Geosciences Journal
Vol. 12, No. 3, p. 215 − 225, September 2008
DOI 10.1007/s12303-008-0022-9
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Tectonic Geomorphology of the North Anatolian Fault Zone in the Lake Sapanca Basin (Eastern Marmara Region, Turkey)

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ABSTRACT: In this study the spatial variations of the Plio-Quaternary tectonic activity and deformation of different fault segments of the North Anatolian Fault Zone (NAFZ) in the eastern Marmara region around Lake Sapanca, are assessed using geomorphic, morphometric and bathymetric approaches. Lake Sapanca is an E-W-trending structure located in the İzmit-Sapanca Corridor. This region is bounded to the north and to the south by the series of mountain ranges. Geomorphic and morphometric data provide evidence for variations between the two mountain front faults regarding levels of tectonic activity. These studies suggest a relatively high degree of tectonic activity along the Sapanca front in the south, in contrast with a low degree of tectonic activity along the Eşme front in the north of the study area. This pattern is also consistent with field evidence and seismic data of the study area. Bathymetric profiles of the lake show that the lake basin consists of different fault segments that slipped in the 1999 Kocaeli earthquake. All these data suggest that the İzmit-Sapanca Corridor is an asymmetric pull-apart basin associated with displacement along the NAFZ in the Late Pliocene. Lake Sapanca also occurs as a pull-apart basin created by the cross-basin fault of the asymmetric pull-apart basin in the Middle Pleistocene.

Key words: North Anatolian Fault Zone, Lake Sapanca, İzmit-Sapanca Corridor, morphotectonics, pull-apart basin, Turkey

1. INTRODUCTION

Tectonic geomorphology is the study on the landforms that result from the interaction between tectonic and geomorphic processes (Mayer, 1986). The quantitative measurement of landscape is based on the calculation of geomorphic indices using topographic maps, aerial photographs and field work (Keller and Pinter, 1996). Geomorphic indices and landform assemblages are useful in regional evaluation to identify relative tectonic activity and sites where rates of active-tectonic processes may be evaluated (Keller, 1986).

The main structural element controlling the geomorphological and structural features in the study area is the North Anatolian Fault Zone (NAFZ). The NAFZ is one of the best known strike-slip faults in the world because of its remarkable seismic activity, extremely well-developed surface expression and importance from the tectonics of eastern Mediterranean region (Ketin, 1968, 1969; Ambraseys, 1969; McKenzie, 1972; Dewey, 1976; Şengör, 1979; Şengör et al., 1985, 2005; Bozkurt, 2001; Fig. 1a). This fault zone is a 1600 km-long, dextral strike-slip active transform fault running through northern Turkey in an E-W direction. Ikeda et al. (1989a, 1989b) have presented some lines of evidence indicating that the NAFZ branches westward into two active fault zones from 30ºE: the northern branch called the İzmit-Sapanca fault zone (Ikeda, 1988), and the southern branch called the İznik-Mekece fault (Sipahioğlu and Matsuda, 1986). These branch faults are synthetic faults, being developed at a low angle to the master fault, mainly in the contractional quadrant, but occasionally in the dilational quadrant (Kim and Sanderson, 2006).

Lake Sapanca is situated in the western part of the NAFZ to the eastern Marmara region (Fig. 1b) and lies between 30º08′40″: 30º20′26″ longitudes and 40º42′48″: 40º43′52″ latitudes of the İzmit-Sapanca Corridor. This corridor is located in a tectonically complex area and this characteristic of the region is reflected in the surrounding morphology of the lake. The characteristics of the NAFZ in the Marmara region became the topic of intense research since the Kocaeli (or İzmit) earthquake in 17 August 1999 (Mw=7.4) (e.g., Okay et al, 1999, 2000; Parke et al., 1999; İmren et al., 2001; Le Pichon et al., 2001, 2003; Yaltırak, 2002; Armijo et al., 2002; Gürer et al., 2003, 2006; Demirbağ et al., 2003). The great Kocaeli earthquake occurred on a 150 km long seismic gap which was previously identified by Toksöz et al. (1979) as having a high likelihood of producing a damaging earthquake (Alpar and Yaltırak, 2002). There were different views concerning the position of the active segment of the NAFZ in the region until this earthquake, and mapped as classically on the southern border of the İzmit-Sapanca Corridor due to morphologic expression. The fault rupture of the 1999 earthquake pass through the depression floor against the previous studies and caused to some controversial interpretations, but none of these interpretations combined in the same model. Recent studies after the Kocaeli earthquake about the tectonics of the NAFZ in the Marmara region classified by Yaltırak (2002) into three models: (1)

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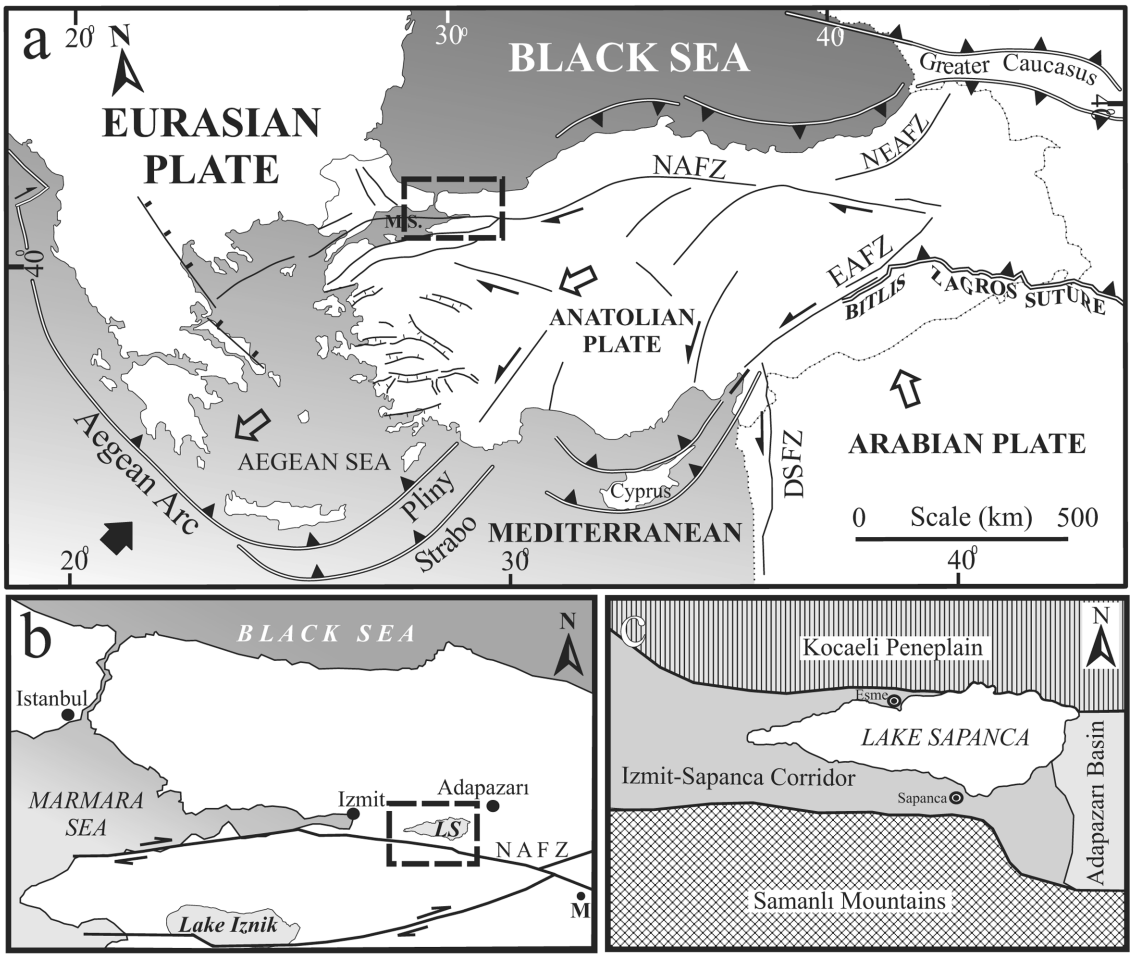


Fig. 1. (**a**) Tectonic outline of Turkey and eastern Mediterranean area. MS: Marmara sea. NAFZ: North Anatolian Fault Zone. EAFZ: East Anatolian Fault Zone. DSFZ: Dead Sea Fault Zone. NEAFZ: North East Anatolian Fault Zone. (**b**) Location map of the study area. LS: Lake Sapanca. M: Mudurnu. **(c)** Major morphotectonic elements that form the boundary of the Lake Sapanca.

pull-apart models (Barka and Kadinsky-Cade, 1988; Wong et al., 1995; Ergün and Özel, 1995; Barka, 1992, 1997); (2) en-échelon fault segmented models (Parke et al., 1999; Siyako et al., 2000; Okay et al., 2000); and (3) single master fault model (Le Pichon et al., 1999; Aksu et al., 2000; Imren et al., 2001).

Evaluation of landforms produced and modified by active dextral strike-slip deformation of the NAFZ around Lake Sapanca provides basic data necessary for estimating long-term deformation and tectonic activity in the region. The fault-generated mountain fronts are the most characteristic landforms. Therefore, geomorphological analysis of mountain fronts, analysis of the drainage networks, and the calculation of several geomorphic indices in this region offer valuable informations on the recorded tectonic history.

The aim of this paper is to assess the spatial variations of Plio-Quaternary deformation and tectonic activity of the NAFZ in the eastern Marmara region around Lake Sapanca. Geomorphic, morphometric and bathymetric analyses were used to elucidate the morphotectonic features of the study area, an area of critical importance for solving the neotectonic problems of the Marmara region. The study endeavours to determine the relative intensity of active tectonics through the study of morphological features, presents a tectonic model about the origin of the İzmit-Sapanca Corridor, and represents the position of the latest faulting of the NAFZ in the region.

2. GEOLOGICAL SETTING

The neotectonic period in the eastern Mediterranean region started by the collision of the Arabian and Anatolian plates along the Bitlis-Zagros Suture Zone in the southeastern Turkey and the westward escape of the Anatolian plate in the Late Pliocene (Hempton, 1987; Koçyiğit et al., 2001; Fig. 1a). The present morphotectonic framework of the study area was mainly set in the Late Pliocene-Quaternary period by the strike-slip tectonic regime of the dextral NAFZ (Emre et al., 1998; Gürbüz and Gürer, 2007). The NAFZ is the most important structural feature con-

trolling the active tectonics in northern Turkey, splays into two major strands to the east of the İzmit-Sapanca Corridor, and the west of Mudurnu valley (Bozkurt, 2001; Fig. 1b). The Adapazarı basin, the İzmit-Sapanca Corridor and the Marmara Sea are located on the northern strand of the NAFZ, which is the seismically most active strand with slip rates of approximately 10-15 mm/yr (Straub et al., 1997). This strand includes the segment that slipped in the 17 August 1999 Kocaeli earthquake (Mw=7.4).

The margins of Lake Sapanca are defined by a series of mountain ranges (Fig. 1c). The Samanlı mountains to the south of the study area were uplifted as a pressure ridge structure and isolated from the surrounding morphology between the northern and southern strands of the NAFZ (Koçyiğit, 1988).

The mountain ranges are composed of Paleozoic to Early Tertiary metamorphic and sedimentary rocks which form the basement of the region. On the Eşme front of the Kocaeli Peneplain to the north of the lake, Paleozoic-Early Tertiary rocks crop out as uplifted basement against the Plio-Quaternary units and consist of sandstone, clayey limestone, marl and interbedded sandstone, shale and siltstone (Fig. 2). The Sapanca front of the Samanlı Mountains, situated on the southern margin of the lake, consists of Paleozoic-Mesozoic rocks that include metamorphic (schist, marble, gneiss and quartzite) and meta-ophiolitic rocks (peridotite, gabbro and amphibolite).

Lake Sapanca developed with its E-W-trending trending

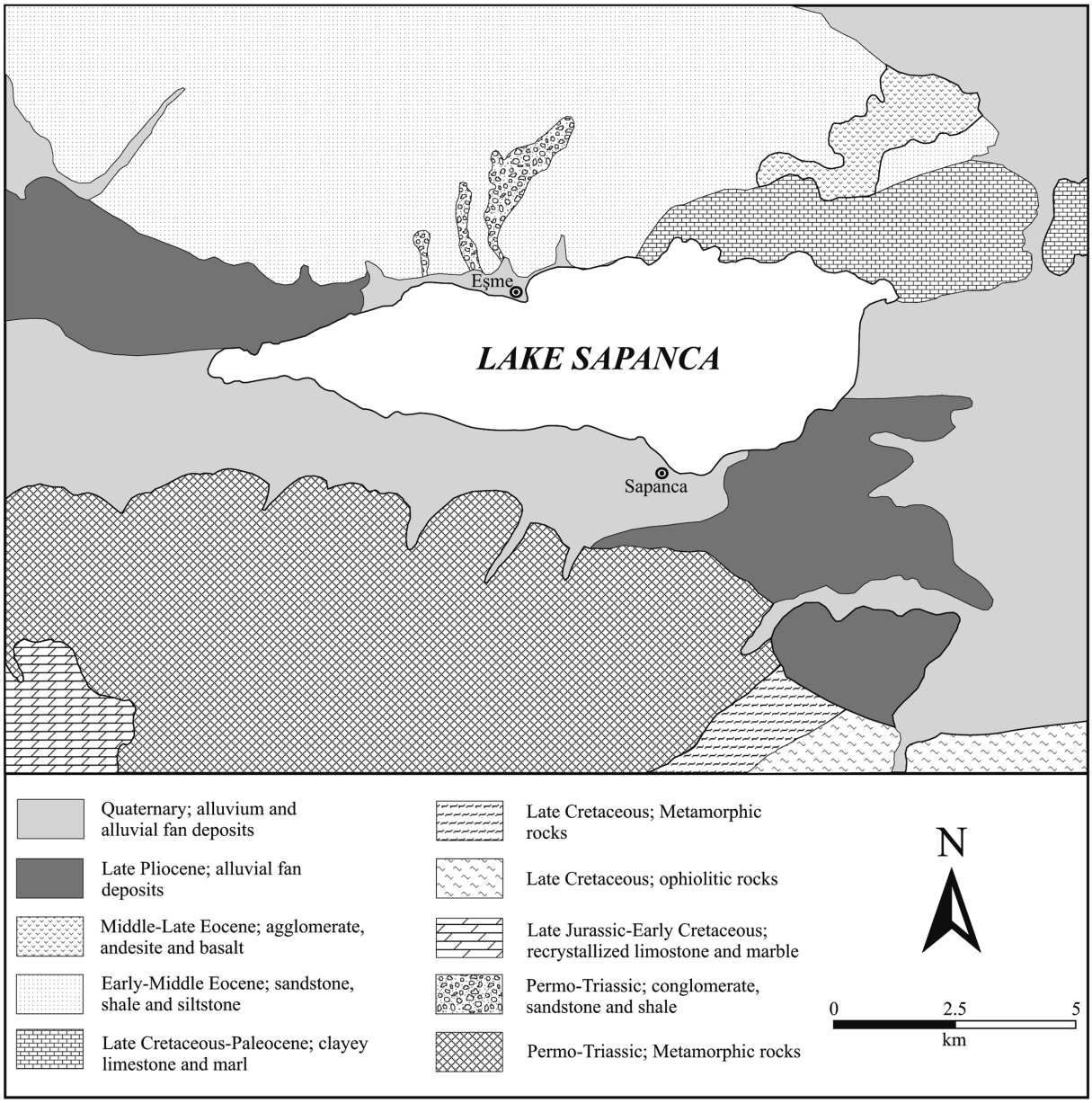


Fig. 2. Geological map of the study area (modified from Herece and Akay, 2003).

elongated morphology on the İzmit-Sapanca Corridor and the floor of the depression is filled with Plio-Quaternary alluvial fan and alluvium deposits.

3. METHODS

In this study we analyze the main morphological features of the mountain fronts, the alluvial fan and fluvial systems sorrounding the lake and the bottom morphology of Lake Sapanca (Fig. 3). The geomorphological and morphometric analyses were carried out in the field, and on 1:25.000 scale topographic maps and digitial elevation models. Six main parameters used in these analyses which involves relative processes between tectonics, lithology, sedimentation and erosion were:

3.1. Mountain Fronts

Mountain front sinuosity (S_{mf}). This reflects the balance between the erosional and tectonic forces affecting a mountain front and is defined as $S_{mf} = L_{mf}/L_s$; where L_{mf} is the length of the mountain-piedmont junction and L_s is the

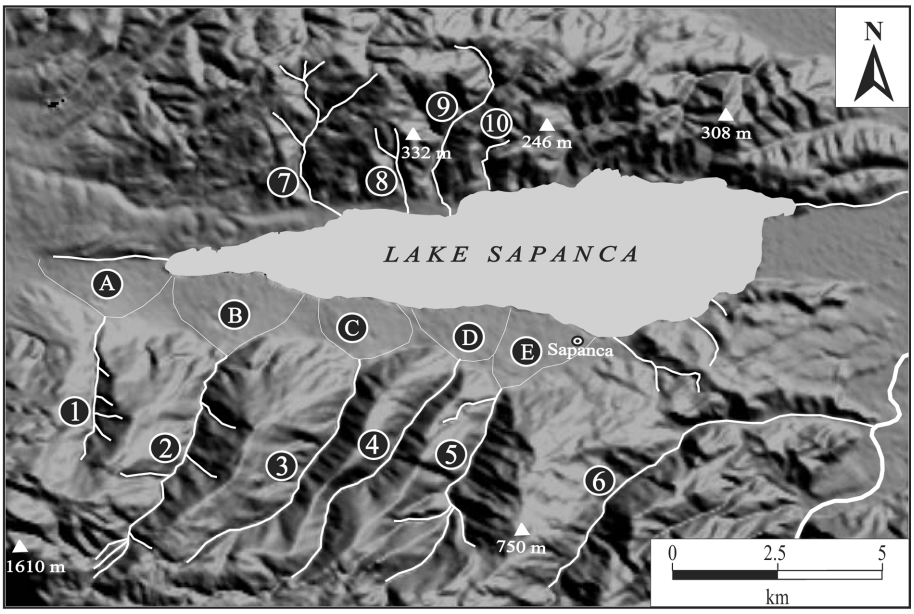
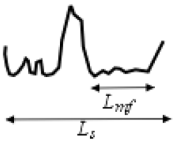
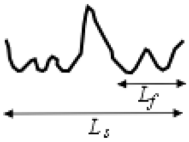
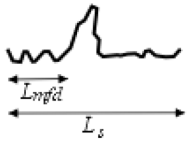
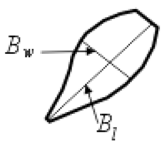


Fig. 3. Physiographic image of the study area. Circled numbers identify each of the 10 fluvial systems and capital letters identify each of the 5 alluvial fans used for the morphometric analysis.

Table 1. Morphometric parameters used in our study (after Wells et al., 1988; Ramirez-Herrara, 1998)

Morphometric parameter	Formula	Calculation procedure	Interpretation	References
Mountain front sinuosity	$S_{mf} = L_{mf}/L_s$		S_{mf} =1.0 - high tectonic activity S_{mf} >1.0 - less tectonic activity	Bull and McFadden, 1977
Percentage faceting along mountain fronts	$F_{cl} = L_f/L_s$		Tectonically active fronts display high percentage faceting	Wells et al., 1988
Percentage dissected mountain fronts	$F_d = L_{mfd}/L_s$		Tectonically active fronts tend to be less dissected	Wells et al., 1988
Drainage basin shape indice $B_s = B_l/B_w$			High tectonic activity expressed by high B values	Ramirez-Herrara, 1998

straight-line length of the mountain front (Bull and McFadden, 1977) (Table 1).

Facets. These are interpreted as variably degraded remnants of fault generated footwall scarps (Wallace, 1977) and are situated between two adjacent drainage structures within a given mountain front escarpments. Two indices related to facet development were used in this analysis; the percentage triangular faceting along mountain fronts ($F_{cl} = L_f/L_s$; where L_{cl} is the cumulative lengths of facets and L_s is the straight-line length of the front) and the percentage dissected mountain fronts ($F_d = L_{mfd} / L_s$; where L_{mfd} is the length of dissected mountain front) (Wells et al., 1988) (Table 1).

3.2. Alluvial fans

Alluvial fan morphology throws light on faulting and reflects the rates of tectonic processes such as uplift of the source mountain. The plan view morphologies and the longitudinal profiles of five alluvial fans in the south of Lake Sapanca were used to define the control mechanisms on the fan development.

3.3. Fluvial systems

The morphology of streams that cross mountain fronts may reflect base-level changes arising from relative tectonic uplift (Wells et al., 1988). To understand this mechanism on fluvial systems, the drainage basin shapes were analysed. Here, the drainage basin shape indice (B_s) is described by an elongation ratio and defined as $B_s = B_l / B_w$ where B_l is the length of the basin, measured from its mouth to the most distant drainage divide, and B_w is the width of the basin measured across the short axis (Table 1). This indice was calculated for the 10 drainage basins of streams crossing the mountain front faults around Lake Sapanca in order to identify the elongated basins which would reveal such downcutting in areas of continuing rapid uplift.

3.4. Lake bottom morphology

The lake bottom morphology was analysed by digitizing Lettis et al.'s (2000) bathymetric map of Lake Sapanca. Longitudinal and transverse profiles were used in this 1 m contour interval map to determine disequilibrium conditions suggesting tectonic disruption of the lake bottom morphology.

4. GEOMORPHIC AND MORPHOMETRIC ANALYSES

The topography of the İzmit-Sapanca Corridor in which the study area is located, is asymmetric and being steeper along the southern side of the corridor where the Samanlı mountains rises steeply to over 1500 m from the depression floor, which is 35 m above sea level. On the northern side, the topography of the Kocaeli Peneplain, which bounds the depression, is more subdued and tilted northward.

The faults along both sides of the depression around Lake Sapanca indicate mainly oblique normal faulting as mountain front faults. This fault pattern is compatible with transtensional regime of the NAFZ in the region. The northern edge of the İzmit-Sapanca Corridor around the study area is fault-bounded but as a result of subdued topography and frail lithology the faults are morphologically less marked. The major faults along the southern side of the depression are deep steeply than the faults along the northern side of Lake Sapanca.

4.1. Mountain Fronts

In this study, mountain fronts were defined as major fault-bounded escarpments with measurable relief exceeding two contour intervals.

4.1.1. Mountain front sinuosity

Within the study area differences occur in the morphological and morphometric expression within fronts, associated with the tectonic environment of Lake Sapanca. Low sinuosity (1.38) of the Sapanca front in the south of the lake, reflects a relatively straight fault-bounded mountain front. On the Eşme front to the north of the lake, application of this indice has presented problems because of its discontinuous front.

4.1.2. Facets

Tectonically active fronts display high percentage of triangular faceting and tend to be less dissected (Bull and McFadden, 1977; Wells et al., 1988). On the Sapanca front, a high proportion of faceting with 40.6 percent, and low values for the proportion of dissected mountain front with 24.5 percent. These suggest a relatively higher degree of tectonic uplift than the values of Eşme front ($F_{cl} = 10.48$ percent; $F_d = 68$ percent).

4.2. Alluvial Fans

Clear examples of alluvial fans are shown on the Sapanca front with ideal characteristics in contrast with the northern fans, where there are Quaternary alluvial fan deposits with unidealized morphologies resulting from the short distance between the Eşme front and the northern edge of Lake Sapanca.

4.2.1. Plan-view morphologies

On the Sapanca front, Middle Pleistocene – Holocene

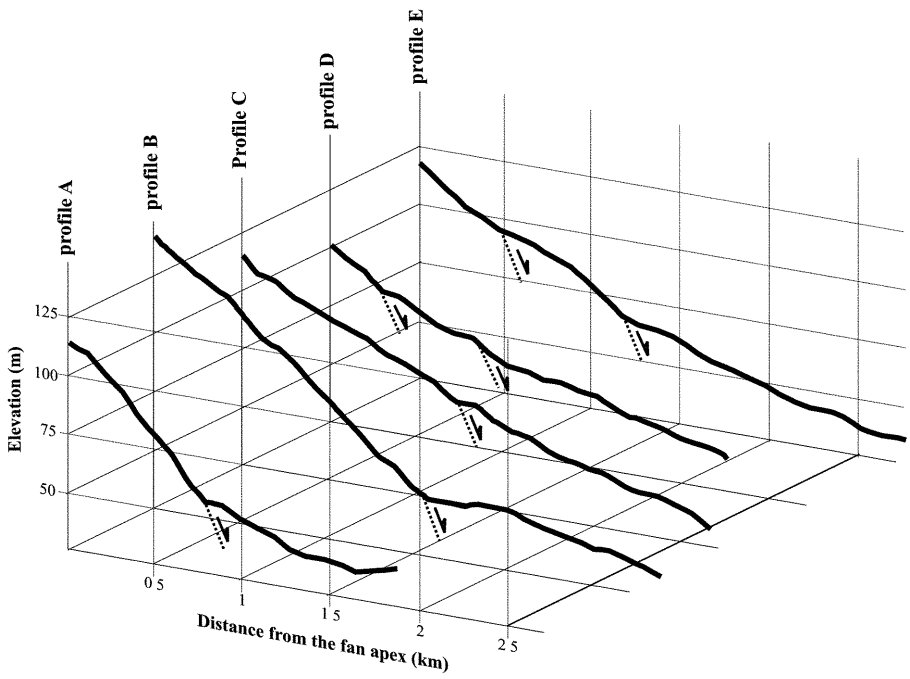


Fig. 4. Fan longitudinal profiles. Slope breaks pointed with dished lines interpreted as faults. Vertical exageration is 10.

alluvial fans covered the Late Pliocene-Early Pleistocene fan deposits with semi-elongated morphologies. The fan areas range from 2.49 to 5.87 km^2 and correspond to a system of coalescent fans (Fig. 3).

4.2.2. Longitudinal fan profiles

The fans generally present a profile with a similar mean slope value of 0.05 (Fig. 4). Fan A has a concave upwards profile with slopes that gradually decrease from the apex down. The profiles of Fans A, B and C are segmented into two parts with constant, but different, slopes; the profiles of Fan D and E are segmented into three parts with similar mean slopes. This slope breaks were determined in the field and some of them were identified by their observable fault plains. Therefore, the pointed slope breaks with dished lines in the longitudinal fan profiles may be caused by tectonic activity (Fig. 4).

4.3. Fluvial Systems

Morphological descriptions of the drainage basins of 10 streams on both sides of Lake Sapanca (Fig. 3), were studied within the context of the specific postulates noted above in Methods.

4.3.1. Drainage basin shapes

The typical shape of a basin in tectonically active mountain range is elongate and becomes progressively more circular after the cessation of mountain uplift (Bull and McFadden, 1977). The planimetric shape of a basin may be described by an elongation ratio of a circle (Cannon, 1976). The elongation ratios (B_s) for the 6 drainage basins of the Sapanca front, range from 2.98 to 5.18 with a mean value of 3.86. This value is higher than the mean value for 4 drainage basins on the northern Esme front (B_s = 1.43).

5. LAKE BOTTOM MORPHOLOGY

The bathymetric map of the lake (Fig. 5a) is one of the most useful tools to understand the lake's morphotectonic aspects. The most important morphological features observed in the lake are shelves, slopes and basin. The shelves comprise approximately E-W-trending elongated areas on both sides of Lake Sapanca, where average depths change from -15 to -35 m (Fig. 5a). The slopes are observed between shelf plain and the edge of the lake, and similarly between shelf plain and basin. The basin is situated in the middle of the lake basin with an E-W-trending elongated morphology, separated from the other morphological features by the fault geometry of the NAFZ in the lake.

Figure 5b shows 4 transverse and 1 longitudinal profiles of Lake Sapanca based on the interpretation of the bathymetric map. Detailed field studies concerning the 17 August 1999 Kocaeli earthquake indicated that the surface rupture entered the lake close to the southeast corner and exited on the western margin as two fault segments defined as Arifiye and Tepetarla segments (Fig. 6) (Emre and Awata, 2003).

The Tepetarla fault segment is distunguished by a prominent scarp on the transverse profiles and bounds the northern margin of the basin (Fig. 5b). The Arifiye fault defines the southern segment and is expressed by bathymetry on profile 4. In the middle of the lake basin, a fault is traced

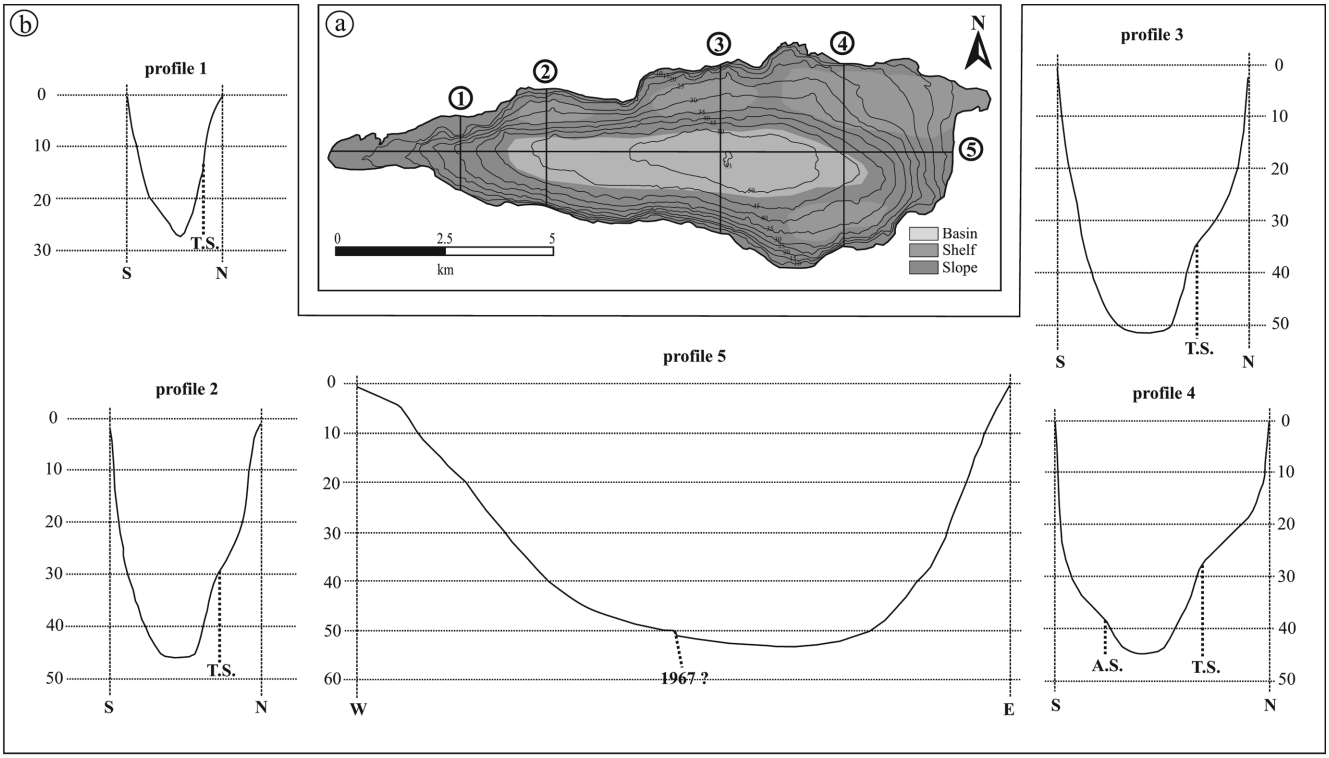


Fig. 5. (**a**) Generalised bathymetric map (5m) (after Lettis et al., 2000) and the bottom morphology of the Lake Sapanca. The locations of the bathymetric profiles in the lake are indicated. (**b**) Faults that interpreted by this bathymetric map. AS: Arifiye segment. TS: Tepetarla segment.

on the longitudinal profile of the lake (profile 5) and the direction of this fault intersects to the rupture of 22 July 1967 Mudurnu Valley earthquake (Mw=7.0), which entered on the southern edge and exited on the northern margin of the lake with NW-SE direction (Fig. 6) (Ambraseys and Zatopek, 1969).

6. DISCUSSION AND CONCLUSIONS

Spatial variation of tectonic activity in different fault segments of the NAFZ in the study area was assessed using geomorphic, morphometric and bathymetric approaches.

The geomorphic approach, applied out in the field studies of the faulted mountain fronts around the lake, suggests the Sapanca front (Samanlı Mountains) was more active than the Eşme front (Kocaeli Peneplain) according to geomorphic evidence of tectonic activity such as alluvial fans, facets, steep fault scarps and elongated ridges.

The morphometric analysis applied to the faulted mountain fronts, alluvial fans and fluvial systems of the İzmit-Sapanca Corridor around Lake Sapanca has a significant value in providing information on the relative rates of tectonic uplift. The morphometric analysis of two mountain fronts associated with active tectonic environments showed marked differences between the two fronts studied. Mountain fronts associated with active uplift are relatively straight (values of S_{mf} indice 1.0 on the most active mountain fronts), but if the rate of uplift is reduced or ceases, erosional processes will begin to form a sinuos front that becomes more irregular with time (Keller, 1986). Also, tectonically high active mountain fronts display prominent and large facets whereas tectonically less active fronts display fewer and dissected facets (Bull, 1978). However, in tectonically active areas where the energy of stream has been directed primarily to downcutting basin widths are much narrower (Ramirez-Herrara, 1998). According to the results of mountain fronts in the study area, low values of sinuosity and basin shape elongation ratio, and high values of percentage of faceting and dissected escarpments that maintained in the Sapanca front characterize the high tectonic activity. In the same way, these values are inverted in the Eşme front due to less tectonism (Fig. 7).

The bathymetric analysis was made by digitizing the bathymetric map of Lettis et al. (2000). Four slopes were traced in the lake bottom morphology, two of which separate the lake water from the land environment while the rest seperate the shelf plains from the basin (Fig. 5a). These two slopes formed by the Tepetarla and Arifiye segments, which slipped during the 17 August 1999 earthquake and show a step-over geometry in the center of the lake (Fig. 6). For this reason the lake is interpreted as a pull-apart basin by some writers (e.g., Barka, 2000; Lettis

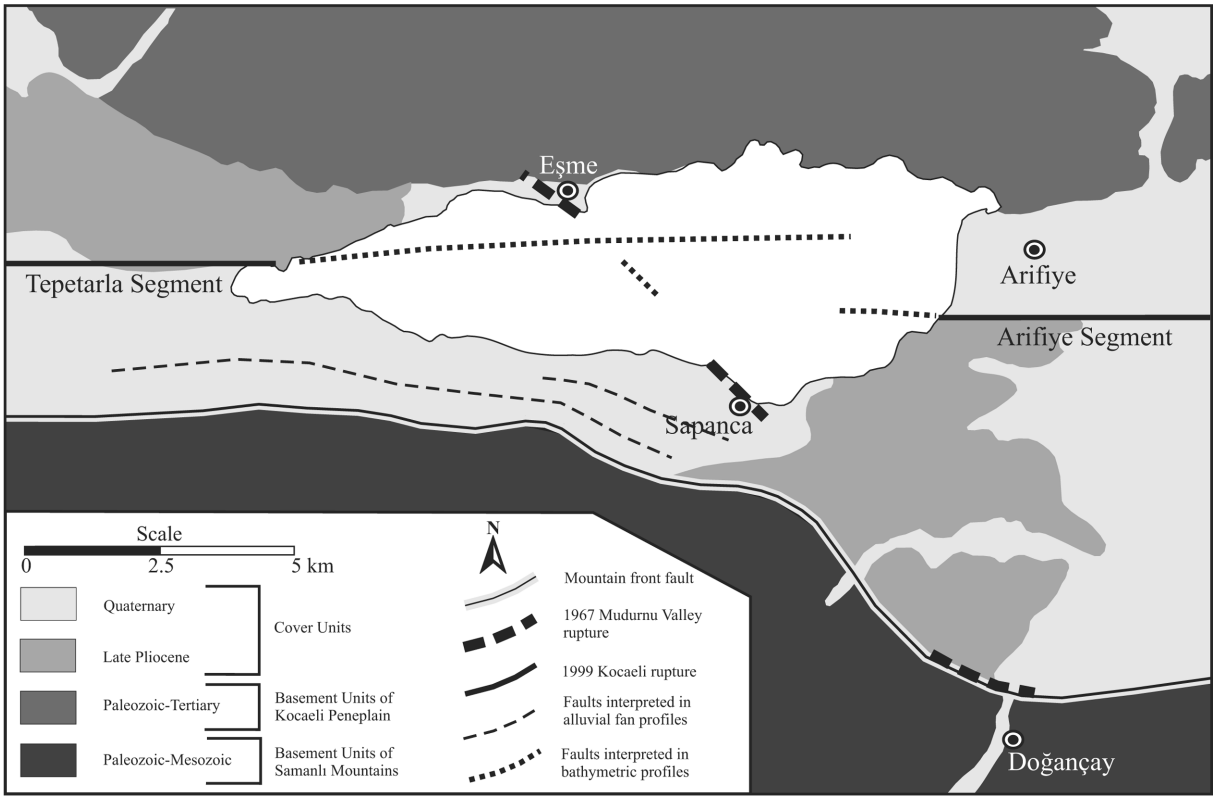


Fig. 6. Fault map of Lake Sapanca and its close vicinity, showing the mountain front faults, the surface ruptures asociated with the 1999 Kocaeli earthquake, the 1967 Mudurnu Valley earthquake (Ambraseys and Zatopek, 1969), and the faults in the lake basin interpreted by the bathymetric profiles of Fig. 5.

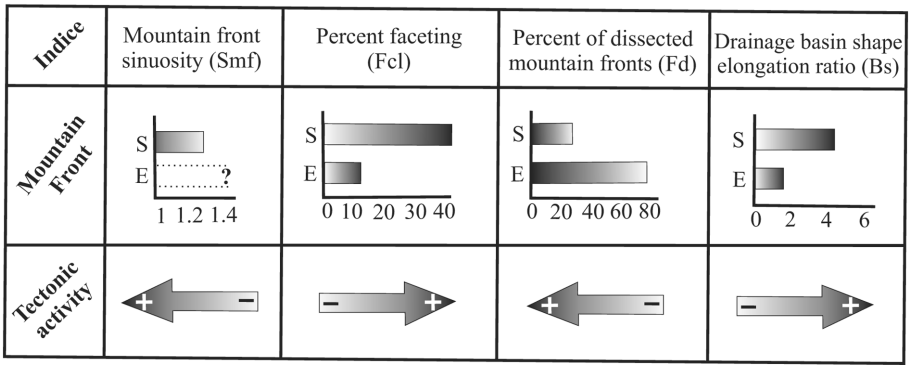


Fig. 7. Geomorphic parameters and relative degrees of tectonic activity. Letters in histograms indicate mountain fronts, S: Sapanca front. E: Eşme front.

et al., 2000).

However, the combination of these data in our study suggests that the Lake Sapanca pull-apart basin is situated in another pull-apart basin (İzmit-Sapanca Corridor) which is asymmetrical in form. There are several core logs in the floor of the İzmit-Sapanca Corridor which were drilled by General Directorate of State Hydraulic Works of Turkey (DSI). Three of them, which are located in the north-central side of the corridor and south-western side of Lake Sapanca, drilled into the basement rocks (Fig. 8). In the core 44155 which is located in the northern side of depression, Late Cretaceous-Early Tertiary sedimentary rocks drilled at fourteenth meter (Fig. 8). The cores 37614 and 37610 that located in the southern part of the depression drilled into Paleozoic-Mesozoic metamorphic rocks at fourtysixth and sixtyseventh meters (Fig. 8). The basement geometry of the corridor which could be surveyed by these core logs represent that the depression has an asymmetrical base.

Asymmetrical pull-apart basins are defined by a master fault on the one side of the basin and the basin axis being near the master fault (Rahe et al., 1998). The other side is characterized by normal faults oriented antithetically to the master fault with less displacement. In addition, a strike-slip fault that cut across the pull-apart basins in the asymmetrical models appeared during mature stages of devel-

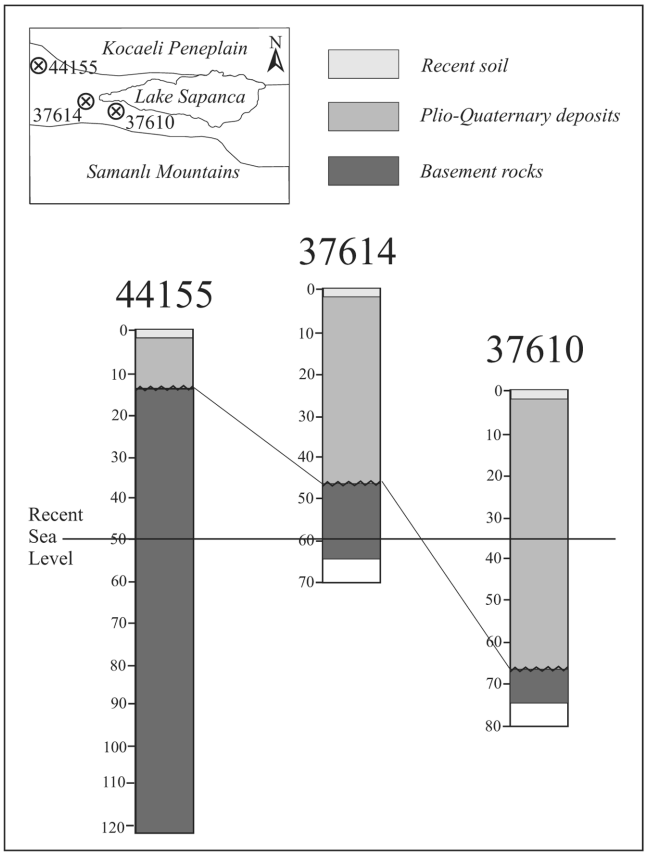


Fig. 8. Locations and stratigraphy of core logs that drilled by General Directorate of State Hydraulic Works of Turkey (DSI) in the İzmit-Sapanca Corridor. Asymmetrical basement geometry of the depression could be surveyed by these core logs.

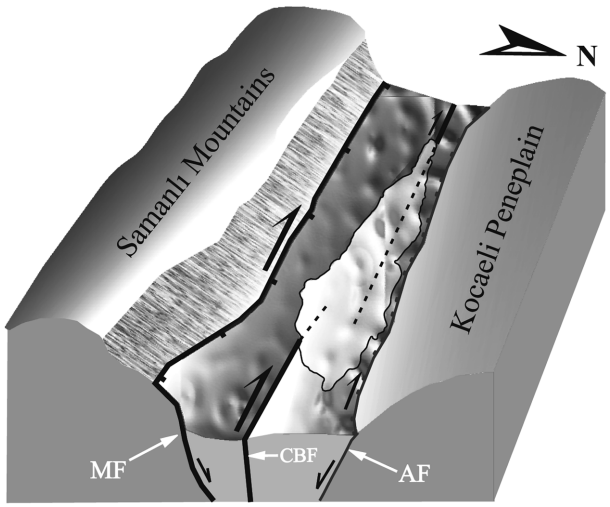


Fig. 9. Schematic block diagram showing the different fault segments of the NAFZ that developed the study area as an asymmetric pull-apart basin from the Late Pliocene to present. MF: Master fault (mountain front fault). CBF: Cross-basin fault (1999 Kocaeli earthquake rupture). AF: Antithetic fault (mountain front fault).

opments in analogue modellings, defined as cross-basin faults (McClay and Dooley, 1995).

The fault geometry in the İzmit-Sapanca Corridor is characterized by mountain front faults on both sides of Lake Sapanca (Fig. 9). The results of the geomorphic and morphometric studies proved that the southern mountain front boundary is more active than the northern one and showed characteristics of a master fault. According to the results of the same analysis, the northern mountain front is suggested as antithetic fault of this master fault.

Surface rupture during the 17 August 1999 earthquake cuts across the İzmit-Sapanca Corridor. It is interpreted that this rupture developed as a cross-basin fault in this asymmetrical pull-apart basin, indicating that this basin is in the mature stages of evolution. In addition, we suggest that Lake Sapanca developed as a pull-apart basin in this asymmetrical pull-apart basin which is defined as the İzmit-Sapanca Corridor.

The suggested fault trace on the longitudinal profile of the lake is well-correlated with the mapped rupture of 22 July 1967 earthquake (Ambraseys and Zatopek, 1969) on land (Fig. 6). The combined view of the ruptures in the 1999 and 1967 earthquakes presents a complex scene. We suggest that this scene related to the stress state within the fault step. According to the results of studies related to the detailed descriptions of strike-slip faults and their damage zones; patterns of strike-slip faults tend to be more complex during the evolution (Kim et al., 2003). The faults are likely to eventually interact with adjacent fault segments. Interacting fault segments will cause them to link in a compact fault zone (e.g., Peacock, 1991; Peacock and Sanderson, 1991; Cartwright et al., 1995; Kim et al., 2001, 2004).

ACKNOWLEDGMENTS: We are grateful to Mrs. Joanna Read and Dr. İrfan Yolcubal for assistances with English exposition, and Drs. Young-Seog Kim and Weon-Seo Kee for their useful reviews.

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Manuscript received November 9, 2007
Manuscript accepted June 9, 2008