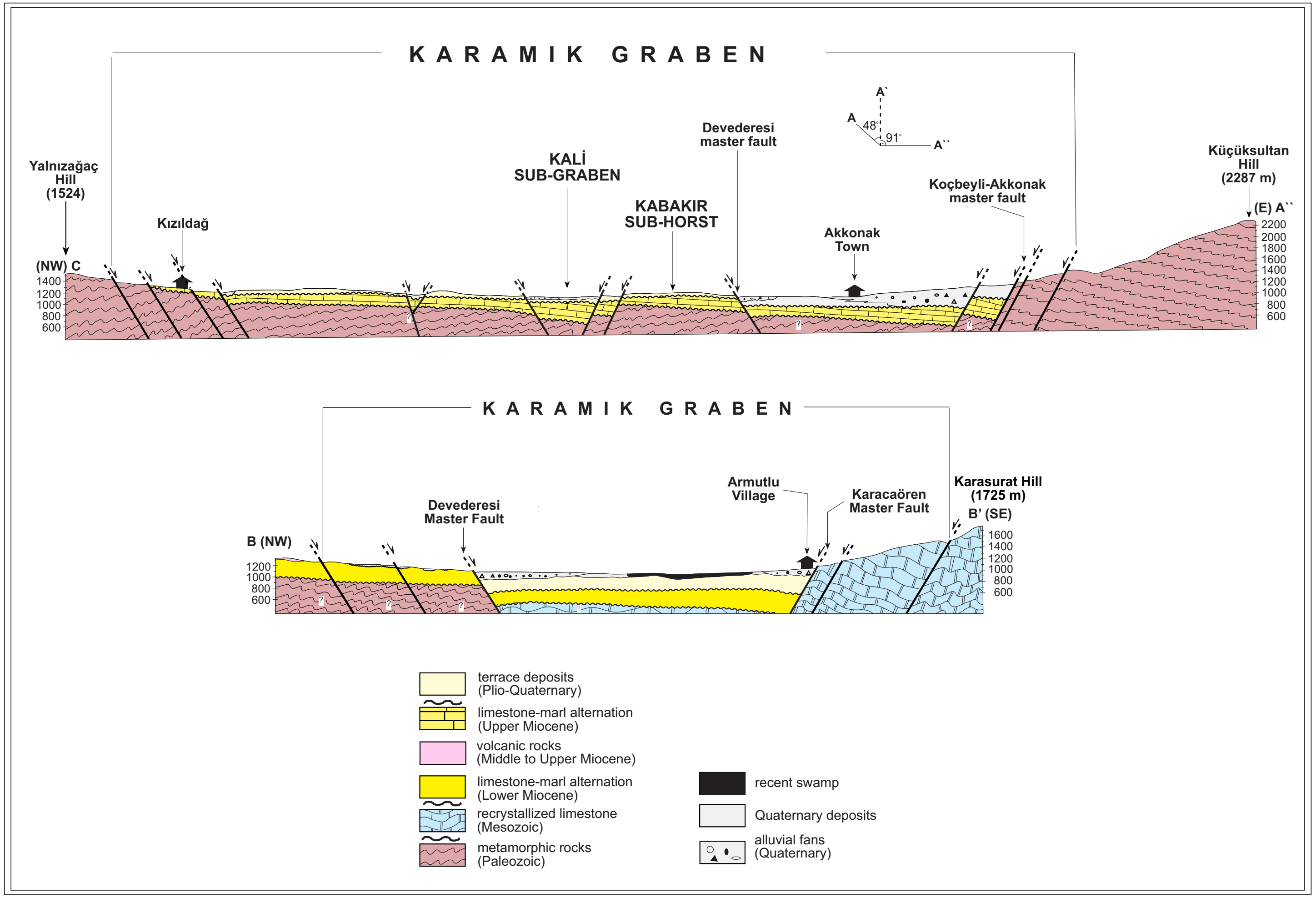


Figure 19. Cross-sections along lines A-A`` and B-B` on Appendix-I.

The Türkbelkavak Formation is also characterized by the well-bedded lacustrine sedimentary sequence. The dip amount of the bedding planes are rarely exceeds 30° near the faulted margin of the graben. It ranges between 15° to 25°. In contrast to the Akın Formation, the beds of the Türkbelkavak Formation reach up to 2 m in thickness (Figure 13) in places, however, a few tens of centimeter-scale thicknesses are common, in particularly, along the Devederesi fault zone.

3.2.1.2. Unconformities

Essentially, three types of unconformities (nonconformity, angular unconformity, and local disconformity) have been observed in and adjacent to the Karamik Graben.

The nonconformity is observed along the western and southern margins of the Karamık Graben in and adjacent to the study area. However, it gives very diagnostic exposures in the near west of the study area, İsalı village. The nonconformity lies between pre-Miocene rocks and whole graben infill. It is first observable between pre-Miocene rocks and Late Early Miocene Akın Formation. This nonconformity is also observable at the bottom of the Late Miocene-Middle Pliocene Türkbelkavak Formation. Because, during and after the time of accumulation of the volcano-sedimentary package of the pre-modern graben infill (Late Early Miocene-Middle Miocene Akın Formation and Middle-Late Miocene Afyon strato-volcanic complex), paleo-Karamık lake likely became larger and invaded the surrounding rocks with an onlapping type of depositional sequence over the formerly non-water-covered pre-Miocene rocks by the water of larger paleo-Karamık lake (Figures 11, 12 &15). Therefore, this unconformity is observed at the bottom of whole units of the graben infill due to the gradational enlargement of the paleolake. But, it is first observed at the bottom of the older graben fill (Early-Middle Miocene Akın Formation).

The angular unconformity has been observed between pre-modern graben infill and modern graben infill. It is observable especially along the southwestern margin of the study area (Appendix-I). This time span corresponds to the time of the short-lived intervening contractional phase, which deformed the Latest Paleotectonic units of Late Early Miocene-Middle Pliocene age, and interrupted the first stage of extension (Figures 20, 21, 22 & Appendix-II) in the evolutionary history of the Karamık Graben. Therefore, the initiation age of the extensional neotectonic regime in the Karamık Graben and its surroundings is Latest Pliocene.

The local disconformity is observable between Quaternary alluvial fans and the older rocks along the margins of the Karamık Graben (Appendix-I).

3.2.1.3. Folds

Folds deforming only the pre-modern graben infill of the Karamık Graben were mapped in the field and analyzed during the laboratory and office work. The folds occur generally as gentle folds in shape with a high frequency and short wavelength particularly in the NNW of Bulanık village and in the north to south of Aşağıdevederesi village (Appendix-I & Figure 20 & 21). They are observable in a series of anticlines and synclines of 1-3 km length, parallel to sub-parallel, and curvilinear axes-trending predominantly in NW-SE occasionally NNE-SSW directions (Appendix-I and Figures 20 & 21). Folds are well exposed in the vicinity of Bulanık and Aşağıdevederesi villages. They are observable mainly within the Akın Formation, particularly in the area of ~1-2 km NE of Aşağıdevederesi village. The short and asymmetric folds with short wavelength are very common. Unfortunately, some of them are not mappable. The contractional origin of NNW-trending folds is strongly supported by also pole plots of well-defined conjugate strike-slip faults observed ~1 km WNW of Bulanık village. (Figure 22).

Stereographic pole plots of 19 bedding planes of the older graben infill indicate that the older graben infill was deformed by a principle compressive stress operated in NE-SW direction, which is orthogonal to general trend of the fold axes. This result is also supported by the pole-plot results of well-defined conjugate strike-slip faults observed ~1 km WNW of Bulanık village (Figures 21 & 22). This is also proved by the fact that the Upper Pliocene-Quaternary units are undeformed or nearly flat lying, and rest unconformably on the erosional surface of the folded older graben infill of the Karamık Graben (Figure 5). Therefore, it is obvious that the age of the short-term contractional period lies between post Early-Late Miocene and pre-Latest Pliocene. Briefly, the age of the short-lived contractional tectonic phase is Middle Pliocene.

It is important to note that the N-S folds, which have been observed along western margin of the Karamık Graben, are diagnostic. They are extension-induced folds (i.e. roll-over folds) (Appendix-I).

3.2.1.4. Strike-slip Faults

No mappable strike-slip fault could be observed in the study area. But, a number of outcrop-scale and well-preserved conjugate strike-slip faulting-related slickensides (Figure 22) were recorded within the Lower Miocene Akın Formation near 1 km WNW of Bulanık village along the southern margin of the Karamık Graben (station-17 in Appendix-I). Stereographic analysis of slip-plane data measured from the Akın Formation indicates that the older graben infill has experienced a NE-SW short-lived phase of contraction after Middle Pliocene before the Latest Pliocene time.

3.2.2. Neotectonic Structures of the Karamık Graben

Based on the age, the neotectonic structures are of two categories: (1) older but reactivated neotectonic structures, and (2) newly formed neotectonic structures.

The common neotectonic structures shaping the study area are the Karamık Graben, the Kali sub-graben and their margin-boundary normal faults. The Karamık Graben was explained briefly at the beginning of this chapter. The rest of the neotectonic structures are described in detail below.

3.2.2.1. Normal Faults

The Karamık Graben is bounded by a series of normal fault zones such as the Karacaören fault zone in the SSE, the Koçbeyli fault zone in the east, the Akşehir fault zone in the north, and the Devederesi fault zone in the west-southwest (Appendix-I). Various characteristics of each of these margin-boundary fault zones will be described in more detail below.

3.2.2.1.1. Karacaören Fault Zone

This is also one of the major extensional neotectonic structures characterizing the Lakes districts sub-neotectonic domain. It has been first recognized, mapped, named, and analyzed by (Koçyiğit, 1983). The Karacaören fault zone is about 4-6-km-wide, 80-km-long and ENE-WSW-to NE-SW-trending zone of deformation dominated by normal faulting. It is located between Eldere village in the southwest and outside of the study area and Sağırlar village in the

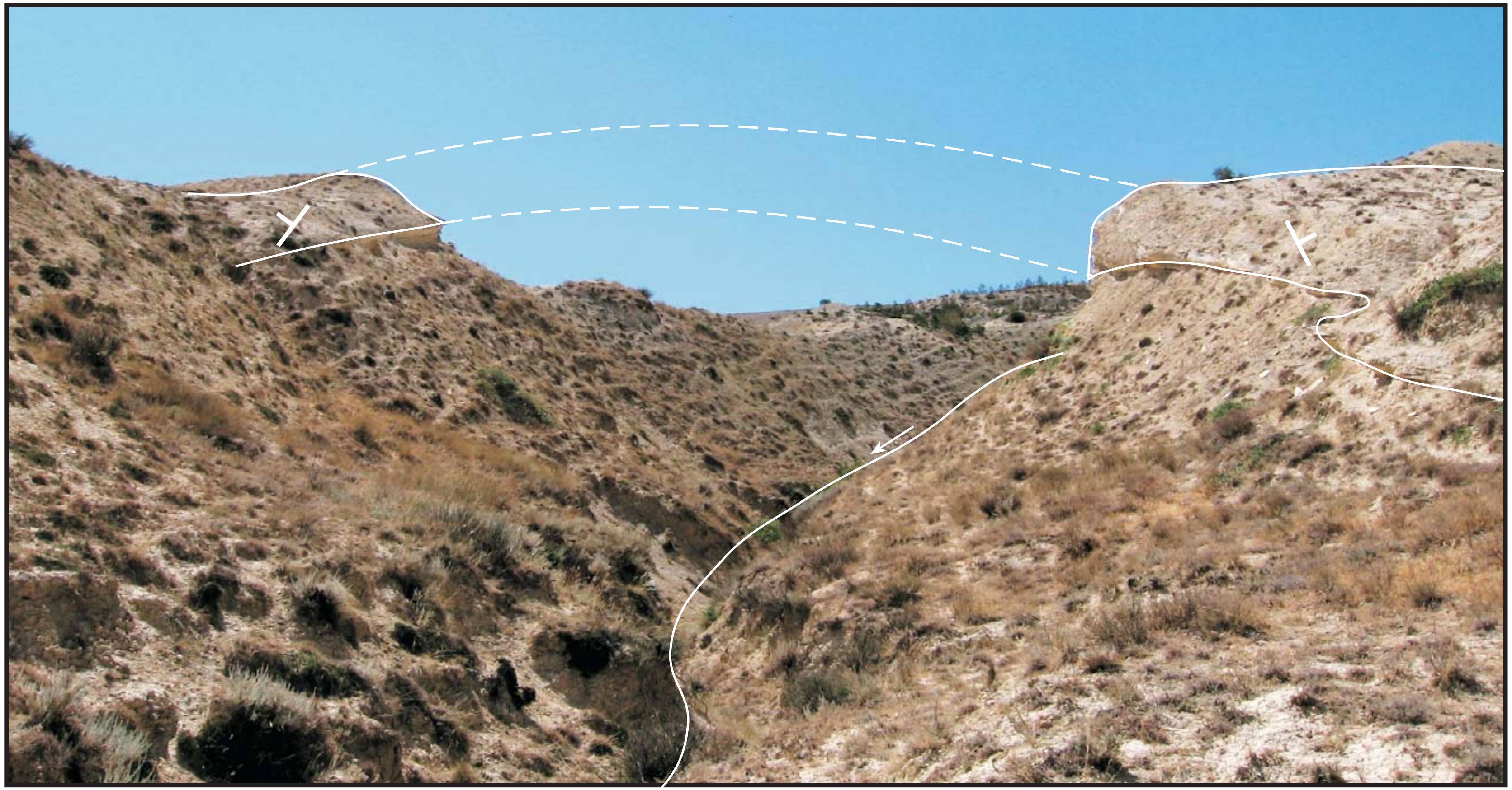


Figure 20. General view of an anticline observed in the Akın Formation (~2 km NE of the Bulanık village, view to NW).

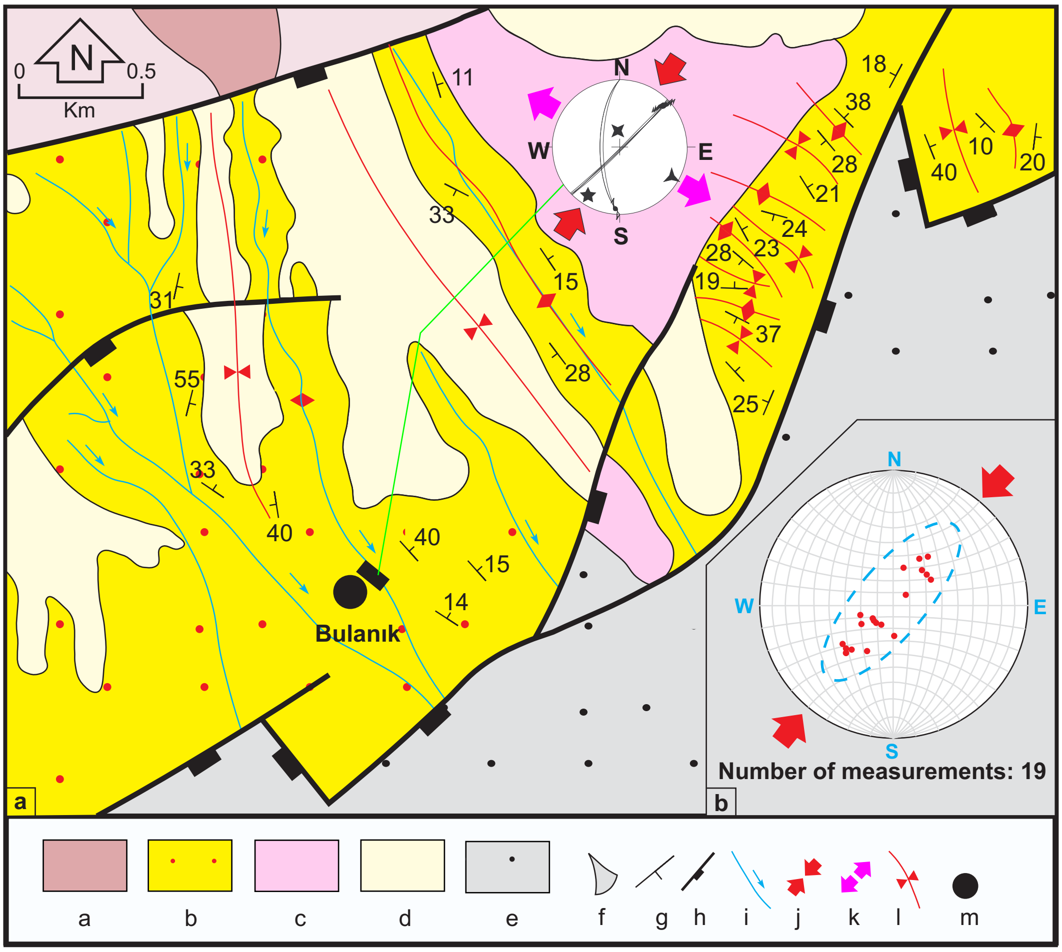


Figure 21. **(a)** Detailed geological map of the Bulanık area (Fig. 19 in Appendix-I), **(b)** poles to bedding on the schmit lower hemi-sphere which illustrates the operation direction of the compressive stress during short-term contract-ional period after sedimentation of older graben infill. **a-** Undifferentiated Paleozoic rocks, **b-** Lower-Middle Miocene volcano-sedimentary Akın Formation.**c-** Middle-Upper Miocene Afyon strato-volcanic complex. **d-** Plio-Quaternary terraced Kızılören Formation. **e-** Undifferentiated Lower-Upper Quaternary (Q2-Q3) fan-apron deposits. **f-** alluvial fan, g- bedding plane, **h-** normal fault, **i-** stream course, **j-** compression/ contraction direction, **k-** extension direction, **l-** fold axis and **m-** village centrum

Figure 22. Close-up view of slickensides and slickenlines of some conjugate strike-slip faults observed within the Akın Formation (Bulanık village, station-17 in Appendix-I).

northeast and also outside of the study area. Approximately 20-km-long northeastern part (the Armutlu section) of the Karacaören fault zone lies in the south and inside the study area. This part (Armutlu section) of the Karacaören fault zone was mapped and analyzed in detail in this study (Appendix-I and Figures 23, 24 & 25). The Armutlu section of the Karacaören fault zone will be described below.

The Armutlu section of the Karacaören fault zone is an about 0.6-km to 5-km-wide, 20-km-long and ENE-WSW-trending zone of normal faulting (Appendix-I). It determines and controls the south-southeastern margin of the Karamık Graben. The Karacaören fault zone consists of a series of parallel to sub-parallel; closely-spaced (130-1330 m) fault sets of dissimilar lengths up to 10 km (Appendix-I). These fault sets cut various rocks of dissimilar age and facies such as the Cambrian-Ordovician shales, Jurassic-Cretaceous marine carbonate sequence (Tauride autochthonous unit) and the Upper Eocene ophiolithic mélange, displace them in vertical direction by about 1 km, and finally juxtapose tectonically them with the Plio-Quaternary modern graben infill along the southern margin of the Karamık Graben (Appendix-I). The structural fault sets dip steeply and display grabenward-facing step-like morphology (Figure 26), which is very diagnostic particularly for normal faults. The fault cuts the Plio-Quaternary and Quaternary fill of the modern graben (mostly fan-apron deposits) (Figure 27) and juxtaposes them with the older rocks. Therefore, it is an active fault zone. Other faults located at higher elevations with respect to the master fault are synthetic faults in character (Figure 26). The steeply-slopping curvi-linear fault scarps, sudden break in slope, fault slickensides (Figures 29, 30 & 31) fault-parallel alignment of superimposed alluvial fans (Figures 18, 24, 25, 27), cold water springs, back-tilting of the older alluvial sedimentary sequences (Figure 28), the transversal streams with deeply carved beds (incised valleys or canyons) (Figures 23 & 26) are common morphotectonic criteria for the recognition of active structural fault sets comprising the Karacaören fault zone. In addition to these morphotectonic criteria, they also display well-developed and preserved slickensides in places (Appendix-I, Table 1 & Figures 29, 30 & 31). The Stereographical pole plots of these slip-plane data measured along this fault zone clearly reveal that: (1) the structural fault segments comprising the Armutlu section of the Karacaören Fault Zone are more or less dip-slip normal faults (Appendix-I & Table 1 & Figures 29, 30 & 31), and (2) the

Karamık Graben has been continuing to extend in dominantly NW-SE-direction (green double arrows in (Appendix-I & Figures 30 & 31) in general in distributed directions along its south-southeastern margin boundary faults. The throw amount calculated along this fault zone is ~400 m and yields ~0.15 mm/yr subsidence rate since Late Pliocene.

3.3.2.1.2. Koçbeyli-Akkonak Fault Zone

Koçbeyli-Akkonak Fault Zone is 1-3-km-wide, 18-km-long and NNE-SSW-trending zone of deformation characterized by normal faulting. This fault zone determines and controls the eastern margin of the Karamık Graben (Appendix-I). It includes a series of closely-spaced, sub-parallel fault segments of dissimilar length (Figures 32, 33, 34 & 35). Fault segments of the Koçbeyli-Akkonak fault zone are characterized by steep fault scarp, graben-ward facing step-like morphology and well-preserved slickensides (Figure 34). In some places, the well-preserved slip-plane data were collected and analyzed in order to reveal the

Figure 23. General view of the Armutlu section of the Karacaören fault zone. (FS: fault scarp, view to south, the length of the hammer is 33 cm).

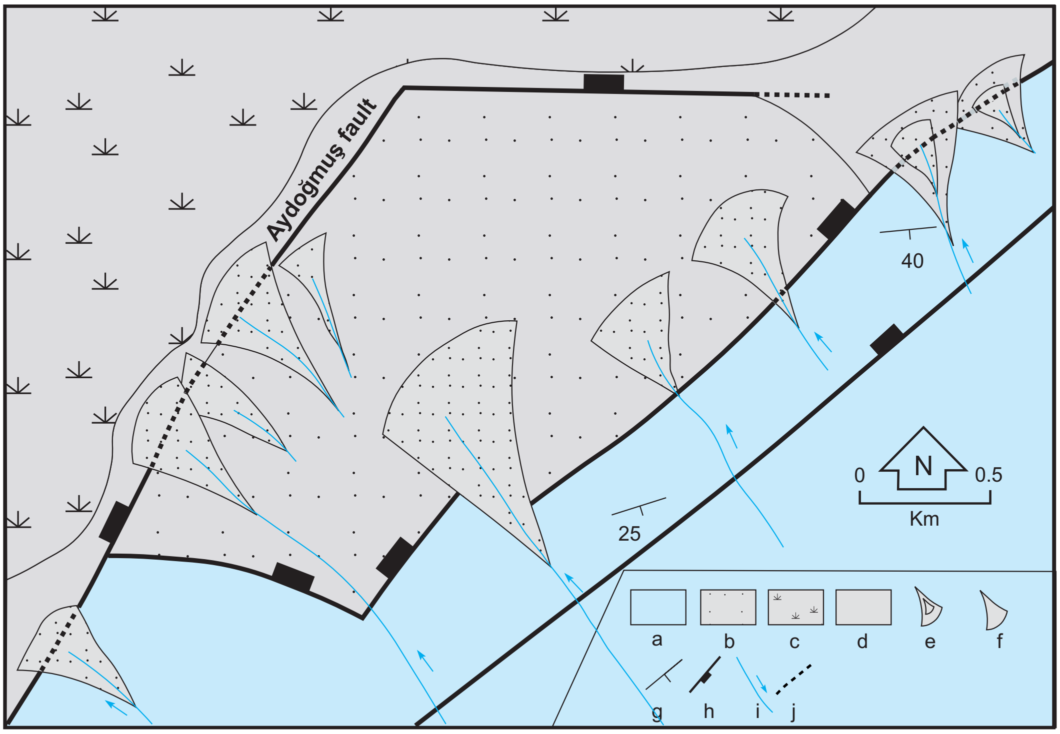


Figure 24. Detailed geological map of the southern part of the Armutlu section of the Karacaören fault zone (see for the location on Fig. 23 in Appendix-I). **a-** Mesozoic rocks, **b-**Undifferentiated Quaternary marginal fan-apron deposits (Q1, Q2 & Q3), **c-** recent swamp, **d-** recent depocentral alluvial sediments, **e-** superimposed alluvial fan, **f-** alluvial fan, **g-** bedding plane, **h-** normal fault, **i-** stream course and **j-** fault trace buried beneath the alluvial fans.

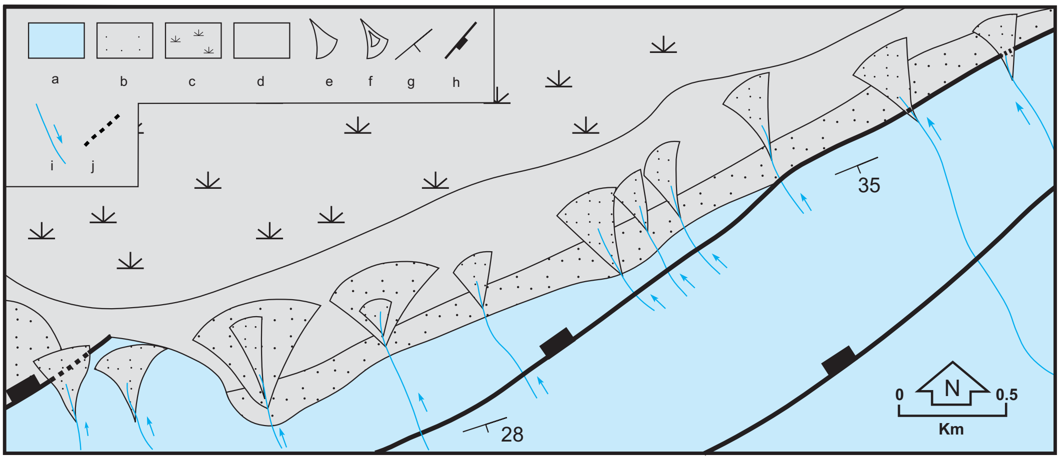


Figure 25. Detailed geological map of the northeastern part of the Armutlu section of the Karacaören fault zone (see for location on Fig. 24 in Appendix-I). **a-** Mesozoic rocks, **b-** Undifferentiated Quaternary marginal fan-apron deposits (Q1, Q2 & Q3), **c-** recent swamp, **d-** recent depocentral alluvial sediments, **e-** alluvial fan, **f-** superimposed alluvial fans, **g-** bedding plane, **h-** normal fault, **i-** stream course and **j-** fault trace buried beneath the alluvial fans.

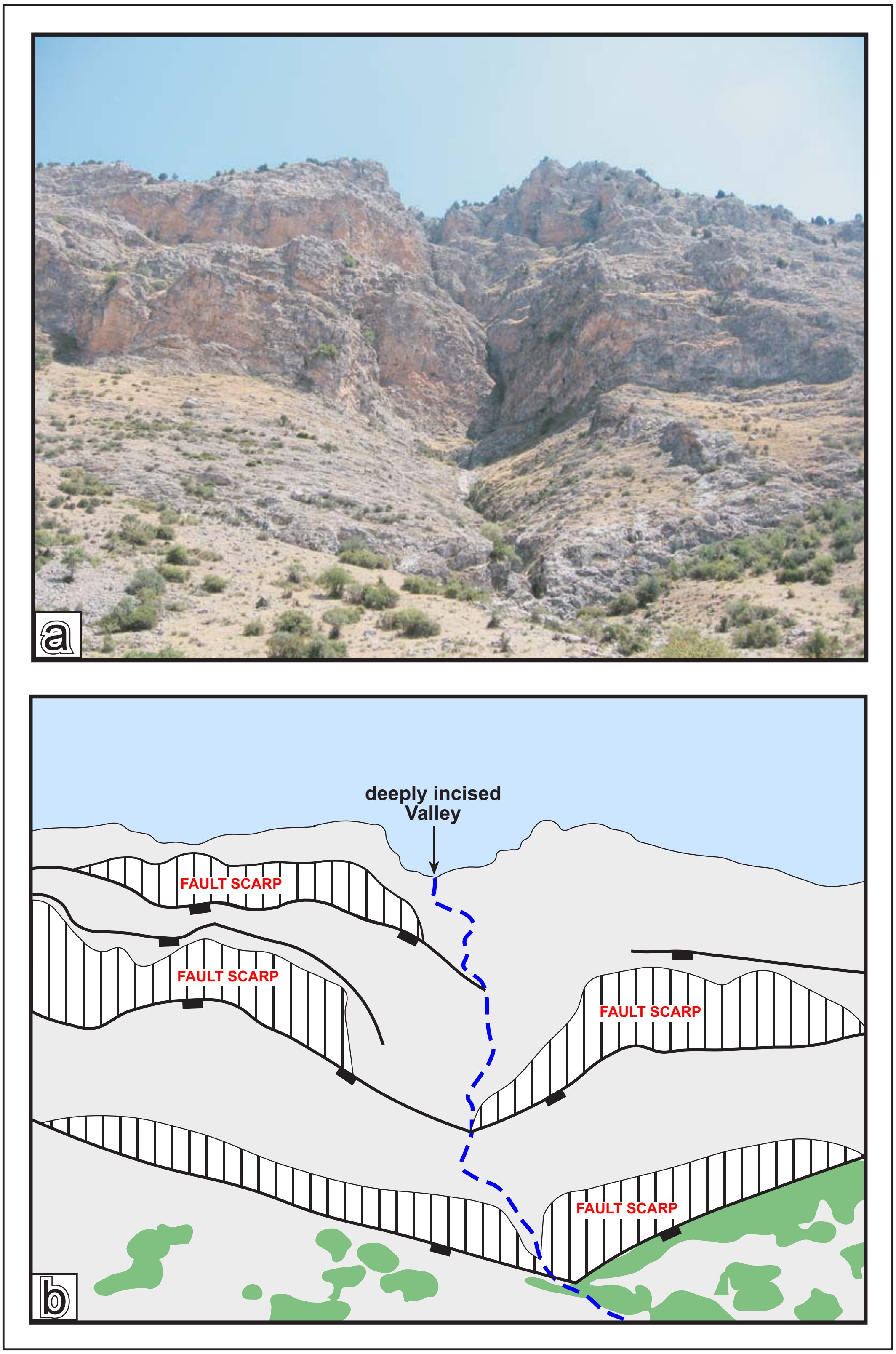


Figure 26. a) General view of step-like normal faults observed within the Armutlu section of the Karacaören fault zone (~3 km SW of the Koçbeyli town, view to south). **b)** Sketched of the structures in the field photograph.

Figure 27. General (Google Earth) view of the southern portion of the Armutlu fault section of the Karacaören fault zone and dissected Quaternary alluvial fans (true to scale, view towards SE, looking angle with respect to horizontal ground is ~ 30). (FS: fault scarp)

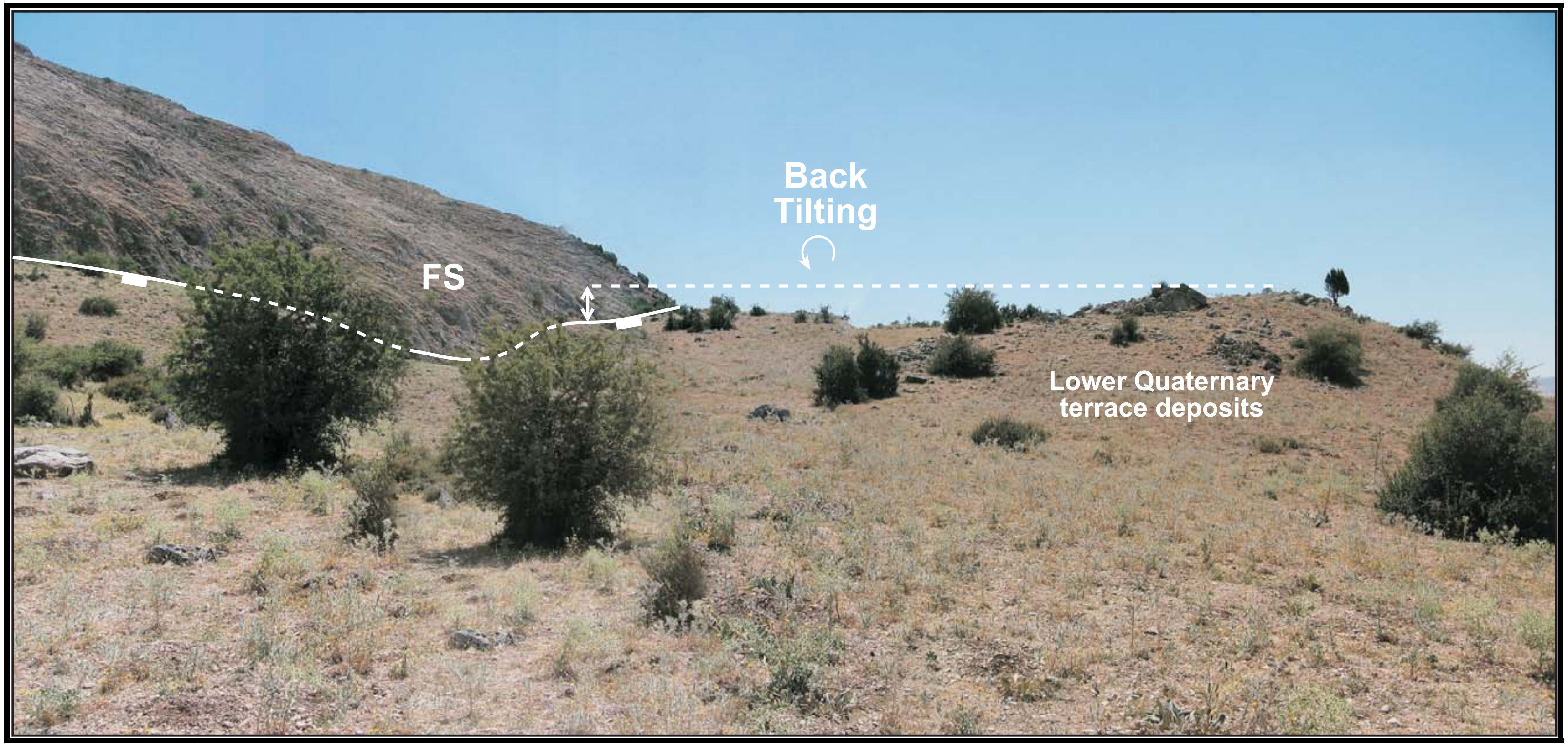


Figure 28. General view of a back tilted Lower Quaternary deposits (~3 km NE of the Armutlu Village, view to SW, FS: fault scarp).

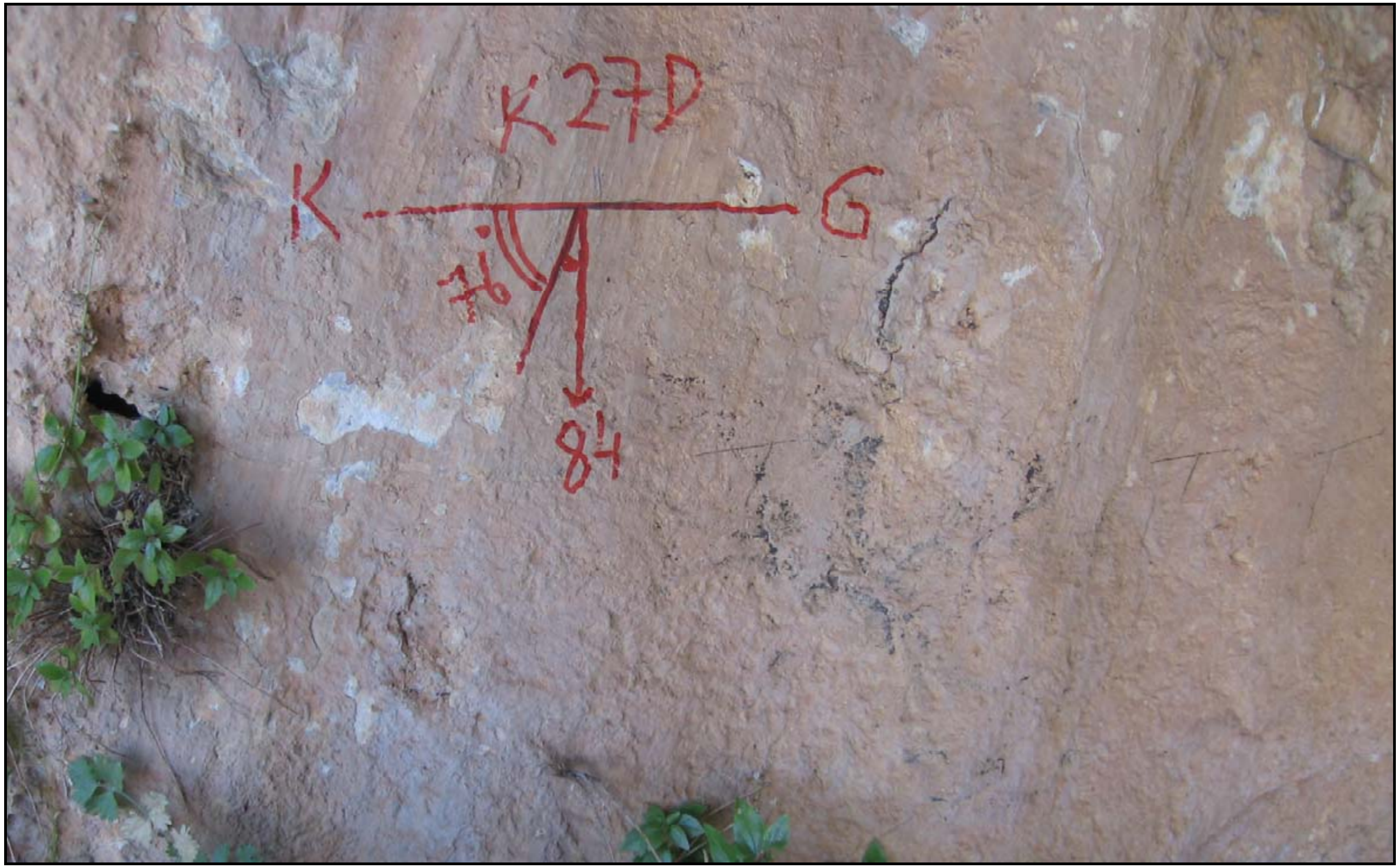


Figure 29. Close-up view of a fault scarp observed along the Armutlu section of the Karacaören fault zone (~3 km SW of the Armutlu village, station-1 in Appendix-I). (K= north, G= south and D= east).

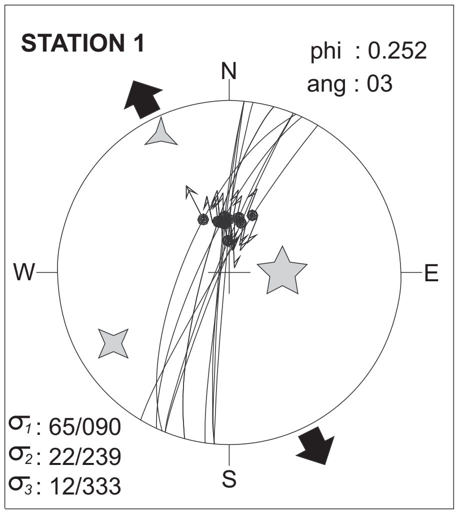
a)

STATION 1

No	Strike	Dip	Rake
1	N15E	78NW	68N
2	N25E	76NW	67N
3	N23E	68NW	72N
4	N05E	88NW	75N
5	N08E	86NW	65N
6	N22E	84NW	64N
7	N22E	86NW	66N
8	N31E	85NW	61N
9	N05E	86SW	67N
10	N05E	85NW	67N
11	N15E	78NW	68N

☆ = σ_1: principal stress axis
⌘ = σ_2 : moderate stress axis
△ = σ_3: least stress axis
⬅➡ = local extension direction

b)



c)

STATION 5

No	Strike	Dip	Rake
1	N46E	62NW	90
2	N47E	56NW	90
3	N42E	65NW	88N
4	N42E	56NW	86N
5	N41E	64NW	79N
6	N48E	54NW	90
7	N35E	56NW	83N
8	N47E	54NW	80N
9	N45E	50NW	80S
10	N40E	62NW	86N
11	N42E	46NW	84N
12	N51E	60NW	85S
13	N40E	61NW	88S
14	N38E	65NW	76N
15	N54E	53NW	87N
16	N70E	47NW	70S
17	N43E	39NW	86N
18	N50E	55NW	83N

d)

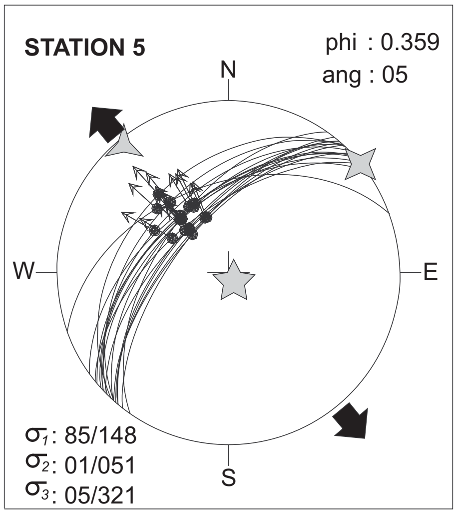


Figure 30. a) Slip-plane data measured on slickenside of faults comprising the Karacaören fault zone at station 1 in Appendix-I, **b)** stereographic plots of slip-plane data measured on station 1 in Appendix-I on Schmidt lower hemisphere net, **c)** Slip-plane data measured on slickenside of faults comprising the Karacaören fault zone at station 5 in Appendix-I, **d)** stereographic plots of slip-plane data measure on station 5 in Appendix-I on Schmidt lower hemisphere net, large black arrows show localized extension direction.

A) Karacaören Fault Zone

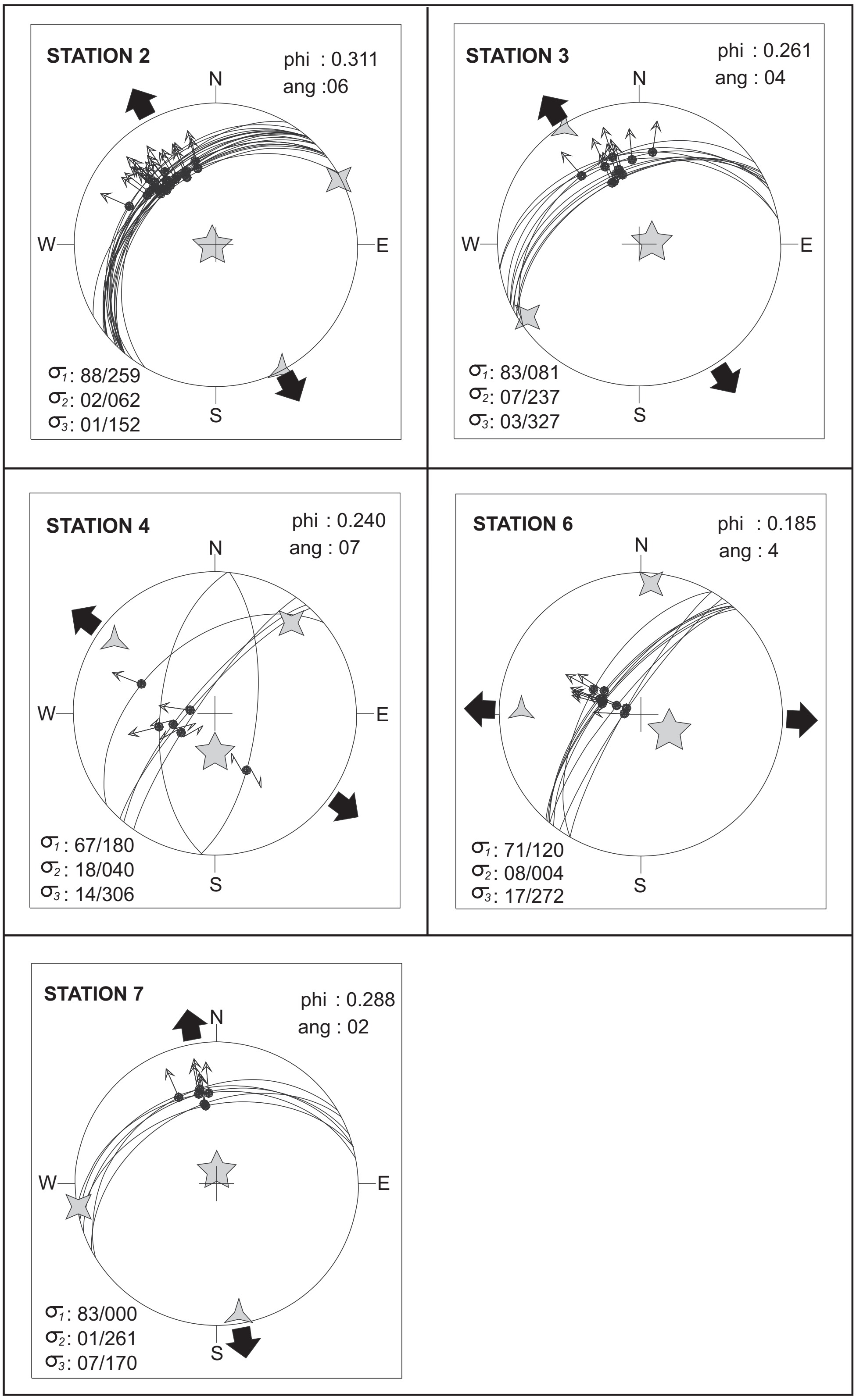
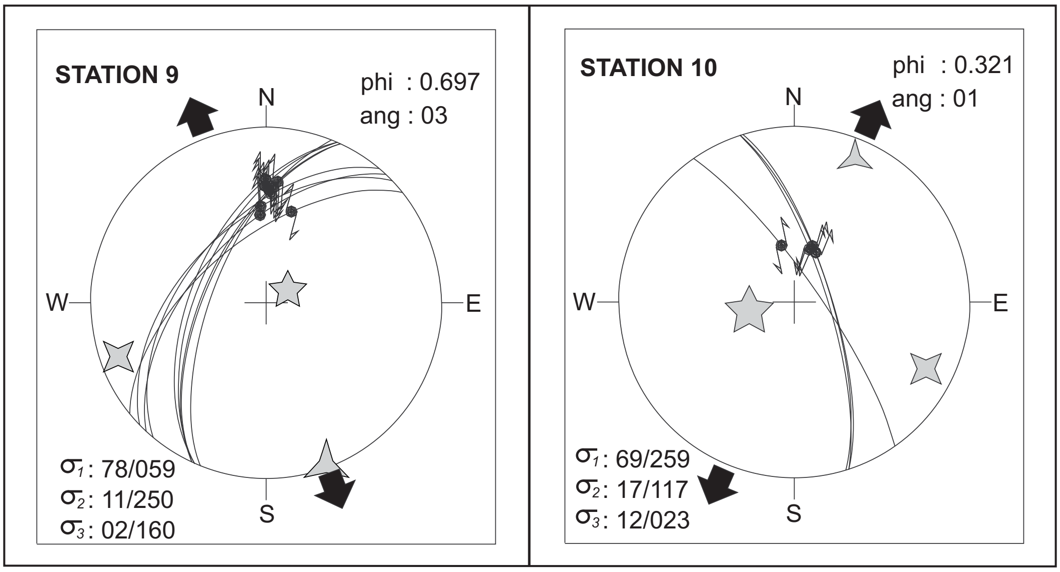


Figure 31. Paleostress results and related parameters obtained from the inversion of the slip-plane data collected in the frame of this study.

B) Koçbeyli-Akkonak Fault Zone



C) Devederesi Fault Zone

D) The strike-slip fault

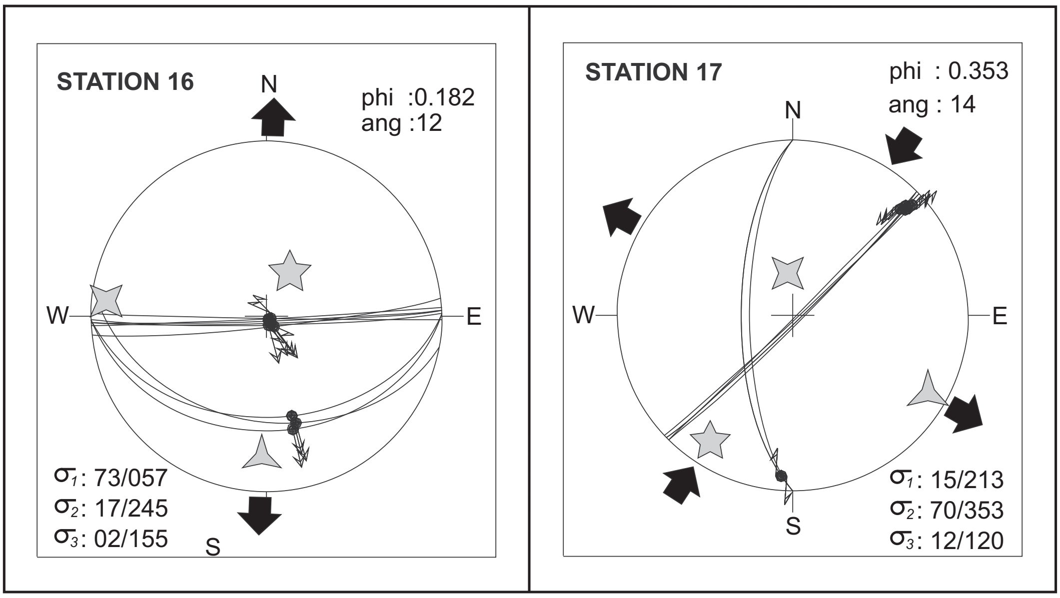


Figure 31. (Continued)

local extension direction. According to the stereographic analysis of the slip-plane data measured along the Koçbeyli-Akkonak fault zone, the extension along the eastern margin of the Karamık Graben is not uniform, in contrast, it is distributed, and multi-directional ranging from WNW to NNE (stations 8-9-10-11 in Appendix-I, Figures 31 & 35)

Based on general trend of the Koçbeyli-Akkonak fault zone. It is divided into two sections: (1) NNW-SSE to N-S-trending Karamık section, and (2) NNE-SSW-trending Pazarağaç section (Appendix-I).

The Karamık section of the Koçbeyli-Akkonak fault zone is 1-4-km-wide, ~8 to 10-km-long; predominatingly NNW-SSE-trending oblique-slip normal fault set, facing towards the Karamık Graben. It controls the southern part of the eastern margin boundary of the Karamık Graben. Quaternary older alluvial fans and various Paleozoic sequences are tectonically juxtaposed along the Karamık section of the Koçbeyli-Akkonak fault zone. In addition to this, break in slope, accumulation of thick slope-scree deposits along the fault scarps, well-developed triangular facets and deeply incised valleys can be related to the activity of the Karamık fault section of the Koçbeyli-Akkonak fault zone. The thickness of the Quaternary alluvial fans accumulated on the western hanged wall block of the Karamık section of the fault zone exceeds 200 m (Çuhadar, 1977). This value indicates from one hand a high rate of sedimentation, from other hand, the activity of the margin-boundary fault around Koçbeyli. In addition, superimposed alluvial fans are the other implications for the activity of the fault segments. However, there is no considerable amount of seismic activity recorded along the Karamık section of the fault zone in the period of 1900-2008. This is the implication for the seismic gap nature of faults in this area. This view was also supported by very recent GPS studies (Erdoğan et al., 2009).

The Pazarağaç fault section of the Koçbeyli-Akkonak fault zone is a 1-3-km-wide, 12-14-km-long and NNE-SSW-trending fault zone. It determines and controls the northeastern margin of the Karamık Graben (Appendix-I). This section of the fault zone starts ~1 km ENE of Orhaniye town and runs through the east of Akkonak town, Karamık-Karacaören town, and Pazarağaç town, where fault segments bend eastward and finally meet with the Akşehir fault zone to the north (Appendix-I). This section of the fault zone consists of a series of NNE-to ENE-WSW-trending nearly parallel, basinward-facing active oblique-slip normal faults. It is very easy to recognize the Pazarağaç section of the fault zone in the field, because it displays a series of well-preserved steep fault scarp, triangular facets, sudden break in slope (Figures 32 & 33), the tectonic juxtaposition of Paleozoic rocks with the Quaternary sequences (Figures 32) and, well-preserved slickenside (Figure 34). The fault segments comprising the Pazarağaç section of fault zone is active, because it cuts and displaces the Quaternary deposits (Figure 36). This was also proved by seismic activity of fault segments reactivated during the 2002, February 3 Çay earthquake.

3.2.2.1.3. Akşehir Fault Zone

The Akşehir Fault Zone was first reported as a single normal fault by (Atalay, 1973). Later on, it was studied in detail, mapped at 1/25000 scale and named by (Koçyiğit, 1984) and (Koçyiğit et al., 2000) as the Akşehir fault. The Akşehir fault zone comprises the Akşehir-Afyon-Doğanhisar section of the Akşehir-Simav fault system of (Koçyiğit & Deveci, 2005). The Akşehir fault zone 2-7-km-wide, 200-km-long WNW-ESE-trending and northerly dipping zone of deformation of normal faulting (Koçyiğit & Özacar, 2003). The Maltepe-Cumhuriyet section of the Akşehir fault zone is included in the study area (Appendix-I).

The Maltepe-Cumhuriyet section of the Akşehir fault zone is 1-3-km-wide, ~17-km-long WNW-ESE-trending and northerly dipping zone of active deformation (Appendix-I). Some segments of it, particularly the master fault segment, was reactivated during the February 3, 2002 Çay (Afyon) earthquakes and caused not only loss of life, but also the severe damages to the structures in the vicinity of the Çay County (Appendix-I). The Maltepe section of the Akşehir fault zone enters into the study area from east, runs through Cumhuriyet and Maltepe towns and Gözsüzlü village, and finally goes out of the study area. It is easy to recognize the Maltepe section of the Akşehir fault zone (Figures 37, 38 & 39). Because, it displays a series of criteria such as abrupt break in slope, linear alignment of ridges, well-preserved triangular facets, deeply incised valleys, tectonic juxtaposition of older rocks with Quaternary alluvial sediments, fault scarps (Figure 38), back-tilted sediments towards fault scarps (Figure 37b) and well-preserved slickenside (Figure 38). Stereographic plots of the slip plane data measured on slickensides (Figure 40) indicate that the local extension direction along the Maltepe-Cumhuriyet fault section is almost N-S (station 12 & 13 in Appendix-I and along the (Figures 38 & 40).

Table 1. Slip plane data collected in this study and their stations in Appendix-I.

A) Karacaören Fault Zone

Station 2

No	Strike	Dip	Rake
1	N50E	46NW	85S
2	N40E	38NW	78N
3	N44E	45NW	78N
4	N45E	40NW	85S
5	N42E	38NW	87N
6	N41E	34NW	87N
7	N50E	42NW	70N
8	N50E	45NW	78N
9	N30E	42NW	80N
10	N40E	44NW	86N
11	N40E	40NW	88N
12	N36E	34NW	80S
13	N41E	40NW	86S
14	N52E	48NW	80N
15	N45E	47NW	88N
16	N51E	46NW	90
17	N50E	42NW	88N
18	N50E	45NW	84N
19	N40E	45NW	83N
20	N60E	45NW	78N
21	N40E	47NW	70N
22	N50E	42NW	88N

Station 3

1	N65E	40NW	90
2	N68E	38NW	86N
3	N55E	37NW	86S
4	N80E	40NW	82S
5	N80E	36NW	75N
6	N60E	51NW	86N
7	N65E	45NW	83N
8	N63E	49NW	81N
9	N59E	51NW	84N

Station 4

1	N35E	80NW	70S
2	N50E	47NW	70S
3	N42E	78NW	82S
4	N05E	58NW	80S
5	N05E	66SE	60S
6	N40E	75NW	70S

Station 6

1	N40E	76NW	85S
2	N30E	59NW	90
3	N40E	65NW	87S
4	N30E	81NW	90
5	N35E	82NW	85S
6	N38E	68NW	83S
7	N42E	68NW	80S
8	N40E	66NW	82S
9	N41E	68NW	81S

B) Koçbeyli-Akkonak Fault Zone

Station 7

No	Strike	Dip	Rake
1	N80E	36NW	86N
2	N70E	37NW	83N
3	N62E	44NW	76N
4	N59E	34NW	84N
5	N75E	33NW	86N
6	N75E	44NW	85N

Station 9

1	N40E	52NW	51N
2	N22E	65NW	35N
3	N24E	55NW	38N
4	N25E	61NW	42N
5	N24E	58NW	41N
6	N40E	52NW	51N
7	N46E	52NW	62N
8	N51E	60NW	55N
9	N43E	57NW	63N

Station 10

1	N16W	73NE	68N
2	N18W	75NE	69N
3	N17W	73NE	71N
4	N35W	79NE	65N

C) Devederesi Fault Zone

Station 16

No	Strike	Dip	Rake
1	E - W	90	90
2	N88E	88SE	90
3	N88E	89SE	88N
4	N88E	88SE	89N
5	N89E	86SE	89N
6	N84E	85SE	87N
7	E-W	42S	80E
8	N80W	40SW	70S
9	E-W	35S	80E

D) The strike-slip fault

Station 17

No	Strike	Dip	Rake
1	N-S	66W	10S
2	N-S	66W	10S
3	N45E	90	15N
4	N47E	88SE	08N
5	N-S	70W	00
6	N46E	87SE	12N
7	N45E	86SE	11N
8	N46E	87SE	13N

3.2.2.1.4. Devederesi Fault Zone

The Devederesi fault zone was first defined by (Çiçek & Koçyiğit, 2008). It is 1-3-km-wide, ~29-km-long and NNE-SSW-trending zone of normal faulting (Appendix-I). The Devederesi fault zone determines and controls the western margin of the Karamık Graben (Appendix-I). It consists of a number of NE-SW-to NNE-SSW-trending oblique-slip normal fault segments. The Devederesi fault zone appears in SSW corner of the study area, around the Kılıçyaka village. It runs in ~NE-SW direction up to the Bulanık village. It bends towards NNE, and then continues in the same trend up to Maltepe village. This fault zone meets with the Akşehir fault zone near Maltepe village and disappears (Appendix-I). The Devederesi fault zone consists of five sections: (1) the Kılıçyaka-Bulanık section, (2) the Aşağıdevederesi section, (3) the Kızıldağ section, (4) the Kali section, and (5) the Kaymakçı section. The Kılıçyaka-Bulanık and Kızıldağ fault sections will be discussed in more detail under this outline. However, the others will be described together with the Kali sub-graben later.

The Kılıçyaka-Bulanık fault section of the Devederesi fault zone is about 9-km-wide, more than 10-km-long and NE-SW-trending zone of deformation (Appendix-I). It determines and controls the SW margin of the Karamık Graben. Each fault segment of the Kılıçyaka-Bulanık section cuts Akşehir fault zone in the field. and displaces various rocks of dissimilar age and facies such as Paleozoic metamorphic rocks, Lower Miocene volcano-sedimentary succession, Middle Miocene Afyon strato-volcanic complex, Upper Miocene-Middle Pliocene limestones, Plio-Quaternary terrace conglomerates, and tectonically juxtaposes them with the Quaternary alluvial sediments of the graben along the southwestern margin of the Karamık Graben (Appendix-I). The fault segments also display graben-ward-facing step-like land shape (Figure 42). Actively growing Quaternary fan-apron alluvial deposits and terraced Quaternary sediments (Figure 23) imply that the Kılıçyaka-Bulanık section of the Devederesi fault zone is active in spite of the fact that any seismic event has not been recorded yet.

The Aşağıdevederesi section of the Devederesi fault zone is 0.5- to 2-km-wide, ~11-km-long and NNE-SSW-trending zone of deformation characterized by oblique-slip normal fault segments. These fault segments cut and displace various rocks such as the Lower Miocene-Middle Miocene Akın Formation, the Middle

Figure 32. General view of the Pazarağaç section of the Koçbeyli-Akkonak fault zone (view to SE).

Figure 33. General view of a NW-SE-trending fault observed in the vicinity of the Pazarağaç fault section of the Koçbeyli-Akkonak fault zone (~3 km ENE of the Karamık-Karacaören town. view to north).

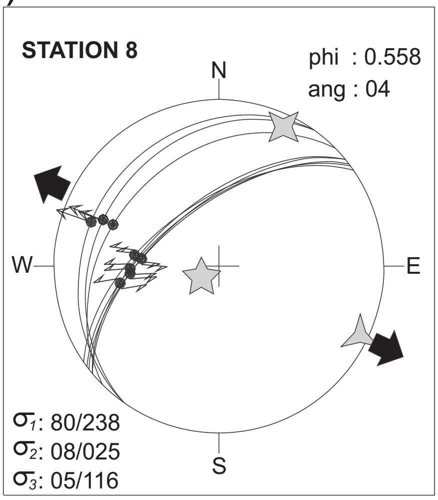
Figure 34. Close-up view of a slickenside scarp observed along Pazarağaç section of the Koçbeyli-Akkonak fault zone- Pazarağaç section (~1.5 km east of the Karamık-Karacaören town, the length of the pen is 14.5 cm).

a)

STATION 8

No	Strike	Dip	Rake
1	N50E	60NW	55S
2	N53E	60NW	55S
3	N35E	20NW	75S
4	N35E	26NW	78S
5	N45E	34NW	70S
6	N50E	58NW	48S
7	N55E	58NW	60S
8	N52E	61NW	63S

b)



c)

STATION 11

No	Strike	Dip	Rake
1	N70E	74NW	85N
2	N68E	71NW	82N
3	N65E	34NW	85N
4	N80E	60NW	80N

☆ = σ_1: principal stress axis
= σ_2: moderate stress axis
△ = σ_3: least stress axis
= local extension direction

d)

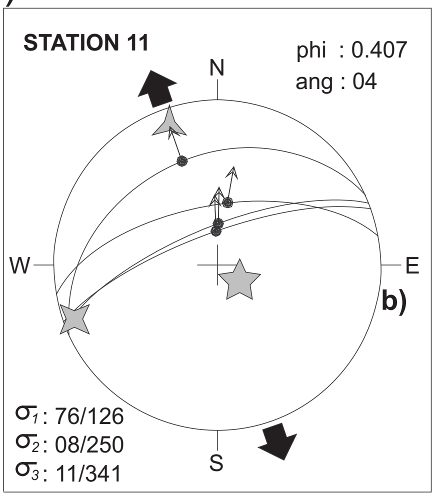


Figure 35. a) Slip-plane data measured on slickenside of faults comprising the Koçbeyli-Akkonak fault zone at station 8 in Appendix-I, **b)** stereographic plots of slip-plane data measured on station 8 in Appendix-I on Schmidt lower hemisphere net, **c)** slip-plane data measured on slickenside of faults comprising the Koçbeyli-Akkonak fault zone at station 11 in Appendix-I, **d)** stereographic plots of slip-plane data measure on station 11 in Appendix-I on Schmidt lower hemisphere net, large black arrows show localized extension direction.

Figure 36. a) Close-up view of a fault cutting and displacing the Quaternary alluvial fans along the Koçbeyli-Akkonak fault zone (station11 in Appendix-**I**, ~2 km east of the Pazarağaç town). **b)** sketch of drawing of Figure a.

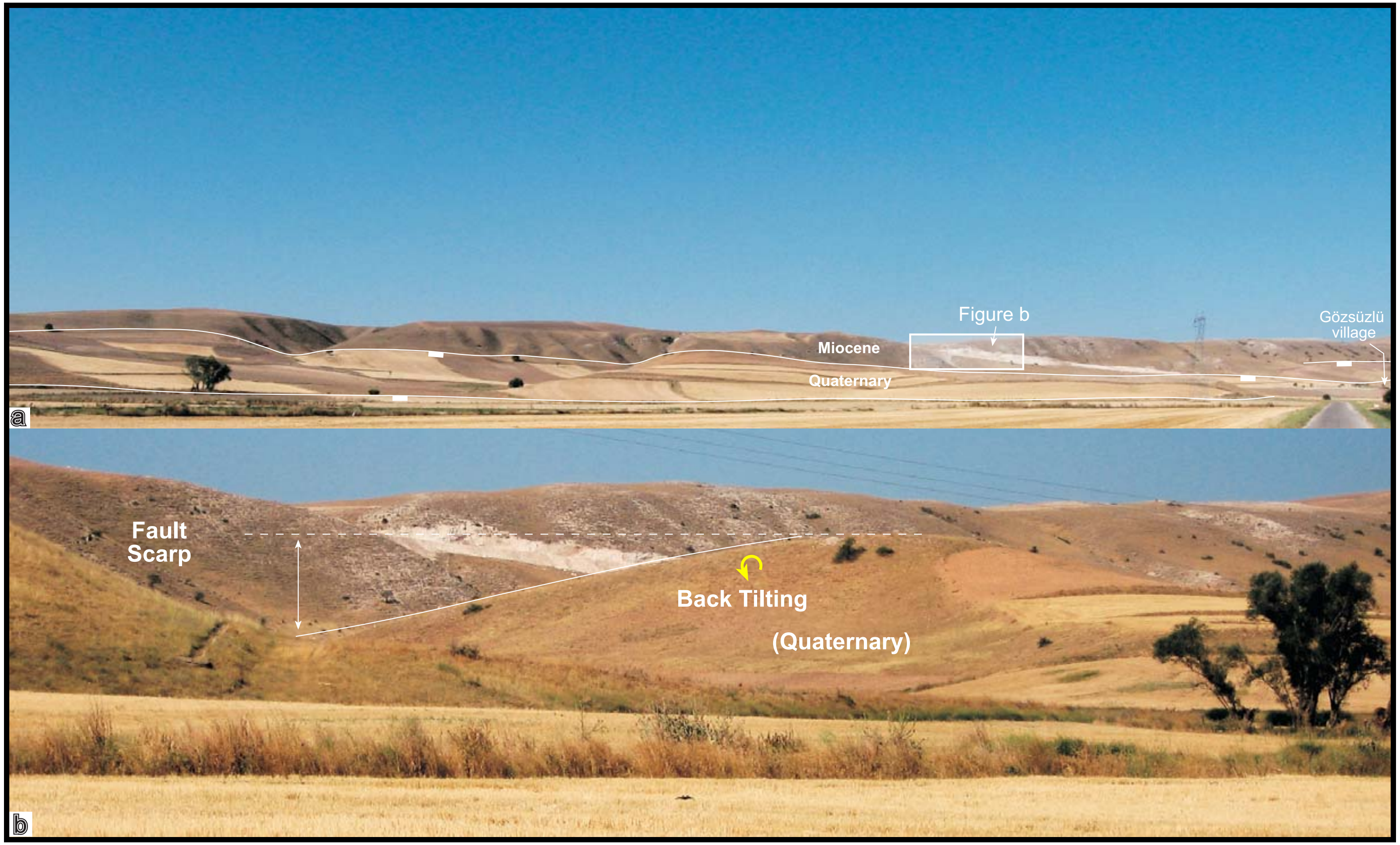


Figure 37. a) General view of the Cumhuriyet section of the Akşehir fault zone (~1 km east of the Gözsüzlü village, view to south). **b)** Close-up view of the rectangle on Figure a.

Figure 38. Close-up view of a slickenline of the Akşehir fault zone (station 13 in Appendix-I, the length of the hammer is 33 cm).

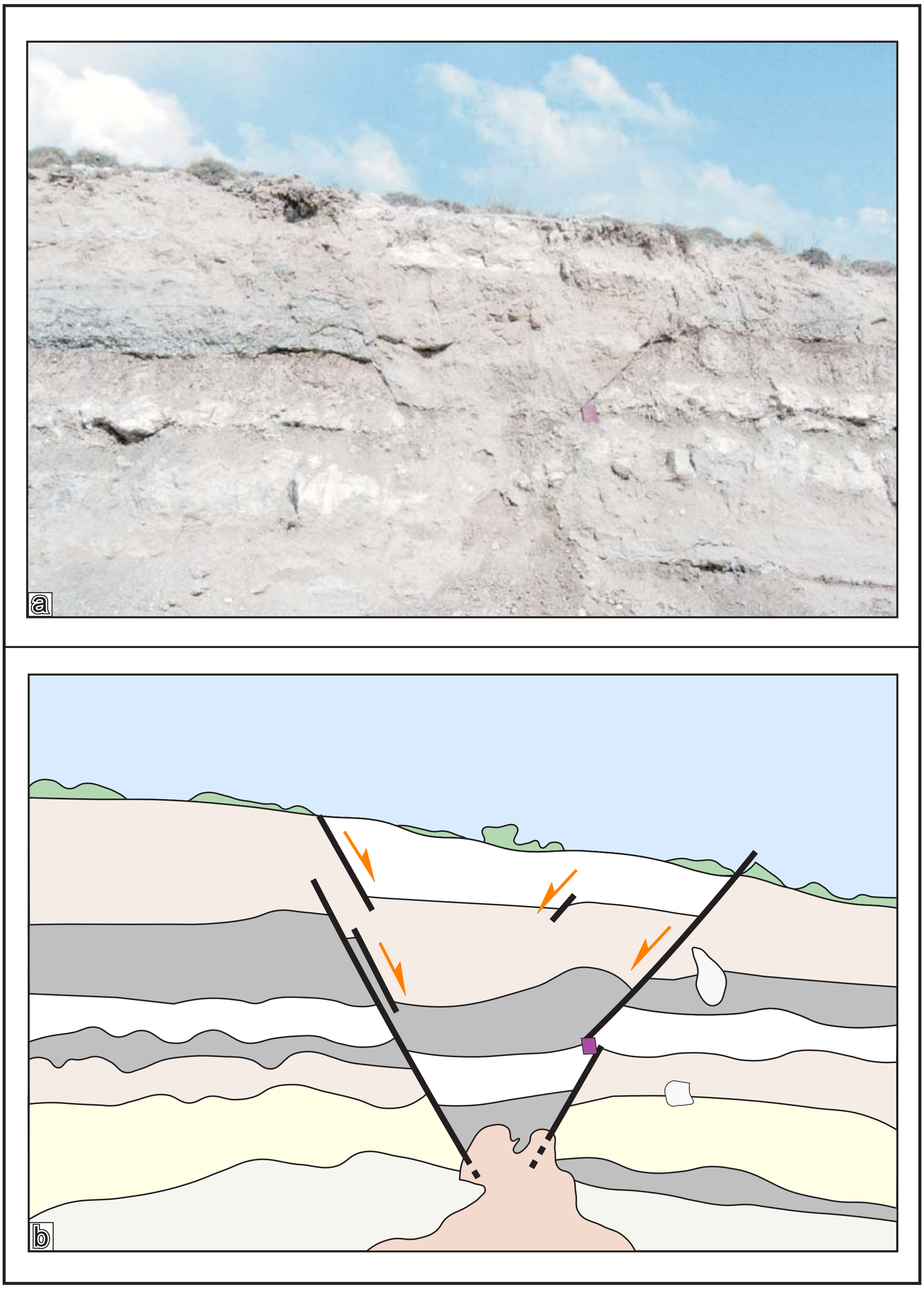


Figure 39. a) General view of a graben-like depression observed along the Akşehir Fault Zone (location of the station 13 in Appendix-**I**). **b)** Sketch drawing of the figure a. above (length of the hammer is 33 cm).

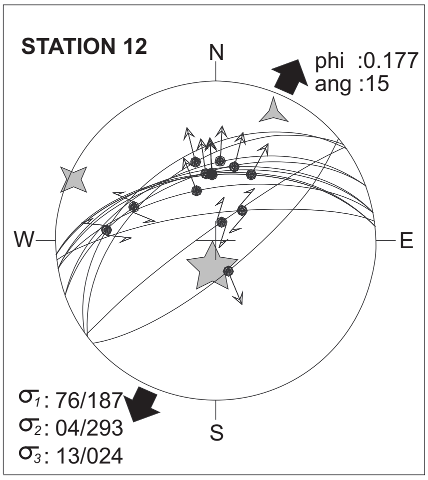
a)

STATION 12

	Strike	Dip	Rake
1	N70E	51NW	75N
2	N80E	63NW	85S
3	N85E	56NW	70N
4	N85E	56NW	90
5	N80E	55NW	90
6	N85E	55NW	90
7	N80E	53NW	75N
8	N83E	76NW	75N
9	N55E	44NW	50S
10	N53E	50NW	75N
11	N54E	84NW	82N
12	N70E	55NW	58S
13	N50E	74SE	85S

☆ = σ_1: principal stress axis
= σ_2: moderate stress axis
△ = σ_3: least stress axis
= local extension direction

b)



c)

STATION 13

	Strike	Dip	Rake
1	N80W	47NE	78N
2	N70W	43NE	89N
3	E - W	45N	70E
4	N75W	52NE	52N
5	N75W	52NE	88S
6	N83W	47NW	85N
7	N52W	49NE	65S
8	N70W	50NE	89N
9	N70W	50NE	85S
10	N55W	50NE	75S
11	N70W	75SW	75S
12	N70W	78SW	85S
13	N70W	78SW	75S
14	E-W	65S	89N

d)

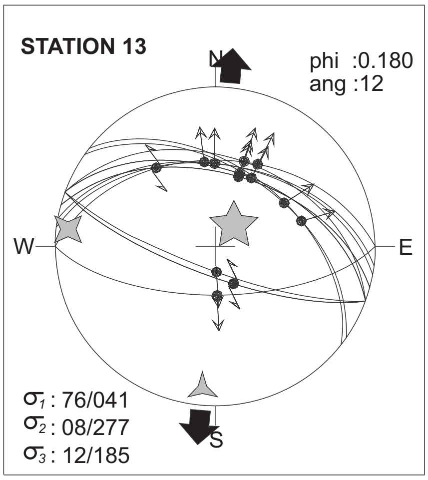


Figure 40. a) Slip-plane data measured on slickenside of faults comprising the Akşehir fault zone at station 12 in Appendix-I, **b)** stereographic plots of slip-plane data measured on station 12 in Appendix-I on Schmidt lower hemisphere net, **c)** Slip-plane data measured on slickenside of faults comprising the Akşehir fault zone at station 13 in Appendix-I, **d)** stereographic plots of slip-plane data measure on station 13 in Appendix-I on Schmidt lower hemisphere net, large black arrows show localized extension direction.

Miocene-Tortonian Afyon strato-volcanic complex, Upper Miocene Middle Pliocene Türkbelkavak Formation and the Plio-Quaternary Kızılören Formation, and tectonically juxtaposes them with the Quaternary alluvial sediments of the Karamık Graben (Appendix-I). Well-developed slickensides, morphotectonic features such as sudden break in slope, triangular facets, deeply carved valleys, faulted, uplifted and dissected fault-perched terrace conglomerates reveal both the existence and also activity of the Aşağıdevederesi section of the fault zone.
The Kızıldağ section is ~3- to 4-km-wide, ~13 long and N-S-trending oblique-slip normal fault set. Although the Kızıldağ fault section has been first studied, mapped and interpreted to be a reverse fault by (Boray et al., 1985), it is a normal fault as indicated by fault scarps and well-preserved slickenside on it (Figures 41 & 43). The Kızıldağ section of the Devederesi fault zone determines the incipient outline of the Karamık Graben along its western margin. This is one of the strongest evidence implying that the pre-modern graben infill deposited under the control of extensional tectonic regime (phase-I extension). It spreads from the İnli town in the south up to the Gözsüzlü village the near west. It cuts and displaces various rocks in vertical direction such as the Paleozoic metamorphics, Upper Cretaceous ophiolithic mélange, Lower-Middle Miocene Akın Formation, Upper Miocene-Middle Pliocene Türkbelkavak Formation, and the Plio-Quaternary Kızılören Formation, and tectonically juxtaposes them with each other. The common field evidence indicating its existence is well-developed triangular facets, sudden break in slope, steep scarp (Figure 43), deflected to offset drainage system, fault parallel aligned alluvial fans and well-preserved slickensides (Figure 41).

The throw amounts calculated along the north and south of the Devederesi fault zone measured as ~400 m and ~550 m, which yield~0.15 mm/yr and ~0.21 mm/yr subsidence rates since the Late Pliocene, respectively.

3.3. Kali Sub-graben

The Kali sub-graben is a 1.5- to 3-km-wide ~10-km-long and NNE-SSW-trending active depression front due to the fragmentation of early formed major Karamık Graben during the Plio-Quaternary neotectonic period. The Kali-sub graben occurs near the northwestern corner of the major graben and bounded by both the Kaymakçı section of the Devederesi fault zone (Appendix-I & Figure 43). The Kaymakçı section of the Devederesi fault zone was first mapped and named by (Erişen, 1972) as Kaymakçı fault. Indeed, it is not a single fault; it consists of parallel to sub-parallel, closely-spaced, graben-ward facing, and steeply dipping, synthetic fault segments. Therefore, they comprise a fault set rather than a single fault. It is an about ~0.5-km-wide, 8-km-long and NNE-SSW-trending oblique-slip normal fault set with curvilinear fault traces. It bounds and controls the western margin of the Kali sub-graben (Appendix-I & Figure 43).

The Kaymakçı section of the Devederesi fault zone cuts and displaces vertically the Upper Miocene-Middle Pliocene Türkbelkavak Formation and the Plio-Quaternary Kızılören Formation by about 200 m. Some morphotectonic features such as well-developed triangular facets, sudden break in slopes, fault parallel alignments, actively growing alluvial fans, cold and hot water springs, tectonic juxtaposition of older Türkbelkavak Formation with Quaternary alluvial deposits altogether reveal the existence and activity of the Kaymakçı section of the Devederesi fault zone (Figure 43). The eastern margin of the Kali sub-graben is determined and controlled by the Kabakır Sub-horst and its western margin boundary fault, namely, Kali section of the Devederesi fault zone (Appendix-I & Figure 43). It is an about 0.5- to 2-km-wide, ~8- km-long predominantly NNE-SSW-trending active zone of deformation in the nature of oblique-slip normal. faulting.

The Kali section of fault zone consists of a number of parallel to sub-parallel, closely spaced active oblique-slip normal fault segments. They cut both the Plio-Quaternary and Quaternary fluvial deposits and tectonically juxtapose them with each other. The fault-controlled drainage system (e.g., the Kali stream) triangular facets, fault terraced deposits and sudden break in slope are common criteria indicating the existence of the Kali section of the Devederesi fault zone. In addition, it was reactivated and caused the development of surface ruptures during 2002, February 3 Çay earthquake (Dirik, 2002; Emre et al., 2003; Ulusay et al., 2004; Koçyiğit & Deveci, 2007). Consequently, the Kali section of the Devederesi fault zone is an also active structure.

3.3. Relay Ramps

One of the structures observed during the field work is ralay ramp. If two segments of a fault dip in the same direction, the transfer zone between them is called as a synthetic transfer zone (Morley et al., 1990) or a relay ramp (Larsen, 1988; Peacock and Sanderson 1991, 1994; Çiftçi & Bozkurt, 2007; Çiftçi, 2007)

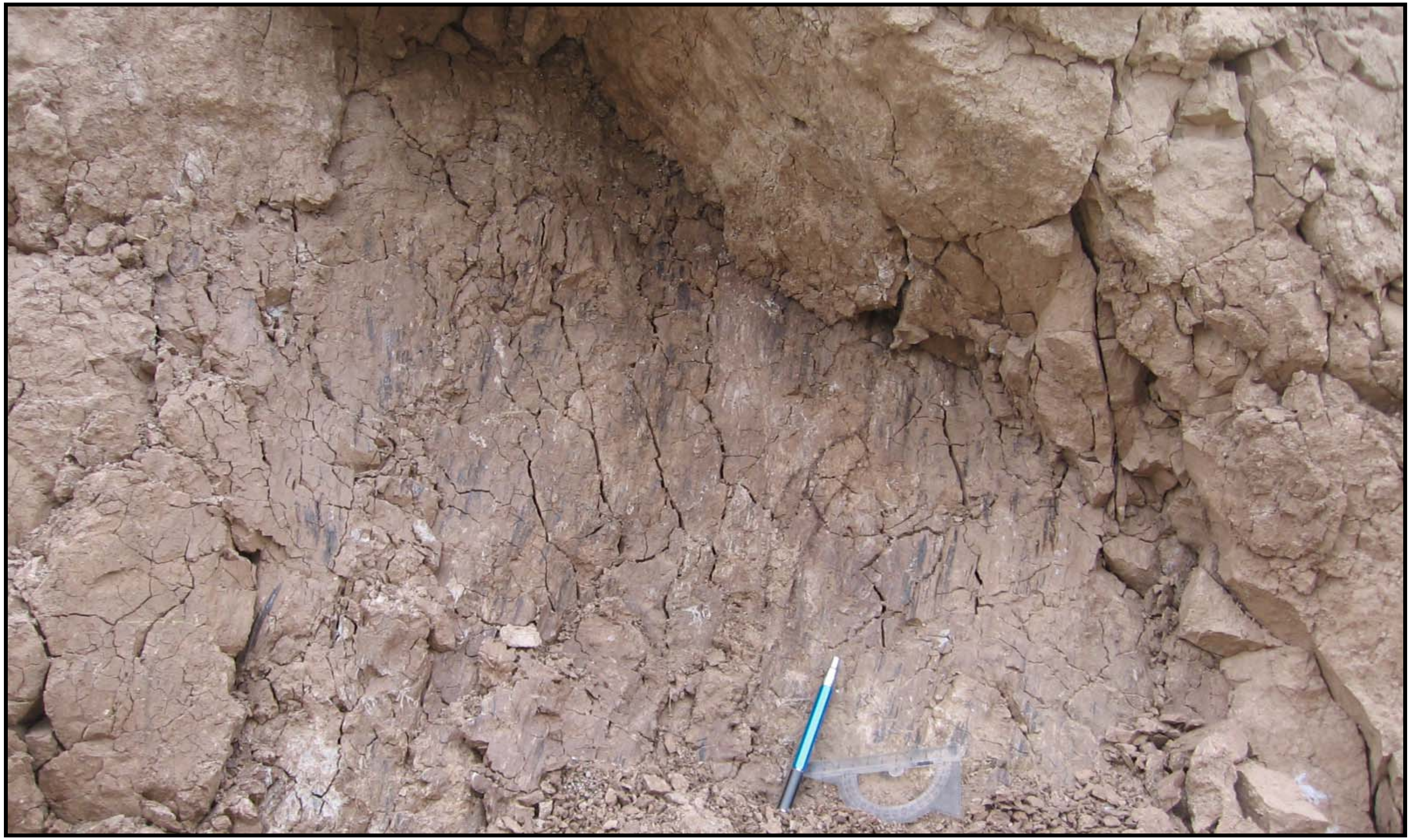


Figure 41. Close-up view of conjugate slickensides of the Devederesi fault zone (station 14 in Appendix-**I**).

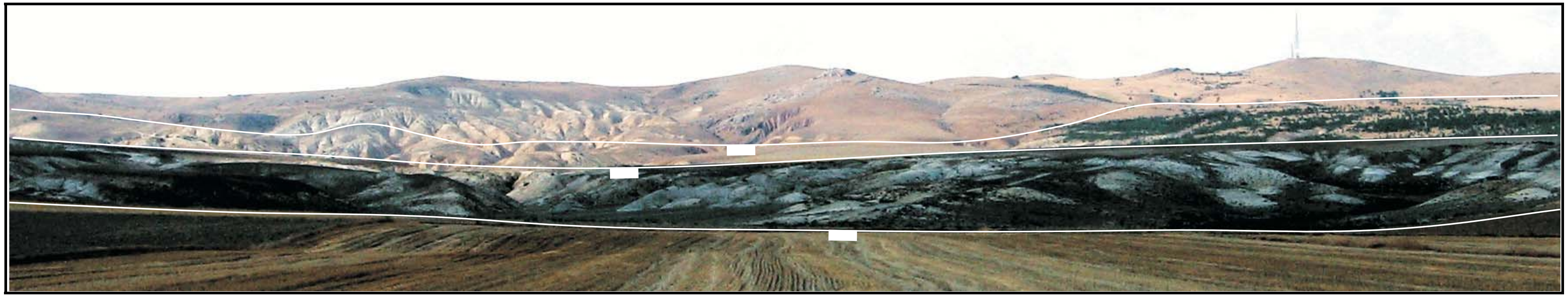


Figure 42. General view of the Kılıçyaka-Bulanık section of the Devederesi fault zone (view to NW)

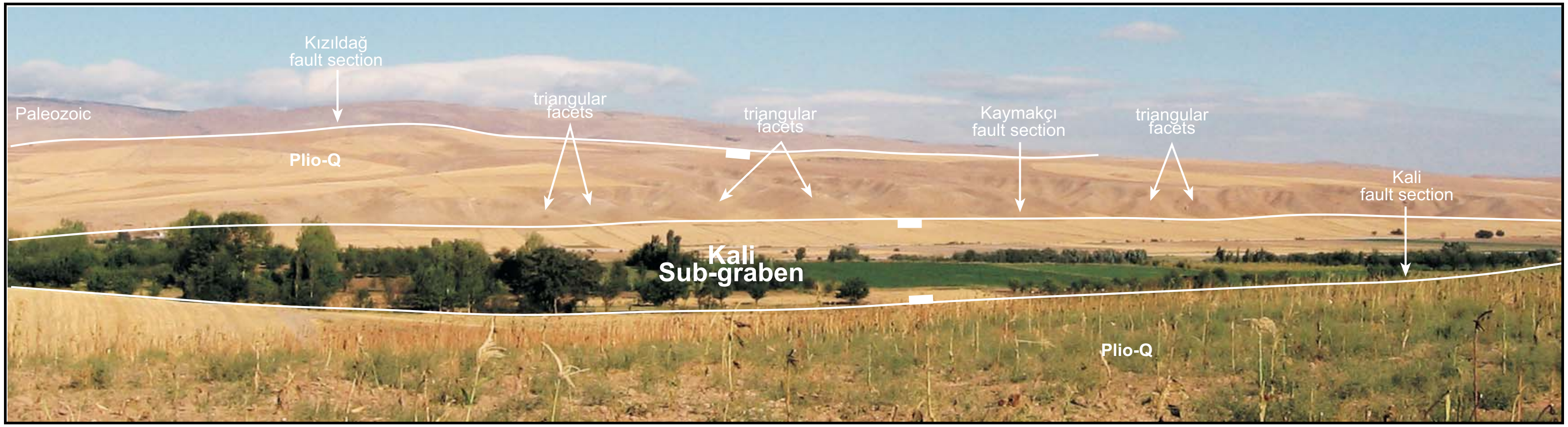
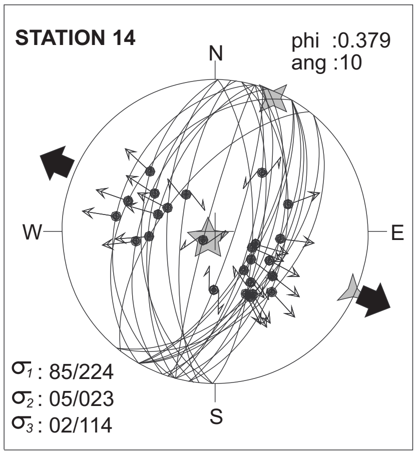


Figure 43. General view of the Kali sub-graben and northern part of the Devederesi fault zone (view to NW).

a) STATION 14

No	Strike	Dip	Rake
1	N15E	55SE	85N
2	N30E	68SE	85N
3	N40E	45SE	85S
4	N30E	51SE	73N
5	N-S	50W	60N
6	N10E	52SE	70N
7	N30E	66SE	80S
8	N08E	54NW	75N
9	N38E	62NW	67S
10	N30E	40NW	82S
11	N18E	80SE	60S
12	N15E	35NW	85S
13	N20E	50NW	72S
14	N-S	64W	78N
15	N15E	58NW	90
16	N30E	57SE	90
17	N18E	67SE	82S
18	N06E	72NW	72N
19	N40E	52SE	78S
20	N-S	70E	82S
21	N10E	65SE	67S
22	N30E	54SE	70S
23	N20E	61SE	65S
24	N15E	71SE	53N
25	N15E	85NW	84S

b)



c) STATION 15

No	Strike	Dip	Rake
1	N15E	55SE	85N
2	N30E	68SE	85N
3	N40E	45SE	85S
4	N30E	51SE	73N
5	N-S	50W	60N
6	N10E	52SE	70N
7	N30E	66SE	80S

☆ = σ_1: principal stress axis
= σ_2 : moderate stress axis
△ = σ_3: least stress axis
⬅➡ = local extension direction

d)

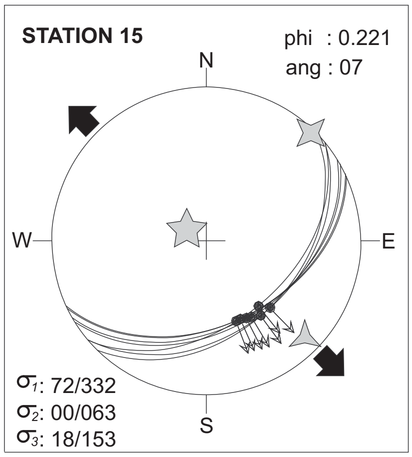
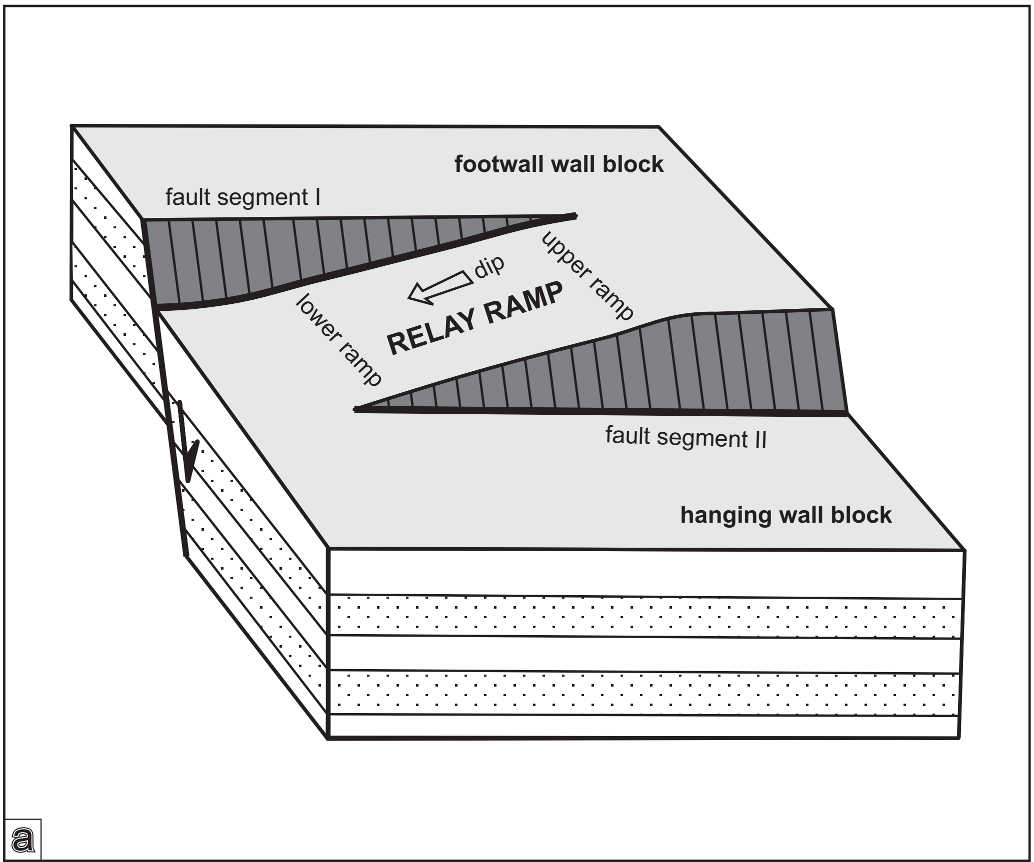


Figure 44. a) Slip-plane data measured on slickenside of faults comprising the Devederesi fault zone at station 14 in Appendix-I, **b)** stereographic plots of slip-plane data measured on station 14 in Appendix-I on Schmidt lower hemisphere net, **c)** Slip-plane data measured on slickenside of faults comprising the Devederesi fault zone at station 15 in Appendix-I, **d)** stereographic plots of slip-plane data measure on station 15 in Appendix-I on Schmidt lower hemisphere net, large black arrows show localized extension direction.



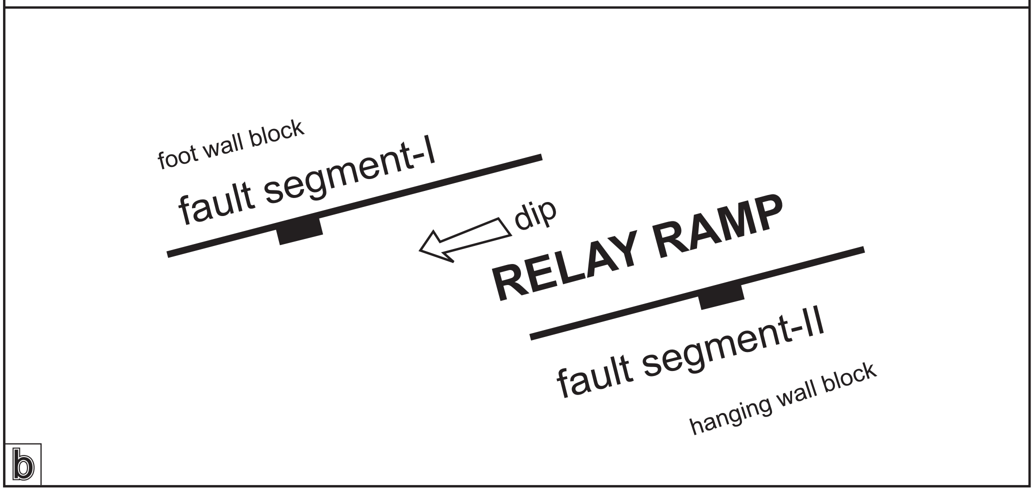


Figure 45. a) Block diagram of two over-stepping normal fault segments dipping in the same direction from (Larsen, 1988; Peacock and Sanderson, 1991; 1994; Çiftçi, 2007). **b)** Map view of the block diagram above. Displacement among the fault segments is transferred by the formation of a relay ramp.

(Figure 45). They are the locies of local stresses. In general, some are mapable while some are not in the field (Çiftçi & Bozkurt, 2007). There are some mappable-scale relay ramps which were observed and mapped (Appendix-I) during this study. The most diagnostic of those are Bulanık relay ramp, Aşağıdevederesi relay ramp A and Aşağıdevederesi relay ramp B, Kızıldağ relay ramp, Armutlu relay ramp A and Armutlu relay ramp B. The first four lie along the Devederesi fault zone whereas the last two are located along the Armutlu section of the Karacaören fault zone (Appendix-I).

CHAPTER 4

EVOLUTIONARY HISTORY OF THE KARAMIK GRABEN

New field-based stratigraphic and structural data presented in aforementioned chapters have allowed us to interpret and reveal the episodic evolutionary history of the Karamık Graben. The Karamık Graben is a superimposed basin as evidenced by two different graben infills, separated from one another by an intervening angular unconformity. (1) Older and deformed (folded to strike-slip faulted) graben infill, (2) younger and undeformed (nearly flat-lying) graben infill or modern graben infill. The older graben infill is composed of mainly the Lower Miocene to Middle Miocene volcano-sedimentary succession, the Middle Miocene Afyon strato-volcanic complex, the Upper Miocene-Middle Pliocene fluvio-lacustrine sedimentary sequence underlain with an angular unconformity by the Paleozoic metamorphics, the pre-Mesozoic platform carbonates, and the Cretaceous-Eocene ophiolithic mélange nappes (Koçyiğit, 1983). On the other hand, the younger graben infill rests with an angular unconformity on the erosional surface of the various deformed rocks of pre-Late Pliocene age. It consists mainly of the Plio-Quaternary terrace conglomerates (Kızılören Formation), older and younger superimposed alluvial fans of Quaternary age, fan-apron deposits, and recent axial plain sediments of the Karamık Graben.

The volcano-sedimentary sequence of the Akın Formation was started to be deposited in a lowland area in the nature of fluvio-lacustrine depositional system comprising the initial outline of the Karamık Graben under the control of extensional tectonic regime during the Late Early Miocene-Middle Miocene (A in Appendix-II). Later on, it was accompanied by the Afyon volcanic activity starting form the Middle Miocene. Thus, the sedimentary packages of the Akın Formation were succeeded by the alternation of both volcanics and sedimentary beds, resulting in a volcano-sedimentary sequence. This comprises the main bulk of the Akın Formation. Onwards, the volcanic activity became predominant, and from one hand it interrupted the sedimentation, in places, from other hand accumulated the very thick lavas, domes and pyroclasts comprising the Afyon strato-volcanic complex in the time slice of Middle to Late Miocene (A in Appendix-II). The sedimentation continued predominatingly starting from Late Miocene to Middle Pliocene. During this time lacustrine environment was enlarged into its maximum size and it transgressed towards land in the nature of onlaps. Therefore, the thick-bedded to massive and very porous carbonates of the Türkbelkavak Formation was deposited with partly transitional and partly erosional contact relationship with both the Akın Formation and the Afyon strato-volcanic complex as in the case of Işıklar area (A in Appendix-II). The origin of the Phase-I extension is thought that it was caused by : (1) the crustal thickening of the southwestern Anatolian lithosphere and orogenic collapse (Dewey, 1988; Seyitoğlu & Scott, 1992), (2) back arc extension in conjunction with roll-back process in southwest Aegean lithosphere (Le Pichon & Angelier, 1979; Meulenkamp et al., 1988) (3) the combination of both the orogenic collapse and roll-back processes related to slab tear (Wortel & Spakman, 2000).

Starting from the end of Early Pliocene, possibly from Middle Pliocene, the phase-I extension was replaced by a contractional tectonic regime, by which the early formed formations and the incipient configuration of the major Karamık Graben were deformed. This has been proved by a series of mappable folds (anticlines to synclines) and strike-slip faults developed in the Akın Formation, the Afyon strato-volcanic complex, and the Türkbelkavak Formation (B in Appendix-II). Accordingly the deformed area was uplifted, started to experience the sub-aerial conditions, and eroded partly (B in Appendix-II). The origin of this short-term contraction may be the change in both the plate configurations and their motion sense (Koçyiğit, 2005).

Starting from the latest Pliocene, the short-term contractional period was replaced by a new extensional neotectonic regime (phase-II extension) which is still lasting neotectonic regime in southwestern Turkey. The early formed and deformed major Karamık Graben and its diagnostic elements such as basin infill (older graben infill) and margin faults have been redeformed by the extensional neotectonic regime and related normal faults. Accordingly, the major Karamık Graben and its surrounding area started to subside along both the reactivated older normal faults and newly formed normal faults. This has resulted in a relatively small but more than one modern graben originated from the fragmentation of the major and large Karamık Graben. At the same time from one hand, older and deformed graben was uplifted, dissected and inverted to fault perched-terraces at higher elevations along the present day modern graben margin, from other hand, the modern graben infill (the Plio-Quaternary Kızılören Formation and Quaternary sediments) were deposited on the erosional surface of pre-Upper Pliocene rocks within the small and narrow throughs or incipient modern graben (C in Appendix-II). The evolution of the modern graben, sedimentation in them, and activity along their margin-boundary faults are still lasting under the control of phase-II extension (neotectonic regime) since Latest Pliocene (~2.6 M.a). These are indicated by the Late Pliocene age of lowermost unit of the modern graben infill, a series of aforementioned morphotectonic criteria for recognition of faults and reactivation of the northern part of the Karamık Graben during 2002.02.03 Çay earthquake.

CHAPTER 5

DISCUSSIONS

First of all, the main scope and aim of this thesis are to illuminate neotectonic development of the Karamık Graben located in Lakes district sub-domain of the SW Turkey extensional major neotectonic domain (Figure 2). Newly obtained and presented raw data in foregoing chapters were analyzed, discussed and a development model for the Karamık Graben has been suggested so as to contribute to the commencement age of the neotectonic period, deformation mode, structural properties and seismicity of the Karamık Graben.

In order to understand, the source of the latest phase of deformation, first of all the latest paleotectonic and the neotectonic units in the study area were mapped in detail at a 1/25000 scale, 182 slip-plane data on slickenside of margin boundary faults were measured and analyzed. Regional stratigraphic correlations, deformation in terms of field geological mapping, measured stratigraphical columnar section and analysis of faults reveal that the Karamık Graben has an episodic evolutionary history accompanied by multiphase of deformation, namely the Miocene phase-I extension, the Middle Miocene contraction and the Plio-Quaternary phase-II extension or extensional neotectonic period (Appendix-II). Hence, the regional compression/contraction is diachronic and presumably related to the diachronic effect of the intraplate interaction (Özacar, 2001). Complex character of the SW Turkey extensional domain has attracted both national and international researches from almost all branches of geology. Its origin, age, mode has become the core of many hot debates particularly since 1970's. Up to now, seven prominent models have been proposed in order to explain the extensional tectonic regime of SW Turkey. (1) *The tectonic escape (extrusion) model* (Dewey & Şengör, 1979): the extension in SW Turkey is originated as a result of Intracontinental collision between Eurasian plate to the north, Arabian plate to the south, and related escape of Anatolian platelet along the North Anatolian and East Anatolian fault systems since Serravalian. (2) *back-arc spreading model* (Le Pichôn & Angelier, 1979; Meulenkamp et al. 1988)*:* the migration of the trench system to the south and southwest gave rise to an extensional regime in the back-arc region in the Hellenic arc. (3) *Orogenic collapse model* (Dewey, 1988; Seyitoğlu & Scott, 1991; Seyitoğlu & Scott, 1996 a, b; Seyitoğlu et al., 2002): the extension has been taking place in relation to the cessation of the Paleogene shortening as a consequence of over-thickening of SW Turkey lithosphere since Late Oligocene-Early Miocene and still continues. (4) *Episodic two-stage extension model with intervening contraction* (Koçyiğit et al., 1999; Koçyiğit et al., 2000; Bozkurt, 2002; Koçyiğit & Özacar, 2003; Koçyiğit, 2005; Bozkurt & Sözbilir, 2004; Bozkurt & Rojay, 2005; Beccaletto & Steiner, 2005 and Koçyiğit & Deveci, 2007) extensional regime is not continuous since Late Oligocene-Early Miocene; instead, in the development history of SW Turkey graben horst system, the extension occurred in two phases separated by a short-lived contractional phase. *Phase-I* extension is restricted to Early Miocene to Early Pliocene and issued from the orogenic collapse while *Phase-II* (current) extension is dominated by tectonic escape of Anatolian platelet and roll back process in the South Aegean (western Cyprus) trench since Late Pliocene. The short-lived intervening contractional phase is thought to prevailed in a time slice of Middle Miocene-Middle Pliocene (Koçyiğit & Özacar, 2003; Koçyiğit, 2005; Koçyiğit & Deveci, 2007). (5) *Two stage extension separated by an intervening erosional period model* (Yılmaz et al., 2000). (6) *Pulsed-extension model:* According to the model, the extension is continuous since Late Oligocene to recent time; not separated by short-term compression (Purvis & Robertson, 2004 and 2005). However, the regime pulsed two-times. The extension commenced in Late Oligocene under the control of the N-S extension, which was phase-I extension induced by the roll-back processes. It caused the development of depressions. Later on, the phase-I extension was pulsed (pulse-I) by the roll-back processes in the eastern Mediterranean subduction zone during Late Early Miocene-Late Miocene (?) time interval. This was followed by the degradation of the phase-II extension and pulsed (pulse-II) into the present day extensional stage (phase-III extension) as a consequence of the westward extrusion of the Anatolian Platelet during the Plio-Quaternary time which is still active. Very similar view is followed by (Alçiçek et al., 2006; Alçiçek, 2007). The basic difference between the former and later followers of the similar model is the timing of the pulses. (7) *Differential plate velocities model* (Doglioni et al., 2002): It is interpreted that the extension in Western Turkey and Aegean is issued from differential plate velocities between Greece and Turkey. The model discusses that the relatively rapid southwestward motion of Greece with respect to Anatolia has given to the emergence extension in the Aegean and adjacent areas.

When the tectonic development of the Karamık Graben is considered in the context of the models aforementioned. It fits well to the model 4 (i.e. two stage extension separated by intervening compression model of (Koçyiğit et al., 1999)).

It is important to note that initiation of the neotectonic regime through apex of the Isparta Angle is discussed in detail by (Koçyiğit at al., 2000; Koçyiğit & Deveci, 2007). They agreed that the initiation age of the neotectonic regime is Late Pliocene. These inferences fit well to the initiation age of the neotectonic regime in the Karamık Graben. Hence, it is once supported that the initiation age of the neotectonic regime in the apex of the Isparta Angle is late Pliocene.

CHAPTER 6

CONCLUSION

Under the light of both literature survey and the newly obtained field data the followings are inferred.

(1) The tectonic development of the Karamık Graben fits well with the episodic two-stage extension model (Koçyiğit et al., 1999). Both the stereographic plots of the folds and conjugate strike-slip faults support the view that the extension is episodic in nature. In the same way, the available data implies that the principal compression operated in NE-SW direction in the study area. Moreover, the stratigraphic and structural data presented above also support that the neotectonic period or current phase of extension (phase-II extension) has commenced in Late Pliocene time and it is still lasting in the apex of the Isparta Angle.

(2) In order to determine the multi-phase deformation, the structural features bounding the Karamık Graben were classified on the basis of their age. As a consequence of these, it has been concluded that the deformation is distributed (multi-directional). It is predominatingly NE-SW, NW-SE- and NNE-SSW-directions (Appendix-II).

(3) Activity of the margin boundary faults has been proved by a series of morphotectonic features such as deeply incised valleys, fault parallel Quaternary alluvial fans, fresh fault scarps, dissected and terraced Quaternary fan-apron deposits (fault terraces), recent seismicity (the February 3, 2002 Afyon-Çay earthquake) and related surface ruptures, in particular, in the northern portion of the Karamık Graben. Because of this, active Kali stream is controlled currently by normal faults.

(4) New slip-plane data picked up during the field studies show that the faults are oblique-slip in character with minor amount of both sinistral and dextral components. The extension direction is distributed (multi-directed) with dominantly NW-SE and NE-SW directions in character. It is thought that this multi-directed extension has probably close relationship with the lower φ ($\varphi = \sigma_2 - \sigma_3 / \sigma_1 - \sigma_3$) values (Figure 30, 31, 35, 40 & 44) (Angelier, 1994; Çiftçi & Bozkurt, 2006;

Çiftçi, 2007; Çiftçi & Bozkurt, 2008). Therefore, it is thought that the multi-directed extension has relationship with the stress permutation between σ_2 and σ_3.

(5) The total throw amounts accumulated along the southern and western margin boundary faults of the Karamık Graben are ~400 m and ~550 m since Late Pliocene, respectively. Hence, these results yield maximum subsidence rates of ~0.15 mm/yr and ~0.21 mm/yr since Late Pliocene.

(6) The settlements situated on the unconsolidated sediments or along the active margin-boundary faults of the Karamık Graben (Appendix-I) are under the threat of earthquake hazards.

REFERENCES

Alçiçek M.C. Ten Veen J.H. Özkul M. 2006. Neotectonic development of the Çameli Basin, southwestern Anatolia, Turkey. In: Robertson, A.H.F., Mountrakis, D. (Eds.), Tectonic Development of the Eastern Mediterranean Region. *Geological Society of London, Special Publication*, vol. 260, pp. 591-611

Alçiçek M.C. 2007. Tectonic development of an orogen-top rift recorded by its terrestrial sedimentation pattern: the Neogene Eşen Basin of southwestern Anatolia, Turkey. *Sedimentary Geology* 200, 117-140.

Angelier, J., 1989, Data base for tectonic orientations "Tector" Version 5.42, aug87-oct88-dec88-aou89 Copyright 1987, 1988, 1989.

Angelier, J., 1990, Inversion of field data in fault tectonics to obtain the regional stress. III. A new rapid direct inversion method by analytical means: *Geophysical Journal International*, v. 103, p. 363−376.

Angelier, J., 1994. Fault slip analysis and paleostress reconstruction. In: Hancock, P.L. (Ed.), Continental Deformation. *Pergamon Press*, Oxford, pp. 53–100.

Atalay, İ., 1973. Akşehir, Eber ve Karamuk Gölleri havzalarının Kuvaterner depoları ve jeomorfolojisi [Quaternary deposits and geomorphology of the Akşehir, Eber and Karamuk Lakes]. *Cumhuriyetin 50. Yılı Yerbilimleri Kongresi*, 365-385.

Atalay, İ. 1975. Tektonik hareketlerin Sultandağı jeomorfolojisine olan etkileri [The effects of tectonic movements on the geomorphology of Sultandağı]. *Geological Society of Turkey Bulletin* **18,** 21–26 .

Aydar, E., Bayhan, H. & Zimitoğlu, O. 1996. Investigation of volcanological and petrological evolution of Afyon stratovolcano. *Earth Sciences* **18**, 87–107.

Akal, C. 2002. Mineralogy and Geochemistry of Melilite Leucitites, Balçıkhisar, Afyon, (Turkey). *Turkish Journal of Earth Sciences* **12**, 215–239.

Akan, B. 2003. Afyon Ömer-Gecek jeotermal sisteminde re-enjeksiyon uygulamalarının rezervuar sıcaklığı üzerine etkilerinin modellenmesi [Modelling the influence of re-enjection application on reservoir temperature in Afyon Ömer-Gecek geothermal system] *Yerbilimleri* **28,** 81-97.

Akyüz, H. S., Uçarkuş, G., Şatır, D., Kozacı, Ö., Dikbaş, A. & Birinci, B. 2006. Çay depremi (3 Şubat 2002, Mw = 6.2) yüzey kırığı üzerinde Paleosismoloji çalışmaları [Paleoseismological investigations on the Çay earthquake (2002, 02, 03, Mw = 6.2) surface rupture]. Aktif Tektonik Araştırma Grubu 6. Toplantısı (ATAG-6), Abstract, p.96 .

Barka, A.A., Reilinger, R.E., Şaroğlu, F. & Şengör, A.M.C. 1995. Isparta Angle: Its importance in the noetectonics of the Eastern Mediterranean Region. In: Pişkin, D., Ergün, M., Savaşçın, M.Y. & Tarcan, G. (eds.), International Earth Science Colloquium on the Aegean Region, Proceedings. 3–18.

Başokur, A. T., Gökten, E., Seyitoğlu, G., Varol, B., Ulugergerli, U. E., Işık, V., Candansayar, E. & Toksöz, E. 2002. Jeolojik ve jeofizik çalışmalar ışığında 03.02.2002 Çay (Afyon) depreminin mekanizması, hasarın nedenleri ve bölgenin deprem etkinliği [Mechanism of the 2002.02.03 Çay (Afyon) earthquake, causes of damage and seismicity of region under the light of geological and geophysical studies] Ankara Üniversitesi Mühendislik Fakültesi Araştırma Raporu, 56 s. .

Beccaletto, L., and Steiner, C., 2005. Evidence of two-stage extensional tectonics from the northern edge of the Edremit Graben, NW Turkey: *Geodinamica Acta*, v. 18, p. 283–297.

Becker-Platen, J.D, Benda, L., and Steffens, P., 1977, Litho- und biostratigraphische Deutung radiometrischer Altersbestimmingun aus dem Jungtertiar der Türkei. *Geol. Jb.,* B25, 139-167

Benda, L., 1971, Grundzüge einer pollenanalytischen Gliederung des türkischen Jungtertiars. *Beih. Geol. Jahrb.,* 113, 45 p.

Bering, D., 1967. Afyon-Sandıklı Meridyonel havzasının linyit etüdü, MTA Report No: 2186, Ankara.

Besang, C., Eckhardt, F.C., Harre, W., Kreuzer, H. & Muller, P. 1977. Radiometriche Altersbestimungen an Neogenen Eruptivgesteinen der Turkei. *Geologischen Jahrbuch Reihe* B 25, 3–36.

Boray, A., Şaroğlu, F. & Emre, Ö. 1985. Isparta Büklümünün kuzey kesiminde D–B daralma için bazı veriler [Evidence for E–W shortening in the north of the Isparta Angle]. Bulletin *of Chamber of Geological Engineers* **23**, 9 – 20 .

Bozkurt, E., 2002, Discussion on the extensional folding in the Alaşehir (Gediz) Graben, western Turkey: *Journal of Geological Society London*, v. 159, p. 105-109.

Bozkurt, E., and Sözbilir, H., 2004, Tectonic evolution of the Gediz Graben: field evidence for an episodic, two-stage extension in western Turkey: *Geological Magazine*, v. 141, p. 63–79.

Bozkurt, E., and Rojay, B., 2005, Episodic two-stage Neogene extension and short-term intervening compression in western Anatolia: field evidence from the Kiraz basin and Bozdağ horst: *Geodinamica Acta*, v. 18, p. 299−316.

Çevikbaş, A., Ercan, T. & Metin, Ş. 1988. Geology and regional distribution of Neogene volcanics between Afyon and Şuhut. *Journal of Pure and Applied Sciences* **21**, 479 –499.

Çiçek, A., & Koçyiğit, A., 2008. A NNE-SSW-trending active graben in the Isparta Angle, SW Turkey: Karamık Graben, its geometry, age and earthquake potential. International Meeting of Young Researchers In Structural Geology and Tectonics Conference Book, *extended abstract*, 223-228.

Ciftci, B.N., and Bozkurt, E., 2006, Gediz Grabeninin normal fay dokusu ve faylanmayı kontrol eden stres rejimi. 10. ATAG Meeting of Turkey, *abstract* p. 16-17.

Ciftci, B.N., and Bozkurt, E., 2007, Anomalous stress field and active breaching at relay ramps: A field example from Gediz graben, SW Turkey: *Geological Magazine*, 144 (4), 2007, pp. 687–699. doi:10.1017/S0016756807003500

Çiftçi, B.N., 2007. Geological Evolution of the Gediz Graben, SW Turkey: Temporal and Spatial Variation of the Graben. PhD Thesis, Middle East Technical University, Turkey. 290 pp.

Çiftçi, N.B., Bozkurt, E., 2008. Pattern of normal faulting in the Gediz Graben, SW Turkey, *Tectonophysics*, doi:10.1016/j.tecto.2008.05.036.

Çuhadar, G. 1977. Akarçay Havzası Hidrolojik Etüt Raporu [Akarçay Basin Hydrological Investigation Report]. General Directorate of State Hydrolic Works (DSİ). 64 pp. .

Demirkol, C., & Yetiş, C., 1985, Sultandağ kuzeybatısındaki allokton birimler ve jeolojisi: [Allocthonous units in the northwest of Sultanmountains and thier geology] *Geological Enginnering Bulletin of Turkey*., 22, 3-11.

Dewey, J.F. ve Şengör, A.M.C., 1979, Aegean and surrounding regions complex multiplate and continuum tectonics in a convergent zone: *Geol. Soc. Am. Bül.,* 90, 84-92.

Dewey, J.F., 1988, Extensional collapse of orogens: *Tectonics*, v. 7, p. 1123-1139.

Dinç, 2003. Afyon-Sultandağı bölgesi hız yapısının yerel deprem tomografisi yöntemi ile belirlenmesi. İstanbul Teknik Üniversitesi [Determination of the velocity structure of the Afyon-Sultandağı region with local tomography method], Natural and Applied Science, Master Thesis, 77 p.

Dirik, K. 2002. Akarçay (Afyon) havzasının tektoniği ve Çay-Afyon (03.02.2002) depreminin önemi [Tectonics of Akarçay (Afyon) basin and significance of the Çay – Afyon (2002.02.03) earthquake] Aktif Tektonik Araştırma Grubu 6. Toplantısı (ATAG-6), Abstract, 32 – 33 .

Doglioni, C., Agostini, S., Crespi, M., Innocenti, F., Manetti, P., Riguzzi, F. & Savaşçın, Y. 2002. On the extension in western Anatolia and the Aegean Sea. *Journal of Virtual Exploration*, 8, 169–183.

Doğdu, M.Ş. & Bayarı, C.S. 2002a. Akarçay Havzası'nda (Afyon) jeotermal kökenli kirlenme: 1.Akarçay Nehri'nde su ve sediman kirliliği [Pollution of geothermal origin in the Akarçay basin (Afyon, Turkey): 1. water and sediment pollution in the Akarçay River]. *Hacettepe Üniv. Yerbilimleri* **25**, 21 – 33 .

Doğdu, M.Ş. & Bayarı, C.S. 2002b. Akarçay Havzası'nda (Afyon) jeotermal kökenli kirlenme: 2. yeraltısuyu kirliliği [Pollution of geothermal origin in the Akarçay basin (Afyon, Turkey): 2. groundwater pollution]. *Hacettepe Üniv. Yerbilimleri* **25**, 35 – 49 .

Dumont, J.F. 1976. Isparta kıvrımı ve Antalya Naplarının orijini: Torosların Üst Kretase tektojenesi ile oluşmuş yapısal düzeninin büyük bir dekroşman, transtorik arızayla ikiye ayrılması varsayımı [The origin of Isparta Angle and Antalya nappes]. *General Directorate of Mineral Research and Exploration (MTA) Bulletin* 86, 56-57 .

Emre, Ö., Duman T.Y., Doğan, A., Özalp, S., Tokay, F., and Kuşçu, i., 2003. Surface Faulting Associated with the Sultandağ Earthquake (Mw=6.5) of 3 February 2002, Southwestern Turkey. *Seismological Research Letters*, v. 74, n.4, p.382-392.

Ercan, E., Dinçel, A., Metin, S., Türkecan, A. ve Günay, A. 1978. Uşak yöresindeki Neojen havzalarının jeolojisi [Geology of the Neogene basins in Uşak region]. *Bulletin of the Geological Society of Turkey*, 21, 97–106.

Erdoğan S., Şahin M., Tiryakiğoğlu İ., Gülal E., and Telli A. K., 2009. GPS Velocity and Strain Rate Fields in Southwest Anatolia from Repeated GPS Measurements . *Sensors*, 9, 2017-2034; doi:10.3390/s90302017.

Ergin, M., Aktar, M., Özalaybey, S., Tapirdamaz M.C., Selvi, O. And Tarancıoğlu, A., 2009. A high-resolution aftershock seismicity image of the 2002 Sultandağı-Çay earthquake (Mw = 6.2), Turkey. *Journal of Seismology* (in press)

Erişen, B. 1972. Afyon-Heybeli (Kızılkilise) jeotermal araştırma sahasının jeolojisi ve jeotermal enerji olanakları [Geology and geothermal energy potentials of the Afyon-Heybeli geothermal investigation area]. Mineral Research and Exploration Directorate (MTA) Report No. 5490, 73 p.

Flecker, R., Poisson, A. & Robertson, A.H.F. 2005. Facies and palaeogeographic evidence for the Miocene evolution of the Isparta Angle in its regional eastern Mediterranean context. *Sedimentary Geology* 173, 277–314.

Gökçe, 1998. Neotectonic and Seismicity of the Western Margin of the Sandıklı Graben, M. Sc Thesis, Department of Geological Engineering, METU 103 pp.

Gökten, E., Seyitoğlu, G., Varol, B. and Işık, V., 2003. 03.02.2003 Çay (Afyon) depreminin mekanizması ve bölgenin sismik riski. *Kocaeli Deprem Sempozyumu*. p. 55-62.

Gutnic, M., Monod, O., Poisson, A., and Dumont, J. F., 1979. Geologie des Taurides occidentales (Turquie). *Mémoires Société Géologie de France*, 137, 112 p.

Kalafat, D., Kara, M., Öz, G., Kekovalı, K., Güneş, Y., Özel, N., Öğütçü, Z., Kılıç, K., Püskülcü, S., Horasan, G., Güngör, A., Yılmazer, M., Köseoğlu, A., Görgün, E., Kılıçer, F. B., Gümüşer, H., Ölmez, Y., Çomoğlu, M., Berberoğlu, A., Deniz, P., Kafadar, N. & Suvarıklı, M. 2002. 3 Şubat 2002 Sultandağı (Afyon) depremi raporu [2002.02.03 Sultandağı (Afyon) earthquake report] Boğaziçi Üniversitesi Kandilli Rasathanesi ve Deprem Araştırma Enstitüsü, 51p .

Keller, J. & Villari, L. 1972. Rhyolitic ignimbrites in the region of Afyon (Central Anatolia). *Bulletin of Volcanology* 36, 342–358.

Kissel, C., Averbuch, S., Frizon de Lamotte, D., Monod, O. & Allerton, S., 1993. First palaeomagnetic evidence for a post-Eocene clockwise rotation of the Western Taurides thrust belt east of the Isparta angle (southwestern Turkey). *Earth and Planetary Science Letters*, **117**, 1–14.

Koçyiğit, A., 1980, Hoyran gölü yöresinin (Afyon - İsparta) stratigrafik ve tektonik özellikleri : Ankara Üniv. Fen Fakültesi, Genel Jeol. Kurs., Doçentlik tezi, 172 s. (Unpublished).

Koçyiğit, A., 1983. Hoyran Gölü (Isparta Büklümü) Dolayının Tektoniği. *Bulletin of the Geological Society of Turkey*. 26, 1-10 p.

Koçyiğit, A., 1984a. Tectono-stratigraphic characteristics of Hoyran Lake region (Isparta Bend). In: TEKEL., O & Göncüoğlu, C. (eds), Geology of the Taurus Belt. International Symposium, 26–29 September 1983, Ankara-Turkey, Proceeding, 53–67.

Koçyiğit, A.1984b. Güneybatı Türkiye ve yakın dolayında levha içi yeni tektonik gelişim [A new intracontinental tectonic regime in southwest Turkey and its close vicinity]. *Bulletin of the Geological Society of Türkey* **27**, 1 – 16 .

Koçyiğit A. 1996. Superimposed basins and their relations to the Recent strike-slip fault zone: a case study of the Refahiye superimposed basin adjacent to the North Anatolian Transform Fault, northeastern Turkey. *Int. Geol. Rev.* 38: 701–13.

Koçyiğit, A., Yusufoğlu, H. ve Bozkurt, E. 1999. Evidence from the Gediz graben for episodic two-stage extension in western Turkey. *Journal of the Geological Society, London* 156, 605−616.

Koçyiğit A., Ünay, E. & Saraç, G. 2000. Episodic graben formation and extensional neotectonic regime in west Central Anatolia and the Isparta Angle: a key study in the Akşehir ─ Afyon graben, Turkey. *Geological Society, London, Special Publication* **173**, 405 ─ 421.

Koçyiğit, A. & Özacar, A. 2003. Extensional Neotectonic Regime through the NE Edge of the Outer Isparta Angle, SW Turkey: New field and seismic Data. *Turkish Journal of Earth Sciences* 12, 67–90.

Koçyiğit, A. & Deveci, Ş. 2005 (a). Akşehir-Simav fay sistemi: güneybatı Türkiye'de neotektonik rejimin başlama yaşı ve depremsellik [Akşehir-Simav fault system: initiation age of the neotectonic regime and seismicity in the southwestern Turkey. Deprem Sempozyumu Kocaeli 2005. *Abstracts Book* s.26 .

Koçyiğit, 2005. The Denizli graben-horst system and the eastern limit of western Anatolian continental extension: basin fill, structure, deformational mode, throw amaount and episodic evoltionary history, SW Turkey. "*Geodinamica Acta*", 18, (2005), p.167-208

Koçyiğit, A. & Deveci, Ş. 2007. A N–S-trending active extensional structure, the Şuhut (Afyon) graben: Commencement age of the extensional neotectonic period in the Isparta Angle, SW Turkey. *Turkish Journal of Earth Sciences*, **16,** 391-416.

Larsen, P.H., 1988, Relay structures in a Lower Permian basement involved extension system, East Greenland: *Journal of Structural Geology*, v. 10, p.3−8.

Le Pichon X. & Angelier, J., 1979, The Hellenic arc and Trench system: a key to the neotectonic Evolution of the Eastern Mediterranean Area: *Tectonophysics*, 60, 1-42.

Metin, S., Genç, Ş., and Bulut, V., 1987. Afyon ve Dolayının jeolojisi. MTA Report No: 8103 [Geology of Afyon and close vicinity] (Unpublished) .

Meulenkamp, J.E., Wortel, M.J.R., Van Wamel, W.A., Spakman, W. & Stratıng, E.H. 1988. On the Hellenic subduction zone and the geodynamic evolution of Crete since the late Middle Miocene. *Tectonophysics*, 146, 203-215.

Morley, C. K., Nelson, R. A., Patton, T. L., and Munn, S. G., 1990, Transfer zone in the East African rift system and their relevance to hydrocarbon exploration in rifts: *American Association of Petroleum Geologists Bulletin*, v. 74, p. 1234-1253

Özacar, A., 2001. The Neotectonic Characteristics of Dombayova graben MSc thesis. Middle East Technical University 107 pp [Unpublished]

Özden, S., Kavak, K. Ş., Koçbulut, F., Över, S. & Temiz, H. 2002. 3 Şubat 2002 Çay (Afyon) depremleri [2002.02.03 Çay (Afyon) earthquakes]. *Geological Bulletin of Turkey* **45,** 49 – 56**.**

Özgül, N., 1976, Toroslar'da bazı temel jeoloji özellikleri: [Some essential geology properties of Taurides] *Türkiye Jeol. Kur. Bült.,* 19,65 - 78.

Peacock, D.C.P., and Sanderson, D.J., 1991, Displacements, segment linkage and relay ramps in normal fault zones: *Journal of Structural Geology*, v. 13, p. 721-733.

Peacock, D.C.P., and Sanderson, D.J., 1994, Geometry and development of relay ramps in normal fault systems: *American Associations of Petroleum Geologists Bulletin*, v.78, p. 147−165.

Piper, J., Gürsoy, H., Tatar, O., İşseven, T. and Koçyiğit, A., 2002. Palaeomagnetic Evidence for the Gondwanian Origin of the Taurides and Rotation of the Isparta Angle, Southern Turkey. *Geological Journal*, 37, p.317-336.

Poisson, A., 1977, Recherches geologiques dans les Taurides oceidentales (Turquieis) : Those d'etat., Univ. de Paris - Sud Orsay, 795 s.

Purvis, M., and Robertson, A.H.F., 2004, A pulsed extension model for the Neogene−Recent E−W-trending Alaşehir Graben and the NE−SW-trending Selendi and Gördes basins, western Turkey: *Tectonophysics*, v. 391, p. 171−201.

Purvis, M., and Robertson, A.H.F., 2005, Sedimentation of the Neogene-Recent Alasehir (Gediz) continental graben system used to test alternative tectonic models for western (Aegean) Turkey: *Sedimentary Geology*, v. 173, p. 373−408.

Saraç, G., 2003. Türkiye omurgalı fosil yatakları [Mammalian fossils localities in Turkey]. Mineral Research and Exploration Directorate (MTA). Report no. 10609, 208 pp. [unpublished].

Seyitoglu, G. & Scott, B. C., 1991. Late Cenozoic crustal extension and basin formation in west Turkey. *Geological Magazine*, 128, 155-166.

Seyitoglu, G. & Scott, B. C., 1996a. The cause of N-S extensional tectonics in western Turkey: Tectonic escape vs. Back-arc spreading vs. Orogenic collapse. *Journal of Geodynamics*, 22, 145 - 153.

Seyitoglu, G. & Scott, B. C., 1996b. Age of Alaşehir graben (west Turkey) and its tectonic implications. *Geological Journal*, 31, 1-11.

Seyitoğlu, G., Tekeli, O., Cemen, İ., Sen, S. & Işık, V., 2002. The role of the flexural rotation / rolling hinge model in the tectonic evolution of the Alasehir graben, western Turkey. *Geological Magazine*, 139, 15-26.

Sickenberg, O., Becker-Platen, J., Benda, L., Berg, D., Engesser, B., Gaziry, W., Heising, K., Hunermann, K.A., Sondaar, P.Y., Schmidtkittler, N., Staesche, U., Steffens, P. & Tobien, H. 1975. Die Geliederung des hoheren Jungtertiars und Altquartars in der Turkei nach Vertebraten und ihre Bedeutung fur die internationale Neogene-Stratigraphie. *Geologischen Jahrbuch Reihe* 15, 167p.

Şaroğlu, F., Boray, A. & Emre, Ö. 1987. Türkiye'nin aktif fayları [Active faults of Turkey] Mineral Research and Exploration Directorate (MTA) Report, no. 8643, 394 pp. (unpublished).

Tatlı, S., 1973, Afyon-Gazlıgöl-Susuz alanının jeolojisi ve jeotermal olanakları [Geology and geothermal potential of Afyon-Gazlıgöl-Susuz area] MTA Report No: 5733 (Unpublished)

Tapırdamaz, M. C., Tarancıoğlu, A., Özalaybey, S., Ergin, M., Selvi, O., Yörük, A., Biçmen, F. & Aktar, M. 2002. Sultandağı (Afyon) depremi (03 Şubat 2002, Mw = 6.2) artçı deprem çalışması [After shocks study of 2002.02.03, Mw = 6.2 Sultandağı (Afyon) earthquake]. Aktif Tektonik Araştırma Grubu 6. Toplantısı (ATAG-6), *Abstract*, 34 – 41 .

Ulusay, R., Kasapoğlu, E., Dirik, K. & Gökçeoğlu, C. 2002. 3 Şubat 2002 Sultandağı (Afyon) depremi ve saha inceleme raporu [2002.02.03 Sultandağı (Afyon) earthquake and field study report]. Hacettepe Üniv. Mühendislik Fak., Jeoloji Müh. Bölümü, Ankara, 44 s.

Ulusay, R.,Aydan, Ö., Erken, A., Tuncay, E., Kumsar, H. & Kaya, Z. 2004. An overview of geotechnical aspects of the Çay ─ Eber (Turkey) earthquake. *Engineering Geology* **73**, 51 ─ 70.

Wortel MJR, Spakman W., 2000, Geophysics - Subduction and slab detachment in the Mediterranean-Carpathian region. *Science*, 290 (5498): 1910-1917.

Yılmaz, Y., Genç, Ş.C., Gürer, Ö.F., Bozcu, M., Yılmaz, K., Karacık, Z., Altunkaynak, Ş., A. Elmas, 2000, When did the western Anatolian grabens begin to develop?, In: Bozkurt, E., Winchester, J.A., Piper, J. A. D. (Eds), Tectonics and Magmatism in Turkey and the Surrounding Area, *Geol. Soc. London, Special Publ.,* 173, 353-384.

APPENDIX A

GEOLOGICAL MAPS AND BLOCK DIAGRAMS

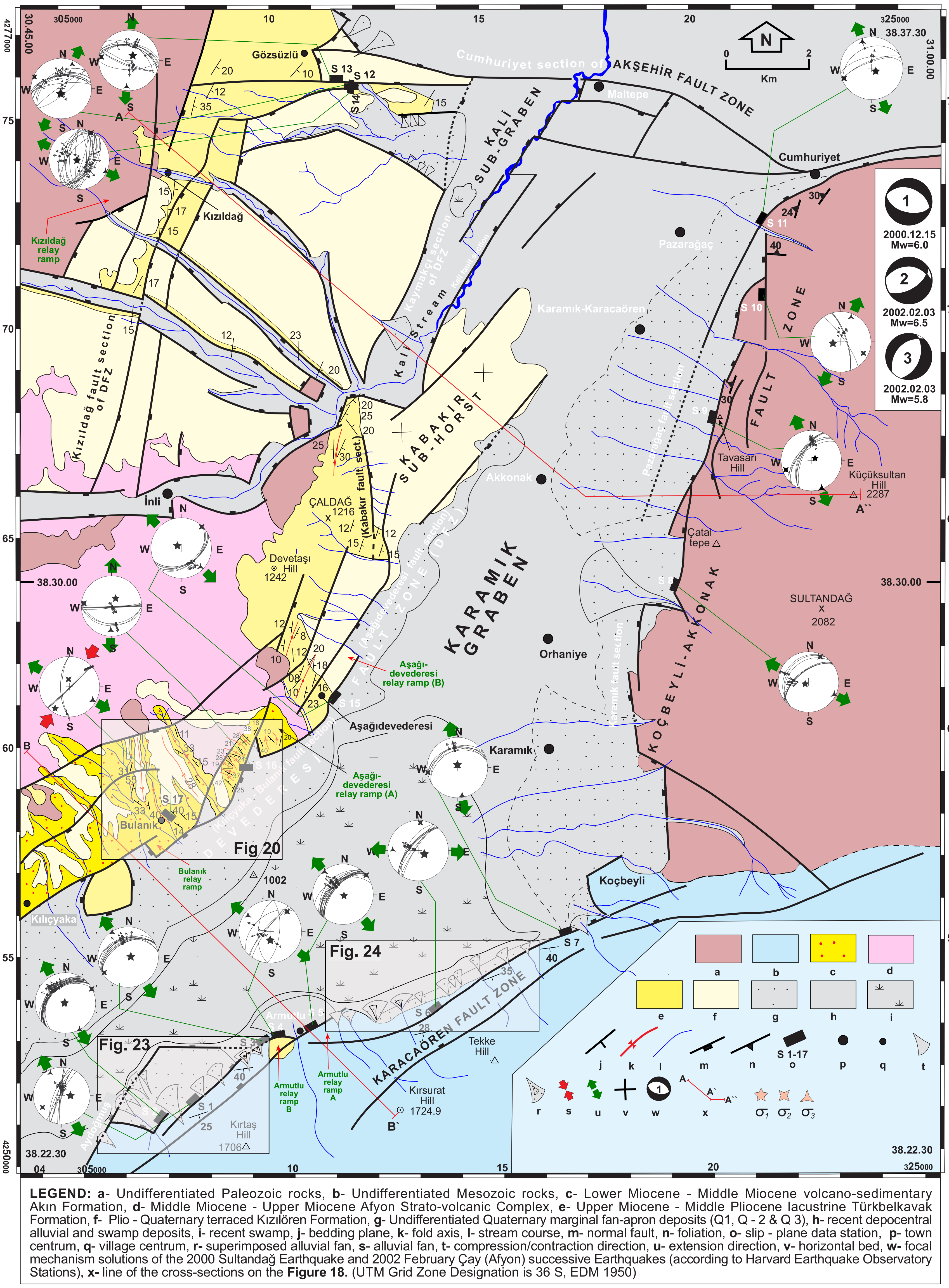


Fig. A. 1. Simplified geological map of the Karamık Graben and adjacent areas.

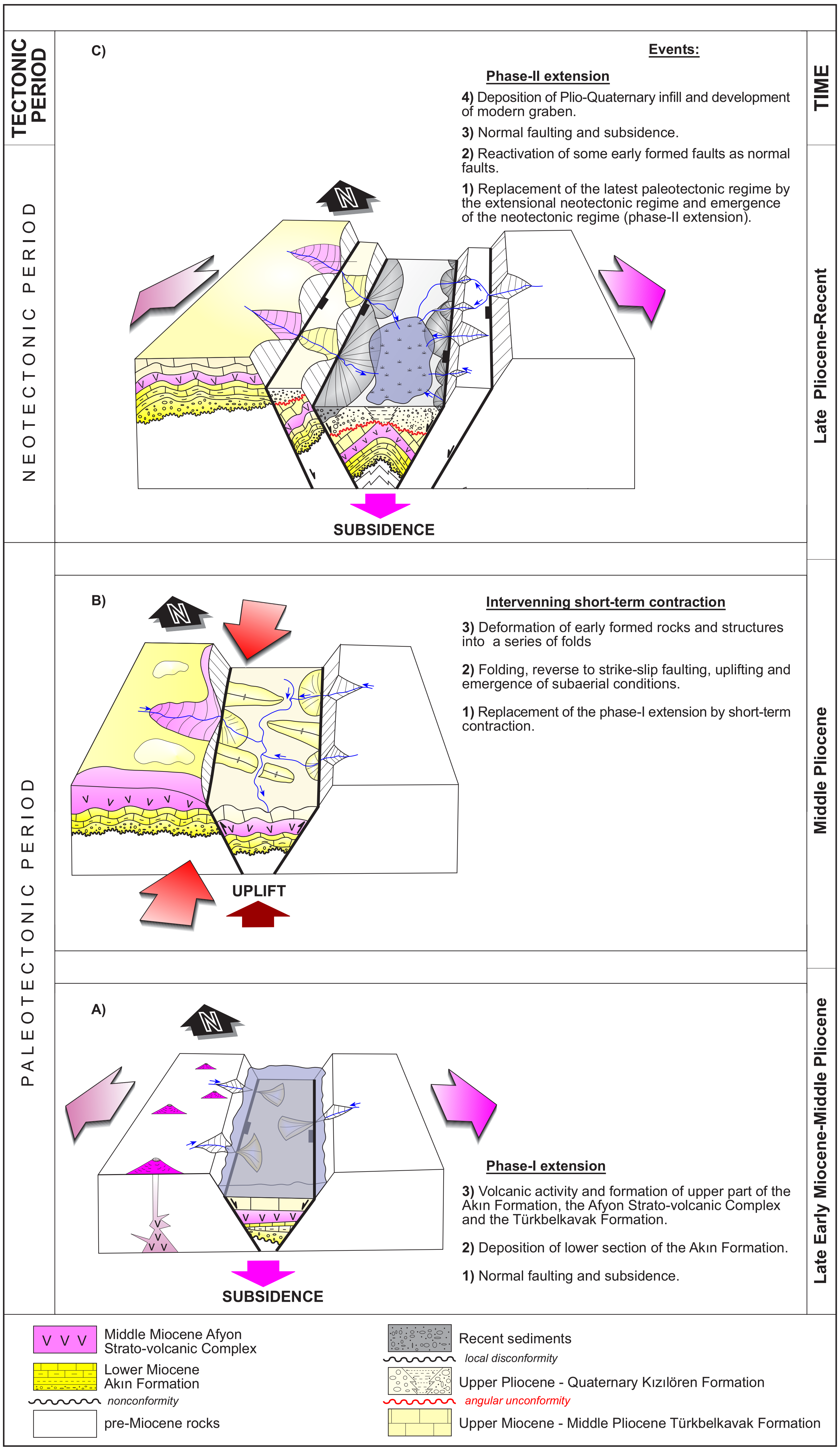


Fig. A. 1. Sketched block diagram depicting the development history of the Karamık Graben

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