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High-altitude Plio–Quaternary fluvial deposits and their implication on the tilt of a horst, western Anatolia, Turkey

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Abstract

This study investigates the origin and regional tectonic implications of high-altitude Plio (?)–Quaternary fluvial deposits developed over the Bozdağ horst which is an important structural element within the horst–graben system of western Anatolia, Turkey.

A total of 23 deposits occur near the modern drainage divide comprising fluvial to occasionally lacustrine deposits. The deposits are all elongated in N–S direction with a width/length ratio of 1/10. The largest of them is of 13 km in length with a maximum observable thickness of about 100–110 m. Morphological, lithological, deformational characteristics of these deposits and the drainage system of the area all suggest that the deposits were formed due to uplift and southward tilting of the Bozdağ horst. This tilting which is estimated as 1.2° to 2.2° caused accumulation of the stream load along channels flowing from south to north. All the deposits were later dissected by the same streams with the exception of one deposit which still preserves its original lake form. These deposits are of Quaternary age, which corresponds to the latest N–S directed extensional tectonic phase in the region.

Keywords: Fluvial deposits; Tilting; Drainage reversal; Bozdağ horst; Western Anatolia; GIS; Küçük Menderes

1. Introduction

Fluvial systems are one of the most important tracers of crustal deformation in tectonically active areas. Tectonic activity in most cases controls morphology of the valleys and determines the nature of the erosional and/or depositional processes that occur within these valleys. Quantitative measurements of these elements allow earth scientists to identify, measure and characterize the tectonic activity affecting a region (Keller and Pinter, 2002). Interactions between tectonic activity and fluvial processes have been well documented for different aspects of fluvial systems such as base-level changes (Harvey and Wells, 1987; Burbank et al., 1996; Bonnet et al., 1998; Humphrey

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and Konrad, 2000; Mather, 2000; Stokes and Mather, 2000), drainage reversal (Kafri and Heimann, 1994; Fisher and Souch, 1998; Ben-David et al., 2002, Ginat et al., 2002), tilt-block tectonics (Cox, 1994; Wende, 1995; Ginat et al., 1998; Synder et al., 2000; Cox et al., 2001; Hsieh and Knuepfer, 2001; Sun et al., 2001; Stokes and Mather, 2003) and general evaluations (Ouchi, 1985; Holbrook and Schumm, 1999).

In order to quantify these effects, many geomorphic or morphometric indices have been developed throughout the literature. Since landforms possess a fractal nature, the indices should be evaluated at two different scales: one regarding the general and regional situation and the other regarding a very local scale which is characterized by the attributes of a pixel in a Geographical Information System. Some of the pixel indices in which the measured attributes are limited to few meters to few hundred meters can be cited as: first derivatives (Slope, aspect, flow path length, profile curvature, plan curvature, etc.), and others as higher derivatives (topographical wetness indices, stream-power indices, radiation indices, temperature indices, etc). An excellent review of these indices can be found at Wilson and Gallant (2000). On the other hand the regional indices deal with much larger areas and reflect the effects of rapid tectonic deformation as recorded by the landform itself. Some of the indices as listed by Keller and Pinter (2002), used to characterize and to quantify tectonic activity are: hypsometric integral (Strahler, 1952), drainage basin asymmetry (Hare and Gardner, 1985; Cox, 1994), stream length-gradient index (Hack, 1973), mountain front sinuosity (Bull, 1977), ratio of valley floor width to valley height (Bull, 1977) and many researchers have explored the relations among these indexes (Silva et al., 2003). As the drainage system itself records the stages and patterns of development and long-term evolution of the landscape that exists (Gelabert et al., 2005) some simple measurements can enlighten the saga of landscape development. Among these measurements, drainage basin asymmetry is the one which can be applied to smaller areas and pin point the measurements to individual drainage valleys while the rest are applicable mainly to more regional approaches with larger systems.

A series of river channels and associated depressions are located over the Bozdağ horst (western Anatolia, Turkey) near the drainage divide between the Gediz graben to the north and Küçük Menderes graben to the south. The important issue about these channels is that twenty-three of these channels are filled with continental deposits, dominantly of fluvial origin. Although the presence of these deposits has been known for a long time, their evolution and relation to regional tectonics have not been characterized. Systematic occurrence and their elevation above base level suggest that these deposits are rare geological features formed under specific conditions.

In the light of the literature and the inherent recording nature of the drainage systems, the purpose of this study is to introduce the geometry, pattern and evolution of Plio (?)–Quaternary active drainage channels and their relevant deposits while interpreting their origin with respect to recent tectonic activity in western Anatolia. In order to reach this goal the analytical capabilities of Geographical Information Systems are utilized.

2. Regional geological setting

The Bozdağ horst is located within the E–W trending Neogene–Quaternary horst–graben system of western Anatolia between Gediz–Alaşehir graben (GAG) to the north and Küçük Menderes graben (KMG) to the south (Fig. 1). It is situated in a seismically active continental extensional terrain where extension has operated since the Early Miocene. In summary, the driving mechanism of neotectonic period in Anatolia and surrounding region resulted from the final closure of Neotethyan oceans due to the collision between promontories of the Eurasian and African plates and the migration of the Anatolian–Aegean Plate in between them onto the African Plate along the Mediterranean ridge. However, the neotectonic extensional history of western Anatolia discussed extensively and various evolutionary models for the system has been proposed. These extensional models based on the rifting process as a continuous rifting or as two stage rifting models are closely associated with the timing of rifting, the order and origin of the extensional processes. The models are; 1) the *tectonic escape model* proposes the rifting since Late Serravalian (12 Ma) (e.g. Dewey and Şengör, 1979), 2) the *roll-back model* ("Back arc spreading model") propose rifting to have occurred between 60 and 5 Ma

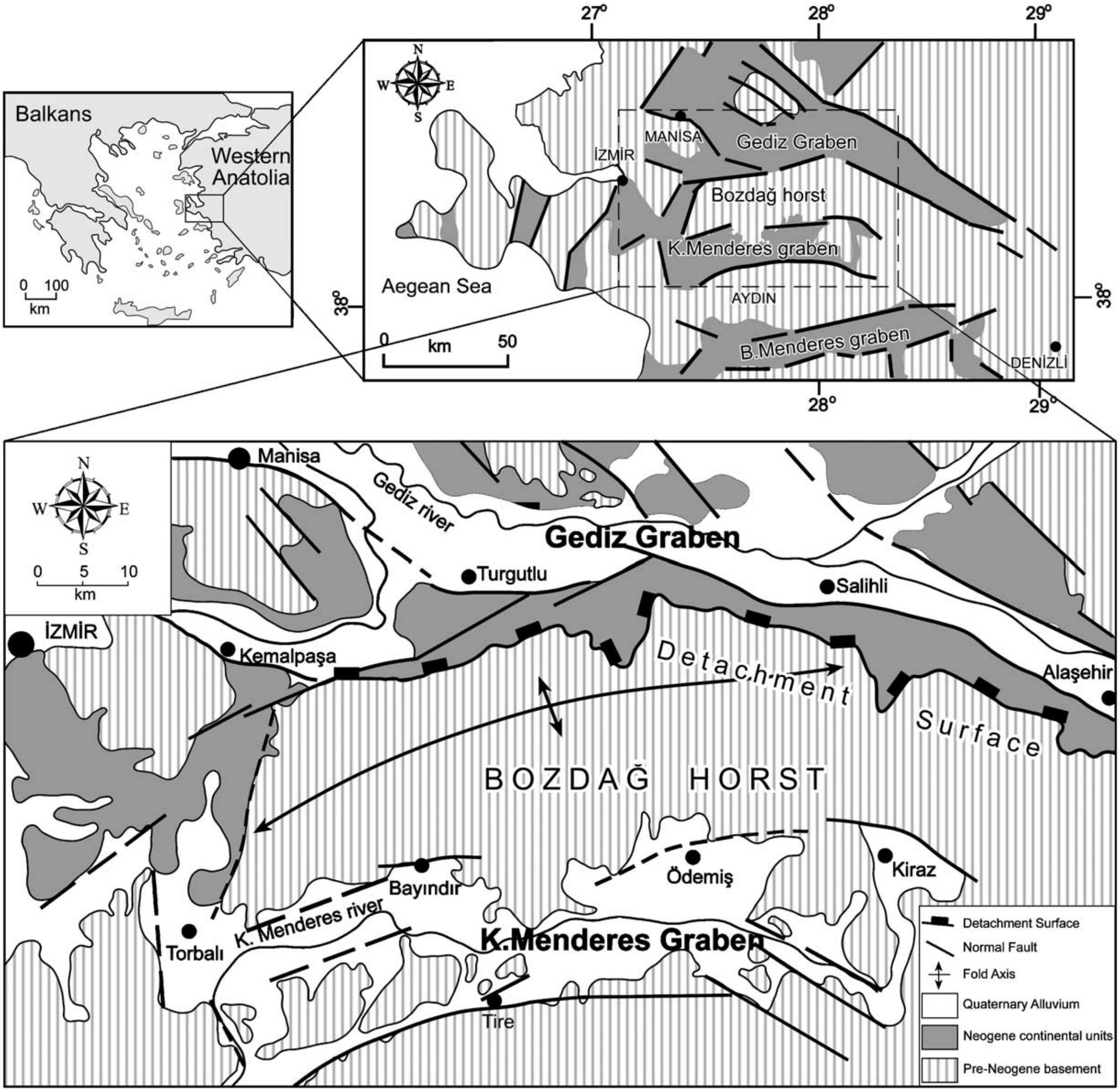

Fig. 1. Regional setting of Bozdağ horst.

(e.g. McKenzie, 1978; Le Pichon and Angelier, 1979), 3) the *orogenic collapse model* ("Gravitational collapse of the over-thickened crust") relating to the latest Oligocene to Early Miocene ($\approx$ 18 Ma) (e.g. Dewey, 1988; Seyitoğlu et al., 1992), 4) the *bilateral extensional symmetric orogenic collapse model* (e.g. Hetzel et al., 1995a), 5) the *two-stage episodic model* ("two stage graben model") (e.g. Bozkurt and Park, 1994; Hetzel et al., 1995b), 6) the *two-stage episodic model with an intervening compressional period* (e.g. Koçyiğit et al., 1999; Bozkurt, 2004), 7) the *bivergent rolling-hinge detachment system model* (Gessner et al., 2001) and 8) the *velocity differences between the overriding plates (Aegean and Anatolian plates) on the African plate model* (Doglioni et al., 2002). These models are supported by paleomagnetic data (e.g. Kissel and Laj, 1988; Kissel and Mazaud, 1986), GPS plus SLR velocity vectors relative to a fixed Eurasia (Oral et al., 1995; Reilinger et al., 1997; McClusky et al., 2000), analogue models (e.g. Gautier et al., 1999) and slip data analysis (Dumont et al., 1981; Angelier et al., 1981; Rojay et al., 2005) that all address a counterclockwise rotation in KMG and the Büyük Menderes graben (BMG) sector of Anatolian Plate.

Western Anatolia is basically composed of three major tectonic terrains as the Pontides to the north, the Taurides to the south and the Menderes Massif in between. However, behind this simplicity, an extremely chaotic zone lies in the north (the so called "Bornova flysch"), a poorly differentiated metamorphic complex in the middle (the so called "Menderes Massif") and an obducted ophioilitic terrain to the south (the so called "Lycian Nappes of the Taurides") that are exhumed and multidirectionally rifted by Neogene grabens.

Although both the GAG and KMG grabens are filled with Miocene fluvial to lacustrine deposits with andesitic to dacitic volcanic intercalations and Plio–Quaternary fluvial clastics, thick Miocene red clastics are missing in a greater part of the Küçük Menderes graben (Rojay et al., 2005). The Plio (?)–Quaternary fluvial–lacustrine clastics are deposited in elevated valleys on the Bozdağ horst between 400–1500 m elevations. These clastics are developed on above mentioned metamorphics so after Alpine metamorphism during the Plio (?)–Quaternary period and situated at higher elevations on the Bozdağ horst.

The horst displays a double plunging anticlinal structure with various north and south verging thrusts of pre-Miocene age. The structure is cross-cut by normal faults both from north and south (Fig. 1). To the north, the margin of the horst is controlled by a detachment surface extending from Kemalpaşa in the west to Alaşehir in the east where the present low-angle normal faults (detachment surfaces) are cross-cut by high angle normal faults. In contrast, the southern margin of the horst is cross-cut by high angle normal faults of KMG. The most distinguishing anisotropic structures of the Bozdağ horst are foliations and shear zones. Analysis of 1474 foliation measurements displays a regionwide plunging antiformal structure to north of the KMG (Toprak et al., 2000; Yazcgil et al., 2000; Rojay et al., 2005). The foliation measurements on the northern sector of the graben reveal a general trend of 168 N, 49 S (N78 E, 49 S) out of 795 measurements. A gradual increase in dip amounts from the basin divide (38 S) on Bozdağ horst to the basin margin (49 S) is well reflected by cuesta structures. The tectonic slivers –as shear zones– are observed in various directions of north and south imbrications. The anisotropic structures are perpendicular and oblique to N–S oriented elevated Plio–Quaternary valleys.

Geomorphologically, the Early–Middle Miocene period is presumed to be where the planation surface at elevations of 1700–1800 m developed. It has gentle slopes referred to as "D-I" surfaces (Erinç, 1955; Erol, 1979). These surfaces were interpreted as exhumation surfaces resulting in the uplift of the central Menderes terrain since Early–Middle Miocene (Bircan et al., 1983). It is clear that Miocene red clastics are missing in the KMG, whereas these thick Miocene red clastics present on the detachment surface (exhumation surface) in the north, along the GAG. This indicates that the source of these Miocene red clastics could be from the south and from higher elevations than today's Bozdağ Mountain.

During the Late Miocene, the planation surface was eroded and N–S valleys were initiated around elevations 1500–1700 m (D-II period). During the Late Miocene, erosion continued and planation surface is truncated during the Pliocene (D-III) period at 600 m of elevation. This is the time where flat topography was developed and elevated areas gain a more stable attitude for site of deposition where mountain lakes evolved (Erol, 1979). The Late Pliocene is interpreted as the period of development of cross-cutting high angle normal faults and as the time of alluvial fan formation (Tmoloschutte deposits—Villafranchtian period) at 250–700 m altitudes along the margins of the Bozdağ horst (Bircan et al., 1983).

A land surface uplift of 100 to a maximum 400 m since the Middle Pliocene is proposed for the region (Bircan et al., 1983; Bunbury et al., 2001; Westaway et al., 2004). High angle step faults cross-cut the alluvial fans during "D-IV" erosion phase (Early Pleistocene period) and the Upper Pliocene surfaces (D-III) are interrupted by V-shaped newly forming Quaternary valleys. Finally today's valley bottom the graben system is developed where some of the mountain lakes are preserved in the valley slopes at elevated terrains.

3. Outline of study

This study involved several steps in analyzing the fluvial deposits observed over the Bozdağ horst. These steps, are as follows:

3.1. Field survey and data collection

This inscribes the recognition of fluvial deposits based on a short literature review on the origin of these deposits. The rest of the section is allocated to introduce the data collected in the field including mapping, lithological characterization, age and deformational properties of the deposits.

3.2. Morphological analyses

Morphological analyses supported by Geographic Information System aims to quantify morphological features of Bozdağ horst and fluvial deposits. Further analyses on the drainage over the horst and on the valley asymmetry are carried out to extract information on the origin of deposits, with inferring a possible evolutionary model of the fluvial deposits while extending the interpretation to the saga of the Bozdağ horst.

4. Field survey and data collection

4.1. Recognition of deposits

Although there is no any particular study on the fluvial deposits over the Bozdağ horst, their presence has been known for a long time. Two of these deposits are shown as “undifferentiated Quaternary deposits” in 1 : 500.000 geological map of Turkey published in 1964 by Mineral Research and Exploration Institute of Turkey. This map modified in 2002 by the same institution shows nine of these deposits and refers to them as “undifferentiated Pleistocene continental clastics”.

Yalcinlar (1955) emphasized glaciation over the Bozdağ horst during the Pleistocene and interprets some of the depressions as cirques.

Bircan et al. (1983) who studied the geomorphology and neotectonics of the area claim that these deposits are the results of the filling of the “hanging valleys” formed due to rapid uplift of the horst during the Plio–Quaternary.

Bozbay et al. (1986) explain these deposits in relation to the Pliocene to post-Pliocene peneplanation in the region. They also refer to several captured rivers which are flowing south today but flowed north during the Pliocene.

In none of the previous works, however, are these deposits indicated to occur systematically at high-altitudes near the drainage divide. The age and evolution of these deposits are not dealt specifically and therefore are still vague in the literature.

4.2. Mapping the deposits

Deposits observed over the Bozdağ horst were mapped in the field using a 10 m contour interval topographic map at 1 : 25.000 scale. This mapping was supported by the interpretation of aerial photographs at 1 : 35.000 and 1 : 60.000 scales. The first step in the mapping was to draw the boundaries of deposits that are easily recognized because: 1) all deposits are located over metamorphic rocks and can be identified lithologically; 2) all deposits have distinct morphological characteristics with respect to slope and drainage texture. An example is illustrated on Fig. 2 using the available topographic information. The next step in the mapping was to collect the data by visiting all the deposits in the field. These data are used to characterize lithology and depositional environment of the deposits.

4.3. Lithological characterization

General lithological characteristics of the deposits are illustrated in the cross section in Fig. 2. The deposits are dominantly composed of bedded sedimentary layers along the axis of the depressions which laterally pass into colluvial deposits. The colluvial deposits are characterized by unconsolidated, poorly sorted, angular sediments with no internal structure indicating a short distance of transportation along the margins. All pebbles are derived from nearby metamorphic rocks. Towards the center of depressions the deposits gradually turn into pink; brown to yellow, bedded, semi-consolidated clastics ranging from mudstones to conglomerates. Sedimentary layers in most of the deposits are characterized by

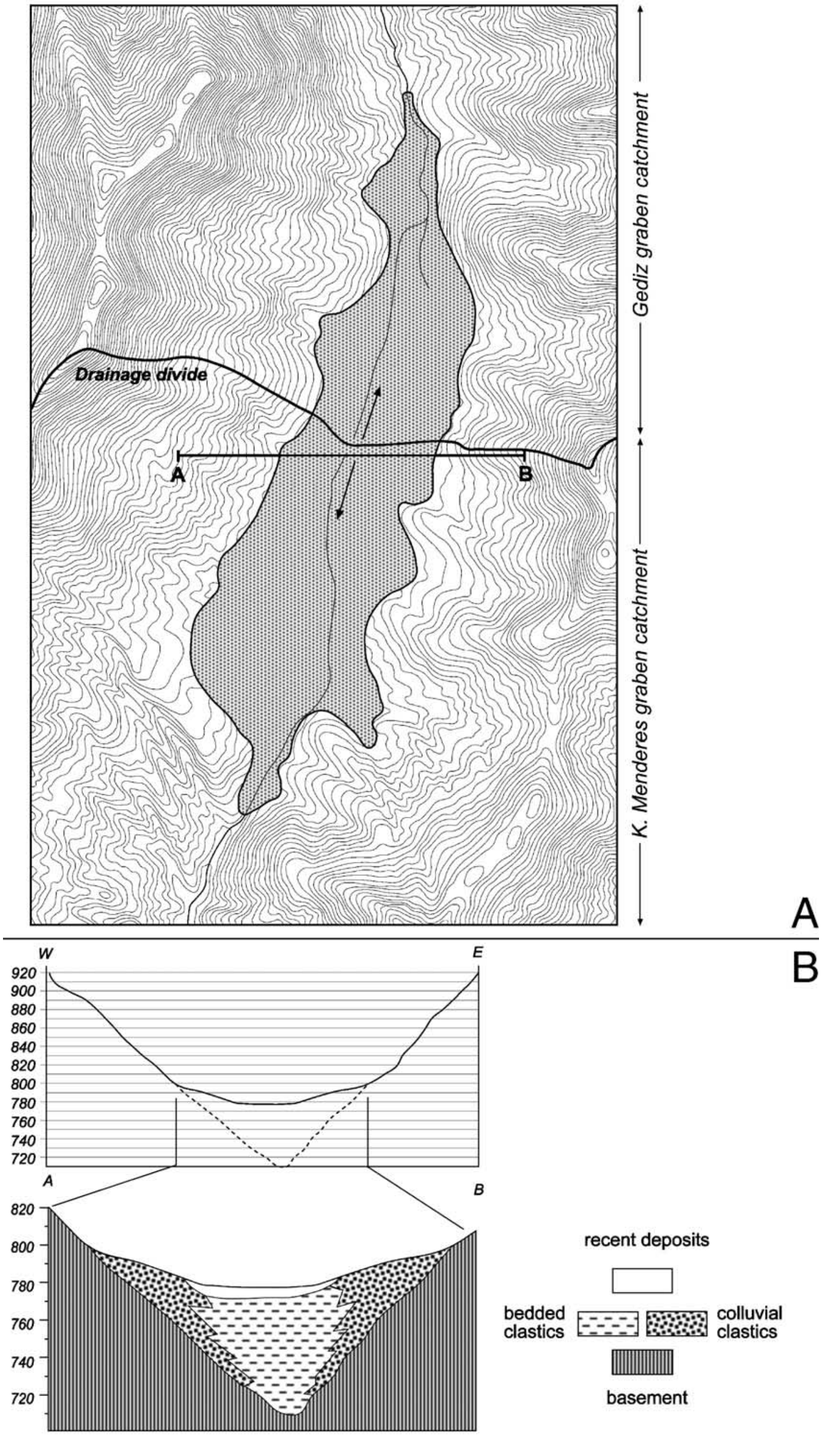

Fig. 2. Sample of fluvial deposits A) Map view, B) cross sections.

cross-bedding (Fig. 3-C) and pebble imbrications. These structures measured in three of depressions indicate a transportation direction towards the north.

Thickness of deposits changes from depression to depression. A maximum observable thickness of 100–110 m is measured in one of the depressions where the sequence is deeply eroded (Fig. 3-A,B). However, total thickness recorded in the boreholes drilled by local people is greater than 170 m.

Based on the lithological characteristics of deposits (Toprak et al., 2000) and Holocene environmental studies on pollen from the SW Anatolian lakes (East-

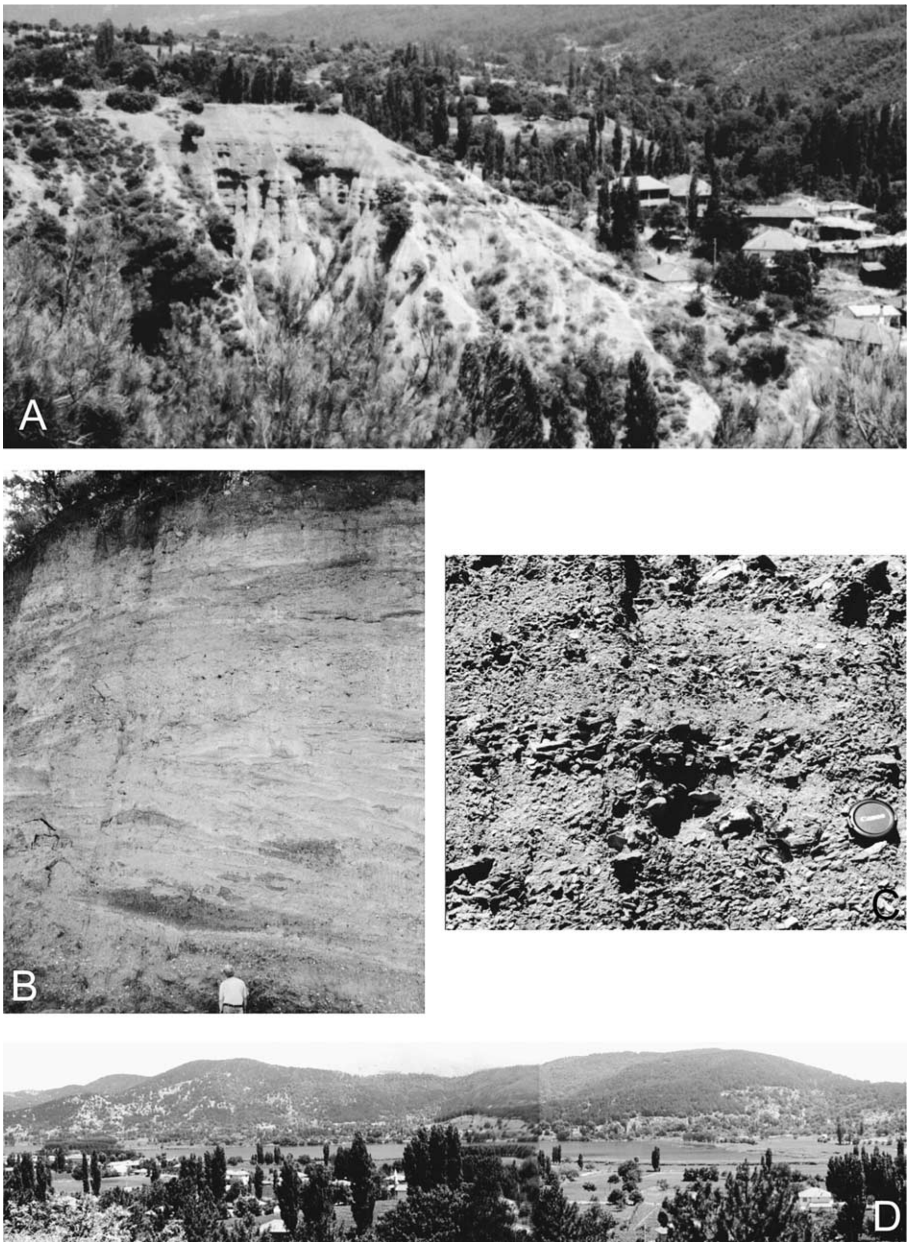

Fig. 3. Views from the depressions: A) general view of sequence, B) general view of sequence, C) closeup view of sequence showing pebble imbrication, D) general view of the only lake (Gölcük depression) preserved in depression.

wood et al., 1999b) the environmental setting is not a glacial setting as proposed by Yalcinlar (1955). There is also no field evidence of glacial activity or glacial deposition within these sites of elevated plains/lakes, whereas the sedimentological characteristics of the deposits reveal a fluvial and lacustrine setting.

4.4. Deformation of deposits

Although, the Bozdağ horst and its surrounding terrain are tectonically active, there is no record of deformation within these clastic deposits. All the sequences are gently dipping towards the center of the depressions suggesting an initial dip and are horizontal at the center. The attitude of the poorly developed bedding planes within these depressions displays no folding and the depressions are free from faults.

4.5. Age of deposits

There are no field data that indicate the age of these deposits. All sedimentary sequences are exposed to erosion and are being highly dissected. One of the basins still preserves its initial form as indicated by the presence of a lake (Gölcük depression) (Fig. 3-D). The borehole data for the upper section of sedimentary fill from this depression reveal, from top to bottom, 8 m of lacustrine mud, 2 m of peat and organic mud with a 12 cm thick tephra deposit, and 2 m of stratified sand and gravel (Sullivan, 1988). According to the dated lower and upper peat beds (7400 ± 140 to 3110 ± 160 yr BP, respectively), the tuff layer is correlated with the Minoan tephra of the Santorini volcano (Sullivan, 1988). Therefore the age of the upper part of the sequence in the Gölcük depression is Mid–Late Holocene.

The stratigraphy of the cores from SW Turkey is very similar to that of those from the Gölcük depression (Eastwood et al., 1999a). The possible equivalent tephra beds exist in SW Anatolia and have yielded radiocarbon ages on the peat beds of 3300 ± 70 and 3225 ± 45 yr BP and can be correlated with the tephra bed in Gölcük depression (Eastwood et al., 1999a). This age range is almost that assigned earlier by Sullivan (1988).

Radiocarbon dating of the peat beds below tephra bed reveals a maximum age of 8605 ± 45 yr BP from an 850 cm thick sequence in SW Anatolia (Eastwood et al., 1999b). Pollen analysis done just below the tephra bed reveals an age range of 3500–3000 yr BP and maximum age of approx. 9500 yr BP (Eastwood et al., 1999b). The rest of the 170 m thick fill below the dated tuff is presumed to be Early–Mid Holocene.

5. Morphological analysis

5.1. Morphology of Bozdağ horst

Bozdağ horst is represented by a topographic high elongated in almost E–W direction with a length of more than 100 km and a width ranging from 25 to 45 km. The highest peak of the horst is about 2100 m and elevation gradually decreases to 100 m on the graben floors on both sides of the horst (Fig. 4).

The northern and southern margins of the horst have different morpho-tectonic characteristics due to the nature of the faults along these margins. The northern margin faults are well developed with considerable vertical movement on both detachment low-angle normal faults and cross-cutting high-angle normal faults. Linear fault scarps and triangular facets are morphological manifestations of the high angle normal faults. The southern margin faults, on the other hand, are concealed in most places by thick alluvial fans and are observed as short and discontinuous fault segments (Toprak et al., 2000). An irregular basin boundary in the south is the main evidence for this fault segmentation.

Morphological characteristics of the horst were investigated using a digital elevation model with 30 m grid interval (Fig. 4). Accordingly, 58% of the horst is included within the drainage basin of Gediz graben and 42% within the Küçük Menderes graben from the histograms for slope and aspect values of northern and southern parts of the horsts, from today's drainage divide to the alluvial basin boundaries (Fig. 5).

Histograms for the slope of both watersheds display similar patterns with maximum slope amount clustering at about $10°–12°$. The horst is, therefore, almost a symmetric ridge with a slightly higher percentage of maximum slopes in the northern (Gediz) watershed.

Histograms of the aspect values for northern and southern watershed areas display different patterns. In the northern area (Gediz catchment) slopes are characterized by two clusters at NNE and NNW directions

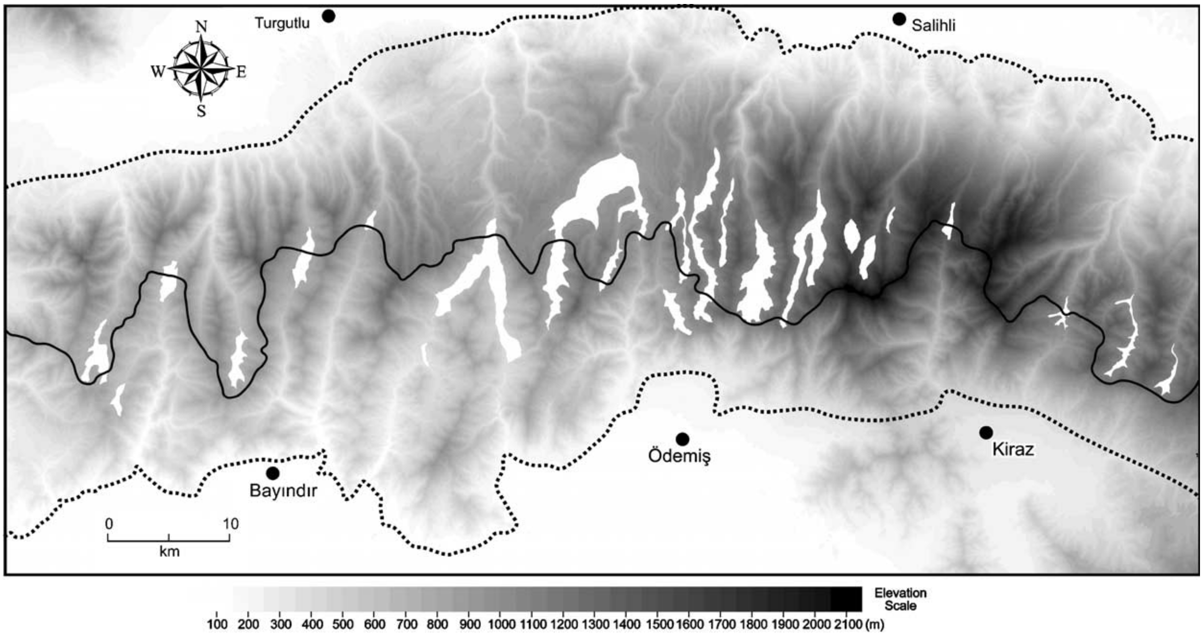

Fig. 4. Morphology of Bozdağ horst. Dashed lines show the limits of the horst considered in this study. Solid line is the present drainage divide. White polygons are fluvial deposits.

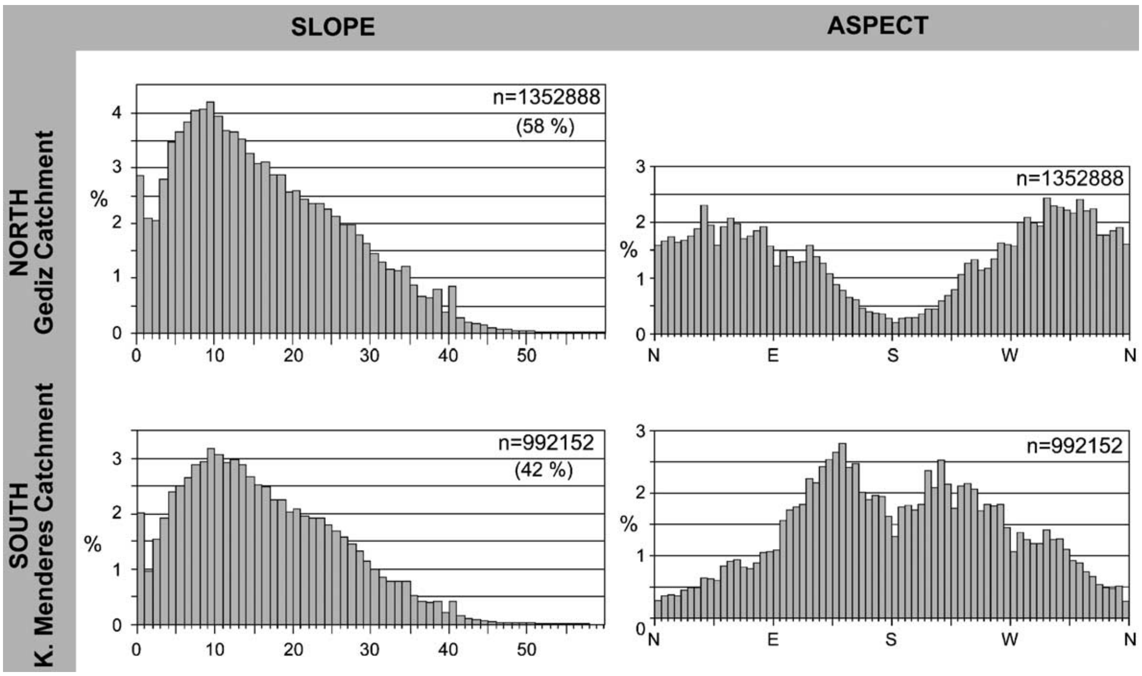

Fig. 5. Histograms showing slope and aspect characteristics of Bozdağ horst. (North and South refer to the northern and southern sector of the horst from drainage divide to basin boundary. No is grid cell frequency with a grid size of 30 m).

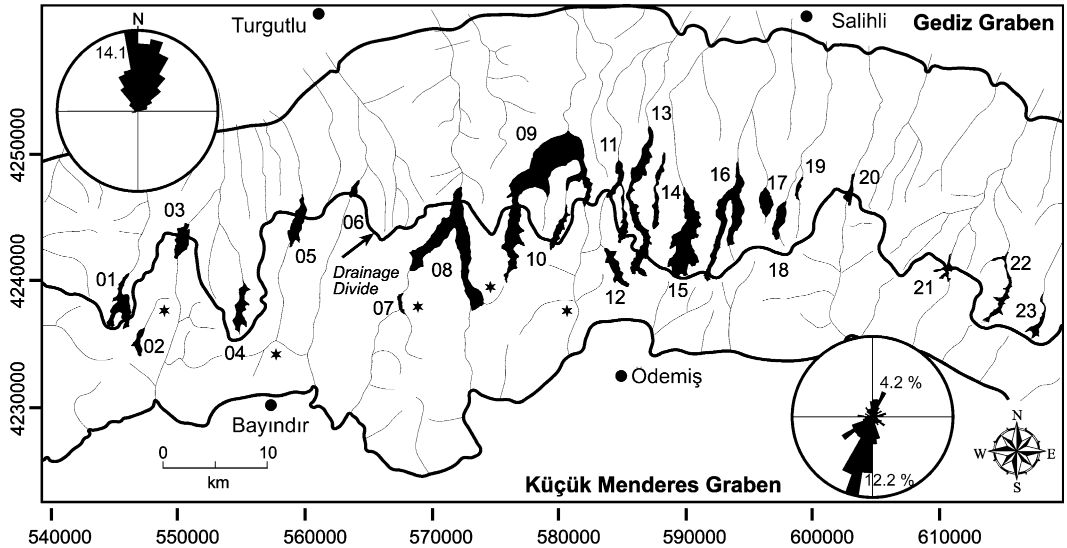

Fig. 6. Drainage map of the Bozdağ horst. Unidirectional rose diagrams show stream direction prepared separately for northern and southern sectors of the horst. Asterisks indicate contorted drainage. (Black polygons are fluvial-lake deposits).

due to the curvature of the horst. NNE-facing slopes belong to the eastern half of the horst (south of Salihli) and, NWW-facing slopes to the western half (SW of Turgutlu). The difference in the percentages is due to the differential lengths of these two slopes. The southern watershed area of the horst (Küçük Menderes catchment), on the other hand, is represented by a profile that suggests a south-facing slope. A sudden decrease of percentage at exactly a southerly direction is due to presence of frequent broad valleys with SE and SW facing slopes and due to the E–W orientation of the drainage divide.

5.2. Morphology of fluvial deposits

Twenty-three depressions filled with fluvial clastics were identified over the Bozdağ horst (Figs. 4 and 6). The depressions are located within a zone extending

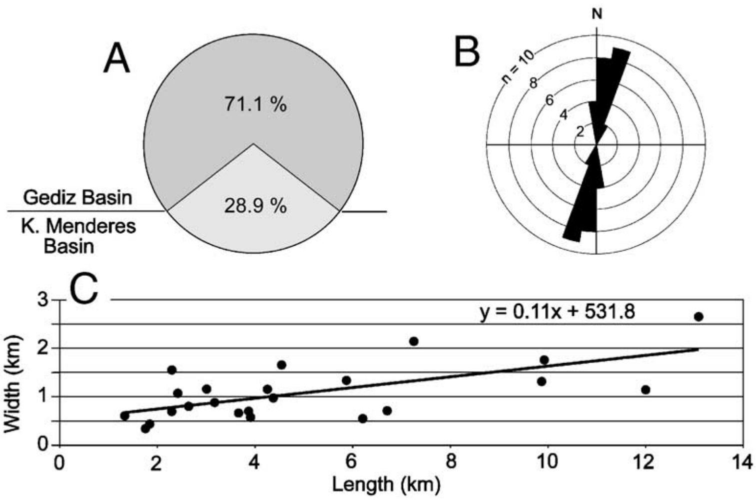

Fig. 7. Some properties of fluvial and lake deposits (depressions): A) location of depressions within two catchment areas, B) orientation of depressions, C) length vs width plot of depressions.

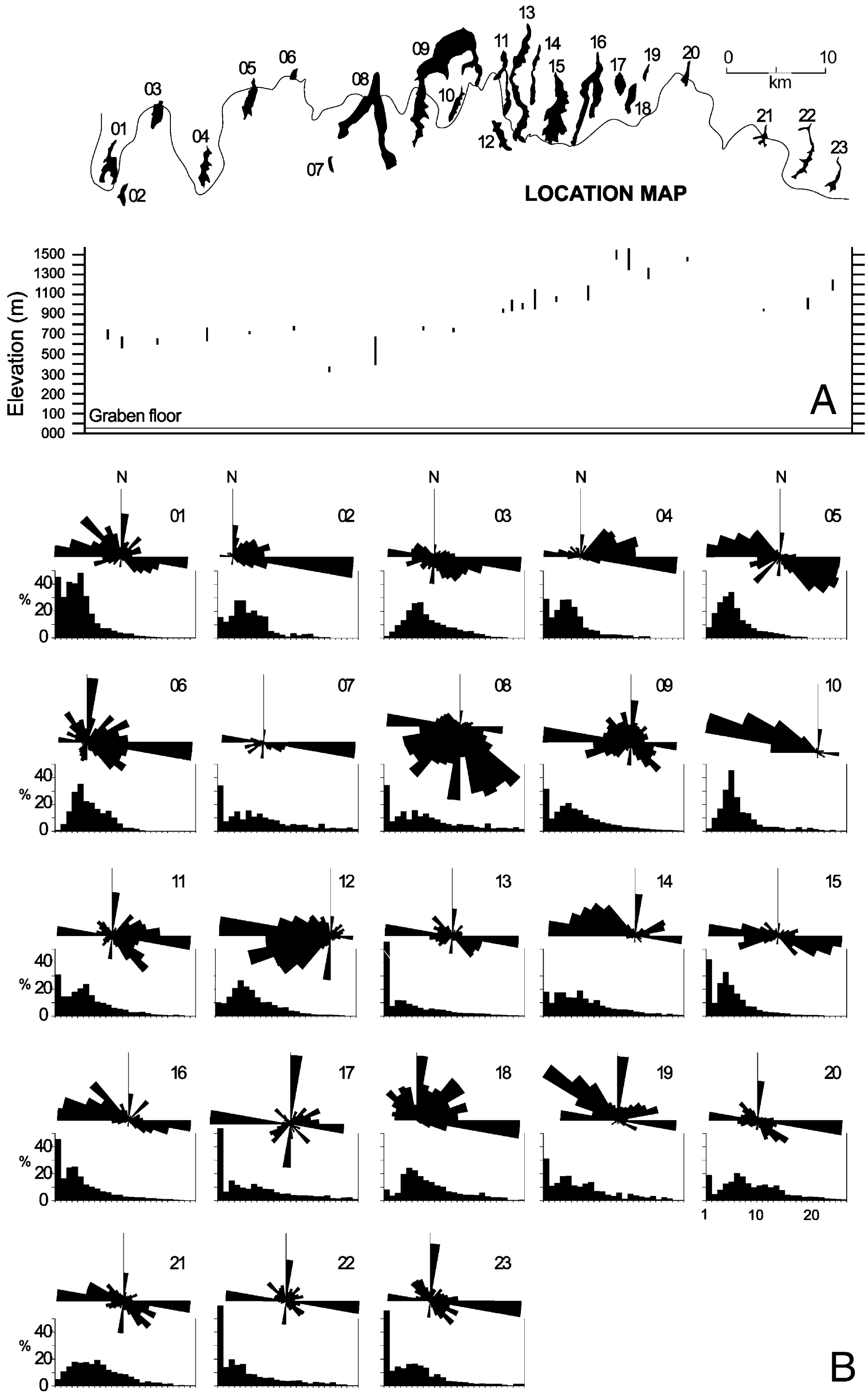

Fig. 8. Morphological characteristics of fluvial deposits: A) elevation of deposits (each line shows bottom and top elevation of deposits), B) aspect (rose diagram) and slope (histogram) distributions of deposits.

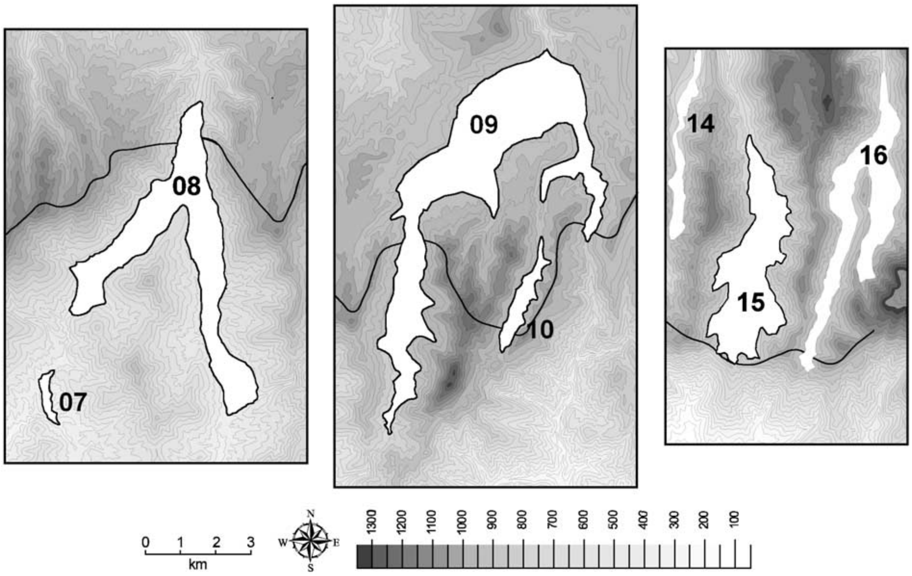

Fig. 9. Examples of detailed morphological features of some selected depressions.

in an E–W direction along today's drainage divide of the horst. Eleven of these depressions are located within the drainage basin of the Gediz graben and three within the Küçük Menderes graben. The other nine deposits extend to both drainage basins. About 71% of the surface area of the depressions is within the Gediz catchments area and the rest within the Küçük Menderes (Fig. 7-A). Orientations of the depressions are almost perpendicular to the main trend of drainage divide and concentrate in N00-20E trends (Fig. 7-B). The long axes of these depressions range from 1.7 to 13 km and the widths from 0.35 and 2.2 km. The plot of width against length is presented in Fig. 7-C.

Shape, pattern and geometry, topographic characteristics and other morphological properties of the fluvial deposits possess valuable information on the mode of origin of these deposits. Some of these properties are illustrated in Fig. 8. Examples of topographic details in the vicinity of the deposits are shown in Fig. 9 by a 10 m contour interval. Basal slope amounts of the deposits are calculated using maximum and minimum topographic elevation of the deposits and are given in Table 1. Following observations can be made, based on the data provided by Figs. 8 and 9 and Table 1:

- All deposits are very close to the modern drainage divide of the Gediz and Küçük Menderes grabens (Fig. 8, Location map). The divide passes through nine of these deposits while it is tangential or very close to the others. Only one deposit, no: 07, is

Table 1
Inclinations of depressions calculated from basal elevations of the highest and lowest points

	Setting	Inclination	Depression no.
North	Within Gediz catchment towards north	1.3°	01
		1.9°	04
		1.8°	06
		0.1°	09
		0.3°	10
		0.3°	11
		0.2°	13
		1.8°	14
		0.7°	15
		0.8°	16
		1.8°	17
		2.5°	18
		2.2°	19
		0.8°	20
		0.1°	21
		1.3°	22
		1.7°	23
	Within K. Menderes catchment towards north	1.9°	02
		1.1°	12
South	Within K. Menderes catchment basin, towards south	1.1°	03
		0.1°	05
		0.8°	07
		1.6°	08

developed at a distance from the divide. This deposit actually is located on the same stream with the western branch of no: 08 and can be regarded as its continuation.

- All deposits spatially coincide with present drainage system. There are no deposits located away from the present stream channels (Fig. 6).
- The size of the deposits greatly differs in different parts of the horst. The largest ones are located in the central part and their size decreases gradually in both directions.
- The altitudes of deposits are indicated by a line which is marked by two elevations, one node for northern and another for the southern tip (Fig. 8-A). The elevation difference ranges from 4 m (no: 5) to 275 m (no: 8). The overall elevation of the deposits suggests a gradual decrease from eastern part of the horst towards the west. Variation in the altitude is dependent on the location of the deposit in relation to the drainage divide. For example, the lowest deposit (no: 7), is at a distance of about 5 km from the divide.
- Bifurcation (V-shape) of the deposits is a common feature, well-developed particularly in nos: 01, 08, 09, 11 and 16. Details of some of these deposits, particularly the largest ones (nos: 08, 09 and 16) are illustrated in Fig. 9. A second order bifurcation is clear in deposit no: 09. Deposition along tributaries in deposits is also common. The best examples of such deposits are the smaller ones located in the eastern part of the horst (nos: 20, 21, 22 and 23). One characteristic feature of all these bifurcations is that the acute angle between two branches always points north (Fig. 9). This is evidence that the streams were flowing northward during the accumulation of the deposits.
- Aspect values of the surface of deposits were investigated with the help of rose diagrams prepared from directions of the unit cells measured from north (Fig. 8-B). Unit grid cell is 30 m. Rose diagrams are unidirectional at 10° interval. These diagrams indicate that majority of the deposits have surfaces inclined in two dominant directions, namely, east and west (deposits nos: 01, 03, 04, 05, 07, 11, 13, 15, 16, 17, 20, 21, 22 and 23). The surfaces of these deposits, therefore, indicate a V-shaped profile along N–S axial line. Although this profile may be the result of recent erosion, it may also indicate the initial depositional surface. A few deposits display a unidirectional concentration in either east or west directions (nos: 02, 10 and 12) suggesting that the recent dissection occurred at the margin of the deposit. In several deposits, a concentration at north or south, directions is observed (nos: 01, 06, 11, 12, 13, 14, 17, 18, 19 20, 21, 22 and 23) that can be attributed to the present flow direction of the streams.
- Slope amount of the surface of the deposits corresponds to the inclination of the ground and is measured from a horizontal surface. Slope amounts are illustrated in the histograms in Fig. 8-B at 1° intervals. Generally the slope values are characterized by 5°–7°, having occasionally some flat surfaces (nos: 13, 16, 17, 22 and 23).
- The basal slope of each depression (actual valley floor) is calculated using maximum and minimum elevations of the depressions (Table 1). The depressions are grouped into 3 categories: a) deposits mostly located within the Gediz drainage basin are inclined towards Gediz (north). There are 17 depressions in this group. The amount of slope ranges from 0.1° to 2.5°, b) deposits totally located within the Küçük Menderes drainage basin are inclined towards the north. There are two deposits in this group with slopes of 1.1° and 1.9°, c) deposits mostly located within Küçük Menderes drainage basin are inclined towards the south. There are 4 depressions in this category with slopes between 0.1° and 1.6°. The most important conclusion derived from basal slopes is that 19 deposits are inclined towards north including two deposits (nos: 02 and 12) that are totally located in the southern sector (Fig. 6, Table 1). The average basal slope is 1.1 degrees for these 19 northerly inclined deposits.

5.3. Drainage system

Drainage characteristics of the Bozdağ horst were studied to extract possible information on the origin and nature of fluvial deposits (Figs. 4 and 6). Major streams flowing over the horst and fluvial deposits were used for statistical analysis. Unidirectional weighted rose diagrams were constructed in order to evaluate the present dominant flow directions. The

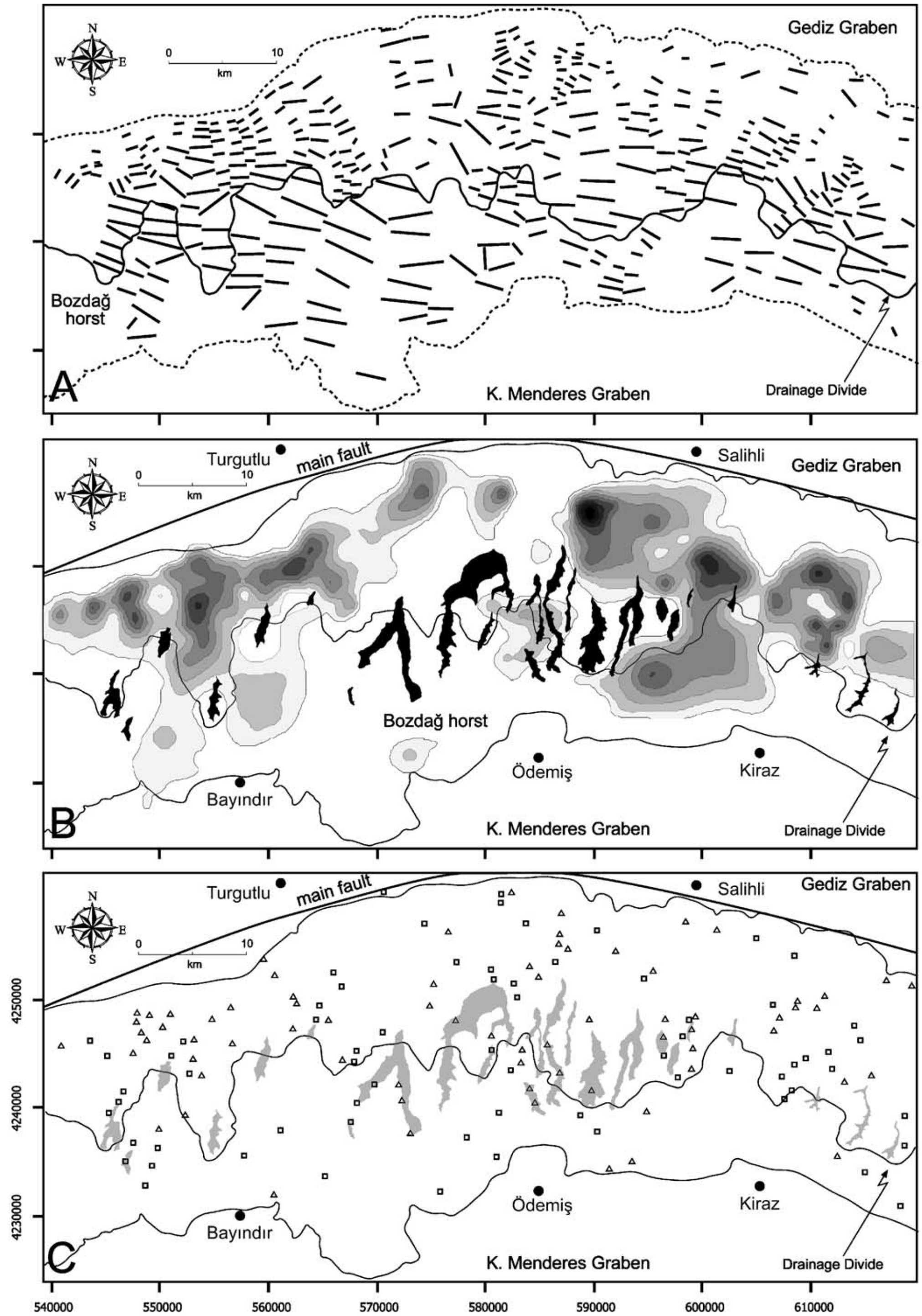

Fig. 10. Dissection and asymmetry analysis: A) lines of measurements to determine valley parameters (374 sites), B) density diagram of dissection for Bozdağ horst, C) spatial distribution of asymmetric valleys. Circles indicate steep western slopes and triangles indicate steep eastern slopes.

following observations are made based on the drainage map and on the rose diagrams:

- The frequency of stream channels is different in the two watershed areas. There are a total of 26 channels in the northern part (Gediz catchment), whereas only 15 exist in the southern one (Küçük Menderes catchment). A parallel drainage pattern is developed in the northern part as indicated by closely spaced straight streams. These streams are mostly straight and do not have any tributaries. The southern area, on the other hand, has a more complicated drainage pattern slightly resembling a dentritic one except the eastern margin of the horst.
- The rose diagram for the stream channels in Gediz watershed indicates that all the streams flow northwards (upper diagram in Fig. 6). However, according to the diagram prepared from Küçük Menderes streams, there are some streams which are directed towards the north (lower diagram in Fig. 6). This is an indication of the contorted drainage observed only in the southern part of the horst. These streams are indicated by an asterisk on the map.
- Major stream channels on both sides of the horst coincide at the same place near the drainage divide almost with the same direction but different sense of flow.
- All of the fluvial deposits over the horst spatially coincide with the recent stream channels. There is no fluvial deposit, which is developed away from the present drainage channels.

5.4. Dissection and asymmetry in the channels

The degree of dissection and the nature of valley asymmetry in the present stream channels were analyzed throughout the horst to indicate any differential uplift and/or tilting of the horst. Valley parameters used in the quantification of dissection and asymmetry were measured at 374 sites along selected lines through all stream channels (Fig. 10-A). The length and azimuth of each line in the figure show the width and orientation normal to the stream channel, respectively.

Total width and height (depth) of valleys were measured to assess the amount of dissection. Total width corresponds to the distance between two opposite ridges of microcatchments. The height, on the other hand, is the distance between the valley bottom and the ridge top. The dissection is calculated by dividing height by width of the valley.

The values of dissection for the Bozdağ horst range from 0.012 to 0.34. The density map prepared for the dissection values is illustrated in Fig. 10-B which is divided into nine classes with an increment of 0.002 starting with minimum dissection value of 0.012. A very distinct feature in the density map is that most of the highly dissected stream channels (dissection concentrations) are aligned in a zone parallel to the curvilinear elongation of the horst. The zone is located to the north of the modern drainage divide within the Gediz catchment. There are some minor concentrations within the Küçük Menderes catchment characterized by lower values that are not systematically distributed.

The asymmetry of the channels was investigated using the projected widths of the two slopes of the channel. Degree of asymmetry is calculated using the relationship “asymmetry = western width / total width” which had been defined by Cox (1994) as Transverse Topographic Symmetry Factor. Accordingly, the valley is symmetric if the value is equal to 0.5. Values smaller than 0.5 threshold indicate an asymmetric valley with steeper western slope whereas a larger value suggests a steeper eastern slope. A histogram prepared from all the values is given in Fig. 11. The pattern of the histogram indicates that the data are almost normally distributed and that most of the channels are symmetric in nature. The spatial distribution of asymmetric valleys is shown in Fig. 10-C. The slopes with steep western and eastern slopes are illustrated with circles and triangles, respectively. As seen in the figure, there is no systematic pattern to the preferred directions of asymmetry within the Bozdağ horst.

6. Discussion

Based on the analysis of fluvial remnants and their channels over Bozdağ horst, it is concluded that the fluvial deposits developed due to the uplift and southward tilting of the horst. The tilted block is located between two main faults that define southern margins of the GAG and KMG (Fig. 12-A).

The absence of deformation of the sequences, with no evidence of faulting in the vicinity of the deposits,

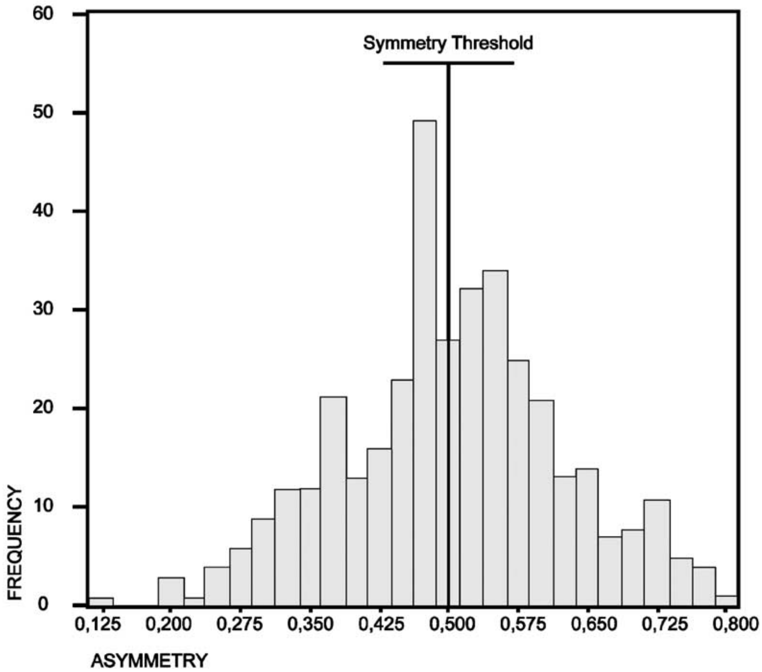

Fig. 11. Distribution of asymmetry values. The value 0.5 named as asymmetry threshold indicate symmetrical valleys.

the lack of field indications of glacial activity and the spatial distribution of the deposits all suggest that the deposits were systematically formed during the tilting that corresponds to the last tectonic event in the region. Since the long axis of the deposits is normal to the regional faults, the tilting should occur in N–S direction. This tilting resulted in the modification of drainage so that southerly sloping channels gradually become horizontal which converted the channels to sites of deposition. The best evidence for this is provided by the maximum degree of dissection along the northern margin of the Bozdağ horst (Fig. 10-B). Deeply dissected stream valleys are aligned to the south and perpendicular to the main fault that defines the southern margin of GAG.

The asymmetrical evolution of the stream channels indicates a pivotal tilting E or W directions on the main N–S tilt of the Bozdağ horst. Locally developed E or W pivotal tilting is possibly eased by the accommodation faults trending perpendicular or oblique to the tilt axis (Fig. 10). It is not easy to assign a direction of the pivotal tilting in E and W directions due to frequent change in the asymmetry of the stream valleys (Fig. 10). However, the N–S tilt is clear and occurred on an E–W extending axis somewhere to the south of Bozdağ Mountain extending parallel to a fault to the south of the KMG graben (Toprak et al., 2000; Fig. 12-A). The northern margin of the horst is relatively uplifted causing a back tilting of the Bozdağ horst. This tilt caused a symmetrical differential downcutting on the horst and later asymmetrical profiles from the E or W directed minor tilts. The north facing faults on the GAG side cross-cut the tilted block first, then the KMG side was faulted during Pliocene–Quaternary period (Rojay et al., 2005).

Absence of Neogene deposits within KMG suggest that the graben is a young structure compared to the GAG (Rojay et al., 2005). Therefore, it is highly probable that tectonic activity along the southern margin of KMG shaped the present graben and caused the tilting of the Bozdağ horst.

Bifurcation of the deposits (Fig. 9) and pebble imbrications observed within the deposits support a northerly flow direction during deposition.

The mountain lakes were situated on relatively mature stream channels (Fig. 9). The young stream channels mainly on the northern margin of the Bozdağ horst developed on the Neogene–Quaternary clastics

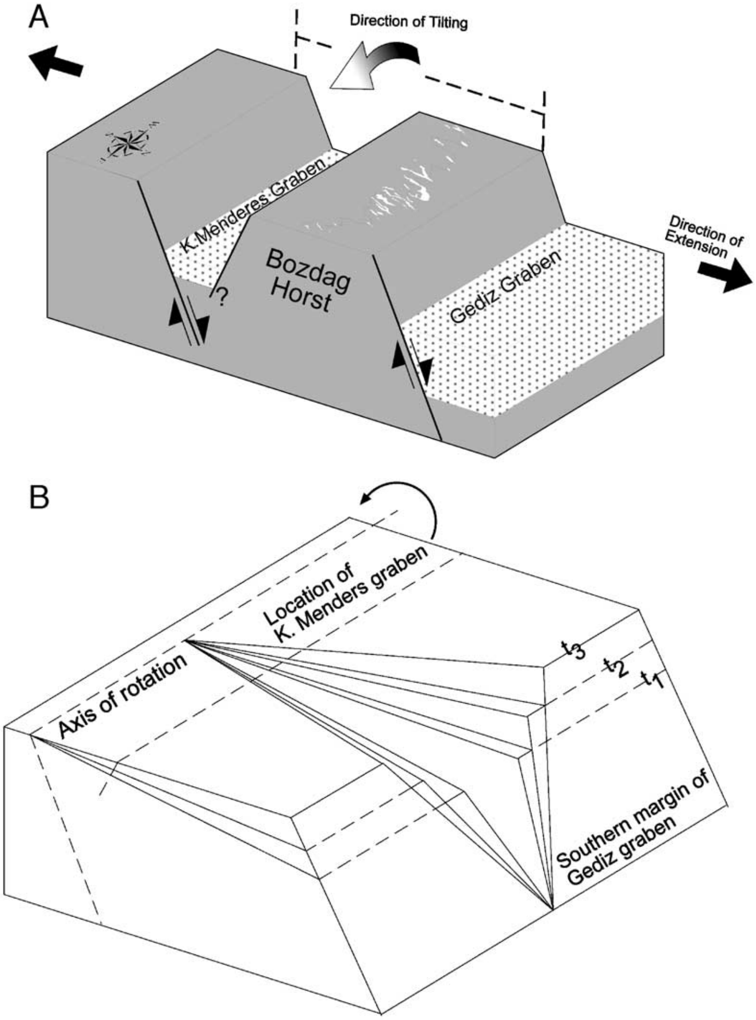

Fig. 12. Block diagrams: A) tilt of Bozdağ horst, B) effect of tilt on river channels (t1: oldest, t3 youngest).

that indicate differential erosion as a result of uplift and N–S rotational tilt on Bozdağ horst as well.

The age of the fluvial deposits is important in order to assess the timing of their evolution within the tectonic framework of the area. Since the purpose of this study is not to assign an absolute age to these deposits, their age will be discussed here only in relation to the tectonic phases so far suggested in the region. Field observations that may imply the age of these deposits are as follows:

- The deposits are all developed along the current drainage network as indicated by the spatial coincidence of the deposits with the recent stream channels (Fig. 6).
- There is no evidence of post-depositional deformation in the sequences although the area is known to have been tectonically active since the Miocene and is still active as indicated by seismic activity (www.koeri.boun.edu.tr/sismo/defaulteng.htm).
- The only way to date the fluvial clastics is indirect dating based on the correlation of a tuff layer intercalated with peat beds present in Gölcük depression with the Minoan tephra of the Santorini volcano (Sullivan, 1988) and peat layers dated just below and above the tephra beds exit in SW Ana-

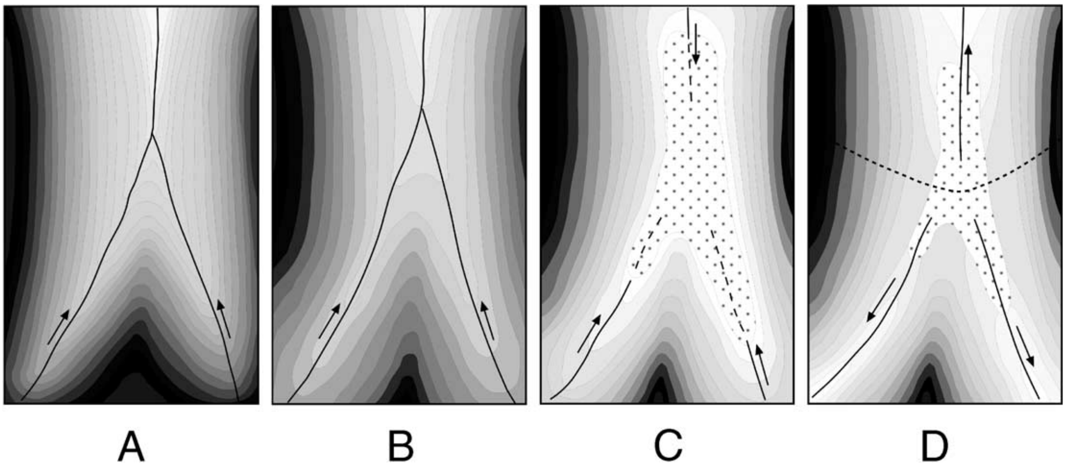

Fig. 13. Four-stage evolution model of fluvial deposits over Bozdağ horst. See text for explanations of stages. Arrows indicate flow direction, Thick dashed line is the drainage divide.

tolian Lakes (Eastwood et al., 1999a,b) (Fig. 8, no: 15). Therefore, the possible age for the parts of these deposits on the Bozdağ horst above the dated tuff bed will be Mid–Late Holocene.

All these indicate that the deposits are quite young so that they are not totally eroded yet, and not deformed. This period, therefore corresponds to the last phase of the extensional regime occurred during Mid–Late Holocene (Bozkurt, 2001).

7. Conclusions

Based on all of the above geological and geomorphological constraints a four stage evolutionary model of the deposits is proposed (Fig. 13). Initially the streams flowed northward with relatively steep channel gradients with V-shape valley profiles (A). As uplift and tilting occurred, the gradients of the stream channels became gentler (B) and then horizontal (C). During this stage the streams started to accumulate their load along the stream channels forming N–S oriented, wide U-shaped depressions. All the depressions were still within the drainage basin of GAG at this stage. In the last stage, the depressions were prone to erosion (D) with the exception of one that preserved its form (depression no: 15). In the latest stage a reversal of drainage occurred for some of the stream channels within the KMG.

The amount of tilting is estimated approximately as 1.2° to 2.2° with an E–W rotational axis facing north based on two parameters: 1) average inclinations of the base of depressions of the 19 northerly deposits (Table 1); 2) presence of 170–200 m thick alluvial deposits accumulated along the northern footslopes of Bozdağ horst. The age of tilt is presumed to be Plio–Quaternary depending on the timing of rifting processes in the region and the age of the fills in the elevated lakes. Accordingly the drainage divide between GAG and KMG has been migrated from south to north through time.

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