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Neotectonics of the Sarıköy-İnova and Çan-Bayramiç-Ezine fault zones: basin formation, age and slip rates, NW Anatolia-Türkiye

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Research Article

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ABSTRACT

The Sarıköy-İnova and the Çan-Bayramiç-Ezine fault zones (SIFZ, ÇBEFZ) comprise the southern strand of the North Anatolian Fault System in the Biga Peninsula. They are located in the area between Sarıköy to northeast and the Dalyan settlement around Bozcaada in the North Aegean Sea to southwest. Both of the fault zones are active. This is evidenced by the 6 March 1737 (Ms =7.0) İnova, 1st February 1809 Hurma (Ms = 6.1), and the 8 February 1826 Güllüce (Ms = 6.2) historical earthquakes resulted from these fault zones. Maximum lengths of fault segments comprising the SIFZ and the ÇBEFZ are 14 km and 15 km, respectively. Based on the maximum lengths of fault segments, the magnitude of the peak earthquakes to be originated from these faults are Mw = 6.3 and 6.6, respectively. Based on both the geological and geographic markers, the total right lateral offsets accumulated on the SIFZ and ÇBEFZ are 12 km and 20 km, respectively. These offset values imply to the slip rates of 4.6 mm/yr and 7.7 mm/yr, respectively. Five pull-apart basins were developed on both fault zones. These are the Sarıköy, İnova, Kazabat, Çan and Ezine-Bayramiç basins. The first three of them are pure strike-slip pull-apart basins, while the type of the rest basins is superimposed. The angular unconformity between the nondeformed basin fill of Quaternary age and the folded to thrust-faulted basement rocks of pre-Quaternary age reveals strongly that the pull-apart basins have formed during the Quaternary time. This relationship also reveals that the commencement age of the strike-slip neotectonic regime and formation of associated fault zones are the Early Quaternary. This work was dedicated to the retirement memory of Dr. Fuat Şaroğlu.

1. Introduction

The North Anatolian Fault System is divided into numerous fault zones around the Sea of Marmara and results in an active deformation zone wider than 120 km. Two of them are the Sarıköy-İnova and the Çan-Bayramiç-Ezine fault zones. They cut across the Biga Peninsula in the area between Ulukır village to northeast and Dalyan to the further southwest and are included in the southern strand of the North Anatolian Fault System (Figure 1). Based on aerial photograph study, seven fault segments within these two fault zones were previously identified and mapped by Barka and Kadinsky-Cade (1988). Later on, four single faults, which comprise these two fault zones, were also observed, mapped and renamed separately by Siyako et al. (1989). These are the Ezine-Bayramiç, Çan, Terzialan-Çomaklı and the İnova-Sarıköy single faults. They also reported that these faults have formed in a neotectonic period that commenced in

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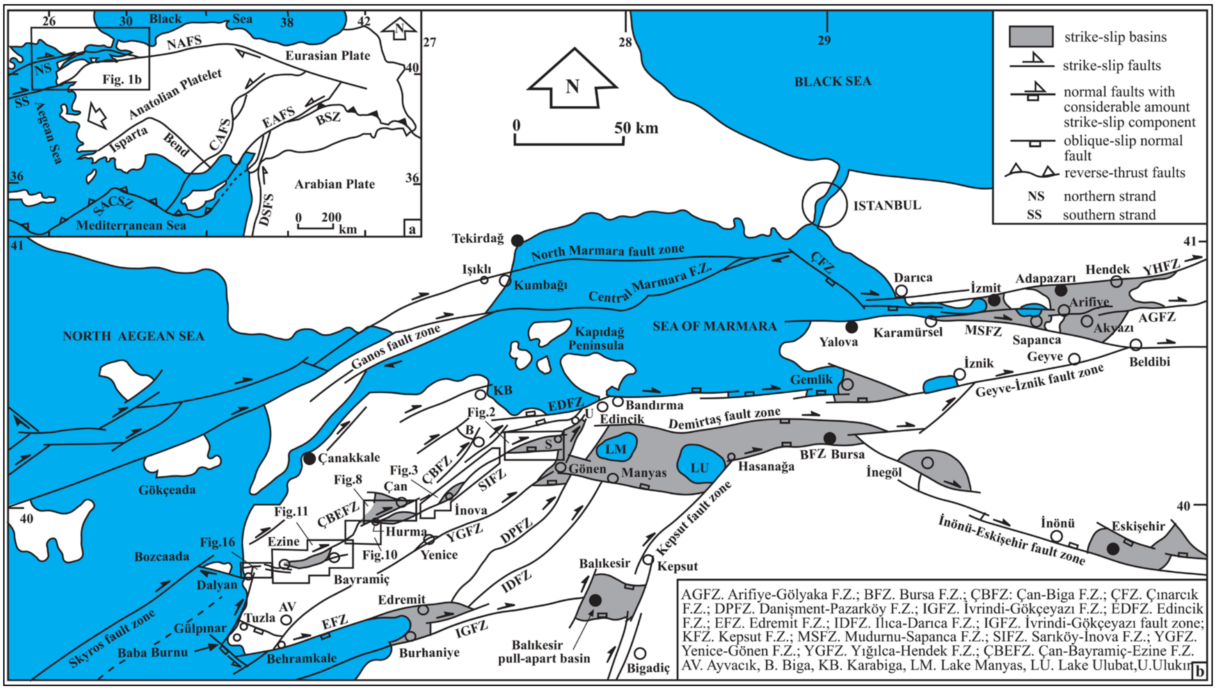

Figure 1- a) Simplified map illustrating plate tectonic configuration of Türkiye and location of study area, b) Simplified fault map illustrating major strands of the North Anatolian Fault system and fault zones comprising them around Sea of Marmara.

the Early-Middle Miocene. Additionally, some dextral offsets, such as the 1.5 km on the Çan fault and 8 km on the İnova-Sarıköy fault, were also determined and reported by the same authors. Later on, these two studies were followed by several researchers (Şaroğlu et al., 1992; Koçyiğit, 2006; Duru et al., 2007; Koçyiğit, 2011; Emre et al., 2011, 2012). Şaroğlu et al. (1992) named the same structures as the Etili fault, Çan-Biga fault zone and the Sarıköy fault, respectively. Duru et al. (2007) carried out a detailed geological map of the İnova area, divided the Sarıköy fault into two segments namely the Asmalı and Tahtalı segments, and then reported 12 km dextral offset on both fault segments. Lastly, same structures were also reevaluated and named as the Biga-Çan fault zone, Sarıköy fault and Gündoğan fault respectively by (Emre et al., 2011; 2012), who also redivided the Biga-Çan fault zone into three fault segments as Çan, Yuvalar, and Biga fault segments. Five pull-apart basins occur along these fault zones. From NE to SW these are the Sarıköy, İnova, Kazabat, Çan and the Ezine-Bayramiç basins. Except for the İnova basin, rest four basins have not been studied yet, whereas, these basins contain valuable stratigraphic and structural data about the commencement age of the neotectonic period, evolutionary history of faults and associated displacements accumulated on them. In terms of this study, some type localities, such as the Sarıköy, İnova, Kazabat, Çan-Etili, Bezirganlar, Ezine-Bayramiç and the Kurudere areas, were mapped in detail on 1/25.000 scale, and new findings were obtained. These new data were obtained by the usage of both the office and field methods. Office studies include computer program T-TECTO 3.0, satellite images and aerial photograph studies, whereas field studies focus on the detailed field geological mapping of rocks and faults carried out directly in the field. In the present day, the debate about the fault pattern, total displacement, and the commencement age of the neotectonic period in the study area is still lasting. This study aims to bring plausible solutions to these debates under the lights of both the newly obtained field data and national to international literature surveys.

2. Fault Zones

Both the Sarıköy-İnova and Çan-Bayramiç-Ezine fault zones are represented by the dextral strike-slip faulting caused by stress field state, in which the maximum principal compressive stress (σ_1) is operating in approximately E-W direction, while the least principal stress axis (σ_3) or extension direction is N-S (Koçyiğit and Gürboğa, 2021). Based on the relationship between the strike of faults and the operation direction of the maximum principal compressive stress axis, the NE-striking faults are dextral strike-slip faults, NW-striking faults are sinistral strike-slip faults, the E-W striking faults are oblique-slip normal faults and the N-S striking faults are oblique-slip reverse faults. In general, as the strikes of the faults approach to the E-W direction, i.e., σ_1 direction, their normal components increase (Wilcox et al., 1973). Consequently, the Biga Peninsula and its neighborhood are being shortened in E-W direction, while it is expanded in N-S direction.

2.1. Sarıköy-İnova Fault Zone (SIFZ) and Related Basins

In general, the SIFZ is 0.2-5 km wide, totally 65 km long, and N45° to 70E°-trending active deformation zone dominated by the dextral strike-slip faulting. It is situated between Ulukır village to the northeast and Hurma village to the southwest (Figure 1b). It begins around Ulukır village and then runs southwestward across the Sarıköy, Armutlu, Geyikli, Tahtalı, Yolindi, Aşağıinova, Yukarıinova, Asmalı, Sameteli and Hurma settlements. Around Hurma village further southwest, it meets with the Çan-Bayramiç-Ezine fault zone (ÇBEFZ) and then terminates. Along the whole length, the SIFZ consists of numerous 0.3-3 km spaced, 0.1-14 km long and NE-, E-W- and NW-trending structural fault segments. In addition, it is divided into five major sections in the pattern of a fault set by the intervening some other strike-slip complexities and related pull-apart basins. These sections or fault sets are, from northeast to southwest, the Sarıköy-Geyikli, Hüseyinbey, Tahtalı-Aşağıinova, Yukarıinova-Asmalı, and the Kazabat fault sets, respectively (Figures 2 and 3). They are 18 km, 14 km, 17 km, 18 km and 12 km in length, respectively. The most diagnostic character of the SIFZ is the anastomosing pattern. The master fault bifurcates and rejoins frequently, divides the earth crust into a series of diverse-sized lensoidal blocks with long axes running more or less parallel to the general trend of the fault zone. Thus, it displays an anastomosing occurrence pattern peculiar to the strike-slip faulting (Figures 2 and 3). Fault segments, which comprise the SIFZ, cut across various rocks (Permo-Triassic Karakaya Complex, Liassic clastic rocks, Jurassic-Cretaceous Limestone and the Oligo-Miocene igneous to volcanic rocks) (Bingöl et al., 1973; Siyako et al., 1989; Okay et al., 1990; Koçyiğit, et al., 1991; Şahin et al., 2010) and tectonically juxtapose them with to each other, and also with the Quaternary basin fill. They also displace older rocks in both vertical and right-lateral directions. Various lithofacies of the Permo-Triassic Karakaya Complex are displaced up to 12 km in dextral direction by the Tahtalı-Aşağıinova section of the SIFZ (X-Y in Figure 4) (Engin et al., 2012). This is also confirmed by the offset drainage system. The Sarıköy Çay, Keçi Stream, Balıklı Çay and the Kaz Stream are fault-controlled drainage systems flowing within the SIFZ. In particular, the Balıklı Çay is offset up to 12 km in the dextral direction by the Tahtalı-Aşağıinova section of the SIFZ (X-Y in Figure 3). Same offset features were also previously reported by Siyako et al. (1989) and Emre et al. (2012). The longest segment of the SIFZ is the 14 km long Tahtalı fault, on which the total displacement accumulated until the present is 12 km. Based on the maximum length of this fault segment, the magnitude of the peak earthquake to be resulted from the Tahtalı fault is M_w = 6.4 based on formula introduced by Wells and Coppersmith (1994). There is a relationship among the slip rate (SR), total displacement (TD) and the age of the fault (A). In the same way, there is a relationship among the slip rate (SR), coseismic displacement (CD) and the return period (RP). It is explained by the equation (RP = CD/SR). Based on this equation, the amount of coseismic lateral displacement to be sourced from the Mw 6.4 earthquake is approximately 2.3 m or 2.5 m.

The SIFZ is a regional active structure. This is proven by two historical earthquakes. These are the 6th March 1737 İnova earthquake of Ms =7.0, and the first February 1809 Hurma earthquake of Ms = 6.1 (Figure 3) (Ambraseys, 2002; Tan et al., 2008). They were sourced from the Aşağıinova and Hurma sections of the SIFZ, respectively. The epicenter localities of these earthquakes are located on the strike-slip complexities, such as the İnova releasing step-over, a single contractional bend and the intersection of two fault zones, where motion on the fault is locked and causes to the accumulation of huge volume of elastic strain energy for the occurrence of earthquakes. However, the main bulk of the SIFZ still retains its seismic gap.

Three strike-slip basins have developed along the SIFZ owing to the strike-slip complexities. These are the Sarıköy, İnova and the Kazabat pull-apart basins. In the near southwest of Geyikli village, the SIFZ bifurcates into two sections such as the NE-trending

Sarıköy and the E-W-trending Hüseyinbey fault sets (Figure 2). This bifurcation results in an eastward widening fault-wedge type of pull-apart basin (Figures 2 and 5). It is bounded by the Sarıköy fault set to north and by the Hüseyinbey fault set to south (F1 and F2 in Figure 5). The 14 km long Hüseyinbey fault set consists of diverse-sized and northerly dipping several normal faults, and a single NW-trending sinistral strike-slip fault (Dereköy fault) (Figure 2). They display well-preserved normal and sinistral strike-slip fault slickensides. The stereographic plot of slip-plane data on Schmidt lower hemisphere stereonet indicates that the Sarıköy basin is under the effect of E-W shortening and N-S expansion (Figure 6). The Sarıköy basin is occupied by an approximately 85 m thick, weakly lithified to unconsolidated, and flat-lying fluvial sedimentary sequence of Quaternary age. This basin fill overlies with an angular unconformity on the erosional surface of the various rocks of pre-Quaternary age (Figure 2).

The second diagnostic structure included in the SIFZ is the İnova pull-apart basin. It occurs along both the Tahtalı-Aşağıinova and the Yukarıinova-Asmalı sections of the SIFZ. Around Aşağıinova village, the master fault of the SIFZ bends first toward left and then jumps to right, and so it results in a releasing type of stepover, which nucleates the İnova strike-slip basin (Figure 3). The southwestern and northeastern sections of the SIFZ were previously named as the Asmalı and Tahtalı segments respectively by Emre et al. (2012). However, this naming is not true, because it contradicts with the definition of structural fault segment, which is a single fault or a part of a single fault confined between two structural complexities, such as the step-over, bend and bifurcation. The İnova pull-apart basin is a 2.5 km wide and 7 km long depression occupied by 70 m thick, loose and non-deformed fluvial sediments of Quaternary age. The basin fill rests with an angular unconformity on the erosional surface of the Permo-Triassic Karakaya Complex (Bingöl et al., 1973).

Around Samateli the SIFZ bends at 25º towards north, bifurcates into several splay faults, and then results in an extensional horse-tail structure, namely the Sameteli horse-tail structure, where the third pull-apart basin occurs. It is the Kazabat depression located on the southwestern tip of the SIFZ (Figures 3 and 7). The Kazabat basin is a 2.5 km wide and 10 km long lense-shaped depression with an E-W trending long axis. It widens up to 2.5 km in the central section, while it narrows and wedges out in both east and west directions. It is bounded by the NE-trending Hurma fault to west, by the E-W to WNW-trending Çekiçler, Korualtı, Büyüktepeköy and Kalburcu fault segments to north, and by the E-W-trending Süleköy and Karakoca fault segments to south (Figure 7).

Both the northern- and southern margin-boundary fault segments gain a considerable amount of normal components greater than their strike-slip components

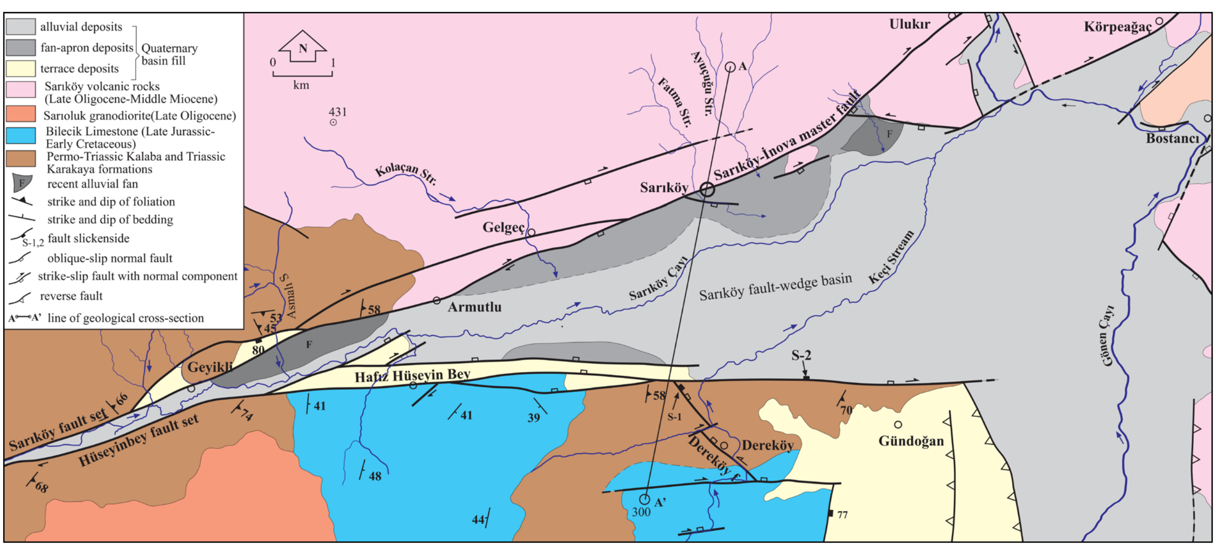

Figure 2- Geologic map of the Sarıköy fault-wedge basin and its near vicinity. Geological cross-section along line A-A’ indicates the Sarıköy basin, its margin-boundary faults, fills and stratigraphical relationships with the pre-Miocene rocks.

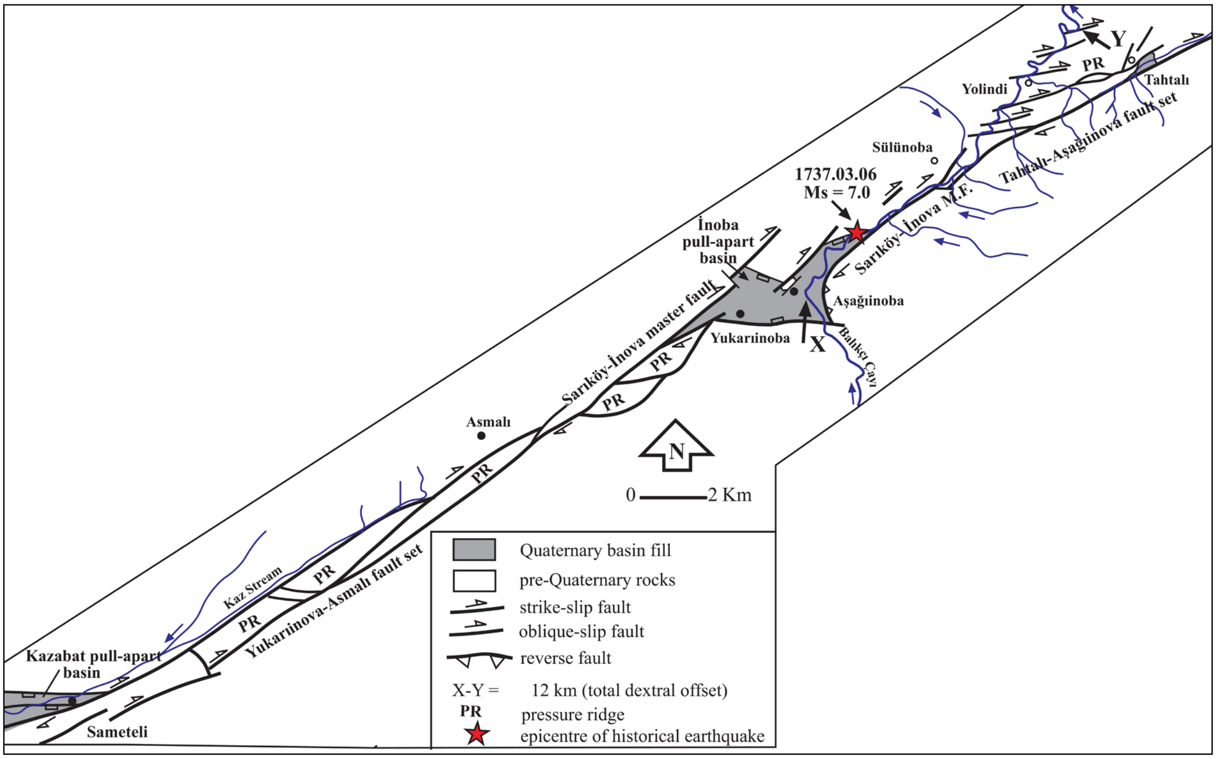

Figure 3- Neotectonic map of both the Tahtalı-Aşağıinova and the Yukarıinova-Asmalı sections of the Sarıköy-İnova fault zone (SIFZ).

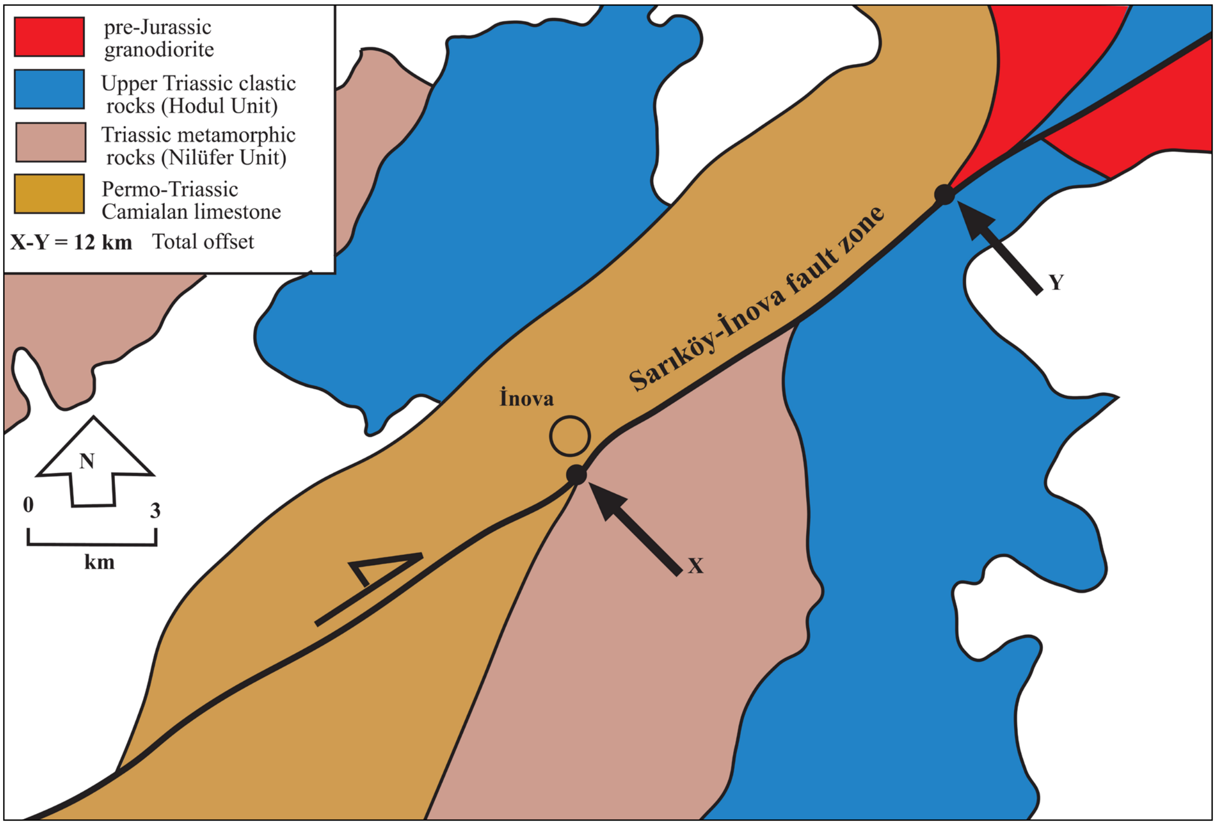

Figure 4- Map of various lithofacies of the Permo-Triassic Karakaya Complex displaced up to 12 km (X-Y = 12 km) in dextral direction by the SIFZ (modified from Appendix 3, Engin et al., 2012).

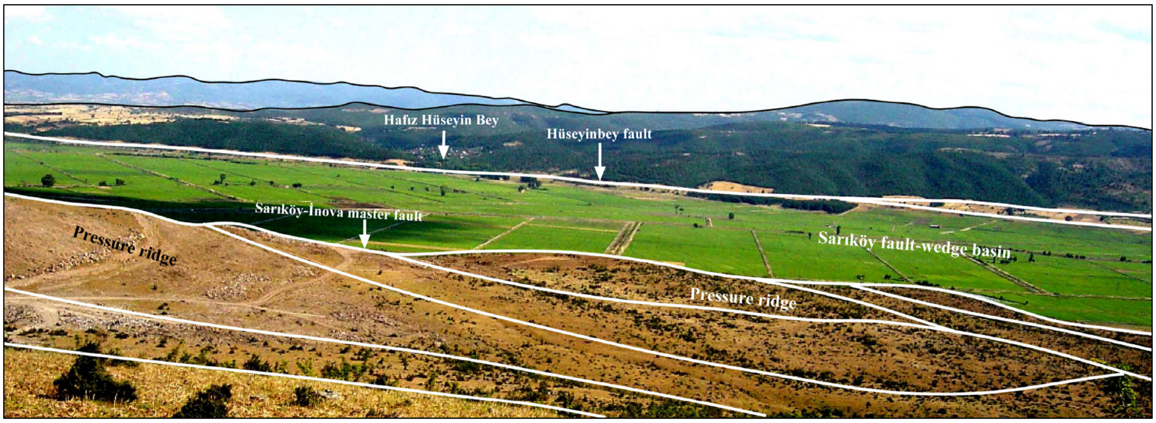

Figure 5- General view of the Sarıköy fault-wedge type of pull-apart basin (view to SSE).

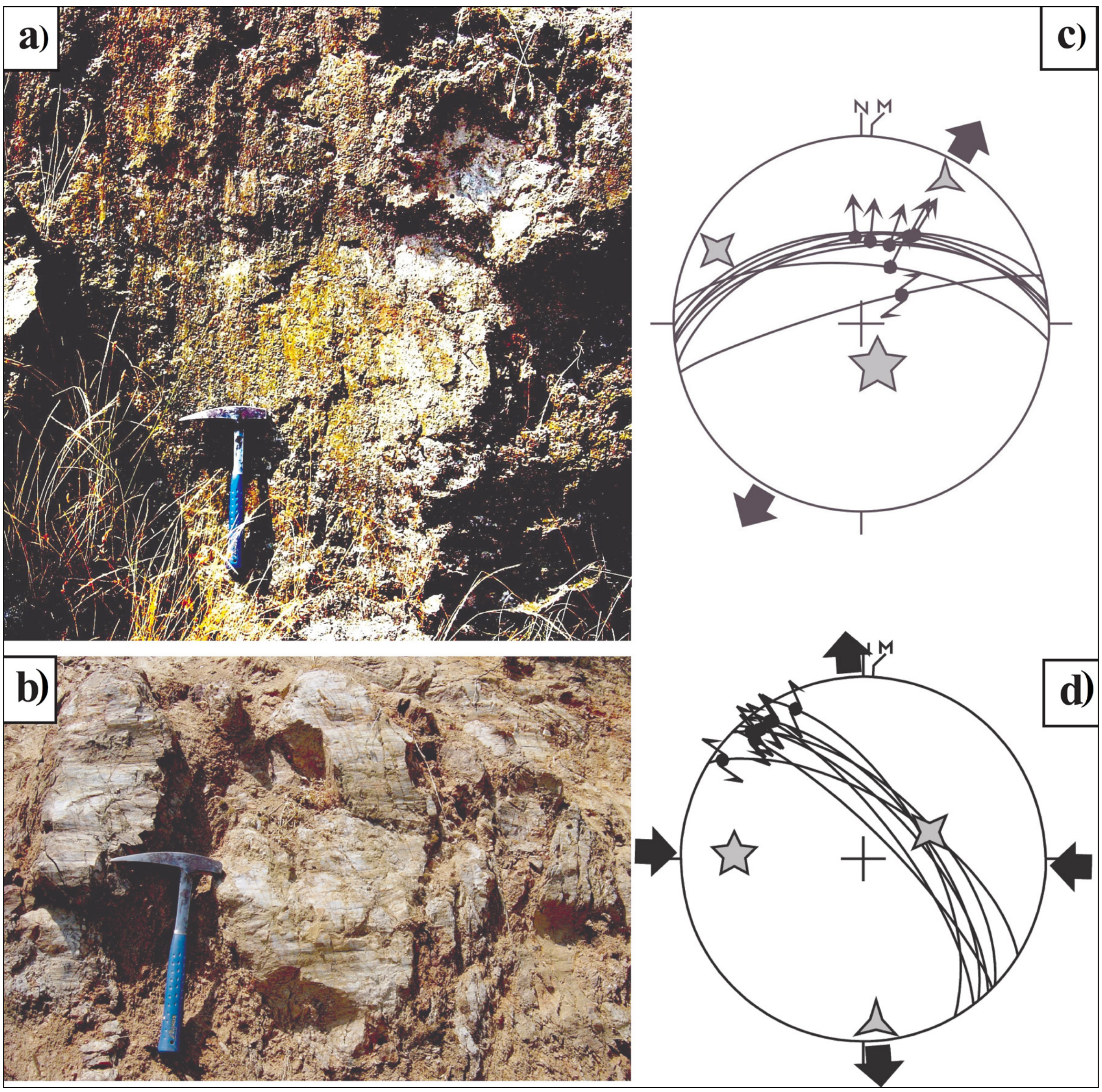

Figure 6- a) Field photographs of the Hüseyinbey oblique-slip normal fault and b) the Dereköy sinistral strike-slip fault slickensides, respectively, at stations S1 and S2 in Figure 2, c) and d) stereographic plots of slip-plane data on Schmidt lower hemisphere stereonet respectively (diverging and converging large arrows indicate expansion and shortening directions respectively.

owing to the kinematic character of the Sameteli horse-tail structure. This situation is also the main cause for the development of the Kazabat basin. This basin is occupied by 108 m thick fluvial to gravity-induced sedimentary fill (Kazabat formation) of Quaternary age (Figure 8). It rests with an angular unconformity on the erosional surface of various pre-Miocene rocks. The basin fill begins with well-bedded and weakly-sorted polygenetic basal conglomerates at the bottom, and then continues upwards with the alternation of weakly bedded to lose fluvial conglomerate, sandstone and siltstone. Towards the top, it is succeeded by both the coarse-grained marginal and finer-grained depocentral lithofacies such as slope-scree, fan-apron, fan and basin floor sedimentary deposits respectively. All the lateral and vertical gradations are observed among these lithofacies. Consequently, the stratigraphy of these pull-apart basins reveals strongly that the formation age of the SIFZ is Quaternary.

2.2. ÇBEFZ and Related Basins

In general, the ÇBEFZ is an 1.5-4.6 km wide, totally 80 km long and ENE- to NE-trending active deformation zone represented by mostly strike-slip faulting. It is situated between Helvacı village (Çan) to northeast and Dalyan Town (Bozcaada) to further southwest (Figure 1b). The ÇBEFZ begins around Helvacı village in the northeast and then runs in

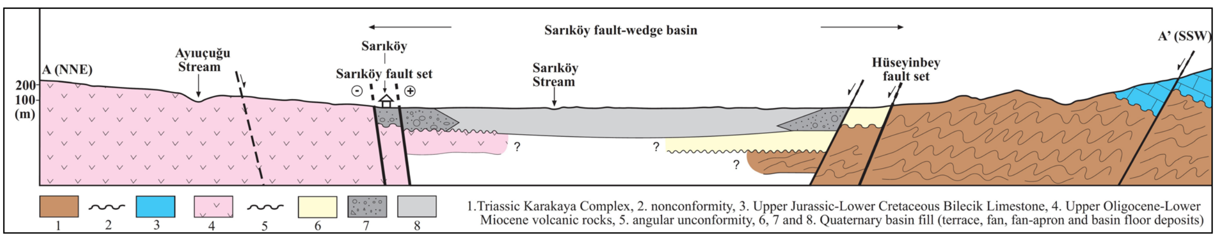

Figure 7- Geological cross-section along line A-A' (given in Figure 2) which illustrates the Sarıköy basin, its margin-boundary faults, fills and stratigraphical relationships with the pre-Miocene rocks.

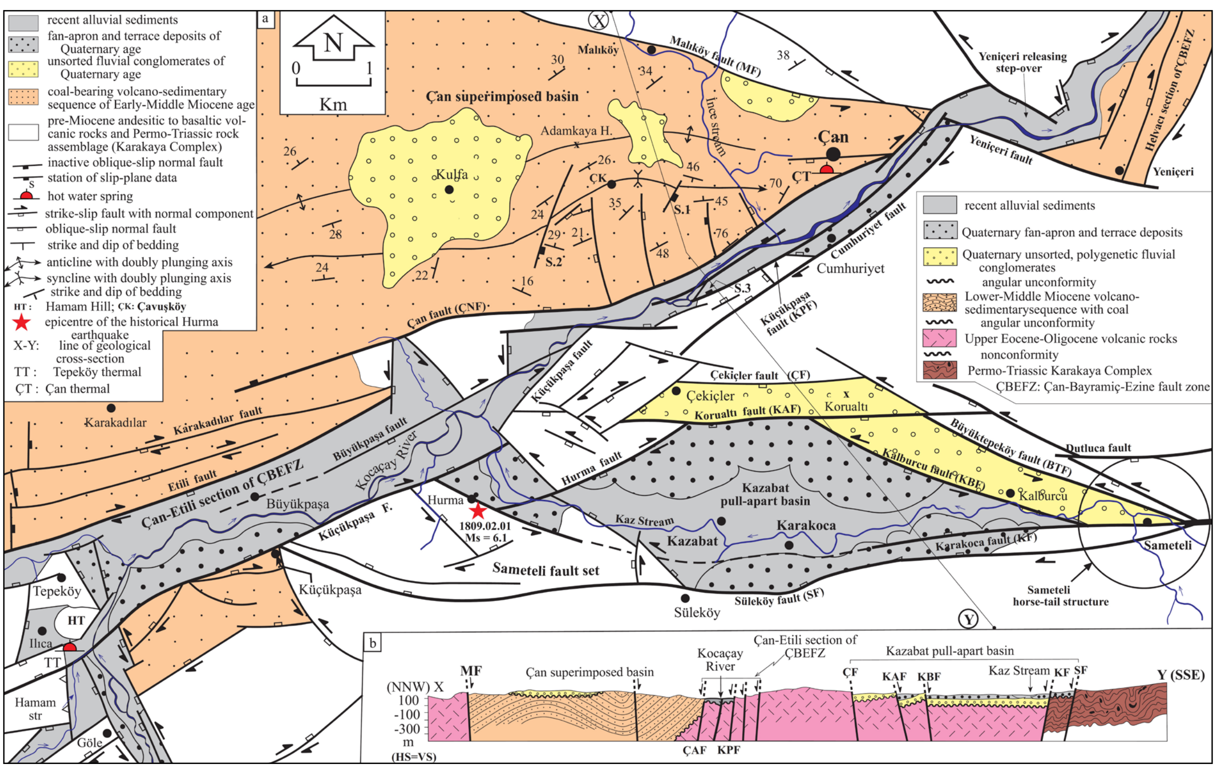

Figure 8- Geological map of both the Çan and Kazabat strike-slip basins, a) and the geological cross-section along line X-Y, b) showing their internal structures.

southwest direction along a series of settlements in the size of village, town and county. Based on some strike-slip complexities, such as the Yeniçeri and Etili releasing stepovers, bifurcation and the Doğancı bend, the ÇBEFZ is divided into five sections. These are, from northeast to southwest, the Helvacı, Çan-Etili, Bezirganlar, Ezine and the Bayramiç-Kurudere sections or fault sets (Figures. 7, 9 and 10).

These sections are 8 km, 16 km, 18 km, 21 km and 45 km in length, respectively. The ÇBEFZ consists of 0.4-15 km long, and E-W-, ENE, NW- to NE-trending numerous fault segments. They cut across various older rocks of different lithofacies, and the Quaternary neotectonic basin fill. These rocks are cut across, tectonically juxtaposed and offset in both lateral and vertical directions by the fault segments. The ÇBEFZ developed along a paleotectonic structure named previously as the Bayramiç and Etili grabens of Miocene age by Yılmaz et al. (2000), i.e., the younger strike-slip tectonic regime and related structures were overprinted on an earlier extensional tectonic regime and associated structures during the Quaternary time. For this reason, most fault segments comprising the

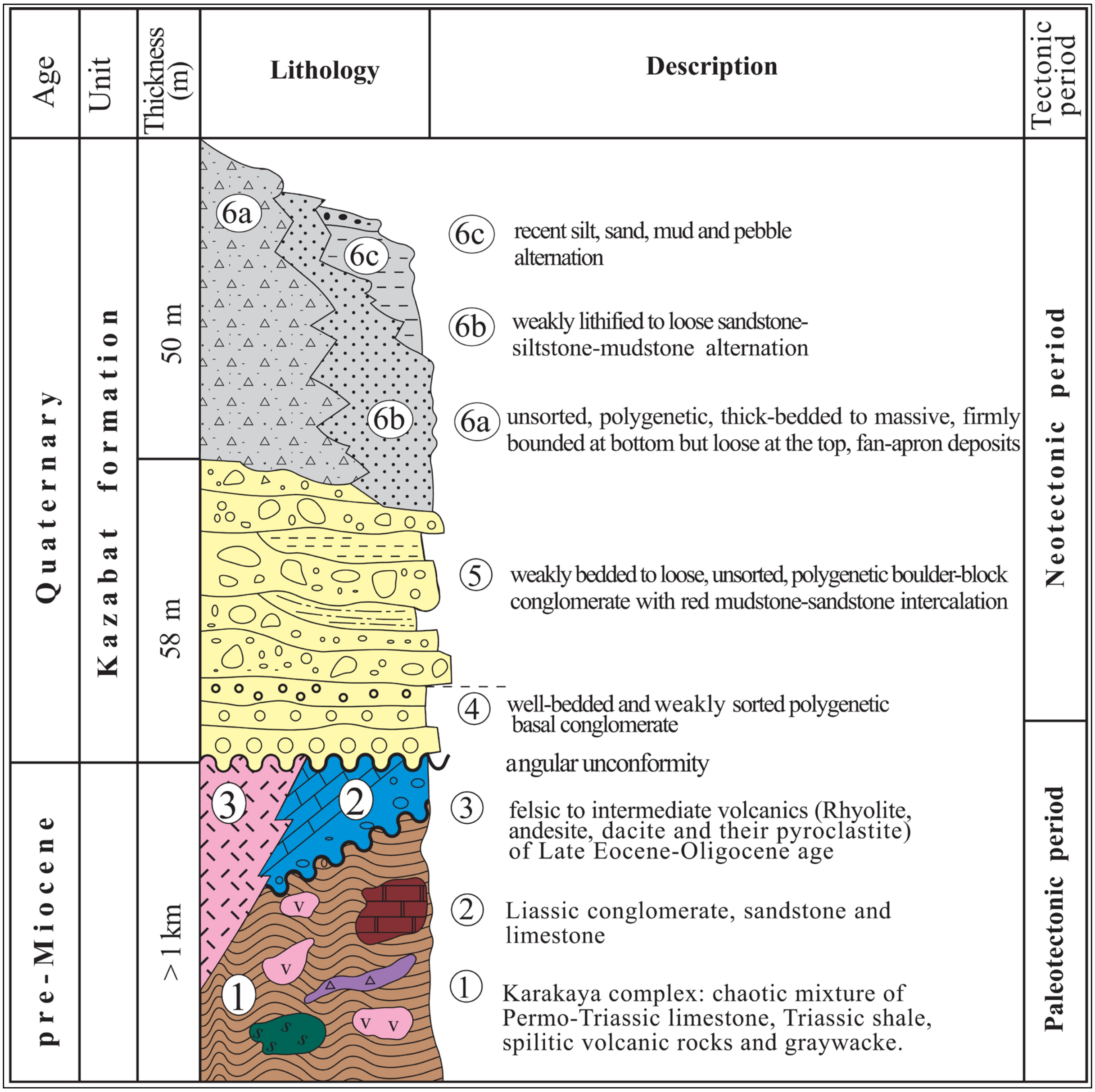

Figure 9- Generalized stratigraphical column of the pure strike-slip basins (Sarıköy, İnova and Kazabat basins).

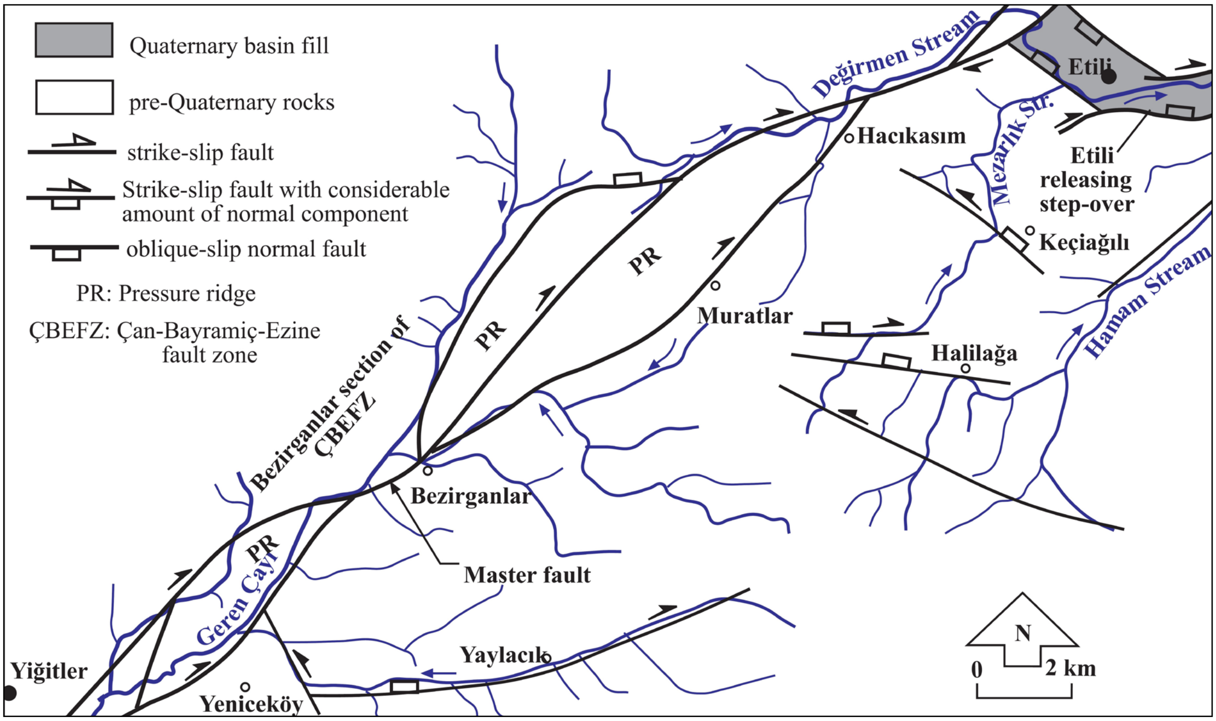

Figure 10- Simplified map illustrating the relationship of the Bezirganlar section of the Çan-Bayramiç-Ezine fault zone (ÇBEFZ) with the drainage system.

ÇBEFZ are reactivated older faults inherited from the Miocene extensional tectonic regime and related grabens. For instance, the Çan, Küçükpaşa and some intrabasinal fault segments in the Çan basin (Figure 7), and the Ezine and Bayramiç faults in the Ezine-Bayramiç basin (Figure 10) are originally reactivated older structures. This is also proven by the superimposed slip-plane features such as slip lines to fault steps and their kinematic analyses (Figure 11).

Both the Kocaçay and Karamenderes Çayı are two major fault-controlled drainage systems flowing in opposite directions within the ÇBEFZ. The Kocaçay River rises from the peak of Kazdağları pressure ridge to south and outside the study area, and then flows towards north. It changes its flow direction towards ENE and then is offset up to 20 km in dextral direction when it enters into the Çan-Etili section of the ÇBEFZ (X-Y in Figure 12). This dextral strike-slip displacement is also proven by a geologic marker, namely the offset formation boundary. The southern boundary of the Lower-Middle Miocene volcano-sedimentary sequence is crossed and displaced up to 30 km in right lateral direction (Figure 7 in Yılmaz et al., 2000). These total dextral offsets indicate the slip rates of 11.6 mm/yr. and 7.7 mm/yr., respectively, and the return period of approximately 400 years for the occurrence of a peak earthquake with the Mw = 7.0. Total geological offsets that have developed in NAF System within last 4-5 million years are compatible with GPS data and explain that the slip rate on Northern strand is about 4 times higher than Southern strand (Sipahioğlu and Matsuda, 1986; Şaroğlu et al., 1987; Koçyiğit, 1988; Emre et al., 1998; Armijo et al., 2002; Meade et al., 2002; Emre and Awata, 2003). The amount of coseismic lateral displacement is about 3-3.5 m. The longest segment of the ÇBEFZ is the 15 km long Güllüce fault. Based on the maximum length of this fault segment, the magnitude of the peak earthquake to have originated from the Güllüce fault is about Mw = 6.5 (Wells and Coppersmith, 1994). The ÇBEFZ is an active regional structure. This is indicated by both a series of morphotectonic structures and the 8th February 1826 Güllüce historical earthquake with the Mw = 6.2 (Tan et al., 2008). This earthquake was sourced from the Güllüce fault (Figure 10). Despite these earthquakes, the main bulk of the ÇBEFZ still retains its nature of seismic gap.

Two basins developed on the ÇBEFZ. These are the Çan and the Ezine-Bayramiç basins (Figures 7 and 10). Both of them are superimposed in nature,

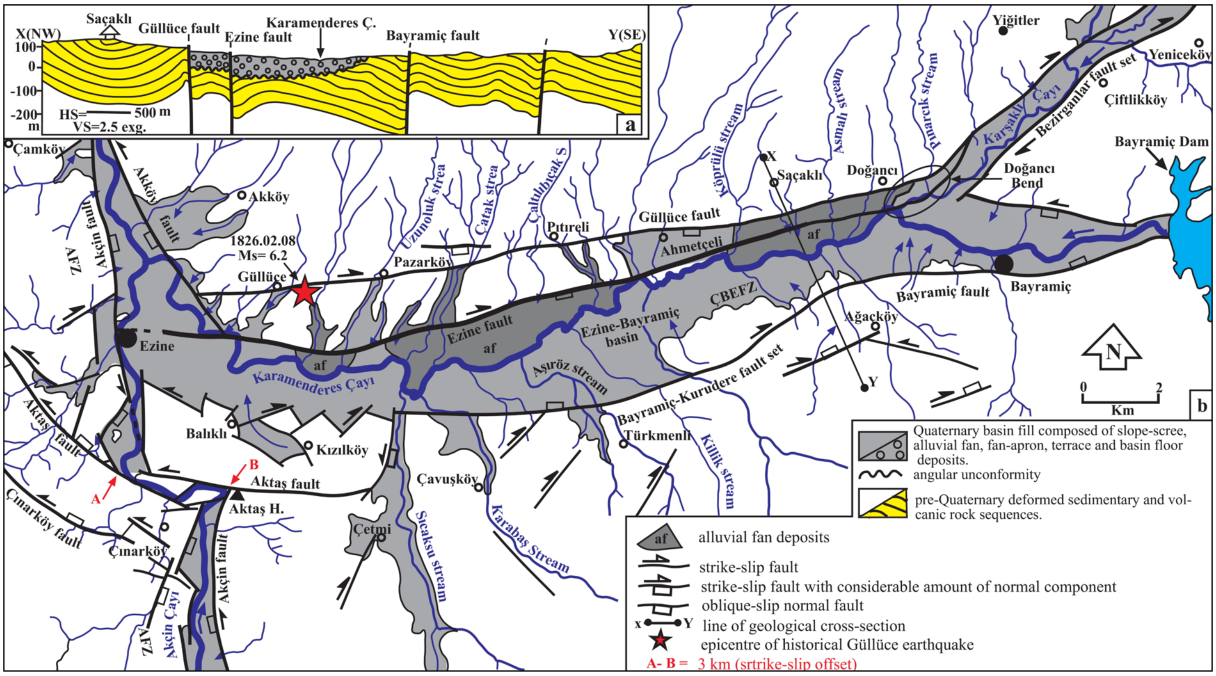

Figure 11- a) Geological cross section along line X-Y and b)neotectonic map of the Ezine and Bayramiç-Kurudere fault sets of the Çan-Bayramiç-Ezine fault zone (ÇBEFZ).

because they have two different infills separated by an intervening regional angular unconformity (Figure 13).

The Çan basin begins from the intersection of both the NE-trending Çan-Etili dextral fault set and the NW-trending Malıköy sinistral strike-slip fault, and then widens up to 5.5 km in westward direction, i.e., it is a fault-wedge basin outlined by these two structures along its southern and northeastern margins, respectively (Figures 7, 12 and 14).

The Ezine-Bayramiç basin is a 4 km wide, 30 km long and ENE-trending rectangular depression. It is bounded by the Ezine and Güllüce faults to the north, and by the Bayramiç fault set to south (Figure 10). In the west, it is outlined by the NNW-trending Akçin fault zone, which is an active deformation zone dominated by mostly the sinistral strike-slip faults with a considerable amount of reverse component. Conversely, in the west, the basin is divided into two arms and they wedge out to the further east. The southern margin of the Ezine-Bayramiç basin is outlined and controlled by the Bayramiç-Kurudere fault set. It consists of diverse-sized, and NE-, NW-, ENE- and WNW-trending numerous fault segments in the nature of both dextral to sinistral strike-slip faults and the oblique-slip normal faults. Some of them are the Bayramiç, Aktaş, Çınarköy and Kurudere faults (Figures 10 and 15).

The totally 45 km long Bayramiç fault set or section begins around Bayramiç Dam to the east and then runs wastwards up to south of Ezine County, where it cuts the Akçin fault zone and displaces it up to 3 km in sinistral direction (A-B in Figure 10). Later on, it continues again in the west direction along the Kurudere drainage system for a distance of 17 km. Lastly, it joins with the Skyros fault zone in the North Aegean Sea and then terminates (Figures 1b and 15) (Papazachos et al., 1984; Pavlides et al., 1990; Koukouvelas and Aydın, 2002; Kürçer et al., 2015; Sakellariou and Tsampouraki-Kraounaki, 2019). The whole of lithofacies of both the older graben fill and the younger neotectonic basin fill, their internal synsedimentary structures, and the top to bottom stratigraphical relationships are observed well in the Çan coal mining quarry excavated deeply inside the Çan superimposed basin (Figure 14) (Bilgin et al., 1976). In this basin. the underlying older fill begins with a polygenetic basal conglomerates on the erosional surface of the Upper Eocene-Oligocene volcanic rocks and then continues upward with the alternation of sand-stone, siltstone, tuff-tuffite, coal seams and a package of various deep lacustrine

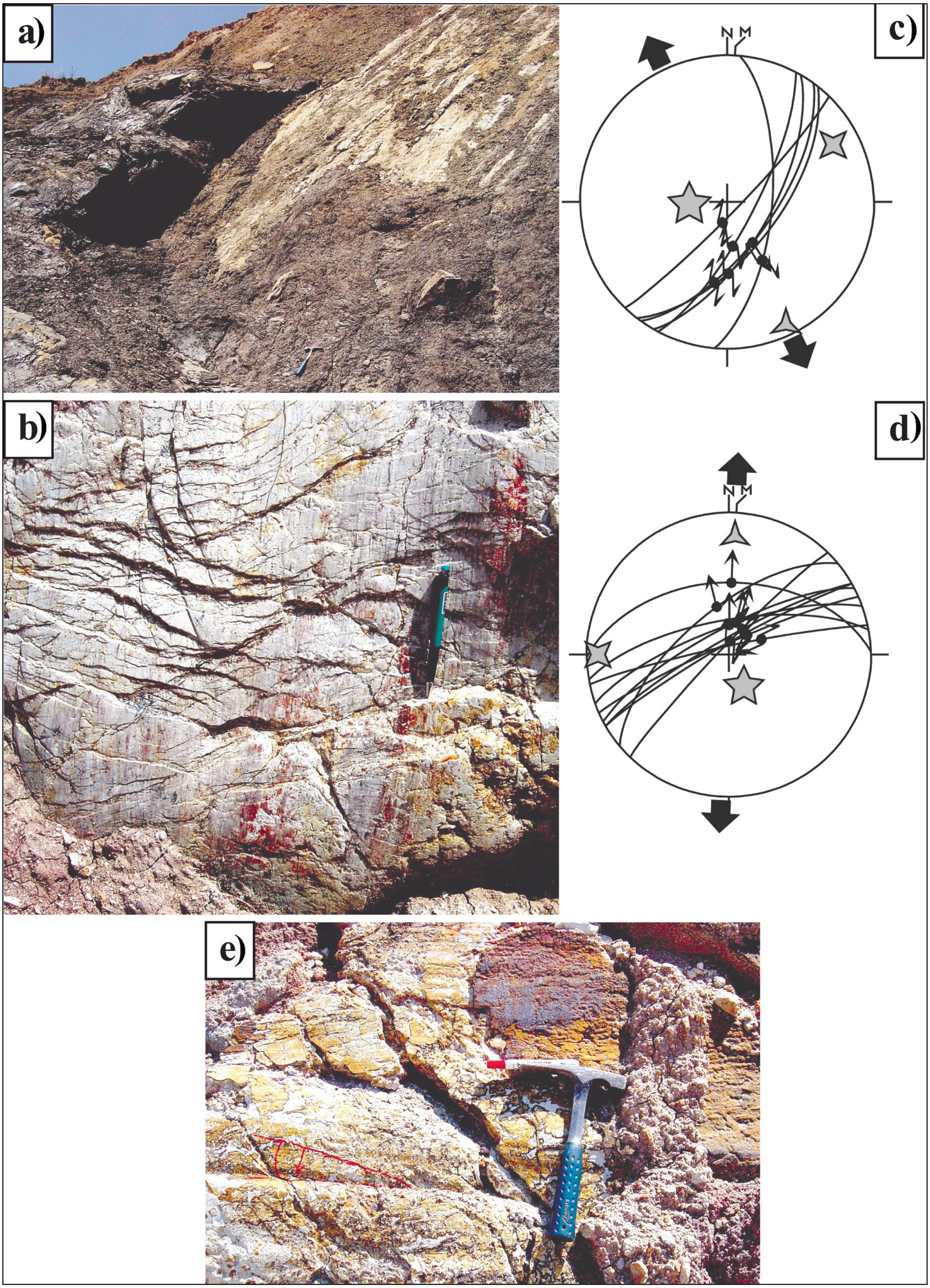

Figure 12- a and b) Close-up views of the Miocene oblique-slip normal fault slickensides, c and d) Stereographic plots of slip-plane data on Schmidt lower hemisphere stereonet respectively (diverging large arrows indicate extension directions); e) Close-up view of the active strike-slip fault slickenside with slip lines parallel to E-W direction.

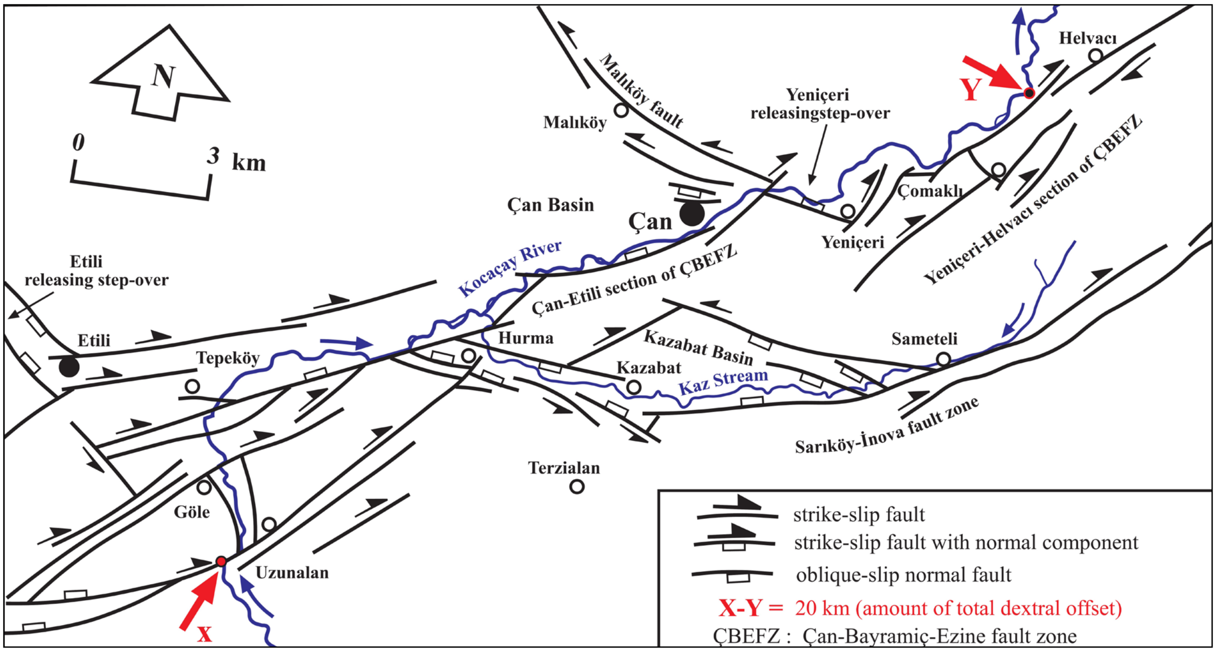

Figure 13- Simplified fault map and associated strike-slip basins. It illustrates the Kocaçay River displaced up to 20 km (X-Y = 20 km) in dextral direction by the Çan-Etili section of the ÇBEFZ.

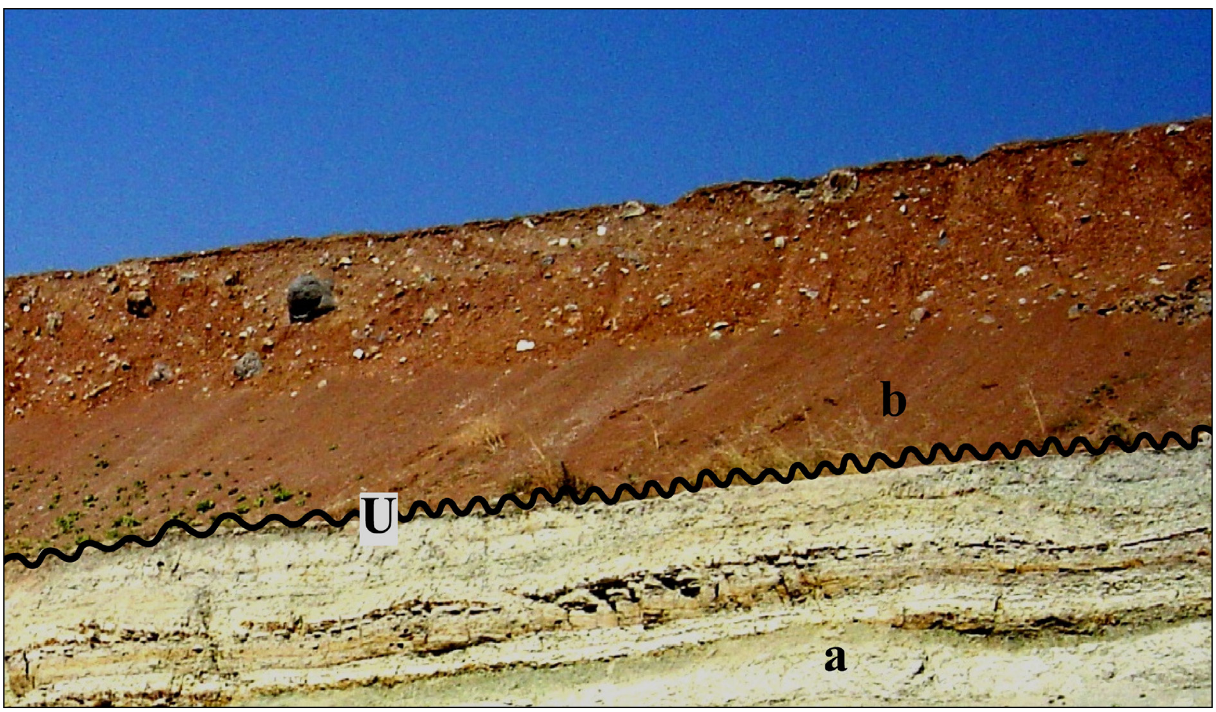

Figure 14- Field photograph illustrating the angular unconformity (U) separating older and deformed graben fill (a) from the flat-lying Quaternary neotectonic fill (b).

sedimentary lithofacies with coal seams intercalations. It is succeeded by a thick package of andesitic to basaltic volcanic breccia at the topmost (Figure 16).

This volcano-sedimentary sequence is overlain with an angular unconformity by the nearly flat-lying fluvial to gravity-induced sedimentary sequence of Quaternary age (Figures 13 and 16). The older sequence was deposited in a tectonically very active graben. This is indicated by some well-developed and preserved synsedimentary slump folds and growth faults (Figure 17).

This older graben fill was deformed and uplifted on a regional scale at the end of Miocene or most probably during Pliocene. This is revealed by the folds with the E-W-trending axes and thrust to reverse faults (Figures 17, 18 and 19).

The comparison of stratigraphical columns of both the superimposed and the pure pull-apart basins reveals that the site of the ÇBEFZ was a deep and very active lacustrine depositional setting accompanied by a volcanic eruption under the control of tensional tectonic regime and related normal faults, i.e., it was a graben during the Early-Middle Miocene; whereas, the site of the SIFZ was a high erosional area, such as a horst, during the same time slice. Starting from the Late Miocene onwards, an inversion occurred in

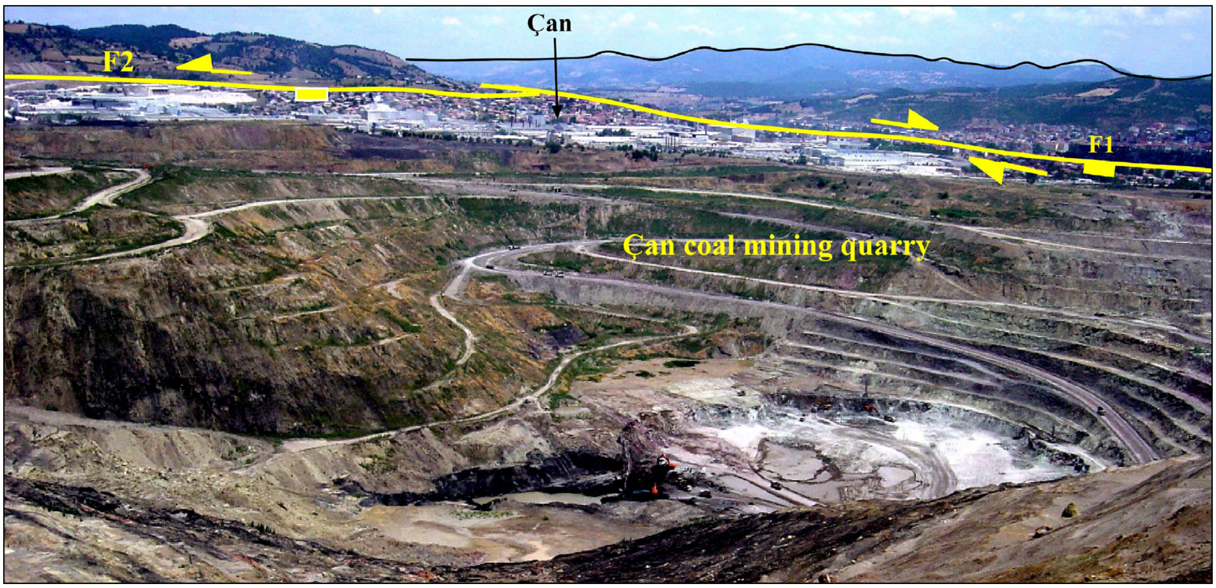

Figure 15- General view of the deeply excavated Çan coal mining quarry (view to SE). F1. ÇanEtili section of the Çan-Bayramiç-Ezine fault zone, and F2. Malıköy sinistral strike-slip fault.

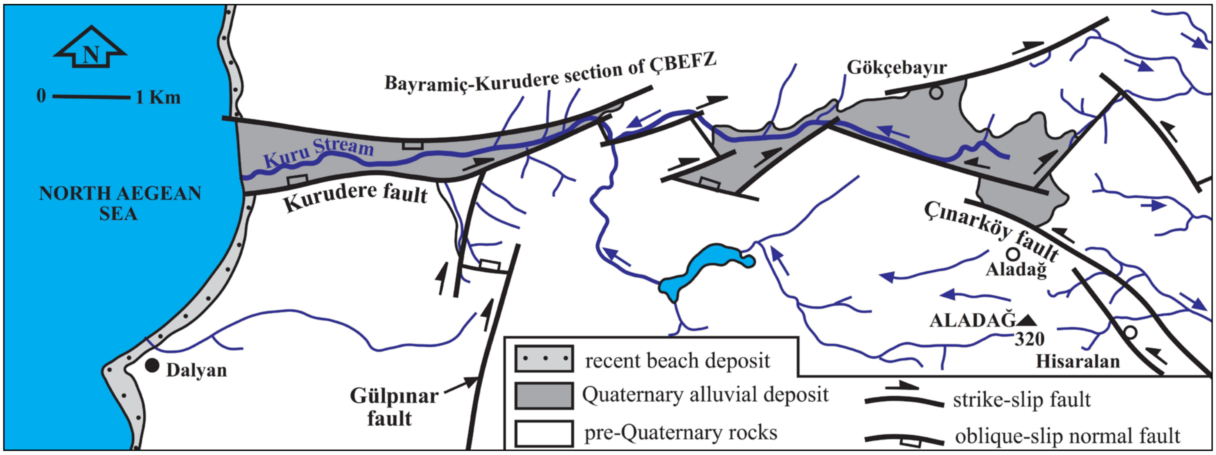

Figure 16- Neotectonic map of the Kurudere section of the Çan-Bayramiç-Ezine fault zone (ÇBEFZ).

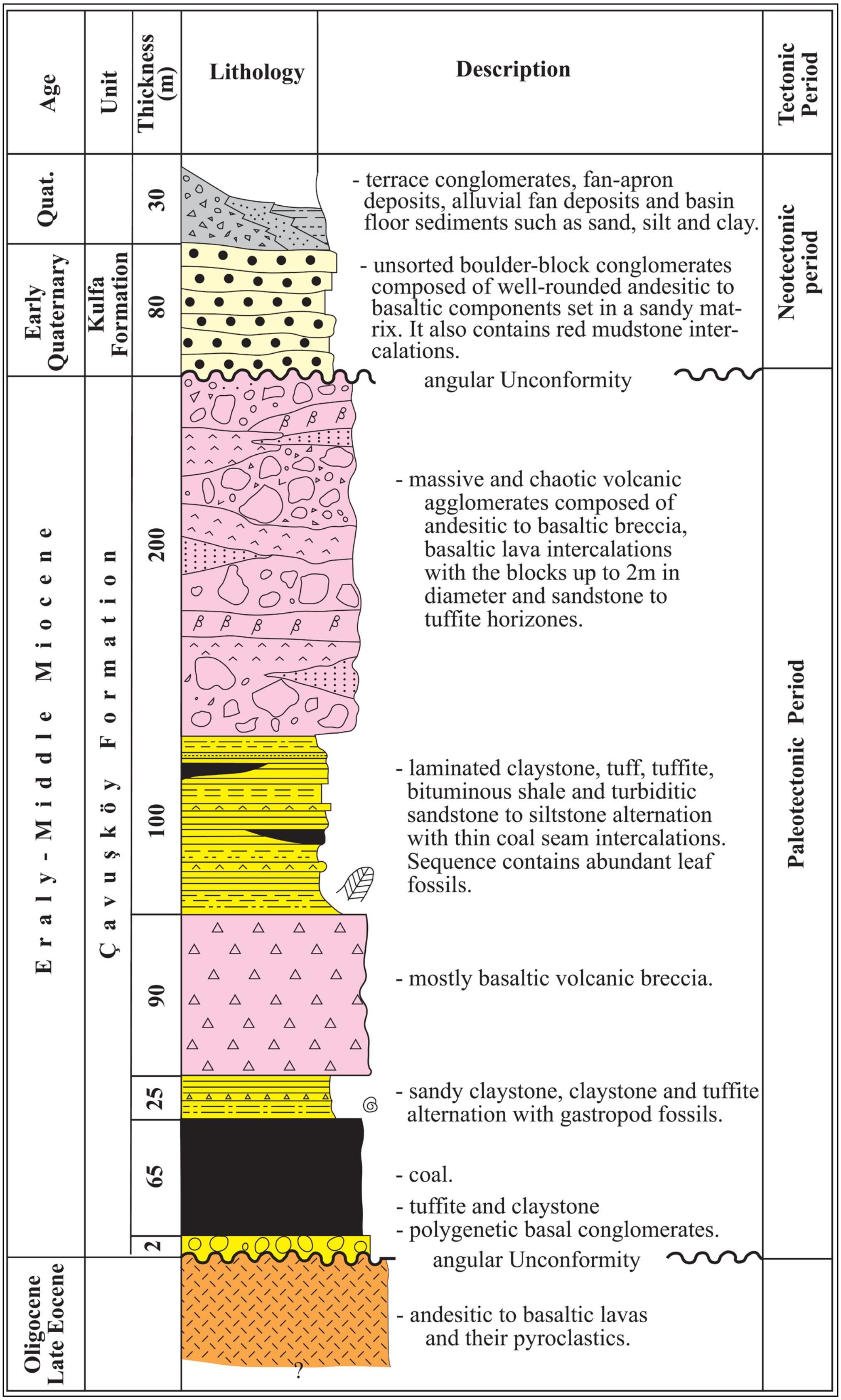

Figure 17- Generalized stratigraphical column of the Çan and Ezine-Bayramiç superimposed basins.

the tectonic regime, i.e., the tensional tectonic regime was replaced by the N-S-directed compressional tectonic regime. For this reason, the Miocene graben and its volcano-sedimentary sequence were deformed, uplifted and became an erosional area during the Late Miocene, or most probably in the Pliocene time. Starting from the Early Quaternary, both areas began to experience a strike-slip tectonic regime governed by a stress field state with the maximum principal compressive stress (σ_1) operating in approximately E-W direction. This new regime led to the reactivation of some older faults and formation of numerous new strike-slip faults. Thus, both the SIFZ and ÇBEFZ formed, and five pull-apart basins, which are drained by the Sarıköy Çay, Balıklı Çay, Kocaçay River and Karamenderes Çayı, developed within them.

3. Regional Geodynamics and Discussion

Both the Aegean Sea and western Anatolia, which comprise the west-southwesternmost frontal part of the Anatolian platelet (Figure 1a), have received much more attention in last three decades (Şengör and Yılmaz, 1981; Ercan et al., 1985; Seyitoğlu and Scott, 1991, 1996; Karacık and Yılmaz, 1998; Ring et al., 1999; Koçyiğit et al., 1999; Yılmaz et al., 2000; Bozkurt, 2001; Koukouvelas and Aydın, 2002; Kaya et al., 2004; Erkül et al., 2005; Bozkurt and Rojay, 2005; Emre and Sözbilir, 2005; Jolivet and Brun, 2010). Although the Aegean Sea and western Anatolia are relatively smaller area, they contain various and complex tectonic processes and related structures such as the subduction tectonics, exhumed HP-LT metamorphic rocks, metamorphic core complexes, intracontinental transform fault (North Anatolian

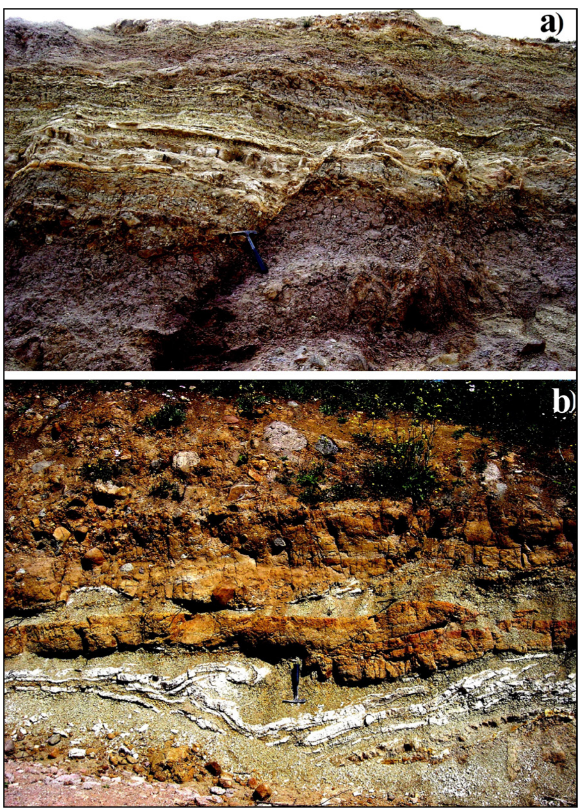

Figure 18- a and b) Field photographs illustrating both the synsedimentary growth fault (a) and slump fold (b) developed during the sedimentation in lower-middle Miocene Çan paleotectonic graben.

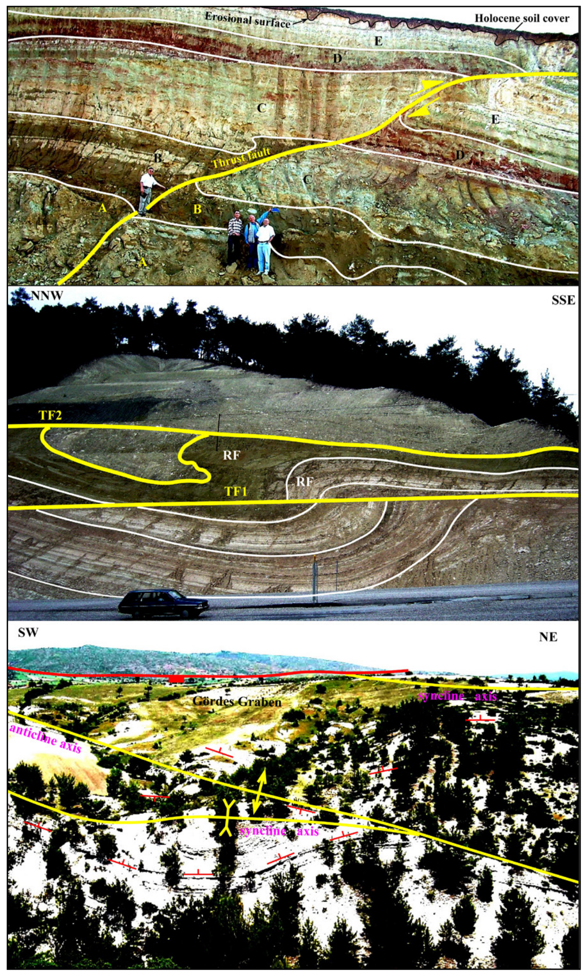

Figure 19- a) Field photograph of a Lower-Middle Miocene recumbent fold (RF) cut and offset by a thrust fault (TF1 and TF2), b) Field photograph illustrating a thrust-faulted to offset Lower-Middle Miocene fluvio-lacustrine sedimentary sequence of A, B, C, and D, and c) Field photograph illustrating the margin-boundary normal fault and folds with approximately E-W trending axes developed in the Miocene basin fill of the NE-trending Gördes graben.

Fault System), Tertiary-Quaternary magmatic rocks, trench, the Plio-Quaternary volcanic arc, back-arc rifting, orogenic collapse, widespread graben-horst system, strike-slip basins and their mutual interactions (Figure 1b).

Some of earlier studies (Şengör and Kidd, 1979, 1985; Dewey et al., 1986; Şaroğlu and Yılmaz, 1986) have reported that the continent-continent collision of Eurasian and African-Arabian plates and the entire demise of the intervening oceanic realm (southern branch of Neotethys ocean) imply to the end of paleotectonic period and onset age of the strike-slip faulting-dominated neotectonic period in eastern Türkiye. In contrast to the ideas of these authors, our detailed field studies (Koçyiğit et al., 2001; Aksoy et al., 2007; Çolak et al., 2012; Koçyiğit, 2013; Koçyiğit and Canoğlu, 2017) carried out directly in the field in a broad area covering both the eastern Anatolia and some parts of Lesser Caucasus indicated that: 1) There is an approximately 9 Ma long transitional period between the paleotectonic and neotectonic periods in eastern Türkiye, 2) the E-W trending folds, thrust-to reverse faults and ramp basins represent the Late Miocene-Middle Pliocene transitional period, and 3) the strike-slip neotectonic regime has commenced in the Late Pliocene. Because, for the wholesale establishment of a neotectonic regime in a region, it has to be preceded by a series of regional inversions such as magmatic activity, style of tectonic regime, deformation pattern, type of basin and sedimentation and the stress field state. Same kind of transitional tectonic periods have also been reported from various parts of Europe (e.g. Becker, 1993). The Late Miocene-Middle Pliocene transitional period separates the pre-Serravallian paleotectonic period from the Plio-Quaternary strike-slip neotectonic period. Starting from the Late Pliocene onwards, the southern part of the Eurasian plate was subdivided into a series of diverse-sized continental wedges bounded by the sinistral to dextral strike-slip faults. The largest of these continental wedges is the Anatolian platelet that has been escaping along its boundary faults, namely the dextral North Anatolian and the sinistral East Anatolian fault systems (NAFS and EAFS), in WSW direction onto the oceanic crust of the Mediterranean Sea since the Late Pliocene (Hempton, 1987; Koçyiğit and Beyhan, 1998).

The NAFS is an intracontinental transform fault structure. It accommodates the westward relative motion of the southerly located Anatolian Platelet (Figure 1a). However, the Anatolian platelet and its westward motion are being tried to be blocked and forced to move in south-southwestward direction by a barrier, namely the mainland Greece. This regional process resulted in a new stress field state, in which the greatest principal compressive stress (σ_1) is operating in approximately E-W direction (Şengör, 1980). Thus, the bifurcation of the NAFS into three major strands, numerous fault zones to single faults, their bending at ~30° towards south to the just west of the Lake Ulubat-Bandırma-Tekirdağ imaginary line (X-Y in Figure 1b) and blocking and forcing of the Anatolian platelet to move southwestwards by the mainland Greece altogether changed the architecture of the westernmost section of the NAFS, and led to the emergence of a new neotectonic province in central to northern Aegean Sea and their nearby onshore areas. It includes the southernmost part of the Rhodope Massif, Thrace basin, the western half of the Sea of Marmara region, Biga Peninsula, Gulf of Edremit, İzmir to Doğanbey Gulfs, and all of central to northern Aegean Sea. This domain is here termed as the central to northern Aegean neotectonic province. It is now under the control of a prominent strike-slip neotectonic regime and related structures (Koçyiğit and Gürboğa, 2021). This new neotectonic domain is outlined by the NNE-trending Balıkesir-İzmir fault zone (BIFZ) to east (Uzel and Sözbilir, 2008; Koçyiğit, 2015; Koçyiğit, 2020), and the E-W-trending Metsa fault zone, which also shapes the southern foot of the Rhodope Massif along the Greece-Bulgarian state border, to north-northwest (Protopopova and Botev, 2020). Along these two major structures, the central to northern Aegean strike-slip neotectonic regime and related structures interact with the extensional neotectonic regimes in both the southwest Anatolia-Türkiye and throughout Bulgaria (Pavlides et al., 1990; Kaya et al., 2004; Uzel and Sözbilir, 2008; Koçyiğit, 2015; Sakellariou and Tsampouraki-Kraounaki, 2019; Koçyiğit, 2020). Based on tensor solution diagrams of earthquakes and the kinematic analyses of slip-plane data obtained from faults, the prominent extension directions change slightly between NNW and NNE in both Southwestern Anatolia and Bulgaria (Koçyiğit, 1984; Nalbant et al., 1998; Koçyiğit et al., 1999; Yılmaz et al., 2000; Koçyiğit, 2005; Tan et al., 2008; Kalafat et al., 2011; Koçyiğit, 2015; Sözbilir et al., 2016; Protopopova and Botev, 2020). This extension direction fits well with the general indirect extension (σ_3) in the central to northern Aegean strike-slip neotectonic domain owing to the contraction operating in approximately E-W direction (Gökaşan et al., 2012; Koçyiğit and Gürboğa, 2021).

In the further east of northwestern Anatolia (around Kargı-Ilgaz area district, outside the study area) (Ayhan and Koçyiğit, 2010), the NAFS bifurcates into three major strands. These are informally: 1) northern strand, 2) central strand and 3) southern strand (Figure 1b). Around Sea of Marmara, the northern strand is represented by the Hendek-Yığılca (HYFZ), northern Marmara (NMFZ), Işıklar (IFZ) to Ganos fault zones and the North Aegean trough (Koukouvelas and Aydın, 2002; McNeill et al., 2004; Görgün et al., 2010; Karimi et al., 2014); the central strand by the Kaynaşlı-Gölyaka-Akyazı (KGAFZ) and the Sapanca-Yalova fault zones (SYFZ) (Figure 1b). However, the southern strand consists of numerous fault zones, fault sets and single faults. The most common of them are the Dokurcun (DFZ), Geyve-İznik (GIFZ), Yenişehir (YFZ), Demirtaş-Taşlık (DTFZ), Edincik-Denizkent (EDFZ), Karabiga (KFZ), Lapseki (LPZ), Sarıca (SFZ), Sarıköy-İnova (SIFZ), Çan-Biga-Ezine (ÇBEFZ), Skyros-Biga (SB), Truva (TF), Gülpınar (GFZ), Yenice-Gönen (YGFZ), Danişment-Pazarköy (DPFZ), Ilıca-Darıca (IDFZ), Bursa (BFZ), Manyas (MFZ), Edremit-Havran (EHFZ), and the Tuzla (TFZ) fault zones to single faults (Figure 1b) (Barka, 1992; Armijo et al., 1996; Koçyiğit, 1988; Koçyiğit et al., 1999; Ring et al., 1999; Okay et al. 1990; Koçyiğit et al., 2000; Kaya and Foulger, 2000; Sözbilir et al., 2003; Koçyiğit, 2009; Sakellariou and Tsampouraki-Kraounaki, 2019). Additionally, in the area between City of Bursa and Lake Ulubat, the southern strand of the NAFS intersects with both the WNW-trending İnönü-Eskişehir Fault System (IEFS) and the NNE trending Balıkesir-İzmir fault zone (BIFZ) (Figure 1b). Both northwestern Anatolia and northern Aegean Sea are crossed and subdivided into numerous strike-slip basins, troughs and structural highlands (pressure ridges) by the faults comprising the NAFS. The most common strike-slip faulting-related structures are the Sakarya basin (SB), the Sapanca-İzmit trough, the Armutlu pressure ridge, the northern Marmara Sea trough, Ganos pressure ridge, Saros-Sporadhes troughs along both the northern and middle strands; the Geyve basin, the İznik trough, Yenişehir basin, the Gemlik basin, the Bandırma-Gemlik trough, the Edincik pressure ridge, the Sarıköy, İnova Kazabat, Çan, Bayramiç-Ezine, Gönen and Yenice basins along the southern strand of the NAFS (Figure 1b).

The BIFZ, MFZ, YGFZ, EHFZ, TFZ, GFZ, and the Truva fault (TF) were previously studied well (Tutkun et al., 2006; Kürçer et al., 2008, 2012, 2017, 2019; Yaltırak et al., 2013; Sözbilir et al., 2016; Sümer et al., 2018; Koçyiğit and Gürboğa, 2021) (readers are referred to these papers). In contrast to these studies, the SIFZ and the ÇBEFZ are still ill-defined and have not been studied in detail. Whereas these two basins, their fills and margin-boundary faults include significant structural and stratigraphic data for the solution of onset age of the neotectonic regime, total displacement and slip rate. For this reason, the SIFZ, the ÇBEFZ and related basins were studied in detail based on the field geological mapping carried out directly in the field in the frame of the present paper (Figure 1b). Five pull-apart basins were developed along the SIFZ and ÇBEFZ. These are, from NE to SW, the Sarıköy, İnova, Kazabat, Çan and Bayramiç-Ezine basins. First three basins are the fault-wedge type of pure pull-apart basins developed along the SIFZ during the Quaternary time. This is indicated by the angular unconformity between the overlying flat-lying Quaternary basin fill and the underlying severely deformed pre-Quaternary basement rocks (Figure 8). However, the rest two basins, namely the Çan and Bayramiç-Ezine basins, are superimposed depressions with two basin fills separated by the intervening angular unconformities (Figure 16). This observation reveals that these two basins have developed episodically. Consequently, the stratigraphy of these pull-apart basins reveals strongly that the formation age of the SIFZ is Quaternary (Koçyiğit and Gürboğa, 2021). This also reveals that the onset age of the strike-slip neotectonic regime in Biga Peninsula is the Early Quaternary (Koçyiğit and Gürboğa, 2021). Whereas it was reported as the Late Miocene-Pliocene in most of the previous works (Herece, 1985, 1990; Siyako et al., 1989; Karacık and Yılmaz, 1998; Yılmaz et al., 2000; Kürçer et al., 2008, 2019). Some new geographic and geological markers were obtained in terms of the detailed field geological mapping. These are the offset drainage systems and rock units. Some of them are: 1) the Balıklı Çayı was offset up to 12 km by the SIFZ in dextral direction (X-Y in Figure 3), 2) in the same way, the Permo-Triassic Karakaya Complex has been cut and displaced up to 12 km by the SIFZ in dextral direction (X-Y in Figure 4), 3) the Kocaçay River was offset up to 20 km by the ÇBEFZ in dextral direction (X-Y in Figure 12), and 4) the southern boundary of the Lower-Middle Miocene volcano-sedimentary sequence in Bayramiç-Ezine basin was crossed and displaced up to 30 km in right lateral direction (Figure 7 in Yılmaz et al., 2000). In the case of the uniform slip rate, there is a close relationship among the age, total displacement and slip rate of an active fault or fault zone. This can be explained by a simple equation (Slip rate = total displacement/age). In this equation the total displacements are 12 km and 20 km, the age of the active faults is Early Quaternary, i.e., 2.588 My BP. Consequently, the slip rate on both the SIFZ and the ÇBEFZ are 4.6 mm /yr and 7.7 mm/yr respectively.

4. Results

Based on data presented in the foregoing chapters, the followings are concluded:

1. In the present, the study area is under the control of a strike-slip neotectonic regime commenced in the early Quaternary. This is proven by the regional angular unconformity separating the folded to thrust-faulted pre-Quaternary rocks and the non-deformed Quaternary strike-slip basin fill. It is also evidenced by the new stress field state with a principal compressive stress (σ_1) operating approximately in E-W direction, whereas it was more or less vertical to sub-vertical in position before the Quaternary period.

2. SIFZ and related basins developed on the uplifted erosional surface of the pre-Miocene rocks. For this reason, the Sarıköy, İnova and Kazabat depressions are pure strike-slip basins of the Quaternary age. In contrast to them, the ÇBEFZ and related basins formed on the uplifted and deformed erosional surface of the Lower-Middle Miocene graben and associated fill. Therefore, Çan and Ezine-Bayramiç depressions are superimposed basins, and the most faults comprising the ÇBEFZ are the reactivated older structures inherited from the Miocene extensional paleotectonic period.

3. Based on both the structural and the geographic markers, the total dextral strike-slip displacements accumulated on the SIFZ and the ÇBEFZ are 12 km and 20 km, respectively. These displacements correspond to an approximately 4.6 mm/year and 7.7 mm/year slip rates on the SIFZ and ÇBEFZ, respectively.

4. The longest fault segments are the 14 km long Tahtalı and the 15 km long Güllüce faults. Based on the maximum lengths of fault segments, the magnitude of peak earthquakes to be originated from these segments are Mw = 6.4 and 6.5 respectively.

5. Both the SIFZ and the ÇBEFZ are active. This is also indicated by the historical earthquakes. In the present, there might be a seismic gap. The return period of peak earthquakes to be resulted from these fault zones seem approximately as 500 years and 400 years, respectively.

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