DOI: 10.26650/JGEOG2019-0017
COĞRAFYA DERGİSİ
JOURNAL OF GEOGRAPHY
2020, (40)
http://jgeography.istanbul.edu.tr

Evaluation of Drainage in the Upper Catchment of the Yeşilırmak River Basin Along the Almus Fault, Northern Turkey

Yeşilırmak Havzası Yukarı Mecrasında Almus Fayı Boyunca Drenajın Gelişimi

Türkan BAYER ALTIN[1], Bekir Necati ALTIN[1]

[1]Ömer Halisdemir University, Faculty of Science and Letters, Department of Geography, Niğde, Turkey

ORCID: T.BA. 0000-0001-8692-1713; BN.A. 0000-0002-9570-9877

ABSTRACT
The Yeşilırmak River Basin is located in the North Anatolian Fault Zone (NAFZ) which is one of the fault zones with intense seismic activity in Turkey. The Almus Fault is a segment of the North Anatolian Fault (NAF). This study aims to reveal the effect of the Almus Fault on the drainage development and morphotectonic evolution of the upper catchment of the Yeşilırmak River Basin and the relative tectonic activity of the fault. Morphometric indices such as, stream length gradient index (SL), mountain front sinuosity (Smf) and fan entrenchment (E) indicate that the downward of the sub-basins is tectonically more active than the upward which is ascribed to the tectonic activities along the Almus Fault. The Smf value is 1.4 at the west and decreases to 1.1 at the mouth of the sub-basins on the east. This indicates that the tectonic activity along the Almus fault in the study area increases from west to east and the uplift rate in the northern part is higher than the southern part of the study area. Development of the drainage network started during Pliocene due to differential uplift and a humid climate then developed under tectonic forcing during Quaternary.
Keywords: Tectonic Uplift, Drainage Development, Almus Fault

ÖZ
Yeşilırmak Havzası, Türkiye'de sismik olarak aktif fay zonlarından biri olan Kuzey Anadolu Fay Zonu'nda (NAFZ) bulunmaktadır. Almus Fayı da, Kuzey Anadolu Fayı'nın (NAF) bir segmentidir. Bu çalışma, Almus Fayının tektonik aktivitesinin Yeşilırmak Havzası'nın yukarı mecrasındaki drenaj gelişimine etkisini ortaya çıkarmayı amaçlamaktadır. Akarsu uzunluğu gradyan indeksi (SL), dağ cephesi sinüositesi (Smf), fan yüksekliği (E), hipsometrik integral (Hi) ve eğri gibi morfometrik indeksler (Hi) Almus Fayı boyunca alt havzaların aşağı mecralarının, yukarı mecralarına göre tektonik olarak daha aktif olduğunu göstermektedir. Smf değeri batı kesimde 1,4, doğu kesimdeki alt havzaların ağzında 1,1'e düşmektedir. Aynı şekilde düşük E değerleri güney bölümde gözlemlenir. Bu durum çalışma alanında Almus fayı boyunca tektonik aktivitenin batıdan doğuya doğru arttığını ve kuzey kısımdaki yükselme oranının, güney kısımdan daha fazla olduğunu göstermektedir. Drenaj ağının gelişimi, yerel tektonik kademeli bir yükselme ve nemli bir iklim nedeniyle Pliyosen'de başlamış ve sonra Kuvaterner'deki tektonik hareketlerin etkisi ile devam etmiştir.
Anahtar kelimeler: Tektonik Yükselme, Drenaj Gelişimi, Almus Fayı

Submitted/Başvuru: 22.06.2019 • **Accepted/Kabul:** 22.06.2019 • **Published Online/Online Yayın:** 03.04.2020

Corresponding author/Sorumlu yazar: Türkan BAYER ALTIN / turkanaltin@yahoo.com
Citation/Atıf: Bayer Altin, T., Altin, B. N. (2020). Evaluation of drainage in the upper catchment of the Yeşilırmak river basin along the almus fault, northern Turkey. *Cografya Dergisi*. Advance online publication. https://doi.org/10.26650/JGEOG2019-0017

1. INTRODUCTION

The development of topography in tectonically active regions is the result of the interplay of denudational processes and tectonic movements together (Topal, 2019). Morphotectonic indices relieve to detect the rates of tectonic movement (uplift and activity). Geomorphic indices are used to understand the tectonic geomorphology of an area (Keller and Pinter, 2002). When structural and geodetic data is insufficient, Digital Elevation Models (DEM) in a drainage basin is utilized to discern the tectonic and climatic conditions affecting the area (Burbank and Anderson, 2001). Bull and McFadden (1977) and Silva et al. (2003) researched the relative tectonic activity of different mountain front facets according to the AF, Smf and Vf indices to imply drainage area tilting. According to Burbank and Anderson (2001), a complex combination of the effects of vertical and horizontal motions of crustal rocks affect topography in tectonically-active areas. Tectonics, among other factors, decide the dimension, place and development of drainage basins and thus, in conjunction with climate and local geology, lead the flux of sediment fed into any fluvial system (Leeder, 1993).

In recent years, studies on investigating active tectonic deformation using quantitative geomorphology have increased. Geomorphic indexes such as the valley width/height ratio, mountain front sinuosity, drainage basin asymmetry and river length-gradient were used to assess the drainage pattern evolutivon and to describe the effects of tectonism on the morphology of drainage basins along the NAFZ in the region surrounding the study area by some of the researcher (e.g., Tüysüz and Erturaç, 2005; Selim et al., 2013; Gürbüz et al., 2015; Khalifa et al., 2018; Softa et al., 2018) and in other parts of the world (Kirby and Whipple, 2001; Harkins et al., 2005; Wobus et al., 2006; Bahrami, 2013; Das et al., 2013; Siddiqui, 2014). The tectonic settings are related to NAF producing various subsidence basins. One of these basins is the Kazova or the Almus corresponding to the Central Pontides (Bozkurt and Koçyiğit, 1996). The Kazova Basin is located in the west part of the study area. The Almus Fault has evident morphological expressions throughout the study area. The previous studies indicated that morphometric indices can be applied to the tectonically active regions. Morphometric analysis of the region between Trabzon and Rize indicates that each part is relatively active and that the area is progressively uplifting at a rate of more than 0.5 mm per year because of this stress, which is progressing due to push-up geometry by thrust faults of the Southeast Black Sea Fault (Softa et al., 2018, 2019). The stress transmitted to the Eastern Pontides and its immediate surroundings by the N-NW compressional movement of the Arabian plate is accommodated by regional uplift (Softa et al.,2019). It is emphasized that the coastal areas of the Eastern Pontides and its close surroundings are controlled by normal faults (Yılmaz 2017). Geological and geomorphological studies have generally analyzed local deformation, total displacement, and slip rates over various timescales along the NAFZ, as well as landforms affected by the zone's tectonic deformation. However, there is a lack of detailed studies on morphometry of the upper catchment of the Yeşilırmak River. In this study, the relative tectonic activity of the Almus Fault, a splay fault system of the NAFZ, will be determined by using morphometric indices, and the geomorphological evolution of sub-basins in the upper course of the Yeşilırmak River during the Neotectonic period was analyzed. The Neotectonic period is considered to cover Late Miocene-Holocene in Turkey (Dirik and Göncüoğlu, 1996; Bozkurt, 2001). The Southern Black Sea upland was exposed to a compressional regime. This regime is related to a palaeotectonic compressional axis during the Neotectonic period (Bellier et al., 1997). These palaeotectonic properties were reactivated in the Neotectonic period in the area (Gürbüz, 2009). This study explains the role of Neotectonic movements on geomorphological units and provides the results of morphometric index-based analysis. Along the mountain fronts located surrounding of the study area controlled the Almus Fault. Along with the most recent tectonic activity, the topography of the region has been controlled by incision driven by fluvial processes.

As is also understood from the above information, there is a lack of researches on morphotectonic properties of the upper course of the Yeşilırmak River Basin. This study is important in terms of filling the gap related to this basin. The main purpose of this study was to reconstruct the geomorphological evolution of the upper catchment of the Yeşilırmak River by analyzing the effects of tectonic movements on drainage systems.

2. GEOLOGICAL AND GEOGRAPHICAL SETTINGS

The study area covers the upper course of the Yeşilırmak River located within the southern Middle Black Sea section between Tokat province and Almus Dam with an area of approximately 295 km². The Yelpe, Kılıçlı, Yalancı and Şenköy streams are right tributaries and merge with the Yeşilırmak from the north and northwest while the Ağacaköy, Kuru, and Korucak streams are left tributaries and join it from the south and southeast (**Figure 1**). The study area includes a 17-km-long, 0.3- to 2-km-wide, E-W trending reach of the Yeşilırmak River. The river valley becomes wider from east to west and its lowest point lies

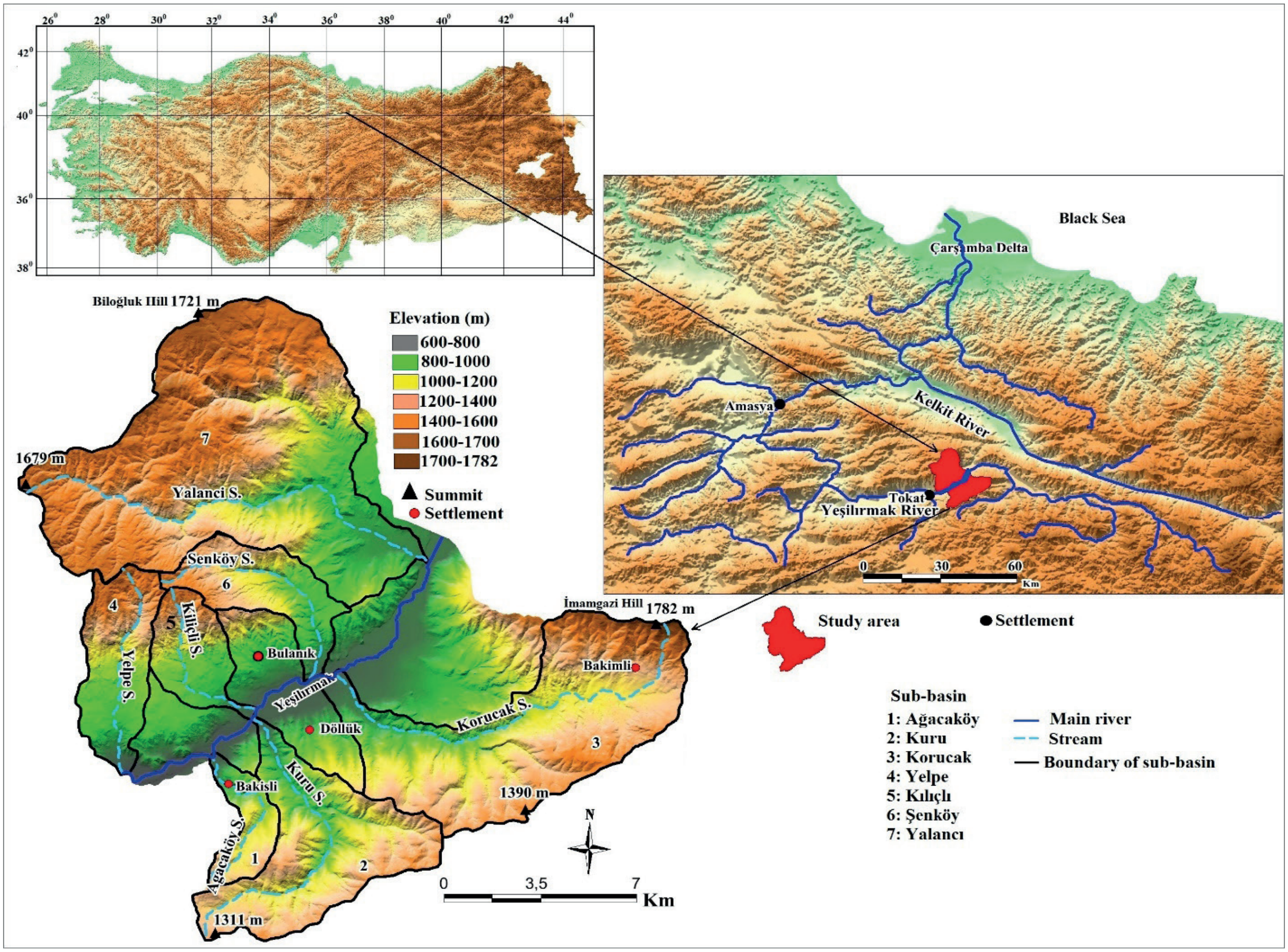

Figure 1: Location map and digital elevation model (DEM) of study area.

600 m above sea level. The highest mountain summits, İmamgazi Hill at the northeastern end of the Korucak sub-basin and Biloğluk Hill on the northern margin of the Yalancı sub-basin, are 1782 m and 1721 m in height, respectively (**Figure 1**). Thus, the maximum relief between the bottom of Yeşilırmak valley and its southern and northern mountains is 1121 m and 1182 m, respectively. The high mountainous areas, which correspond to the watershed of the sub-basins, have been deeply incised by streams and display convex slopes with disjoined erosional surfaces. The sub-basin tributary streams coming from the highlands have incised meanders, terraces and alluvial fans along their lower course.

The study area includes Tokat metamorphics, ophiolite melange, continental clastics and Quaternary-age alluvium and slope debris (**Figure 2b**). The Tokat metamorphics consist of schist, marble, metabasite and crystallized limestones (Sümengen, 2013). The ophiolitic melange contains limestones of various ages with blocks and pebbles of ophiolite and continental clastic rocks, unconformably built from conglomerate, sandstone and limestones (Sümengen, 2013). Continental clastic rocks consist predominantly of pelagic limestones but also include turbitic clastic rocks and olistostromes with ophiolitic detritus (Yılmaz and Yılmaz, 2004). Quaternary units occur along the bottom of valleys and their slopes. The study area is located in the Central Pontides, one of the orogenic belts in Turkey. The study area includes a segment of the Almus Fault, a splay fault system of the NAFZ (Bozkurt and Koçyiğit, 1996) (**Figure 2b**). The Almus Fault Zone (AFZ) is an active dextral strike-slip fault. This system extends for approximately 150 km from Reşadiye to the east to the town of Iğdır to the west (Bozkurt and Koçyiğit, 1996). Numerous fresh traces of the active fault segments of the Almus Fault occur along the Yeşilırmak valley. For example, alluvial fans unconformably overlying ancient

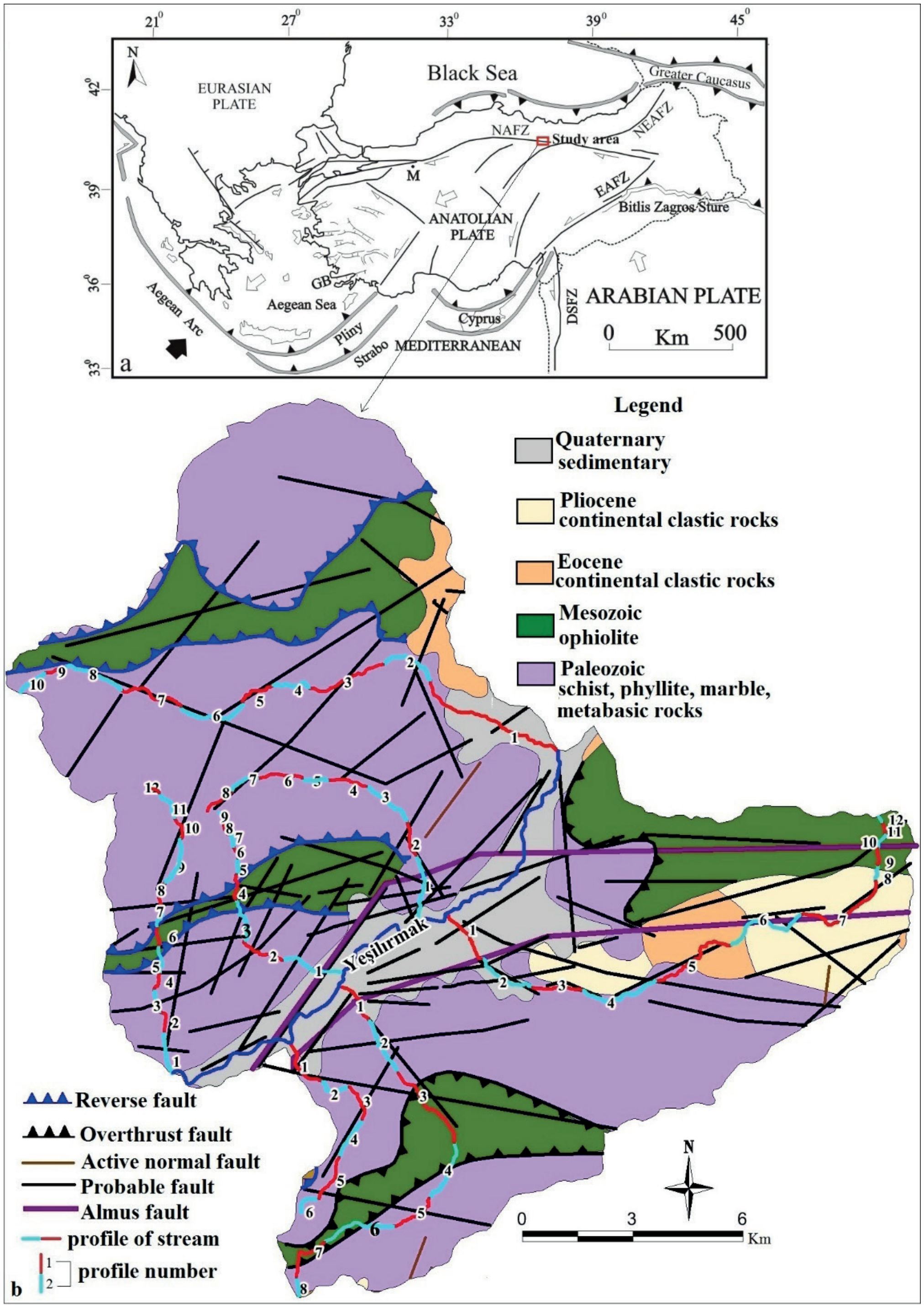

Figure 2: a) Simplified neotectonic map showing some major neotectonic structures of Turkey and continental extrusion of the Anatolian block away from the Arabia-Eurasia collision zone (modified from Koçyiğit, 1989). **b)** Geological map of study area and reaches of the streams, in red and blue, for SL index analysis. This map was drawn up at 1/500.000 scale (MTA, 2002). Probable faults were digitized from 1:25000 geological maps.

alluvial fans and terraces are aligned along the fault-bounded sides of the valley (**Figure 3a**). The AFZ is seen as branched west of the village of Bakımlı into numerous parallel to sub-parallel smaller fault segments resulting in a simple horse-tail strike-slip fault pattern in the Kazova Basin (**Figure 3b**), which is located within the AFZ and is a splay fault system of the NAFZ in the Central Pontides (Bozkurt and Koçyiğit, 1996). This pattern is seen in the westernmost part of the study area. According to Hubert-Ferrari et al. (2002), the basin may be affected from the initial fault extension process before the main fault formed its present marks. A terrace morphology on both margins of the valley was formed by the AFZ. This is interpreted

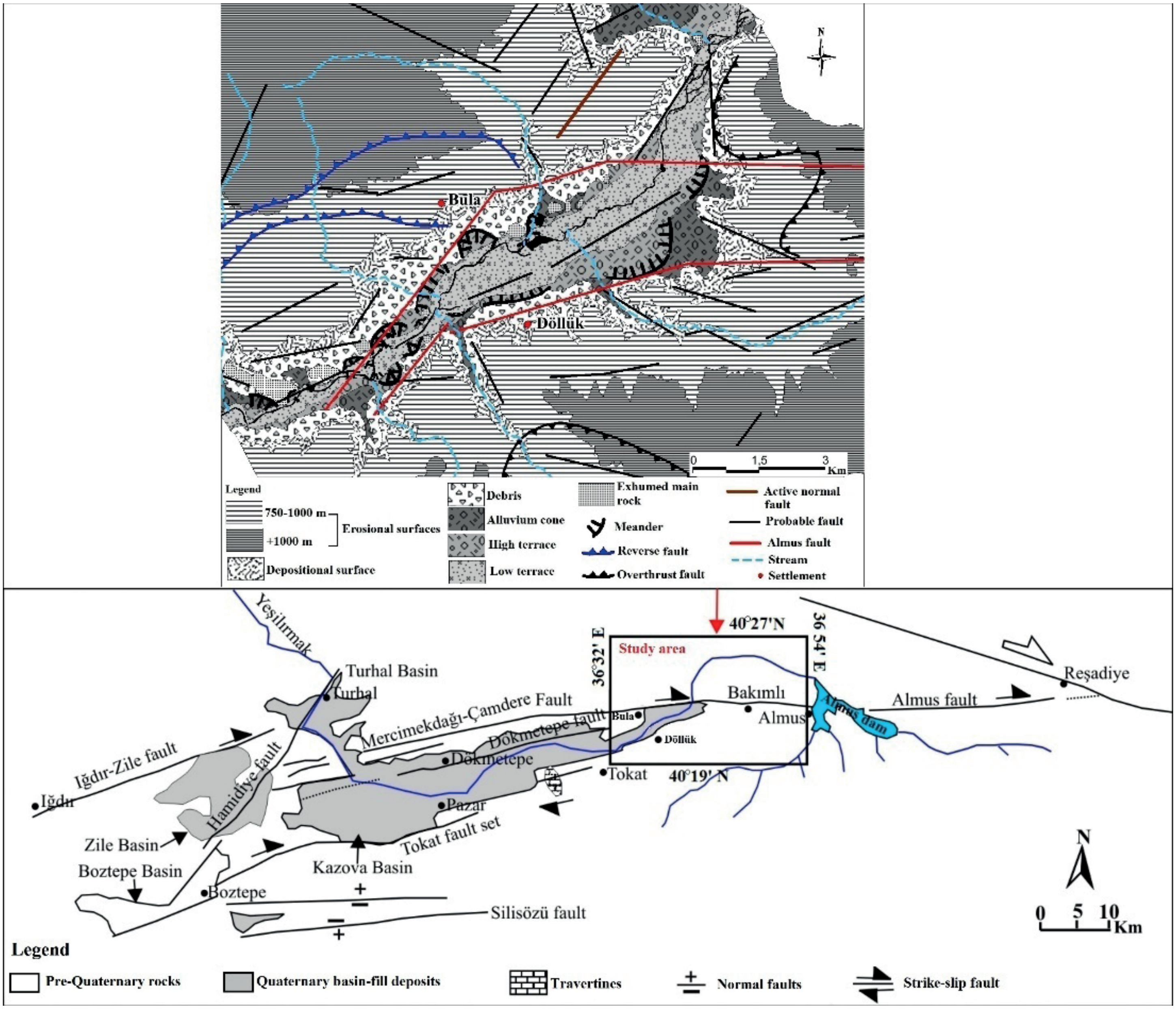

Figure 3: a) Geomorphology map of study area (modified from Bayer Altın et al., 2017). **b)** horse-tail strike-slip fault pattern in Kazova Basin. The half arrows show the relative motion on the faults (modified from Koçyiğit and Bozkurt, 1991).

as one of the major splays of the NAFZ (Koçyiğit and Bozkurt, 1991; Bozkurt and Koçyiğit, 1995). In general, although the typical faulting style is strike-slip along its traces, the AFZ also includes sections with high-angle reverse faulting characteristics, such as around the village of Bakımlı (Bozkurt and Koçyiğit, 1996).

The study area is a tectonically-active area located close to traces of the North Anatolian Fault Zone (NAFZ), one of the largest active strike-slip fault systems in the world (Şengör et al., 2005). The right-lateral North Anatolian Fault (NAFZ) is the northern border of Anatolian block moving westward. It connects the compressional regime in eastern Anatolia with the extensional regime in the Aegean Sea region (McKenzie, 1972; Şengör, 1979; Barka, 1992) (**Figure 2a**). This process was initiated by the collision between Arabia and Eurasia (Dewey et al., 1986) dating from Late Cretaceous to Pliocene, with most estimates ranging between 35 and 20 Ma (McQuarrie and Van Hinsbergen, 2013). This collision is characterized by the uplift of the Anatolian Plateau, the narrowing of marine area (Gelati, 1975; Şengör et al., 1985) and the beginning of act in the North Anatolian Fault (Şengör et al., 1985; Barka, 1992; Hubert-Ferrari, 2009). The age of all basins located along the North Anatolian eastern coast were suggested unambiguously as Late Miocene using Biostratigraphic data (Şengör et al., 2005). Most of the depressions are alined along the NAFZ and its major splays (Bozkurt, 2001), one of which is the Kazova Basin, where the study area is located. The basin developed along the AFZ and has a negative flower structure delimited by strike-slip faults. These faults show a considerable amount of prolongation (Bozkurt and Koçyiğit, 1996). The Pontides, together with the Anatolian mainland, emerged during the Late Eocene and gained peneplain morphology during the Oligocene-Middle Miocene as a result of denudational processes (Emre et al., 2009). These landforms are composed of melange complexes from a northern branch of the Neotethys. and they were folded and faulted during the Alpide orogeny (Okay, 2008). The study area is located in the Central Pontides (**Figure 4a**). Erosional surfaces in the northern sector of the Yeşilırmak valley are higher than surfaces located in the southern sector (**Figure 3**). This difference is caused by local tectonic movements from the Almus Fault. According to Erkal (1993), the Yeşilırmak valley is an anteconsequent valley formed by an uplift of the region in Early Quaternary. Moreover, the terraces are a result of fluvial erosion and tectonic movements as shown by local subsidence

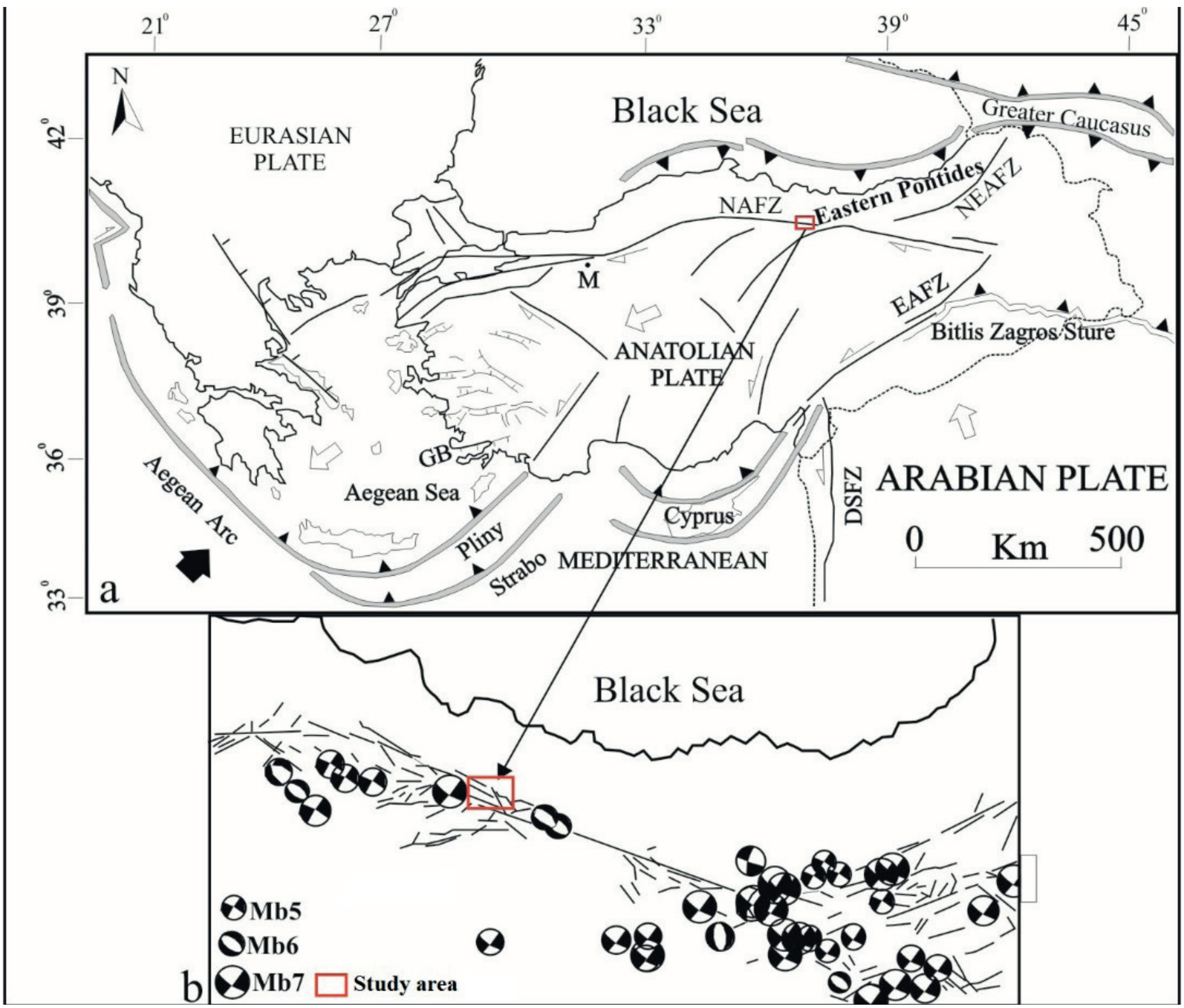

Figure 4: a) Simplified neotectonic map showing some major neotectonic structures of Turkey and location of the Eastern Pontides (modified from Kocyiğit, 1989). **b)** distribution of earthquakes with M>4 that occurred between 1939 and 2012 (modified from CMT catalog and Şengör et al., 2005).

and changes in the local base level. Recent tectonic activity of the Yeşilırmak River basin is evidenced by the presence of seismicity: slight earthquakes (3-3.5 magnitude on Richter scale) occur biannually and strong earthquakes (8, 8.5 or 9 magnitude) occur at 50- or 100-year intervals (Erkal, 1993). The largest M7.8–8.0 earthquakes are detected and entirely observed along the older eastern part of the NAFZ (Bohnoff et al. 2016) (**Figure 4b**).

3. MATERIAL AND METHODS

In this study, 1:25,000 scale topographic maps for Tokat province (ref. H36-37) were used as basic data for the analysis. A 10-m spatial-resolution digital elevation model (DEM) representing the topography of the sub-basins was used. The model was derived from these digitized sheets to extract morphometric indices for the surface dynamics analysis. The study area is located between latitude 40º29’48’’ and 40º19’06’’ north and longitude 36º34’02.23’’ and 36º49’21.06’’ east. In addition, field studies, satellite image analysis, GPS measurements and conventional altimeter readings were used to map the location and size of faults and alluvial fans.

The studied basin was divided into two sectors along the Almus Fault. The north sector of the catchment includes Yelpe, Şenköy, Kılıçlı and Yalancı sub-basins. The south sector includes Ağacaköy, Kuru and Korucak sub-basins. These sub-basins belong to the lateral tributaries of the Yeşilırmak River.

In this study, morphometric indices were applied in the drainage basins and along the mountain front upstream of the Almus Fault to determine the relative tectonic activity. Eleven geomorphic indices were examined by taking into consideration the diversity of the morphogenetic characteristics. These indices are stream length (L), fault length (FL), stream order (Nu), dissection index (Di), basin asymmetry (AF), mountain front sinuosity (Smf), valley floor width-to-height ratio (Vf), fan entrenchment (E), stream length-gradient index (SL), and hypsometric integral (Hi) and curve. In addition, the slope, elevation and direction of the fault traces were derived from the DEM and calculated for the study area. In addition, numerous combinations of the SL and Vf, and other morphometric indices (stream orders and fault density in square kilometer) was used due to the evolution of tectonic activity along the Almus Fault.

Stream length (L) and stream order (Nu): rivers of the first-order are outermost tributaries (Strahler, 1952). A high number of first-order streams implies tectonically-active highland dissected zones. High L values occur due to structural complexity and distorted drainage patterns and regional upliftment across the drainage basin (Horton, 1945). In addition, the highest total length of first-order streams implies that the basin is exposed to denudation and also that some areas of the basin are featured by variation in topography and lithology (Singh and Singh, 1997). The number of the stream order ensures a definition of the basin geometry to understand the initial slope or disparity in the rock rigidity and structural controls of the drainage basin (Strahler, 1964). In addition, it gives information about the stage of the geomorphic development of the area (Moges and Bhole, 2015).

Dissection index (Di): Dissection index (Di) is expressed as the ratio of relative relief to absolute relief. It reflects the rating of drainage basin vertical erosion and the stage of landform progress (Nir, 1957; Mukhopadhyay, 1984). The Di values in this study were grouped into five categories: 0.0-0.02 low Di, 0.02-0.04 moderate Di, and 0.14-0.2 high Di.

Di was computed as follows:

$$\mathrm{Di}=\frac{Rr}{Ar}\ (1)$$

Where Ar is the absolute relief and Rr is relative relief.

Basin asymmetry (AF): AF is a morphometric index used to detect the existence or absence of regional tilt on a basin or regional scale (Keller and Pinter, 2002). To understand the formation of the drainage basin and the amount of tectonic control in its development. The index is one of the methods used to explain the formation of drainage basin and the status of tectonic control in its development (Cox, 1994; Hare and Gardner, 1985). AF should equal about 50 and is susceptible to tilting vertical to the trend of the main line (stream) (Keller and Pinter, 2002). According to this index, AF values greater or less than 50 may suggest tilt (Keller and Pinter, 2002). The AF index equation is;

$$\mathrm{AF}=\frac{Ar}{At}*100\ (2)$$

Where Ar is the area of the basin to the right (facing downstream) of the main stream. At is the total area of the drainage basin.

Mountain front sinuosity (Smf): Smf is a measure of the degree of disorder or sinuosity at the base of a topographic escarpment (Bull and McFadden, 1977; Bull, 1978; Keller, 1986). Active mountain fronts show straight profiles with lower values of Smf. Inactive or less active mountain fronts are noted by irregular or more eroded profiles, with higher Smf values (Wells et al., 1988). Tectonically-active mountain fronts tend to be of high relief and straight with Smf<1. Tectonically-inactive mountain fronts will increase to a Smf value of ~1 or >1 (Bull, 1978). Smf was computed as follows:

$$\text{Smf}=\frac{Lmf}{Ls} \quad (3)$$

Where Lmf is the length of the mountain front along the foot of the mountain. L is the straight-line length of the mountain front (Bull and McFadden, 1977; Keller and Pinter, 2002).

Valley floor width-to-height ratio (Vf): The Vf ratio increases with decreasing amounts of tectonic activity as valley bottoms down cut and laterally erode over time (Bull and McFadden, 1977). In other words, high values of Vf are related to low uplift rates. Low values of Vf (<1) reflect narrow, steep V-shaped, deep valleys (high relief) that contain streams arising from mountain fronts. These fronts are actively incising and commonly related to uplift (Keller and Pinter, 2002). The index is a measure of incision and not uplift. However, incision and uplift are nearly matched in an equilibrium state (Jayappa et al., 2012). For each sub-basin in this study, the valley width and height were obtained along the valley's cross-section vertical to the drainage basin axis and the Vf was calculated. Azor et al., (2002) intimated that high values of Vf usually show low tectonic activity, while low values show areas of high tectonic activity with comparatively rapid uplift and valley incision. Here, the Vf values were calculated at a determined distance varying between 1 and 5 km from the mountain front, based on the size of the sub-basins in the study area. Vf was computed as follows:

$$\text{Vf}=\frac{2Vfw}{(Eld-Esc)+(Erd-Esc)} \quad (4)$$

Where Vfw is the width of the valley floor. Esc is the elevation of the valley floor. Eld and Erd are elevations of the left and right valley divides, respectively. (Bull and McFadden, 1973).

Fan entrenchment (E): Fan entrenchment was used to interpret the relationship between the quantitative properties of alluvial fans and the active tectonics of the study. High E values indicate steep slopes on high-gradient mountain fronts, and low values show the opposite (Bahrami 2013). Highly entrenched fans with high Tectonically-active mountain fronts having steep V-shaped valleys (with higher Vf values) have high sweep angles. and fault scarps. The sweep angle (SA) of fans is of a quantitative value that was obtained through measuring the angle between the two outermost positions of the channels of a fan (Viseras and Fernandez, 1994). E was computed as follows:

$$\text{E}=\frac{(A-C)+(B-C)}{2} \quad (5)$$

Where A is the maximum elevation of the fan surface on the left side of the channel. B is the maximum elevation of the fan surface on the right side of the channel. C is the channel bed elevation.

Stream length-gradient index (SL): High SL values show declination in cross-sectional river profiles from their idealized, equilibrium form (Hack, 1973). In this analysis, SL values was detected to the influence lithological and tectonic controls on river profiles across the fault belt. The SL index is used to describe actual tectonic activity that implied anomalously high index values in an area with particular rock types. A region with high SL, including soft rock, may show actual activity. (Keller and Pinter, 2002). In the current study, SL values were calculated to be from about 0.5 m to 1 km (for Ağacaköy stream and others, respectively) along the length of the main stream channels in the sub-basins. SL was computed as follows:

$$\text{SL}=\frac{\Delta H}{\Delta L} * L \quad (6)$$

Were ΔH is elevation difference of the river, ΔL is the length of the river, L is distance between the valley and peak (Hack, 1973).

Hypsometric integrals (Hi) and hypsometric curve: Hypsometric analysis has been used to differentiate between erosional landforms at different stages during their evolution (Strahler, 1952; Schumm, 1956). Hypsometric analysis has been used to discriminate between erosional landforms at varied stages during their development (Strahler, 1952; Schumm, 1956). Hypsometric integrals and hypsometric curves are important indicators of watershed conditions in terms of basin geometry and basin relief (Lifton and Chase, 1992; Hurtrez et al., 1999; Ritter et al., 2002; Chen et al., 2003). Thus, a measure of the disperson of landmass volume remaining beneath or above a basal reference plane is ensured. Hypsometric curves and integrals can be interpreted in terms of the degree of basin dissection and relative landform age. Thus, convex-up curves with high integrals shows young, undissected (disequilibrium stage) landscapes. Smooth, s-shaped curves show mature (equilibrium stage) landscapes, and concave-up curves with low integrals show old and deeply dissected landscapes (Strahler, 1952). The Hi index equation is:

$$Hi=\frac{Hm-H\min}{H\max-H\min} \quad (7)$$

Where Hm is mean elevation of the basin, Hmax is the elevation of the highest point within the basin and Hmin is the basin mouth.

In theory, relative tectonic activity is divided into three classes by El Hamdouni et al. (2008). Class 1 is Hi>0.5, class 2 is 0.4<Hi<0.5 and class 3 is Hi<0.4. Hi values close to 0 show highly eroded tectonically inactive regions, whereas those close to 1 show slightly eroded tectonically active regions (Keller and Pinter, 2002). Based on the DEM in this research, the study area was divided into 20,434 square grids of 70m x 70m and detailed morphometric analysis (Di and Hi) was carried out for each grid using software such as ArcGIS10.

3. RESULTS

The analysis of morphometric indices find out differences in drainage development on the west part and east part of the upper catchment of the Yeşilırmak valley along the Almus fault. These differences of drainage development are defined in below sections.

3.1. Stream order (Nu) and Stream Length (L)

Kuru and Yelpe sub-basins were identified as fifth order, and three sub-basins (Ağacaköy, Kılıçlı and Şenköy) were identified as fourth order. Stream order analysis shows that the Yalancı and Korucak sub-basins belong to the sixth order. The highest cumulative order was identified in the Yalancı sub-basin (ΣNu: 2001) to the north and Korucak sub-basin (ΣNu: 874) to the south. Ağacaköy sub-basin had the lowest cumulative order (ΣNu: 93). The total stream order value of the Ağacaköy, Kılıçlı, Yelpe and Şenköy sub-basins was under the mean value (**Figure 5a, b**). The total order number increased from west to east in both the southern and northern sectors of the study area. In addition, the highest first-order (N1) value was observed in the Yalancı and Korucak sub-basins. These high values are due to the narrow, deep and young valleys where river incision occurred as tectonic forcing accelerated the landscape erosion rate by rejuvenating the gradient of landslide slopes. Analysis of the total length of streams (L) indicates that the Yalancı (611.3 km) and Korucak (288.6 km) sub-basins had the highest L value, whereas the Ağacaköy (33.6 km) and Kılıçlı (70.5 km) sub-basins had the lowest L value. Values of these sub-basins are under the mean value (**Figure 5c, d**). Stream length is a indicator of evoluation of the hydrological characteristics of the bedrock

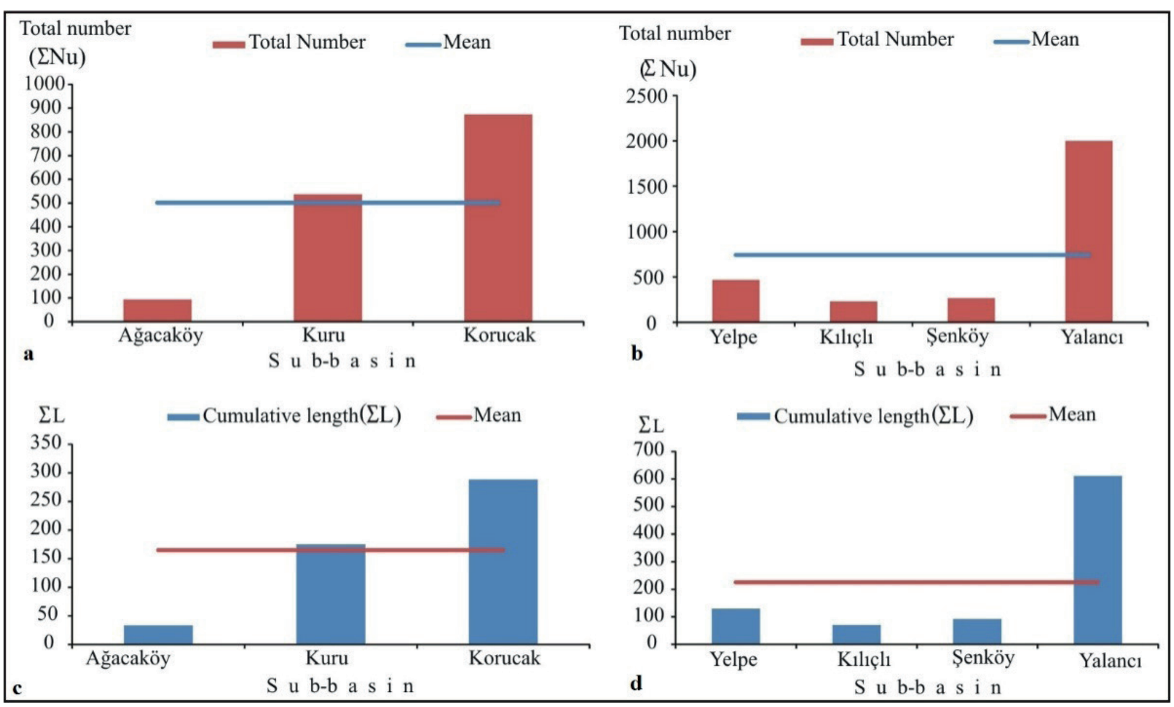

Figure 5: Total number of stream orders and cumulative length of southern sector, **a, c)** and northern sector **(b, d)** of study area.

and extent of the drainage. In the present study, the existence of many streams over the oldest rock crossing fault lines (**Figure 2**) may indicate that the streams acquired well-developed course before they were affected by rock fractures and fault lines during their early development. This evidently shows that the sub-basins are older than the onset of tectonic activity such as faulting and folding in the area. This tectonic activity based on the fault lines led to rejuvenation of the channels.

3.2. Dissection Index (Di), Hypsometric Integral (Hi) and Hypsometric Curve

The Di was calculated using DEM, and Di values ranged from 0.04 (very low) to 0.20 (very high). Analysis of the dissection map (**Figure 6a**) shows that most of the study area is constituted of denudational hills in dissected areas, corresponding to steep and very steep slopes (**Figure 6b**). In the northern and southern sector of the study area near the plateau divide, the streams are superficially incised in the metamorphic and ophiolite formations. Di values indicate that the rate of dissection is high in the hilly area, the middle course and downward of the sub-basins (Di=0.04-0.2), moderate in the plateau area (Di=0.02-0.04) but low in the mountainous area and along Yeşilırmak valley (Di=0.0-0.02) due to lack of sufficient streams, comparatively hard rock and vertical cliff-shaped hills. The occurrence of high Di values in the lower course of the streams implies a significant tectonic uplift, corresponding to steep slopes and high stream gradients with increased slope values (**Figure 6b**).

According to Hi values, the sub-basins in the study area indicate differences in their maturity. In particular Hi values of the sub-basins controlled by the Almus Fault and their hypsometric curves show that the Ağacaköy, Kuru and Yalancı sub-basins are in the young phase, and the Kılıçlı, Korucak, Şenköy and Yelpe sub-basins are in the mid-mature phase. The hypsometric integral (Hi) range is between 0.2 and 0.8 and is normally distributed over the entire study area (**Figure 7**). The mean value of Hi in the study area is 0.5, indicating that the landscape is a dissected plateau cut by deeply-incised streams with an intermediate (mature) stage of evolution. According to the results of the this study, low values of Hi are associated with smooth uplands and the bottom of valleys. High values of Hi indicate deep incision and rugged relief caused by faults, especially the Almus Fault.

The effect of the Almus Fault is in evidence between the Kuru, Şenköy sub-basin and the Korucak sub-basin, and in the upper

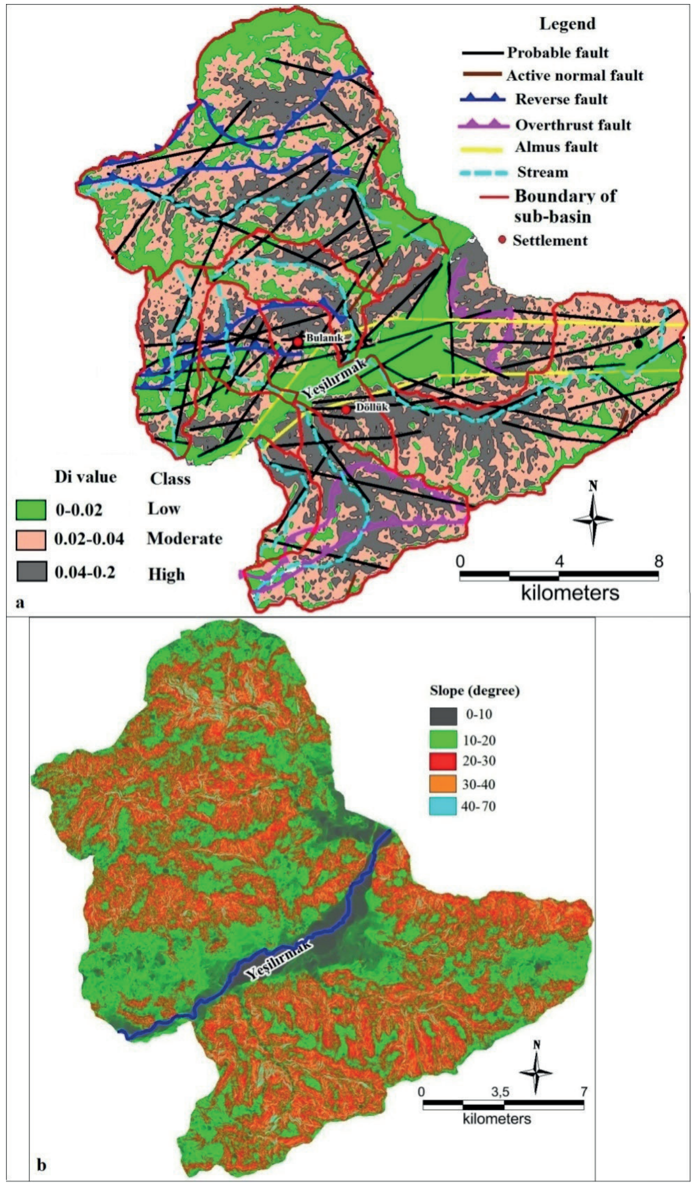

Figure 6: a) Di values and distribution of **b)** slope values of sub-basins.

course of other sub-basins, as supported by the profile of the hypsometric curve. The hypsometric curves of the sub-basins differ significantly from each other (**Figure 8**). Differences on the curve may be associated with tectonic activity on the faults. The curves of the Kuru, Korucak and Şenköy sub-basins are upwardly convex, while the curves of the Yalancı, Yelpe, Ağacaköy and Kılıçlı sub-basins are downwardly convex. The values suggest that these three sub-basins are in a relatively youthful stage of geomorphic evolution compared to the other four sub-basins. In particular, the convex-shape of Hi curve in the down course indicates tectonic activity of the Almus Fault and other fault lineaments during the Pleistocene.

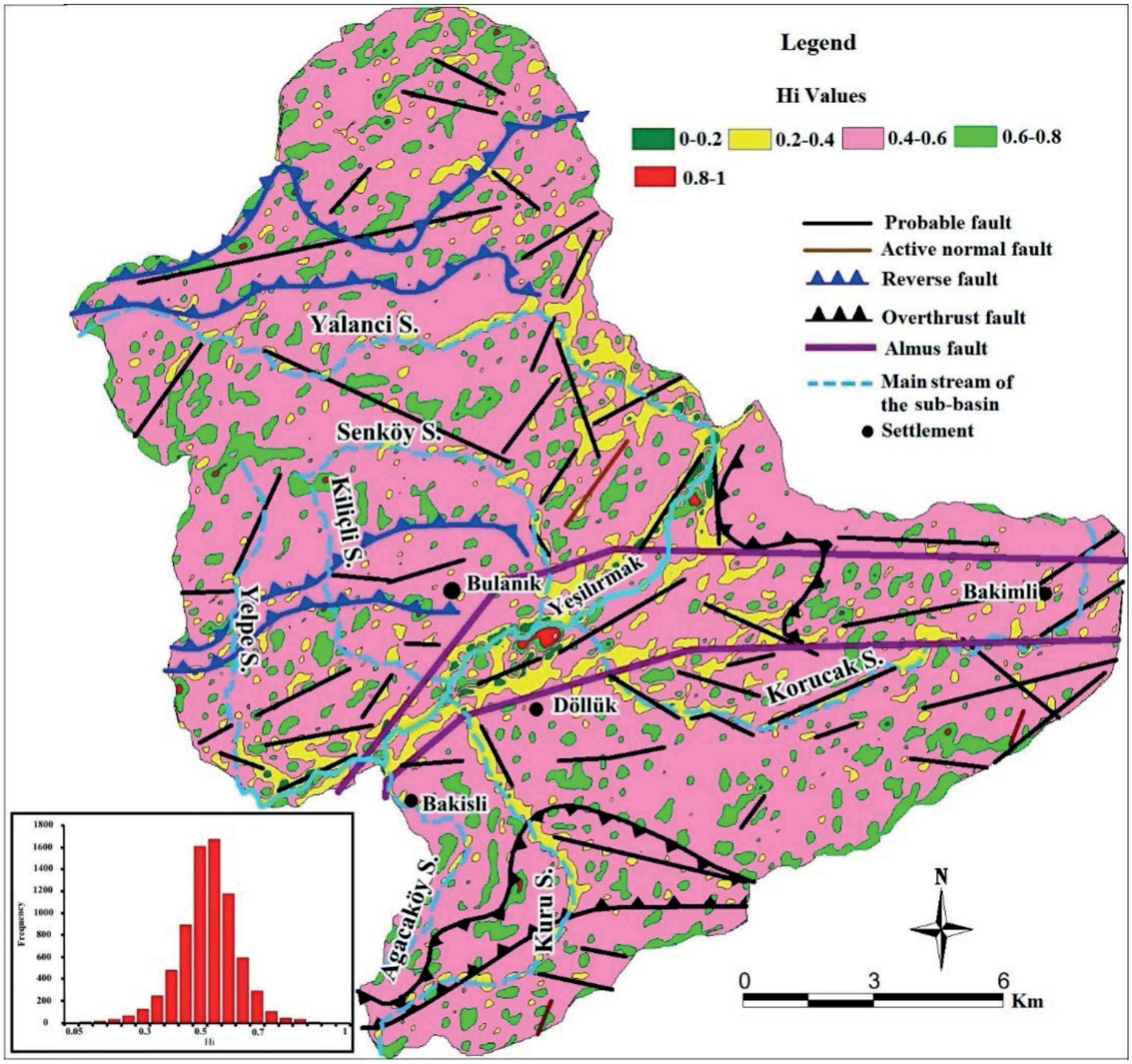

Figure 7: Spatial distribution of Hi values extracted from DEM at 10 m resolution.

3.3. Basin Asymmetry (AF) and Fault Direction

The AF value for the sub-basins varies between 30 in the Korucak sub-basin and 69 in the Kurudere sub-basin (**Figure 9**). The Şenköy sub-basin is an almost symmetric sub-basin (AF: 52.6), whereas the Kuru, Korucak, Ağacaköy, Yelpe and Yalancı sub-basins are highly asymmetric. The Kılıçlı sub-basin is a medium asymmetric sub-basin (AF: 44.4). With the exception of the Şenköy and Kılıçlı sub-basins, the other sub-basins have high asymmetry factors that correspond well with the approximately W-E trending faults (**Figure 9**).

The high values of AF in the Ağacaköy, Kuru and Yalancı sub-basins indicate that the tributaries flowing from the east side (right) of the main stream are longer, relative to the tributaries on the west side (left). AF values characterizing the Korucak and Yelpe sub-basins indicate an opposite direction of asymmetry. This implies that the second phase of uplift in the area during Pliocene is responsible for the westward tilting of the drainage basin. The tilting has resulted in the occurrence at different elevations of fluvial terraces (**Figure 3a**) and formation of an active negative flower structure on the Almus Fault Zone.

Numerous tectonic lineaments stand out in the study area (**Figure 9**), having developed as normal and strike-slip faults as a result of activity on the Almus Fault during the Neotectonic period (**Figure 10a, b, c, d, e**). The direction of tectonic lineaments within the northern and southern sectors of the Yeşilırmak valley reflects the direction of sub-basin tilting due to tectonic effects of the Almus Fault. In the southern sector, W-E trending (70.33º) tectonic lineaments are dominant,

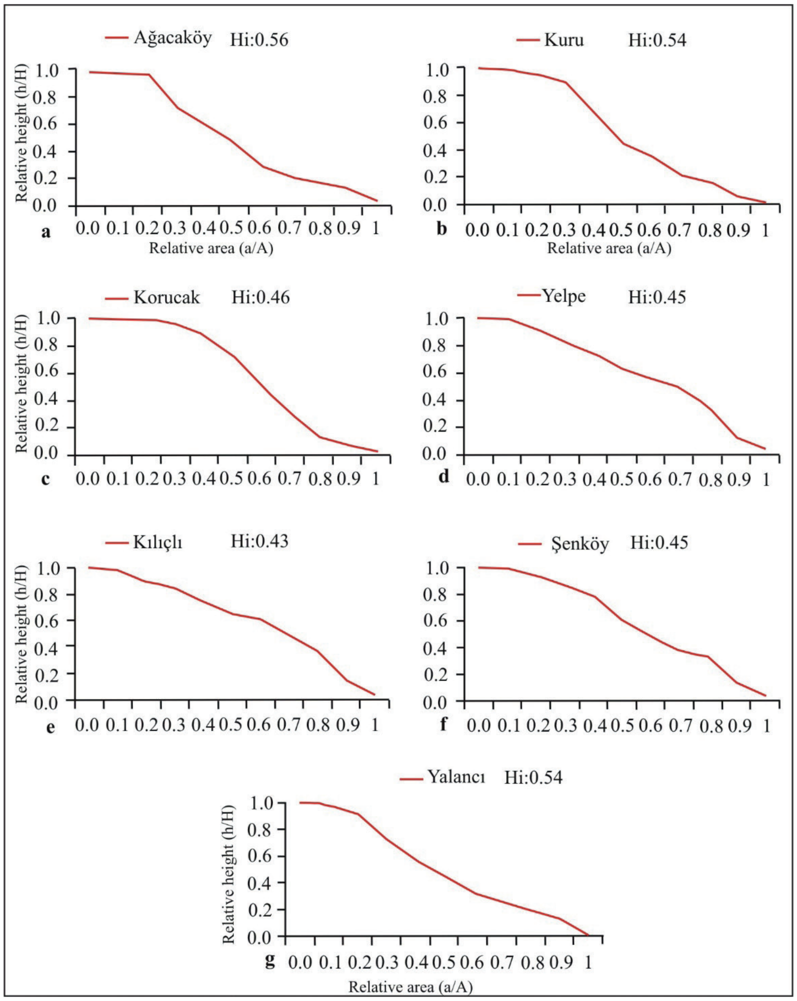

Figure 8: Hypsometric curve of the seven sub-basins.

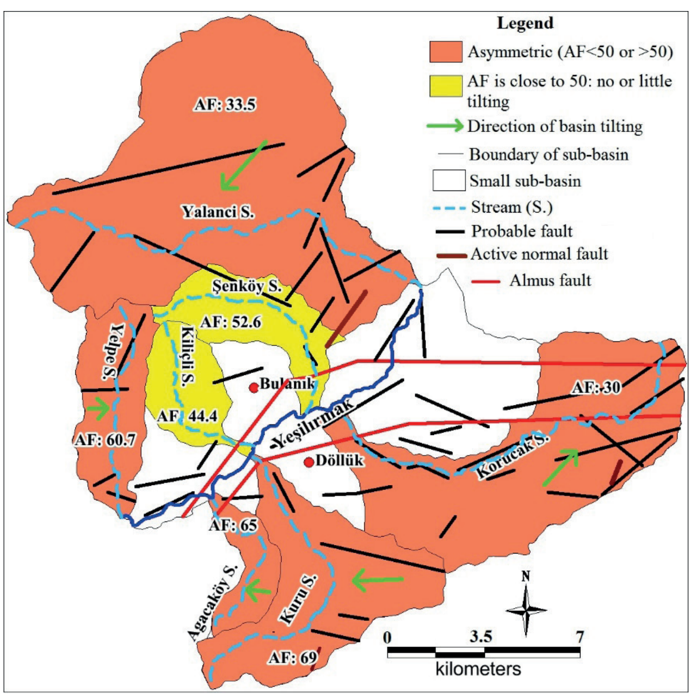

Figure 9: AF values of the seven sub-basins.

whereas in the northern sector, WSW-ENE trending (65.13º) lineaments predominate (**Figure 10f**). This pattern can be regarded as a result of block movement caused by the Almus Fault tectonic regime.

3.4. Mountain-Front Sinuosity (Smf) and Fan Entrenchment (E)

Smf values were calculated for 16 locations on the fault scarps with steep (30%-40%) and very steep (+40) slopes (**Figure 11a** and **Table 2**). Smf values range between 1.1 and 1.4. Except for the mouth of the Kuru sub-basin, with an Smf value of 1.4 (or 1.2), elsewhere the Smf values are low and suggest that the upper course of the Yeşilırmak valley may be controlled by tectonic activity of the Almus Fault; with this activity apparently increasing from west to east along the southern side of the valley. The Smf value is 1.4 at the mouth of Ağacaköy stream and decreases to 1.1 at the mouth of the Korucak sub-basin on the southern side and to 1.1 at the mouth of the Yalancı sub-basin on the northern side of the

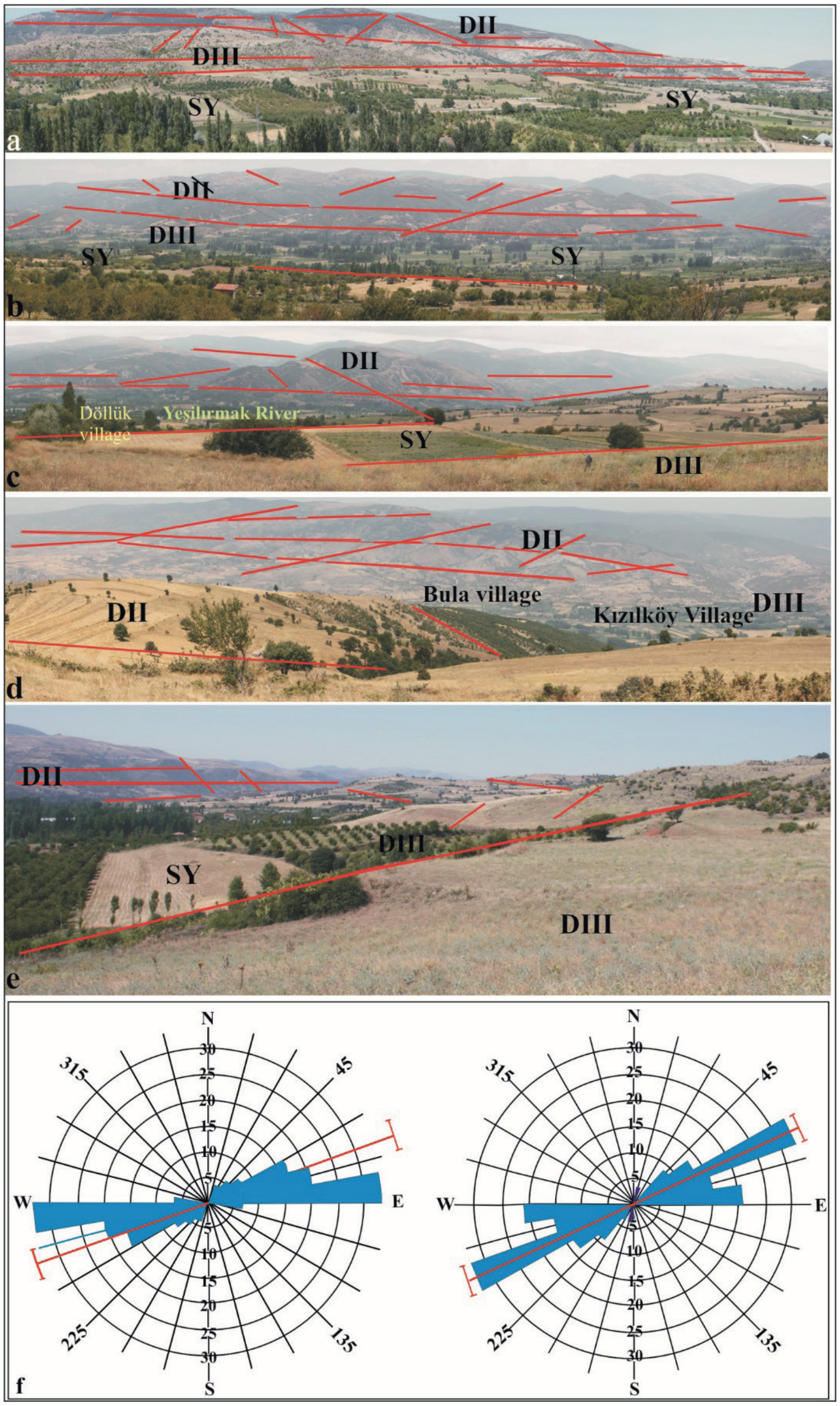

Figure 10: According to Erol (1983), formation of the erosional surfaces (DII and DIII) and terrace (SY) was triggered by climatic change and tectonic activity. The red lines are fault lineaments formed by the Almus Fault. **(a)**. Looking towards the east from Kılıçlı village and on the line between Yelpe-Bula-Şenköy villages, the erosional surface of the Upper Pliocene (DIII) system is found at 1100-1150 m elevation, with deposits covering the metamorphic rocks and the SY of Yeşilırmak River at an elevation of 650 m. In the background the profiles of the Upper Miocene erosional surfaces (DII) are visible. **(b, c)**. Looking towards the south from Bula village, the conical hills (DII) of the same age are clearly seen in the picture, having been eroded by the Yeşilırmak River during Pliocene (DIII). SY was formed due to deep vertical erosion of the Yeşilırmak River stimulated by the Almus Fault during Quaternary **(d)**. Looking north from Döllük village and **(e)** southwest from Bula village, a shaped depression of Pliocene age (DIII) is observed. The Yeşilırmak valley extends along this depression **(d).** In the background, the Anatolian Peneplain surface cuts across the ophiolite of the Mesozoic melange formations **(d).** The 1500-1400 m elevated Upper Miocene erosional surfaces and DIII surfaces that penetrate the DII surface are also seen. In the foreground is the 1150 m elevated fluvial accumulation surface of Pliocene age (DIII). Step-like terraces (SY) developed along the valley due to continuous subsidence during Quaternary **(e)**. **(f)** Direction of faults located in southern sector (left) and northern sector (right) of study area.

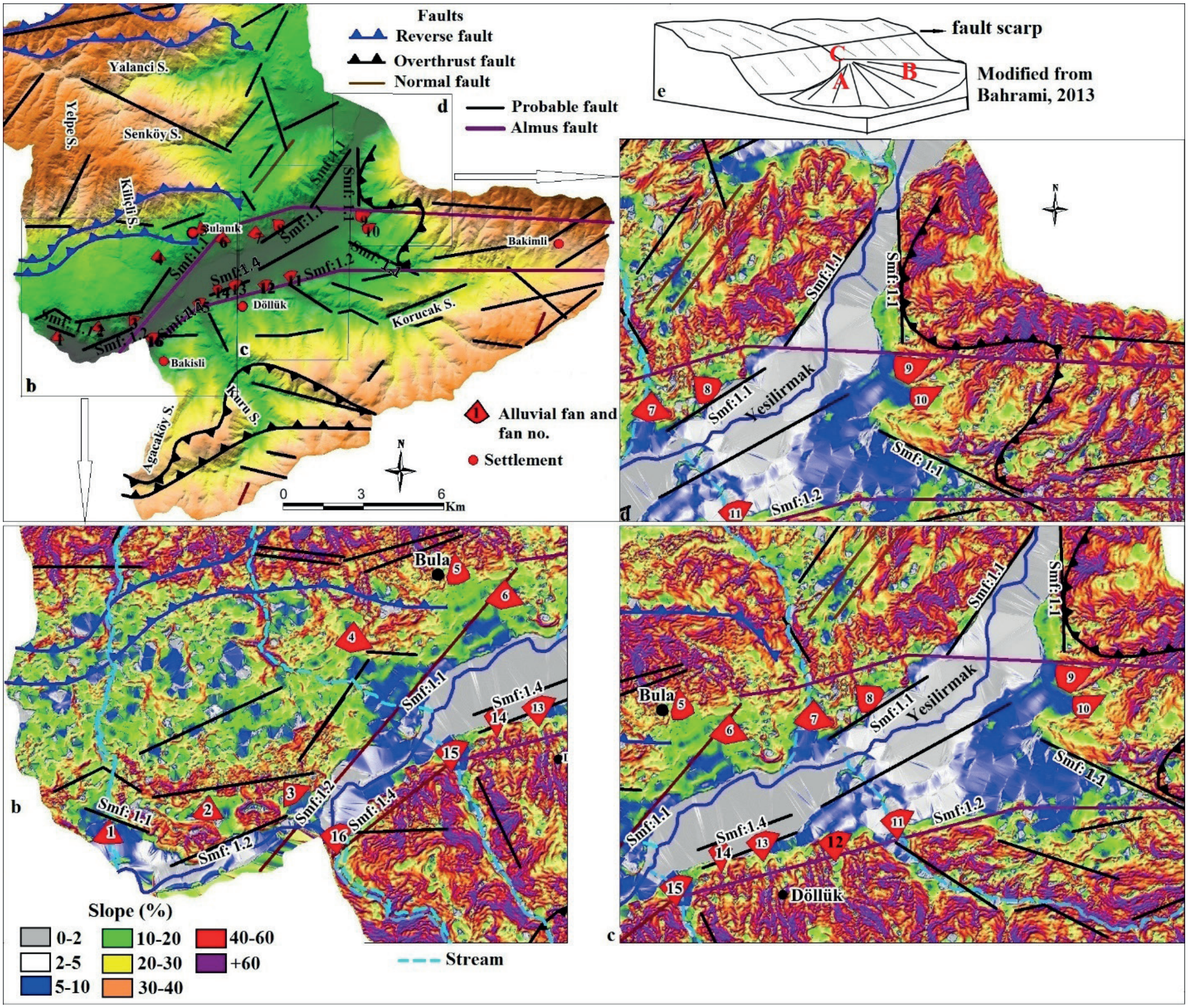

Figure 11: (a). Smf values and location of fans on steep slopes on the west side (b), central side (c), east side (d) and schematic representation of A, B and C in fan entrenchment formula (e).

fault. This trend indicates that the Almus Fault and its segments extending along escarpments throughout the length of the southern and northern Yeşilırmak valley have a high rate of incision, which is related to tectonic uplift.

All fans mapped in the study area are located in front of fault scarps detected during field trips. The values of fan entrenchment (E) are given in Table 2. The size of E varies from 6 to 25 m. The higher values of E are associated with fault scarps with high slope values (30-40 and +40). For example, the highest E (25 m) is associated with fans 1, 3 and 6 occurring in front of a fault scarp with high slope values (Figure 11). The lowest values of E (6, 7, 7.8 and 8 m) belonging to fans 14, 13, 12 and 11, respectively in the southern part of the study area reflect a very low slope inclination (10-20%). Moreover, high values of E are found in fans located in areas with low Smf values, whereas fans 13 and 14 occur in areas with high Smf values (1.3) (Figure 11b, c, d). For this reason, the results indicate a strong positive correlation between slope value and fault scarp and a relatively strong negative correlation between Smf and E. The location of the alluvial fans indicates tectonic activity arising from the Almus Fault and the effect of strong, active tectonics on the geomorphology.

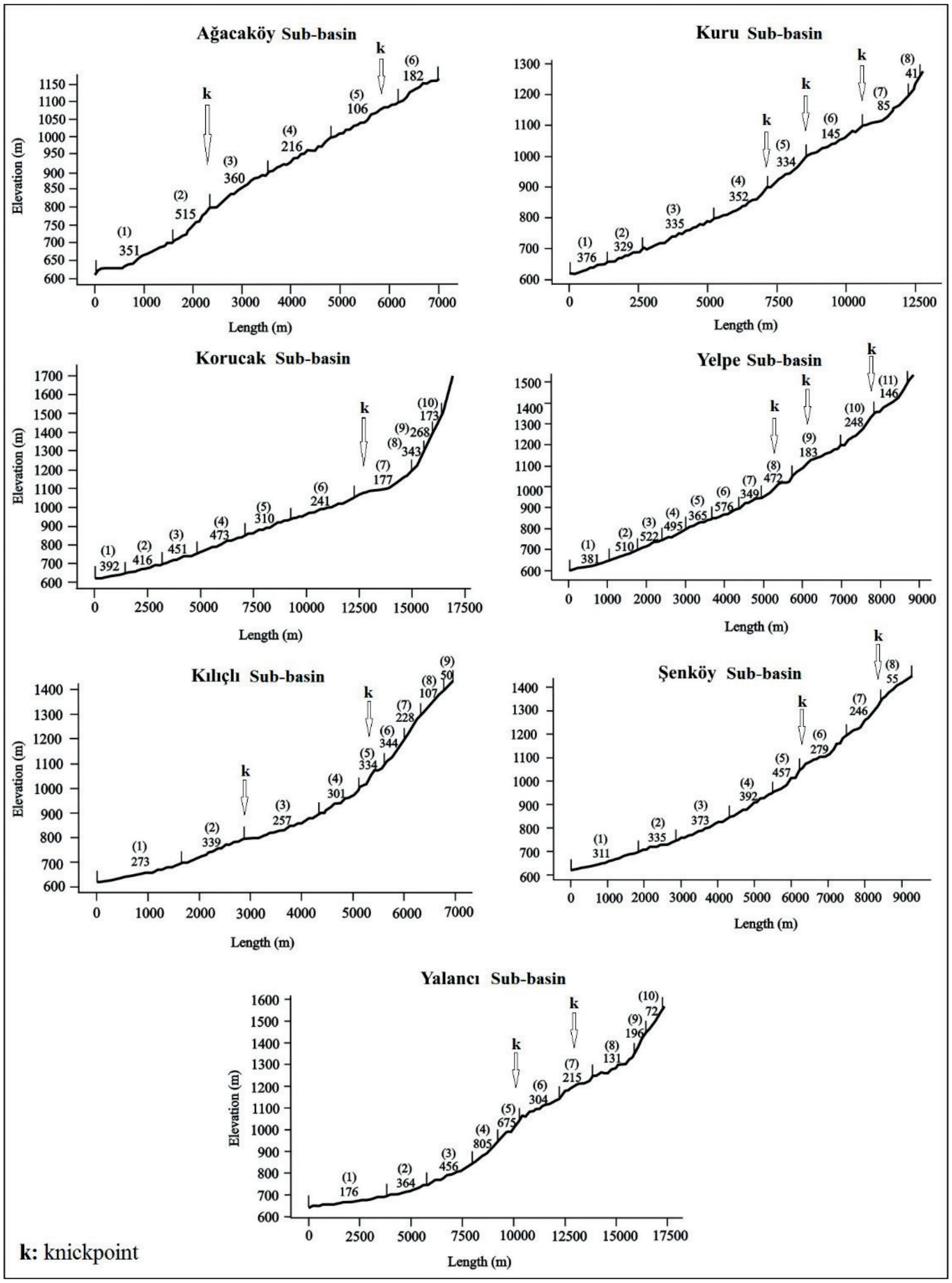

Figure 12: SL values of sub-basins and knickpoints along valley.

3.5. Stream Length Gradient Index (SL) and Valley Floor Width-to-Height Ratio (Vf)

Intervals calculated range between 500 m and 1000 m for each main branch in sub-basins. The SL index values vary between 41 (Kuru sub-basin) and 805 (Yalancı sub-basin). Segments of the SL index are shown on the geological map (see **Figure 2**). Anomalies of the SL index are drawn on the longitudinal profile (**Figure 12, Table 3**).

High SL values occur in the lower and middle reaches of the Yelpe (SL of the 2nd, 3rd and 4th reaches is > 400), in the middle reaches of the Şenköy stream (SL of the 5th profile suddenly increases to 457) and the Yalancı stream (SL of the 3rd, 4th and 5th profiles is > 450), as well as the lower reach of the Ağacaköy stream (SL of the 2nd profile is > 500). The mean SL value of the northern sector is higher than that of the southern sector. In the northern sector, SL values of the Yalancı stream are higher than those of other streams. High SL values indicate faults near

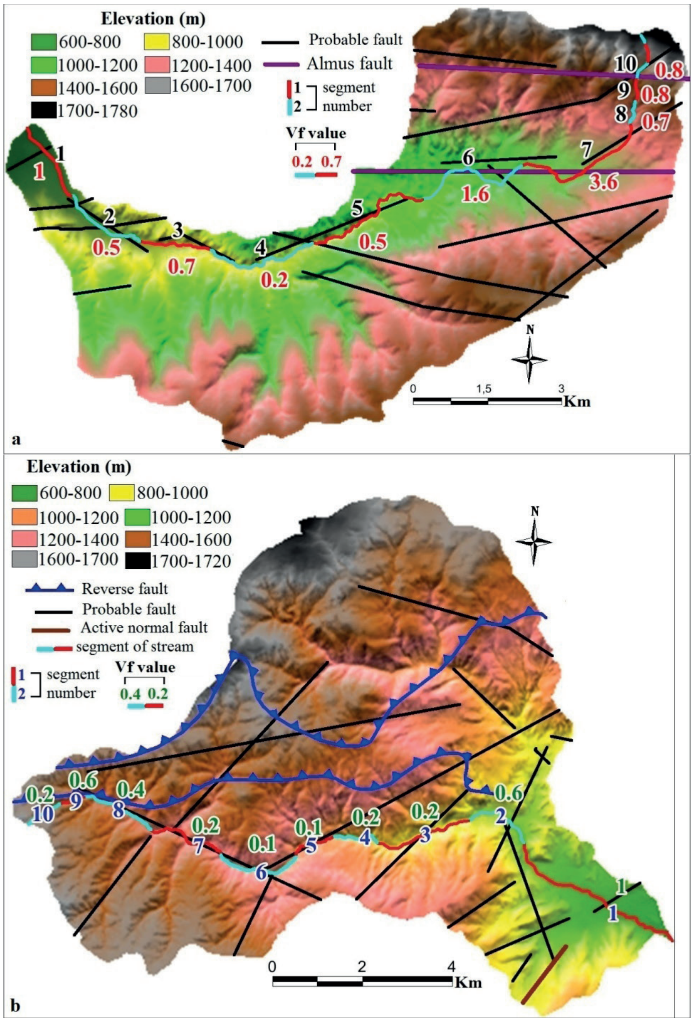

Figure 13: SL and Vf values along (a) Korucak stream valley and (b) Yalancı stream valley.

reaches where the streams change direction, showing that fault formation retains the bend and contraction of the area.

In addition, low values in the upper reaches of the Ağacaköy (SL of 5th reach is 106), Kuru (SL of 7th and 8th reaches is ≤ 85), Kılıçlı (SL of 9th reach is ≤ 50), Korucak (SL of 7th and 10th reaches is ≤ 177), Yelpe (SL of 9th and 11th reaches is ≤ 183), Kılıçlı (SL of 8th and 9th reaches is ≤ 107), Şenköy (SL of 8th reach is 55) and Yalancı streams (SL of 8th, 9th and 10th reaches is ≤ 196) point to the fact that the faults move along a straight line and occur at the lithological contact zone between ophiolite and metamorphic rocks (**Figure 2**). Indeed, much of the geomorphological evidence (e.g. surface features) of the study area is a consequence of past spatial location and ground deformation and currently-active faults within the splay fault system (e.g. Almus Fault) of the North Anatolian Fault Zone as

Table 1: Smf and E values and slope values of hillsides with fans.

Location of fan	Fan no.	Slope (%) of fault scarp	E (m)	Smf	Inferences
Yelpe subbasin	1	40-60	25	1.1	Tectonically active
Yelpe-Kılıçlı	2	20-30	20	1.2	Tectonically active
Near the Kılıçlı subbasin	3	30-40	25	1.2	Tectonically active
Kılıçlı	4	20-30	15		
Kılıçlı	5	40-60	20		
Kılıçlı	6	20-30	25		
Şenköy subbasin	7	10-20	15		
Şenköy subbasin	8	40-60	20	1.1	Tectonically active
Korucak	9	40-60	20	1.1	Tectonically active
Korucak	10	30-40	20	1.3	Slightly active
Kuru subbasin	11	5-10	7.8		
Kuru subbasin	12	10-20	8		
Kuru subbasin	13	5-10	7	1.3	Slightly active
Kuru-Ağacaköy	14	10-20	6	1.2	Tectonically active
Ağacaköy	15	40-60	9	1.2	Tectonically active
Ağacaköy	16	20-30	9	1.2	Tectonically active

well as the juxtaposition of blocks of different rock types due to movement along these faults. Although the down courses (1st and 2nd profiles) of the streams consist of alluvium, the SL values are relatively high (> 300).

The thalweg of the streams indicates deviations in the longitudinal stream profiles from their idealized equilibrium form. Their step-like shape may be indicative of rapid uplift associated with faulting in the area. Knickpoints corresponding to different cycles of erosion are present along the thalweg and they migrate upstream. Knickpoints occurring downstream correspond to a new cycle of erosion as well as convex bending in the middle and upper courses of the streams (**Figure 12**). The dominant lithology is generally metamorphic rocks; hence, the river channel crosses the same lithologies (with the exception of the Korucak stream). Thus, these results suggest that the knickpoints in the valleys, especially downstream, exist due to active tectonism.

Moreover, the main rocks formed during the Paleozoic era share the majority of the drainage area followed by the ophiolite and schist each cover 15.2 % and 52.8% of the total area of the

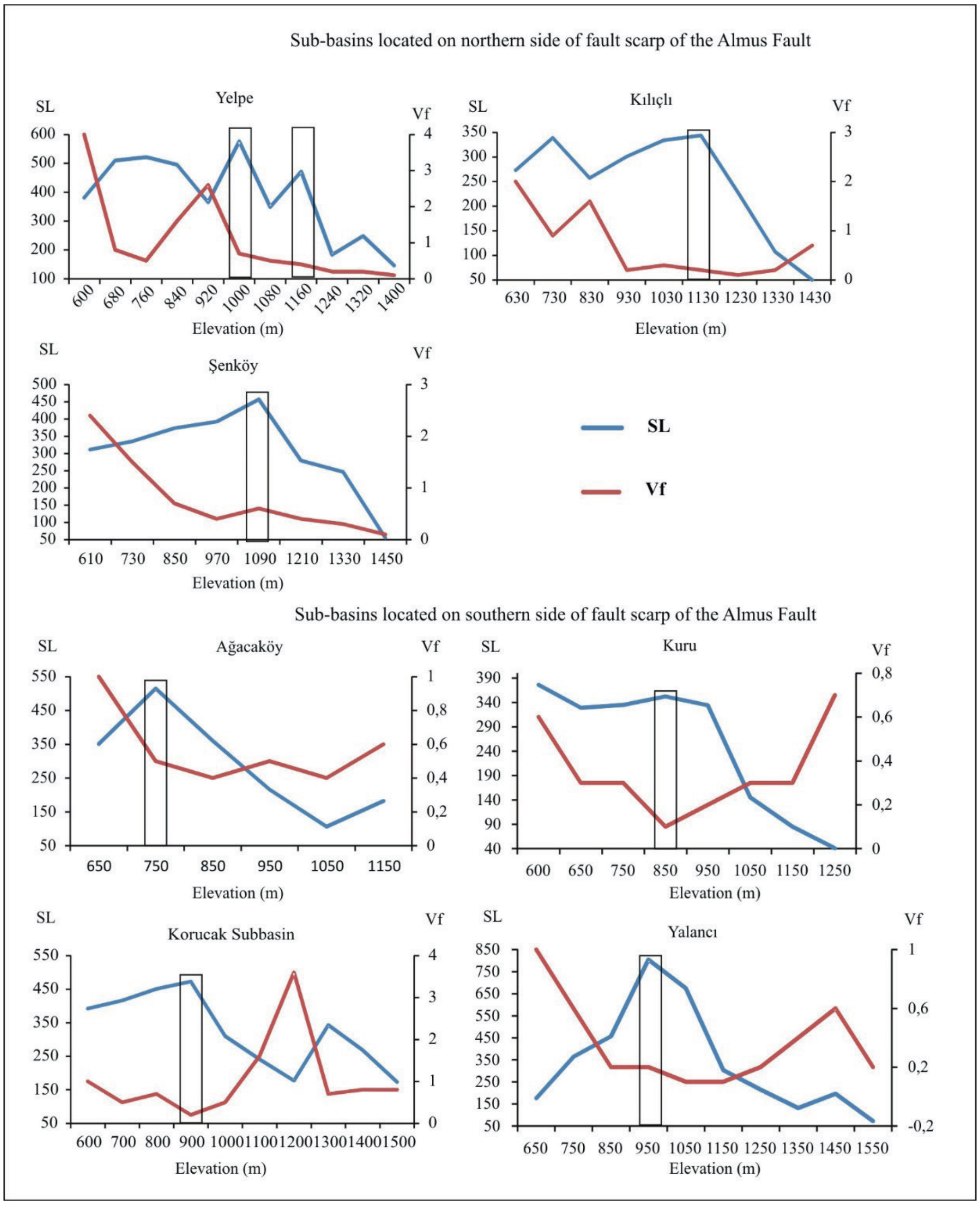

Figure 14: Correlation of SL and Vf values.

sub-basin, respectively (**Table 3**). Rock persistence and fault lines are properly accepted as the major controlling factors of valley developments at the early stages of drainage formation. The existence of many streams over the oldest rock crossing the fault lines and only few of them follow the line of fractures and fault lines in the upper course of the sub-basins such as Ağacaköy, Yelpe, Şenköy and Kuru sub-basins (**Figure 2**). This shows that most streams obtained well developed routes before they were influenced by fault lineaments during their early development. This evidently shows that the SL values are affected by lithological features and both tectonic movement, and drainage formation is older than the start of tectonic activities such as fault scarp, folding in the sub-basins.

In the this study, the mean Vf values range from 1.06 to 0.36 in different sub-basins. Deep and narrow valleys have Vf values lower than < 1 (**Table 2**). These valleys, which can be classified as “V”-shaped valleys, are tectonically active due to local faults. The middle and lower reaches of the streams crossing faults of the Almus Fault system are characterized by deeply incised valleys with steep flanks, straight courses and low Vf values. These streams are actively incising into the bedrock. The 11th,

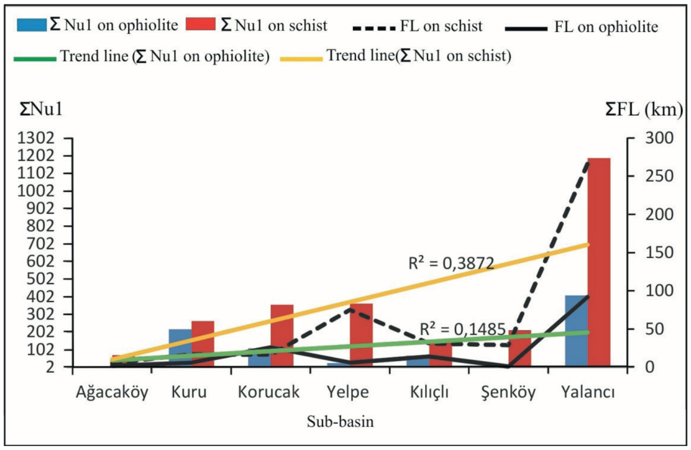

Figure 15: Relationship between lithology, first stream order and fault.

7th and 6th reaches of the Korucak stream have Vf values greater than 1 (Vf: 1.3, 3.6 and 1.6, respectively) (**Figure 13a**) and are subject to major lateral erosion due to the lateral motion of the faults. In the northern sector, the mean Vf values decrease to 0.3 towards the east (Yalancı stream) (**Figure 13b**). This may indicate active uplift in this sector.

Correlation of the SL and Vf indices indicates that a combination of SL and Vf values can provide quantitative information regarding the relative degree of tectonic activity and uplift rate. It is noticed that the northern side of the fault zone clearly displays relatively higher SL and lower Vf values in upper reaches of the valleys; whereas on the southern side these values are observed in lower reaches of the valleys (**Figure 14**). This is evidence that tectonic activity of the Almus Fault is stronger along the lower reaches of the valleys on the southern side. Moreover, on the northern side, the tectonic uplift is higher than the southern side of the Almus Fault Zone and gradually increases towards the east. The mean elevation (1100 m) of the northern side is higher than the southern side (1022 m), due to local faults. 4.6 Relationship between first order total (ΣNu1) and length of fault on main rocks.

As shown in **Table 3**, ΣNu1 ranges from 8 to 1189. Although the surface of the basins where ophiolite rocks are exposed in the Ağacaköy, Kuru, Kılıçlı, Şenköy and Yalancı sub-basins is smaller than the surface where metamorphic rocks are present, the ΣNu1 on metamorphic rocks is higher than ΣNu1 on ophiolite. ΣNu1 values follow an increasing trend in the area where ΣFL values increase (**Figure 15**). Marked differences between the main rocks are associated with faults and their activity. ΣFL values range from 1 km to 266 km. The highest ΣFL values occur on schist. In other words, the length of faults on schist is much longer per unit area than the length of faults on metamorphic rocks. The relationship between ΣNu1 and the main rocks shows that the order number is not influenced by rock type but rather, is an indicator of recent tectonic uplift and tectonic activity. In the uplands, high ΣNu1 is an indicator of rejuvenation in the form of young topography, featuring narrow, deep and rapidly-incised

Table 2: SL and Vf values.

	SUBBASIN						
Profile	Ağaca-köy	Kuru	Korucak	Yelpe	Kılıçlı	Şenköy	Yalancı
No	SL / Vf	SL / Vf	SL / Vf	SL / Vf	SL / Vf	SL / Vf	SL/Vf
1	351 / 1	376 / 0.6	392 / 1	381 / 4	273 / 2	311 / 2.4	176 / 1
2	515 / 0.5	329 / 0.3	416 / 0.5	510 / 0.8	339 /0.9	335 / 1.5	364 / 0.6
3	360 / 0.4	335 / 0.3	451 / 0.7	522 / 0.5	257 / 1.6	373 / 0.7	456 / 0.2
4	216 / 0.5	352 / 0.1	473 / 0.2	495 / 1.6	301 / 0.2	392 / 0.4	805 / 0.2
5	106 / 0.4	334 / 0.2	310 / 0.5	365 / 2.6	334 / 0.3	457 / 0.6	675 / 0.1
6	182 / 0.6	145 / 0.3	241 / 1.6	576 / 0.7	344 / 0.2	279 / 0.4	304 / 0.1
7		85 / 0.3	177 / 3.6	349 / 0.5	228 / 0.1	246 / 0.3	215 / 0.2
8		41 / 0.7	343 / 0.7	472 / 0.4	107 / 0.2	55 / 0.1	131 / 0.4
9			268 / 0.8	183 / 0.2	50 / 0.7		196 / 0.6
10			173 / 0.8	248 / 0.2			72 / 0.2
11				146 / 0.1			
Mean SL	288	249	324	386	248	306	339
Mean Vf	0.57	0.35	1.06	1.05	0.6	0.8	0.3

Table 3: ΣNu1 and ΣFL values of main rocks.

Subbasin	Main rock	Area (km²) of main rock	Nu1	FL total length (km)
Ağacaköy	ophiolite	0.6	8	2.4
	schist	5.8	71	4.7
Kuru	ophiolite	12.7	217	5.9
	schist	19.3	264	17.3
Korucak	ophiolite	8.7	109	26.1
	schist	26.9	357	16.1
Yelpe	ophiolite	1.6	25	6.4
	schist	15	363	75
Kılıçlı	ophiolite	2.7	68	14
	schist	7.7	141	30.8
Şenköy	ophiolite	0.2	4	1.2
	schist	14.7	212	29.4
Yalancı	ophiolite	18.5	410	92
	schist	66.7	1189	266

fluvial valleys with gorges formed by Neotectonic activity of the faults. This activity exhibits itself more in the northern sector than the southern sector. Such differential uplift along the faults with vertical faulting, particularly local faults formed in relation to the Almus Fault.

4. DISCUSSION

Results obtained morphometric analysis for the sub-basins indicate that structural control plays an important role in the development drainage network. Seven sub-basins and eleven morphometric indices were used to detect the tectonic activity of the upper catchment of the Yeşilırmak River.

The high L value and total order number indicates that the tectonic uplift of the Yalancı and Korucak sub-basins was responsible for headward erosion of high relief topography, such as an elevated plateau, and thus enlarged the fluvial basins. Existing rock fractures and lineaments are commonly accepted as the decisive controlling factors for initiating drainage and valley development in the early stages of drainage formation. Many authors suggested that the response of the drainage network due to forcing factors, tectonic uplift may be shown by actually dependent on scale (e.g., Mayer, 1986, Merritts and Vincent, 1989; Hurtrez et al., 1999). This requires considering the hierarchical system of the drainage network by the ordering technique submitted by Strahler (1952). Merritts and Vincent (1989) analyzed that the first and second order streams are more susceptible to uplift in terms of their gradient, length, area, and drainage density. Moreover, the detection of thresholds and the effect of controlling factors can be formed by scaling relationships.

In the southern sector of the Yeşilırmak River, the high Di value to the SW corresponds to a higher relative uplift and steep slopes associated with W-E trending fault segments. The incision rates are higher in the lower and middle parts of the streams. This geomorphology indicates that the effect of vertical block tectonics in the Almus Fault tends to be magnified in these parts of the sub-basin. High dissection analysis indicates that rejuvenation stages caused severe erosion and down cutting activity of faults in the past and it is still sensitive to surface erosion at the present time. The Hi values suggest that these three sub-basins are in a relatively youthful stage of geomorphic evolution compared to the other four sub-basins.

The high asymmetry is associated with recent tectonic activity in the uplifted areas. The Late Miocene and Early Pliocene phases of the uplift of the mountainous area in the upper catchment of the Yeşilırmak were due to vertical uplift (Yıldırım et al., 2011) and thus elevated the area to its current height. Westaway et al. (2003, 2004) suggested that the NAF first became active toward the Upper Miocene, but its modern geometry evolved in Pliocene. The AF index is sensitive to change in catchment inclination perpendicular to the mean channel direction (El Hamdouni et al., 2008). The AF values imply tilting and relative active tilting/uplifting for all basins along NAFZ and the East Anatolian Fault (EAF) representing strike slip fault zone (Selim et al., 2013; Sarp et al., 2013; Khalifa et al., 2018). In the Yeşilırmak Basin, surface uplift beginning in the Upper Miocene to Early Pliocene (Armijo et al., 1999; Hubert-Ferrari et al., 2002; Cengiz et al., 2011) resulted in fluvial incision. Khalifa et al. (2018) obtained findings show that low Vf values in the central valleys indicate a higher uplift and incision ratio than in the southern and northern parts of EAF. Keller and Pinter (2002) suggest that Smf values of 1.0–1.6 are proof of active range-bounding fault zones. Results of the current study indicate weak variations and practically uniform values of Smf along the fault, implying tectonic activity along the whole Almus Fault. Similarly, the peak values of SL index values are found in the areas dislocated by the southern branch of the NAF. The Smf values show that faults belonging to the southern branch of the North Anatolian Fault (NAF) and the south Marmara sub-region (NW Turkey) imply a high rate of incision related to tectonic uplift (Selim et al., 2013). Evolution of the alluvial fans reflecting tectonic activity was mostly controlled by the Almus Fault and its segments in the study area.

When SL values and longitudinal profiles are evaluated together, SL values are seen to increase abruptly in points close to the fault lineaments and fault scarps of the Almus Fault (**Figure 14**). According to Topal (2019), abrupt changes in SL values near the fault show that these values are affected by the movement of the fault rather than lithology. High SL values further suggest that development of the sub-basins was controlled by recent tectonic activity in the study area. A similar result was also found in Softa et al. (2018)'s study. Their results indicated that each river has a knickpoint which marked fault zones determined in the area. The knickpoint is affected by more than one synthetic fault inclined northward. This shows that the zone is tectonically active in the Eastern Pontides. At the same time, high SL values and those having knickpoints show that the drainage basins analyzed are in disequilibrium and the ephemeral feature of the area is due to incomplete uplifting (Softa et al., 2018). In the southern sector, the SL values of the Korucak stream are greater than the other streams. According to Yıldırım (2014), sudden changes SL values on rocks with low strength largely show active tectonic deformation. According to Softa et al. (2018), SL values abruptly increase and decrease regardless of the rigidness of the main rocks due to mountain fronts with very low- and low-hardness rocks.

The highest elevations in the study area are found along the Almus Fault, especially in the Korucak sub-basin, from tectonic activity of the Almus Fault. These results indicate that sub-basins exhibit different characteristics of tectonic activity according to the Almus Fault and its segments. Smf values imply that all segments are young and active along the fault and likely exposed to tectonic uplift. High ΣNu1 shows evidence of rejuvenation in the form of young topography in the upper course in the sub-basins. This indicates that the study area is under compressive stress according to the historical and instrumental focal mechanism that characterizes the seismicity of the area (Karasözen et al., 2014).

Geomorphological evidence of the AFZ along the Yeşilırmak River can be used to define the history of the drainage system and the geomorphic response to tectonic effects. The present study shows that the tectonic process in the upper course of the Yeşilırmak River was probably caused by a combination of the Almus Fault's tectonic deformation and its overlapping fault segments propagating towards each other, which resulted in uplift of the highlands and subsidence of the river bed. Alluvial fans, terraces and incised meanders between the valley margins and slopes indicate that this uplifted surface is most likely related to the splay fault system. The Yeşilırmak River has incised its valley by ~11 m during the last 24 ka (Bayer Altın et al., 2017). In addition to findings by Rockwell et al. (1984), the region was found to be uplifting more than 0.5 mm per year in the Eastern Pontides. Previous studies state that the Eastern Pontides were uplifted at a rate from 0.59 to 1 mm per year in Quaternary (Softa et al., 2017). Yıldırım et al. (2013) suggests that when the morphology of the Central Pontides is considered the Central Pontides uplifts at a rate of 0.23 mm/yr. This rate of uplift is higher than 0.23 for the Eastern Pontides. Both the morphological analyses and rate of uplift suggest that the coastal section of the Eastern Pontides is highly active. (Softa et al., 2018).

Both margins of some basins (e.g., the Kazova and middle-lower course of Yeşilırmak valley) show a well-developed step-like morphology produced and limited by active right-lateral strike-slip and normal fault segments (with a considerable amount of dip-slip) that contain the AFZ and NAFZ (Bozkurt and Koçyiğit, 1996; Erkal, 1993; Keçer and Tüfekçi, 1986). Sarp (2014) suggested that that subsidence and uplift associated with motions along several faults violently influence AF and HI in the pull-apart basin.

Several moderate and large earthquakes have taken place in the Yeşilırmak River drainage basin area (**Figure 4b**) (Şengör et al., 2005; Gürbüz et al., 2015). The three largest earthquakes happening in the last century along the North Anatolian Fault Zone left long signs as surface splits. Thus, geomorphic properties on various scales associated with strike-slip faulting are well conserved in the Yeşilırmak River basin (Gürbüz et al., 2015).

The most important parameters affecting the deposition and entrenchment of alluvial fans are tectonics and climate (Pepin et al., 2010; Salcher et al., 2010). There is a close relationship between climate and sea level changes in the Black Sea region (Tarı and Tüysüz, 2015). Palaeoclimate records indicate that prominent climatic changes have been formed in the Black Sea region since 600 ka (Badertscher et al., 2011). Similar changes may have affected the region along the Neotectonic period about 11 Ma (Şengör, 1979). Undoubtedly, some geomorphological properties are associated with these climatic changes. However, according to Tarı and Tüysüz (2015) the geomorphological differences or anomalies seen in the study area likely derive from lithological differences and tectonics, rather than climate. If there is no important climatic disparities in a region and the lithology remains consistent, in this case, anomalies in stream profiles can be attributed to tectonic processes affecting the area (Tarı and Tüysüz, 2015). Therefore, tectonic processes were more affective on drainage development than climatic changes since traces of glaciation from the Pleistocene do not exist in mountainous areas around the study area.

Changes formed in the level of the Black Sea implicitly affected the study area. The shallow seismic data collected by Demirbağ et al. (1999) point out that the shoreline prior to drowning of the Black Sea shelf was located about at -105 m compared to the actual sea level. This depth is related to the actual border of the shelf, inferring a terrestrial state of the present shelf area prior to the last transgression. Another critical factor that influences vertical changes and their related incision along with aggradation in the drainage basin is a rise or fall in the sea level (Gürbüz et al., 2015). The whole drainage system of the Yeşilırmak River and its channels, network properties and incised valleys of the lower and middle courses, and also the general slope in its basin were changed by the Black Sea level that changed during glacial periods (Hubert-Ferrari et al., 2002). Moreover, both seasonal variations and rapid deposition were implied by the presence of regressional and transgressional vertical and lateral facies, changing between coarse-grained marginal facies and fine-grained central facies in the basin-fill deposits both due to increased tectonic activity (Bozkurt and Koçyiğit, 1996). The existence of numerous parallel and sub-parallel smaller fault segments in the study area, exhibiting a simple horse-tail strike-slip fault pattern, is similar to the Kazova Basin (Bozkurt and Koçyiğit, 1996).

Along with the above findings, calculation of geomorphic indices (e.g. Vf values) provides a quantitative approach to define the effect of tectonic activity on landscape morphology and drainage development. The Vf index shows that all the profiles are signed by V-shaped valley floors, indicative of river incision caused by active tectonic uplift along the Almus Fault and its segments.

Based on Smf values, the uplift rate in the southern sector of the study area is lower than in the northern sector. This difference is related to fault geometry and is caused by fault behavior and dissimilarities between horizontal and vertical fault motions of the Almus Fault due to inversion of movement on the fault. This implies a negative flower structure, which forms a depressed area (Bozkurt and Koçyiğit, 1995, 1996). The basins located along the western sections of the main trace of the North Anatolian Fault Zone (NAFZ) display contrasting tectonic activity characteristics (Sarp et al., 2013). In that study, the Hi values in basin areas vary between 0.17 and 0.49 and Smf values vary between 1.2 and 1.5; whereas Hi and Smf values in the present study area are higher. Judging by the applied indices, the most tectonic sub-basin activity (in ascending order) occurs at Yelpe (lowest) followed by Ağacaköy, Kılıçlı, Kuru, Korucak and Yalancı (highest). It was found that tectonic activity decreases westwards along the Almus Fault.

The inception of the drainage system of the Yeşilırmak River basin and its network has been proposed as occurring in Pliocene (Erkal, 1993; Keçer and Tüfekçi, 1986). Indeed, after the Oligo-Miocene uplift of the Anatolian Peninsula (Şengör, 1979; Erol, 1983; Erol, 1991) as a result of tectonic movements, during Pliocene the region was generally exposed, commencing formation of the Pliocene erosional surface. According to Erol (1991) and Fairbridge et al. (1997), at the onset of Pliocene a new sub-humid-subtropical period started and fluvial landform generation dominated the Anatolian Peninsula. Thus, the outline of the drainage system of the Yeşilırmak basin was based in the Pliocene period. The NW-SE trending tectonic lineaments formed during the Neotectonic period were added to the relatively older NE-SW-trending tectonic lineaments. Selim et al. (2013) pointed out that the geologic slip rates of the active faults have been calculated depending on the length of the tectonic displacements in rivers and streams since Late Pliocene.

At the beginning of Quaternary, uplift of the region was continuous and affected drainage. As a result of the uplift that triggered incision, a series of terraces, incised meanders and alluvial fans then formed along the Yeşilırmak valley, similar to other basins (Bozkurt and Koçyiğit, 1996). The geomorphic development of alluvial fans was controlled by fan catchment, tectonics and climate (Harvey, 2005). The existence of normal faults formed on top of old alluvial fans and fluvial terraces in front of these fans are evidence of movement in the Almus Fault in Quaternary. Alluvial fans merge each other and degrade in places. This causes a fault-parallel alluvial fan apron (Bozkurt and Koçyiğit, 1996). Control by the North Anatolian Fault System (NAFS) of the tectonic development of basins in the eastern sector is evident in Quaternary. Indeed, results of analysis indicated that the alluvial fan and fan catchment morphology in the Erzincan pull-apart basin and Yeşilırmak River Basin, both situated within the eastern section of the NAFZ (**Figure 3b**), are mainly controlled by the continuing tectonic activity of the NAFZ (Hubert-Ferrari et al., 2002; Sarp, 2015). Results of a specific morphotectonic study on the east part of NAFZ indicate that the geologically-constrained mean Neogene slip rate of 6.5 mm/yr (over 13 Myr) was followed by a higher Holocene slip rate of about 20 mm/yr (Hubert-Ferrari et al., 2002).

Interestingly, fans can grow in areas that are tectonically passive. For example, in front of the high Atlas Mountains (Morocco), the morphological progress of alluvial fans is related to sediment derived from large landslides occurring within some of the basin that generate tributary fans (Stokes and Mather, 2015). However, in Zagros region (Iran), the evolution of alluvial fans is related to high-gradient mountain fronts and actively-growing fold structures (Bahrami, 2013).

The upper Yeşilırmak valley in the study area has incised meanders. This indicates the existence of faulting and uplift in the upper course, due to the rise of the North Anatolian Mountains since Late Miocene (Emre et al., 2009). Geomorphic evolution of the Yeşilırmak valley has been directed by normal faults, strike-slip faults and climatic change since the Pliocene.

6. CONCLUSION

The Central Pontides, where the upper course of Yeşilırmak is located, is one of the most seismically active district under the strike-slip faults in Turkey. As a result of the movements of these faults, many E-W trending subsidence basins developed. The study area consists of numerous active faults which show a considerable amount of extension depending on the Almus Fault.

Morphometric indices for the sub-basins in the study area were calculated. Results of morphometric indices and previous studies show that inception of the drainage network of the Yeşilırmak River began during Early Pliocene. Its development continued under the effect of Quaternary tectonism and climate changes and is primarily controlled by the continuing tectonic activity of the Almus Fault. An increase in stream length ratio from lower to higher order is one of the effects of tectonic activity in the study area. The SL, especially the high values in points close to the fault lineaments and fault scarps of the Almus Fault, show that the drainage basins controlled by the Almus Fault are immensely influenced by the fault and experienced actual uplift. Fan entrenchment values show that the vertical block movements induced by the Almus Fault controlled lower and middle channels of the streams during Quaternary. Low values of Smf show that the drainage areas near mountain fronts were controlled by tectonic activity of the Almus Fault; with this activity apparently increasing from west to east along the southern side of the valleys. In addition, results of morphometric indices indicate that the sub-basins located on the southern and northern sides have contrasting tectonic activity characteristics. The tectonic activity and Upper Pliocene-Pleistocene uplift rate of the sub-basins on the northern side are greater than the southern side and increase from west to east on both sides of the valley. These differences play a considerable role in the development of sub-basin drainage and the Yeşilırmak valley. A combination of SL and Vf suggest that the tectonic uplift is higher than the southern side of the Almus Fault Zone and gradually increases towards the east. The AF indices showed the southern sector was generally tilted towards the W-E trending, whereas in the northern sector was tilted towards the WSW-ENE trending. The sub-basins were uplifted and tilted by the Almus Fault and its segments; thus, step-like terraces, alluvial fans and incised meanders have developed along valleys due to rejuvenation of the local base level.

Acknowledgements: This study forms part of the project ****************. We thank the reviewers for their constructive comments that helped us to greatly improve the manuscript.

Peer-review: Externally peer-reviewed.
Conflict of Interest: The authors have no conflict of interest to declare.
Grand Support: The authors declared that this study has received no financial support.

Hakem Değerlendirmesi: Dış bağımsız.
Çıkar Çatışması: Yazarlar çıkar çatışması bildirmemiştir.
Finansal Destek: Yazarlar bu çalışma için finansal destek almadığını beyan etmiştir.

REFERENCES

Armijo, R., Meyer, B., Hubert, A., Barka, A. (1999). Propagation of the North Anatolian fault into the northern Aegean: Timing and kinematics. *Geology, 27*, 267–270.

Azor, A., Keller, E. A, Yeats, R. S. (2002). Geomorphic indicators of active fold growth: South Mountain-Oak Ridge anticline, Ventura basin, southern California. *Geol Soc Am Bull, 114*, 745–753.

Bahrami, S. (2013). Tectonic controls on the morphometry of alluvial fans around Danehkhoshk anticline, Zagros, Iran. *Geomorphology, 180–181*, 217–230.

Barka, A. (1992). The North Anatolian fault zone. *Ann. Tecton. Supp l6*, 164–195.

Bayer Altın, T., Altın, B. N., Öztürk, M. Z. (2017). Climatic and tectonic effects on terrace formation during the Late Quaternary in the upper Yeşilırmak valley, Northern Turkey. *Geogr. Fis. Dinam. Quat, 40*, 123–136.

Bellier, O., Over, S., Poisson, A., Andrieux, J. (1997). Recent temporal change in stress state and modern stress field along the North Anatolian Fault Zone (Turkey). *Geophys. J. Inter*., *131*(6), 1–86.

Bohnhoff, M., Martínez-Garzón, P., Bulut, F., Stierle, E., Ben-Zion, Y. (2016). Maximum earthquake magnitudes along different sections of the North Anatolian fault zone. *Tectonophysics, 674*, 147–165.

Bozkurt, E., Kocyiğit, A. (1995) Almus Fault Zone: its age, total off set and relation to the North Anatolian Fault Zone. *Turkish Journal of Earth Sciences, 4,* 93–104.

Bozkurt, E., Kocyiğit, A. (1996). The Kazova basin: an active negative flower structure on the Almus Fault Zone, a splay fault system of the North Anatolian Fault Zone, Turkey. *Tectonophysics, 265*, 239–254.

Bozkurt, E. (2001). Neotectonics of Turkey – a synthesis. *Geodinamica Acta, 14* (1-3), 3–30.

Bull, W. B, McFadden, L. D. (1977). Tectonic geomorphology north and south of the Garlock Fault, California. In *Geomorphology in Arid Regions.Proceedings at the Eighth Annual Geomorphology Symposium.* [Doehering, D.O. (ed)]. State University of New York, Binghamton, pp. 115–138.

Bull, W. B. (1978). Geomorphic tectonic activity classes of the south front of the San Gabriel Mountains, California: U.S. Geological Survey Contract Report 14- 08-001-G-394, Office of Earthquakes, Volcanoes, and Engineering, Menlo Park Press, California.

Burbank, D. W., Anderson, R. S. (2001). Tectonic Geomorphology. Blackwell Science, Malden Press.

Chen, Y. C, Sung, Q. C, Cheng, K. Y. (2003). Along-strike variations of morphometric features in the western foothills of Taiwan: tectonic implications based on stream gradient and hypsometric analysis. *Geomorphology, 56*, 109–137.

Cox, R. T. (1994). Analysis of drainage-basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: An example from the Mississippi Embayment. *Geological Society of America Bulletin, 106*, 571–581.

Das, P., Let, S., Pal, S. (2013). Use of Asymmetry Indices and Stability Indices for Assessing Channel Dynamics: A Study on Kuya River, Eastern India. *Journal of Engineering, Computers and Applied Sciences, 2*(1), 24–31.

Demirbağ, E., Gökaşan, E., Oktay, F. Y., Simsek, M., Yüce, H. (1999). The last sea level changes in the Black Sea: Evidence from the seismic data. *Marine Geology, 157,* 249–265.

Dewey, J. F., Hempton, M. R., Kidd, W.S.F., Şaroğlu, F., Şengör, A.M.C. (1986). Shortening of continental lithosphere: the neotectonics of eastern Anatolia-A young collision Zone. In *Collision Tectonics*. [Coward, M. P., Ries, A.C. (eds)]. *Geological Society of London, Special Publication, 19*, 3–36.

Dirik, K., and Göncüoğlu, M. C. (1996). Neotectonic characteristics of Central Anatolia Inter. *Geol. Rev*., *38*, 807–817.

El Hamdouni, R., Irigaray, C., Fernandez, T., Chacón, J., Keller, E. A. (2008). Assessment of relative active tectonics, southwest border of Sierra Nevada (southern Spain). *Geomorphology, 96,* 150–173.

Emre, Ö., Tüysüz, O., Yıldırım, C. (2009). Uplift of Pontide orogenic belt since the late Miocene, paper presented at 2nd International Symposium on the Geology of the Black Sea Region, https://www.jmo.org.tr/resimler/ekler/370ed268c7bc0d2_ek.pdf (Accessed on 16 April 2019).

Erkal, T. (1993). Yeşilırmak deltası ve çevresinin jeomorfolojisi. *Jeomorfoloji Dergisi, 20,* 13–28.

Erol, O. (1983). Türkiye'nin genç tektonik ve jeomorfolojik gelişimi. *Jeomorfoloji Dergisi, 11*, 1–22.

Erol, O. (1991). The relationship between the phases of the development of the Konya-Karapinar obruks and the Pleistocene Tuz Gölü and Konya pluvial lakes, Turkey. *Deniz Bilim ve Cogr. Enstitüsü Blt*., *7*, 5–49.

Fairbridge, R., Erol, O., Karaca, M., Yilmaz, Y. (1997). Background to Mid-Holocene climatic change in Anatolia and adjacent regions. In *Third Millennium BC Climate Change and Old World Collapse*. [Dalfes H.N., Kukla, G., Weiss. H. (eds)]. NATO ASI series, 149, pp 595–609.

Gelati, R. (1975). Miocene marine sequence from Lake Van eastern Turkey. *Rivista Italiana di Paleontologia e Stratigraphia, 81*, 477–490.

Gürbüz, A. (2009). Orientations of palaeotectonic features as a key to understanding the neotectonic block rotation of the Kocaeli peninsula, NW Turkey. *International Geology Review, 51*(4), 329–344.

Gürbüz, E., Kazancı, N., Gürbüz, A. (2015). Strike—slip faulting, topographic growth and block movements as deduced from drainage anomalies: the Yeşilırmak River basin, northern Turkey. *Geomorphology, 246*, 634–648.

Hack, J. T. (1973). Stream-profile analysis and stream–gradient index. U.S. Geological Survey *Journal of Research,* 1, 421–429.

Hare, P. W., Gardner, T. W. (1985). Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica. In *Tectonic geomorphology.* [Morisawa M and Hack JT. (eds.)]. Proceedings of the 15th Annual Bighampton Geomorphology Symposium, Allen and Unwin, Boston.

Harkins, N. W, Anastasio, D. J., Pazzaglia, F. J. (2005). Tectonic geomorphology of the Red Rock fault, insights into segmentation and landscape evolution of a developing range front normal fault. *Journal of Structural Geology, 27*, 1925–1939.

Harvey, A. M. (2005). Differential effects of base-level tectonic setting and climatic change on Quaternary alluvial fans in the northern Great Basin, Nevada, USA. *Journal of the Geological Society of London, 251,* 117–131.

Horton, R. E. (1945). Erosional development of streams and their drainage basins; Hydro physical approach to quantitative morphology. *Geological Society of America Bulletin, 56*(3), 275–370.

Hubert-Ferrari, A., King, G., Van Der Woerd, J., Villa, I., Altunel, E., Armijo, R. (2002). Long-term evolution of the north Anatolian fault: new constraints from its eastern termination. *J. Geophys. Res., 107*, 22-35.

Hubert-Ferrari, A., King, G., Van Der Woerd, J., Villa, I., Altunel, E., Armijo, R. (2009). Long term evolution of the North Anatolian Fault: new constraints from its termination. In *Collision and Collapse at the Africa-Arabia-Eurasia Subduction Zone*.[Van Hinsbergen, D. J. J, Edwards, M. A, Govers, R., (eds.)].*The Geological Society of London, Special Publications, 311*, 133–154.

Hurtrez, J. E and Lucazeau, F. (1999). Lithological control on relief and hypsometry in the Herault drainage basin (France), Comptes Rendues Acade mie des Sciences de la terre et des planets. *Earth and Planetary Sciences, 328*(10), 687–694.

Karasözen, E., Özacar, A. A., Biryol, B. C., Beck, L. S. (2014). Seismicity, focal mechanisms and active stress field around the central segment of the North Anatolian Fault in Turkey. *Geophysical Journal International, 196*, 405–421.

Jayappa, K. S., Markose, V. J., Nagoraju, M. (2012). *Identification of geomorphic signatures of neotectonic activity using DEM in the Precambrian terrain of western Ghats, India*. In Proceedings of International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences., 2012.XXII ISPRS Congress, XXXIX-B8, Melbourne.

Khalifa, A., Çakır, Z., Owen, L. A., Kaya, Ş. (2018). Morphotectonic analysis of the East Anatolian Fault, Turkey. *Turkish Journal of Earth Sciences, 27,* 110–126.

Kirby, E., Whipple, K. X. (2001). Quantifying differential rock-uplift rates via stream profile analysis. *Geology, 29,* 415–418.

Keçer, M., & Tüfekçi, K. (1986). Kuzey Anadolu Fayı'na bağlı olarak neotektonik dönemde oluşan Suşehri Havzası'nın evrimi. *Jeomorfoloji Degisi, 14,* 57–63.

Keller, E. (1986). Investigation of active tectonics: use of surficial earth processes. In *Active Tectonics studies in Geophysics*. [Wallace, R. E. (eds)]. Nat. Acad. Press, Washington, D.C.

Keller, E. A., & Pinter, N. (2002). *Active Tectonics. Earthquakes, uplift and landscape*. New Jersey: NJ, Prentice Hall.

Koçyiğit, A. (1989). Suşehri Basin: an active fault-wedge basin on the North Anatolian Fault Zone, Turkey. *Tectonophysics, 167,* 13–29.

Koçyigit, A., & Bozkurt, E. (1991). Dokmetepe (Turhal-Tokat) çöküntüsünün kökeni ve Kuzey Anadolu Fay Zonu ile ilişkisi. Middle East Tech. Univ., AFP-90-03-09-02.

Leeder, M. R. (1993). Tectonic controls upon drainage basin development, river channel migration and alluvial architecture: implications for hydrocarbon reservoir development and characterization. *Special Publications,Geological Society, 73*, 7–22.

Lifton, N. A., and Chase, C. G. (1992). Tectonic, climatic and lithologic influences on landscape fractal dimension and hypsometry: implications for landscape evolution in the San Gabriel Mountains, California. *Geomorphology, 5,* 77–114.

McKenzie, D. P. (1972). Active tectonics of the Mediterranean region. *Geophys. Journal of the Royal Astronomical Society, 30,* 109–185.

McQuarrie, N., Van Hinsbergen, J. J. D. (2013). Retrodeforming the Arabia-Eurasia collision zone: Age of collision versus magnitude of continental subduction. *Geological Society of America, 41*(3), 315–318.

Moges, G., and Bhole, V. (2015). Morphometric Characteristics and the Relation of Stream Orders to Hydraulic Parameters of River Goro: An Ephemeral River in Dire-dawa, Ethiopia. *Universal Journal of geoscience, 3*(1), 13–27.

MTA 2002. 1/500,000 Scaled Geology Map. General Directorate of Mineral Research and Exploration, Ankara.

Mukhopadhyay, S. C. (1984). *The Thisa Basin–A Study in Fluvial Geomorphology*, K.P. Banchiand Co., Calcutta.

Nir, D. (1957). The Ratio of Relative and Absolute Altitude of Mt. Carmel. *Geographical Review, 27*, 564–569.

Okay, I. A. (2008). Geology of Turkey: A Synopsis. *Anschnitt, 21,* 19–42.

Pepin, E., Carretier, S., Herail, G. (2010). Erosion dynamics modelling in a coupled catchment–fan system with constant external forcing. *Geomorphology, 122,* 78–90.

Ritter, D. F., Kochel, R. C., Miller, I. R. (2002). *Process Geomorphology*. McGraw Hill, Boston.

Salcher, B. S., Faber, R., Wagreich, M. (2010). Climate as main factor controlling the sequence development of two Pleistocene alluvial fans in the Vienna Basin (eastern Austria)—a numerical modelling approach. *Geomorphology, 115,* 215–227.

Sarp, G., Toprak, V., Düzgün, S. (2013). Activity Level of Tectonic Basins, Western Section of the North Anatolian Fault Zone, Turkey. *International Geology Review, 55*(3), 350–366.

Sarp, G. (2014).Tectonic controls of the North Anatolian Fault System (NAFS) on the geomorphic evolution of the alluvial fans and fan catchments in Erzincan pull-apart basin; Turkey.*Journal of Asian Earth Sciences, 98*, 116–125.

Sarp, G. (2015).Tectonic controls of the North Anatolian Fault System (NAFS) on the geomorphic evolution of the alluvial fans and fan catchments in Erzincan pull-apart basin; Turkey. *Journal of Asian Earth Sciences, 98*, 116–125.

Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geol Soc America Bull, 67*, 597–646.

Selim, H. H., Tüysüz, O., Karakaş, A., Taş, K. Ö. (2013). Morphotectonic evidence from the southern branch of the North Anatolian Fault (NAF) and basins of the south Marmara sub-region, NW Turkey. *Quaternary International, 292,* 176–192.

Siddiqui, S. (2014). Appraisal of active deformation using DEM-based morphometric indices analysis in Emilia-Romagna Apennines, Northern Italy. *Geodynamics Research International Bulletin, 3*(1), 34–62.

Silva, P. G., Goy, J. L., Zazo, C., & Bardaji, T. (2003). Fault generated mountain fronts in Southeast Spain: geomorphologic assessment of tectonic and earthquake activity. *Geomorphology, 50*(1-3), 203–226.

Singh, S., & Singh, M. C. (1997). Morphometric Analysis of Kanhar River Basin. National Geographical. *J. of India., 43*(1), 31–43.

Softa, M., Spencer J. Q. G., Emre, T., Sözbilir, H., Turan, M. (2017). Late Quaternary rapid uplift deduced from marine terraces in Eastern Pontides, Turkey. *Geological Society of America Abstracts with Programs, 49*(6). doi:10.1130/abs/2017AM-305129.

Softa, M., Emre, T., Sözbilir, H., Spencer, J. Q. G., Turan, M. (2018). Geomorphic evidence for active tectonic deformation in the coastal part of Eastern Black Sea, Eastern Pontides, Turkey. *Geodinamica Acta, 30*(1), 249–264.

Softa, M., Emre, T., Sözbilir, H., Spencer, J. Q. G., Turan, M. (2019). Field Evidence for Southeast Black Sea Fault of Quaternary Age and Its Tectonic Implications, Eastern Pontides, Turkey. *Geological Bulletin of Turkey, 62,* 17–40.

Stokes, M., Mather, A. E. (2015). Controls on modern tributary-junction alluvial fan occurrence and morphology: High Atlas Mountains, Morocco. *Geomorphology, 248,* 344–362.

Strahler, A. N. (1952). Hypsometric (area-altitude) analysis of erosional topography. *Geological Soc. Am. Bull., 63,* 1117–1141.

Strahler, A. N. (1964). Quantitative geomorphology of drainage basins and channel networks. In *Handbook of Applied Hydrology*. [Chow, VT. (ed.)]. Section 4II. McGraw Hill Book Company, New York, 4-39/4-76.

Sümengen, M. (2013). 1/100,000 ölçekli Türkiye jeoloji haritaları serisi, Tokat-H37 paftası, No: 188. Maden Tetkik Arama Genel Müdürlüğü, Ankara, Turkey.

Şengör, A. M. C. (1979). The North Anatolian Transform Fault, Its age offset and tectonic significance. *J. Geol. Soc., 136*, 269–282.

Şengör, A. M. C. Görür, N., Şaroğlu, F. (1985). Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In *Strike-Slip Faulting and Basin Formation.* [Biddle, K. T., Christie-Blick, N. (eds.)]. *Spec. Publ. Soc. Econ. Paleontol. Mineral, 37*, 227–267.

Şengör, A. M. C., Tüysüz, O., İmren, C., Sakınç, M., Eyidoğan, H., Görür, N., Le Pichon, X., Rangin, C. (2005). The North Anatolian Fault: A new look. *Annual Review of Earth and Planetary Science, 33,* 1–75.

Tarı, U., and Tüysüz, O. (2015). The effects of the North Anatolian Fault on the geomorphology in the Eastern Marmara Region, Northwestern Turkey. *Geodinamica Acta*, doi: 10.1080/09853111.2015.1065308.

Topal, Ş. (2019). Evolution of relative tectonic activity along the Priene-Sazlı Fault (Söke Basin, Southwest Anatolia): Insight from geomorphic indices and drainage analysis. *J.Mt.Sci., 16*(4), 909–923.

Tüysüz, O., and Erturaç K. M. (2005). Kuzey Anadolu Fayı'nın Devrez Çayı ile Soruk Çayı arasındaki kesiminin özellikleri ve fayın morfolojik gelişimdeki etkileri. In İTÜ Avrasya Yer Bilimleri Enstitüsü, Türkiye Kuvaterner Sempozyumu, TURQUA-V, İstanbul.

Viseras, C., and Fernandez, J. (1994). Channel migration patterns and related sequences in some alluvial fan systems. *Sedimentary Geology, 88*, 201–217.

Wells, S. G., Bullard, T. F., Menges, T. M., Drake, P. G., Karas, P. A., Kelson, K. I., Ritte, J. B., Wesling, J. R. (1988). Regional variations in tectonic geomorphology along segmented convergent plate boundary, Pacific coast of Costa Rica. *Geomorphology, 1,* 239–265.

Westaway, R., Pringle, M. S., Yurtmen, S., Demir, T., Bridgland, D., Rowbotham, G., Maddy, D. (2003). Pliocene and Quaternary surface uplift of western Turkey: revealed by long-term river terrace sequences. *Current Science, 84*, 1090–1101.

Westaway, R., Pringle, M. S., & Yurtmen, S. (2004). Pliocene and Quaternary surface uplift of western Turkey: the Gediz River terrace staircase and the volcanism at Kula. *Tectonophysics, 391,* 121–169.

Wobus, C., Whipple, K. X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B., & Sheehan, D. (2006). Tectonics from topography: Procedures, promise, pitfalls. In *Tectonics, climate and landscape evolution*. [Willett, S., Hovius, N., Brandon, M., Fisher, D. (eds.)]. *Geological Society of America, AGU. Special Paper, 398*, 55–74.

Yıldırım, C., Schildgen, T. F., Echtler, H., Melnick, D., Strecker, M. R. (2011). Late Neogene and active orogenic uplift in the Central Pontides associated with the North Anatolian Fault: implications for the northern margin of the Central Anatolian Plateau, Turkey. *Tectonics, 30*(5), TC5005, doi: 1029/2010TC002756.

Yıldırım, C., Melnick, D., Ballato, P., Schildgen, T. F., Echtler, H., Erginal, A. E, Kıyak, N. G., Strecker, M. R. (2013). Differential uplift along the northern margin of the Central Anatolian Plateau: Inferences from marine terraces. *Quaternary. Science Review, 81,* 12–28.

Yıldırım, C. (2014). Relative tectonic activity assessment of the Tuz Gölü fault zone; Central Anatolia, Turkey. *Tectonophysics, 630*, 183–192.

Yılmaz, A., and Yılmaz, H. (2004). Geology and structural evolution of the Tokat massif (Eastern Pontides, Turkey). *Turkish J. Earth Sci., 13*, 231–246.