Türkiye Jeoloji Bülteni
Geological Bulletin of Turkey
69 (2026) 303-322
doi:10.25288/tjb.1956532

Morphotectonic Segmentation and Uplift History of the Yalakdere Fault (NW Türkiye): Results from χ Analysis and River Profile Inversion

Yalakdere Fayının (KB Türkiye) Morfotektonik Segmentasyonu ve Yükselme Geçmişi: χ Analizi ve Akarsu Profili Ters Çözümleme Sonuçları

Seray Çınar Yıldız[1*], Süha Özden[2], Savaş Topal[3]

[1] *Çanakkale Onsekiz Mart University, School of Graduate Studies, Department of Geological Engineering, Çanakkale, Türkiye*
[2] *Çanakkale Onsekiz Mart Üniversitesi, Mühendislik Fakültesi Jeoloji Mühendisliği Bölümü, Terzioğlu Kampüsü, Çanakkale/Merkez, Türkiye*
[3] *Pamukkale Üniversitesi, Mühendislik Fakültesi B Blok, Jeoloji Mühendisliği Bölümü, 20160 Kınıklı Kampüsü, Pamukkale/Denizli, Türkiye*

• Geliş/Received: 22.05.2026 • Düzeltilmiş Metin Geliş/Revised Manuscript Received: 30.07.2026 • Kabul/Accepted: 03.08.2026
• Çevrimiçi Yayın/Available online: 24.08.2026 • Baskı/Printed: 31.08.2026

Araştırma Makalesi/Research Article *Türkiye Jeol. Bül. / Geol. Bull. Turkey*

Abstract: Northwestern Anatolia contains many active fault segments with different strikes, tectonic regimes and slip rates. In this study, the tectonic control on topography along the Yalakdere Fault, a right-lateral strike-slip fault located south of the Gulf of İzmit, is investigated using a multi-scale morphometric approach. Mountain front morphology (Smf, Vf), basin-scale indices (AF, Bs, HI, HC), channel steepness (ksn), and drainage divide stability (χ) analyses are integrated with river profile inversion modeling to constrain the spatial and temporal variability of uplift. Results reveal significant morphotectonic contrasts between the southwestern and northeastern segments of the fault. River profile inversion results show that uplift rates have varied throughout the Pleistocene, with peak uplift occurring during the Early Pleistocene. These findings demonstrate that the morphotectonic evolution of the Yalakdere Fault is controlled by fault segmentation, lithological variability and differential uplift. The results further indicate that tectonic forcing, rather than climatic variability, represents the dominant control on landscape evolution.

Keywords: Morphotectonic, NW Anatolia, segmentation, uplift, Yalakdere Fault.

Öz: *Kuzeybatı Anadolu, farklı doğrultulara, tektonik rejimlere ve kayma hızlarına sahip aktif fay segmentlerinden oluşmaktadır. Bu* çalışmada, *İzmit Körfezi'nin güneyinde yer alan sağ yanal doğrultu atımlı bir fay olan Yalakdere Fayının tektoniğin topoğrafya* üzerindeki *etkisi ve* çok ölçekli *morfometrik bir yaklaşım kullanılarak araştırılmıştır. Dağ* önü *morfolojisi indisleri (Smf, Vf), havza* ölçekli *indisler (AF, Bs, HI, HC), kanal diklik indisi (ksn) ve drenaj bölümü stabilitesi* (χ) *analizleri, yükselmenin mekânsal ve zamansal değişkenliğini sınırlandırarak, akarsu boyu profil ters* çözüm *modellemeleriyle birlikte değerlendirilmiştir. Elde edilen sonuçlar, fayın güneybatı ve kuzeydoğu segmentleri arasında belirgin morfotektonik farklılıkların bulunduğunu ortaya koymaktadır. Akarsu boyu profil ters* çözüm *sonuçları, yükselme oranlarının Kuvaterner boyunca zamansal değişimler gösterdiğini ve maksimum yükselmenin Erken Pleyistosen döneminde gerçekleştiğini göstermektedir. Bulgular, Yalakdere Fayı'nın morfotektonik evriminin fay segmentasyonu, litolojik değişkenlik ve diferansiyel yükselme tarafından kontrol edildiğini ortaya koymaktadır. Sonuçlar ayrıca, bölgenin evriminde baskın kontrolün iklim değişkenliğinden ziyade tektonik kuvvetlerden kaynaklandığını göstermektedir.*

Anahtar Kelimeler: *KB Anadolu, morfotektonik, segmentasyon, Yalakdere Fayı,* yükselme.

[*] Correspondence / *Yazışma*: seraycinar@gmail.com

http://tjb.jmo.org.tr
http://dergipark.gov.tr/tjb

INTRODUCTION

NW Anatolia is one of the most tectonically dynamic regions in the world, mainly characterized by active strike-slip fault systems developed under a compressional regime. Strike-slip faults are not limited to horizontal displacements; they commonly involve vertical components and complex deformation patterns that play a significant role in shaping topographic evolution. However, the long-term geomorphic impacts of such faults, particularly their uplift history at the segment scale and their influence on drainage systems, remain insufficiently constrained. The Yalakdere Fault is an active right-lateral strike slip fault (Emre et al., 2018) located south of the Gulf of İzmit, extending along a morphologically prominent mountain front (Figure 1). Although the regional topography exhibits clear morphotectonic indicators such as linear mountain fronts, asymmetric valleys, and well-organized drainage networks, the temporal evolution of these features and their relationship with fault kinematics have not been systematically investigated. In particular, the impact of localized uplift and subsidence along strike-slip faults on drainage systems requires quantitative morphometric approaches beyond classical fault geometry interpretations.

In recent years, morphometric indices (e.g., Smf, Vf, AF, Bs, HI, HC), channel-scale analyses (e.g., ksn, χ), and river profile inversion models have emerged as powerful tools for disentangling tectonic signals from topography. Nevertheless, the integrated application of these methods within a multi-scale framework remains limited, especially in the context of resolving the spatial and temporal variability of uplift rates along strike-slip fault zones. This study aims to investigate the tectonic control on topography along the Yalakdere Fault using a multi-scale approach. In this context, mountain front morphology is characterized using Smf and Vf indices; basin-scale deformation is evaluated using AF, Bs, HI, and hypsometric curve (HC) analyses; and channel-scale processes are analyzed using the normalized steepness index (ksn) and drainage divide stability parameter (χ).

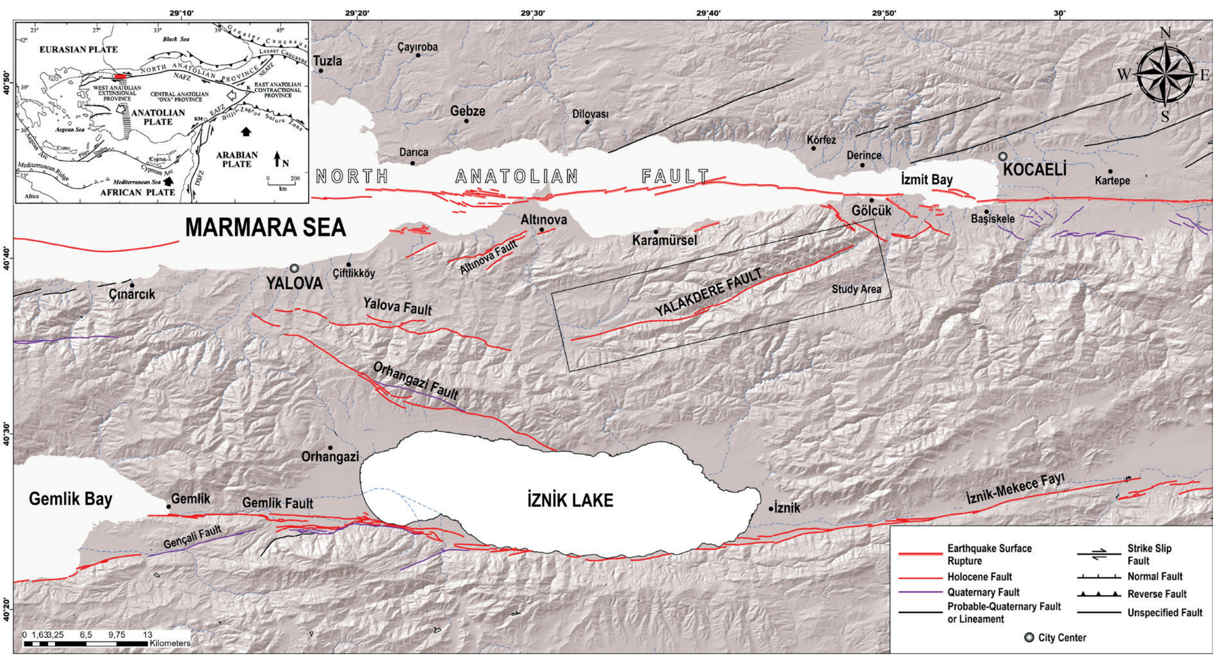


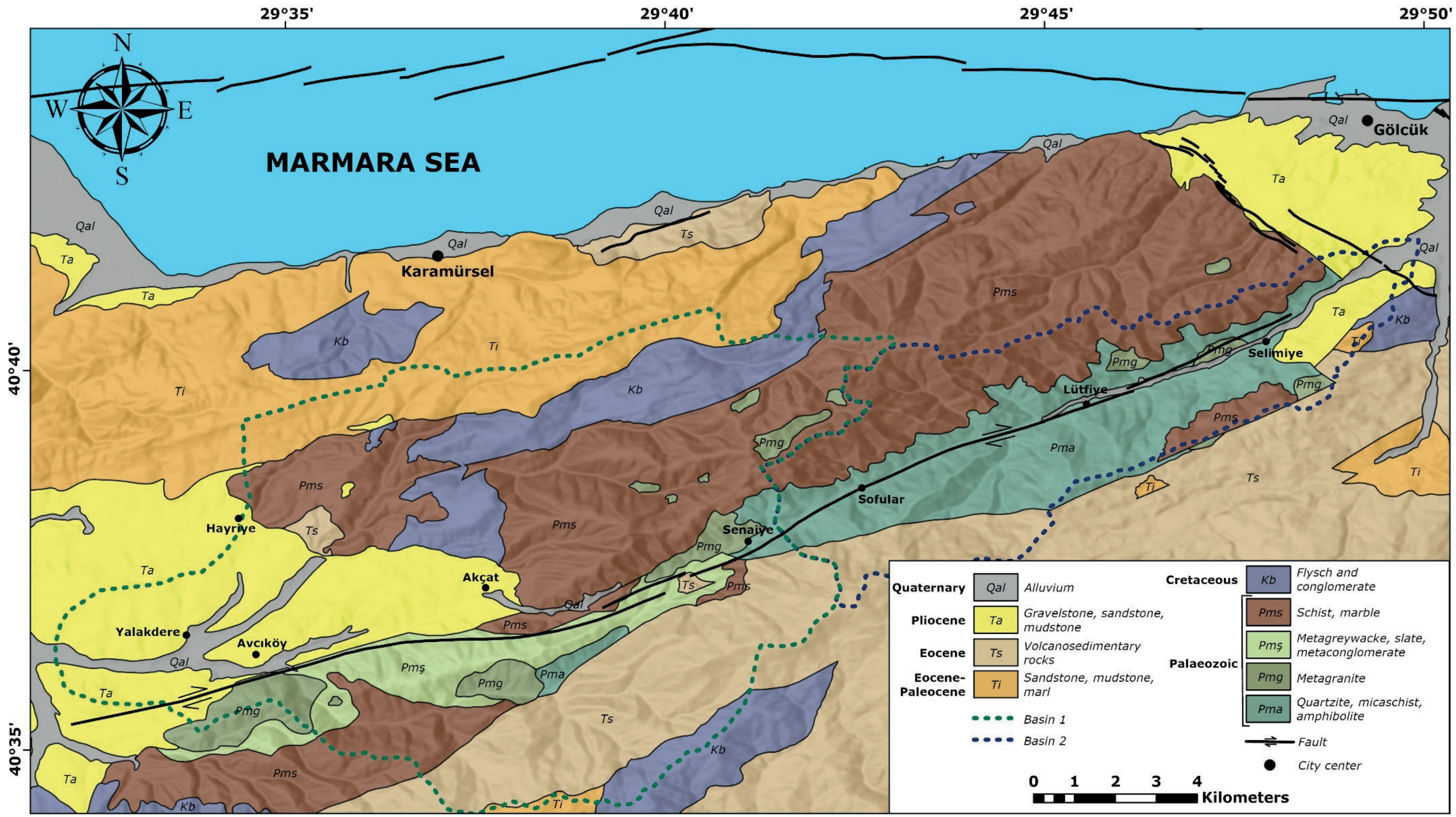
Figure 1. Location map of the study area.

Şekil 1. *Çalışma sahasının yer bulduru haritası.*

In addition, a river profile inversion model is applied to longitudinal stream profiles to quantitatively constrain the spatial and temporal variations in uplift rates along the fault. The primary objective of this study is to reveal not only the surface morphology of the Yalakdere Fault but also its long-term tectonic evolution and segmentation behavior. The results are expected to contribute to ongoing discussions about the geomorphic response and seismic potential of strike-slip faults in NW Anatolia.

REGIONAL GEOLOGICAL SETTING

The study area is located in the eastern part of the Armutlu Peninsula and the southern part of the Kocaeli Peninsula in northwestern Anatolia. According to Yiğitbaş et al. (2004), the eastern Marmara region is composed of several major morphotectonic domains, including the Thrace–Kocaeli Peneplain, the Armutlu–Almacık Highland, the Çamdağ–Akçakoca Highland, and the Marmara Basin, all of which are structurally related to the evolution of the North Anatolian Fault Zone. The Western Pontides represent a tectonic mosaic formed by the progressive accretion of continental and oceanic fragments during the Paleozoic and Mesozoic periods (Yiğitbaş et al., 1999). Rock assemblages belonging to the İstanbul and Sakarya zones were brought into contact along the Intra-Pontide suture, which developed as a result of the closure of the Intra-Pontide Ocean during Early Eocene-Oligocene time. The North Anatolian Fault currently follows the trace of this suture zone (Şengör and Yılmaz, 1981; Okay and Görür, 1995). The neotectonic evolution of the eastern Marmara region began during the Late Miocene–Early Pliocene with the initiation of the North Anatolian Fault Zone, which subsequently evolved into a broad fault system composed of several active strands in northwestern Anatolia (Yiğitbaş et al., 2004). The Armutlu-Ovacık Zone is defined as a mixing zone between these two tectonic units, bounded by the İstanbul Zone to the north and the Sakarya Zone to the south (Elmas and Yiğitbaş, 2005). The Armutlu-Ovacık Zone comprises a metamorphic sequence ranging from Lower Paleozoic to Upper Cretaceous in age, an Upper Cretaceous ophiolitic melange, and relics of Neo-Tethyan ophiolites (Yılmaz et al., 1995). These units are unconformably overlain by an Upper Cretaceous sedimentary succession initiated by marine transgression, within which four mega sequences developed between the Late Cretaceous and Eocene (Özcan et al., 2012). The first mega sequence consists of Turonian-Late Campanian volcanic and volcanoclastic rocks interbedded with turbidites and calciturbidites, representing arc-related and forearc basin deposits. The overlying unit is composed of pelagic limestones and marls deposited from the Late Campanian to Late Paleocene. The third sequence corresponds to a thick Early Eocene flysch wedge deposited unconformably, whereas the fourth sequence comprises a thick volcanic and volcaniclastic succession spanning from the Early to Middle Eocene (Özcan et al., 2012; Yiğitbaş et al., 1999). These basement units are unconformably covered by Miocene and younger sedimentary deposits (Figure 2). The spatial distribution of these sediments indicates that Neogene units are predominantly preserved on elevated topography, whereas Quaternary deposits are concentrated within depression zones developed along the North Anatolian Fault (Emre et al., 1998). The Neogene succession is characterized by Late Miocene-Pliocene fluvial and alluvial fan-delta deposits, consisting of alternating conglomerate, sandstone, siltstone, mudstone, and claystone (Gökten, et al., 2001). These deposits are overlain by Late Pleistocene fluvial terraces above an angular unconformity. The overlying sequence, which records a transgressive–regressive series, is composed of loosely consolidated, fossil-rich sands, clayey silts, and marls (Bargu and Sakınç, 1989). Quaternary sediments accumulated under the influence of the evolving North Anatolian Fault system, with Late Pliocene–Pleistocene basin fills and alluvial fan deposits recording continued tectonic activity in the region (Yiğitbaş et al., 2004). The youngest deposits in the region are Quaternary alluvium, composed of unconsolidated block-, gravel-, and sand-sized materials deposited along river valleys and coastal zones (Figure 2).



igure 2. Geological map of the study area and surroundings (Modified from Göncüoğlu et al., 1986; Bargu and Sakınç, 1989).

Şekil 2. Çalışma alanı ve çevresinin jeoloji haritası (Göncüoğlu vd., 1986; Bargu ve Sakınç, 1989'dan değiştirilmiştir).

Geology Along the Yalakdere Fault Zone

The Yalakdere Fault extends from south of Gölcük to Yalakdere village and is approximately 25 km long, with NE-SW strike and forms a segmented structure along the valley. Along the fault trace, basement rocks belonging to the Armutlu–Ovacık Zone are exposed, including Paleozoic units of the İznik Metamorphics and Pamukova Metamorphics (Figure 2). The Pamukova Metamorphics represent high-grade metamorphic rocks in the study area, consisting predominantly of amphibolites and metagranites, along with metaclastic units containing quartzite and granitic clasts. The lower levels comprise quartzite, mica schist, amphibolite, and volcanogenic amphibolite (Pma). Upsection, metagranites, altered granites, and aplite dykes (Pmg) become dominant. The uppermost part of the sequence consists of metaclastic rocks, including metagreywacke, slate, and metaconglomerate (Pmş), which unconformably overlie the underlying units (Göncüoğlu et al., 1986). The İznik Metamorphics (Pms) include multiple lithological levels. The lower parts are represented by a low-grade metamorphosed volcaniclastic flysch sequence, whereas the upper levels consist of an olistostromal unit containing blocks, lenses, and wedges of ophiolite and marble embedded within sedimentary and volcanic rocks (Göncüoğlu et al., 1986). These units are overlain by a Lower Upper Cretaceous deep-marine volcanosedimentary assemblage, followed conformably by an Upper Late Cretaceous regressive sandstone sequence containing plant fragments, coal debris, and blocks derived from underlying units (Yiğitbaş et al., 1999). The Maastrichtian succession (Kb) begins with flysch and conglomerate and consists of sandstone, shale, mudstone, and limestone, incorporating both autochthonous and allochthonous blocks within a heterogeneous matrix (Göncüoğlu et al., 1986). In the northwestern part of the study area, an unconformable unit (Ti) composed of alternating sandstone, mudstone, and marl is observed. This Paleocene–Eocene flysch sequence begins with a basal conglomerate and includes volcanic intercalations toward the upper levels (Göncüoğlu et al., 1986). It gradationally transitions into the Eocene volcanosedimentary succession (Ts), which crops out extensively in the southwestern part of the study area and more locally south of Ereğli. This unit starts with marl at the base and continues upward with alternating sandstone, siltstone, and marl, including limestone levels and three distinct tuff horizons (Bargu and Sakınç, 1989). Another widespread unit (Ta), exposed south of Gölcük and around Yalakdere, Avcıköy, and Hayriye villages, consists mainly of weakly-cemented clastic rocks with local cross-bedding. This Miocene–Pliocene unit comprises gravelly sand and medium-grained sand at the base, transitioning upward into sand, silt, and locally sandy limestone (Bargu and Sakınç, 1989). Finally, Holocene alluvial deposits (Qal), consisting of block-, gravel-, and sand-sized materials transported by rivers, are widely distributed along valley floors (Bargu and Sakınç, 1984).

Tectonic Framework of the Study Area

The study area is located in the northwestern part of Türkiye, within the Eastern Marmara region. The North Anatolian Fault (NAF), which constitutes the present-day tectonic framework of the region, is a right-lateral strike-slip transform fault system that separates the Eurasian and Anatolian plates (Ketin, 1957; Şengör, 1979). The NAF extends approximately 1500 km in an east–west direction from Karlıova to the North Aegean Sea. The fault zone is commonly subdivided into three main segments, known as eastern, central, and western NAF. While the eastern and central segments are characterized by a narrow deformation zone, the western NAF exhibits a broader deformation zone (Emre et al., 2018). In the Eastern Marmara region, the NAF bifurcates into northern and southern branches. The southern branch, which diverges in a right-stepping manner between Bandırma and the Dokurcun Valley, consists of three major fault segments: Geyve, İznik and Gemlik extending from east to west (Özalp et al., 2013). The northern branch of the NAF enters the Gulf of İzmit from Bolu and continues westward toward the North Aegean Trough in a segmented structure. The study area is located between these two major branches, south of the Gulf of İzmit. Small-scale fault segments surrounding the main strands of the North Anatolian Fault are interpreted as secondary structures developed under a right-lateral shear regime, commonly exhibiting low-angle oblique components (Alpar and Yaltırak, 2002). The Yalakdere Fault is situated between the northern branch of the NAF extending through the Gulf of İzmit and the southern branch extending westward south of Lake İznik. It initiates on the northern valley slopes east of Selimiye village (Gölcük) and continues in a N70°E orientation toward Lütfiye village. Approximately 1 km east of the village, it steps southward and continues along the southern valley slope, maintaining a similar trend. Between Senaiye and Akçat villages, the fault exhibits a segmented and discontinuous geometry. The western segment of the Yalakdere Fault steps southward east of Akçat and continues with a northward bend toward Yalakdere (Figure 1). According to the Active Fault Map of MTA (2018), it is mapped as a right-lateral strike-slip fault with an approximate length of 25 km.

METHODS

In this study, a multi-scale morphometric analysis approach was applied to investigate the tectonic control on topography along the Yalakdere Fault. The analyses were conducted at three principal scales: (i) mountain front morphology, (ii) basin-scale morphometry, and (iii) channel network and river profile analyses. This multi-layered framework enables the evaluation of both the spatial distribution and temporal evolution of fault activity. Drainage networks and basin boundaries were automatically extracted from a Digital Elevation Model (DEM) within a Geographic Information Systems (GIS) environment. All geomorphic analyses were performed using ArcGIS, MATLAB, and TopoToolbox v2 (Schwanghart and Scherler, 2014), which provides quantitative tools for topographic and river-profile analyses in tectonically active landscapes. The topographic dataset used in this study consists of a 12.5 m spatial resolution ALOS PALSAR DEM obtained from the Alaska Satellite Facility database. Prior to the analyses, the DEM was hydrologically corrected using sink-filling algorithms to ensure continuous flow routing. Flow direction and flow accumulation grids were subsequently derived, and drainage networks were extracted using an area threshold approach. Basin boundaries and channel networks were manually checked and corrected where necessary. River profiles were normalized using the χ-transformation in order to separate tectonic signals from topographic and drainage-area effects. A reference concavity value (m/n) of 0.45 was used throughout the analyses following commonly adopted values for tectonically active landscapes (Wobus et al., 2006; Perron and Royden, 2013). The reference drainage area ($A0$) was set to 1 m^2.

Mountain Front Morphometry

Mountain front morphology represents one of the most prominent geomorphic expressions of active tectonics (Bull and McFadden, 1977). In this study, mountain front sinuosity (Smf) and valley floor width-to-height ratio (Vf) indices were used to evaluate the relationship between tectonic activity and mountain front geometry. Lower Smf values generally indicate relatively linear mountain fronts associated with active uplift, whereas Vf values provide information about valley incision and valley-floor development (Table 1; Figure 3).

Table 1. Indices and methods for multi-scale morphometric analyses along the Yalakdere Fault.
Çizelge 1. *Yalakdere Fayı boyunca çok ölçekli morfometrik analizlerle elde edilen indeksler ve yöntemler.*

Scale	Indices	Formula / Approach	Explanation	Reference
Mountain front	Mountain front sinuosity, Smf	Smf = Lmf / Ls	Indicates whether the mountain front is linear; low values suggest high tectonic activity	Bull and McFadden, 1977
	Valley floor width-to-height ratio, Vf	Vf = 2Vfw / [(Eld − Esc) + (Erd − Esc)]	A tectonic activity indicator based on valley cross-sectional geometry	Bull and McFadden, 1977
Basin	Asymmetry factor, AF	AF = (Ar / At) × 100	Reveals the direction of basin tilting and tectonic inclination	Hare and Gardner, 1985
	Drainage basin shape, Bs	Bs = Bl / Bw	Reflects the degree of basin elongation and structural control	Schumm, 1956
	Hypsometric integral,HI	HI = (hmean − hmin) / (hmax − hmin)	Indicates the degree of erosion and topographic maturity	Strahler, 1952
	Hypsometric curve, HC	—	Evaluates morphological evolution based on the elevation–area relationship	Strahler, 1952
Channel	Normalized steepness index, ksn	ksn = ks × A^θ	Enhances sensitivity to uplift by normalizing channel slope	Wobus et al., 2006
	χ (chi)	χ = ∫ (Ao/A)^(m/n) dx	Used to assess drainage equilibrium and divide stability	Perron and Royden, 2013
Time-series analysis	Linear inversion of river profiles	z(x) = zo + ∫ U(t)·G(x,t) dt	Determines the temporal and spatial variation of uplift rates based on knickpoint migration	Goren et al., 2014

Basin-Scale Morphometric Analyses

To evaluate tectonic deformation at the basin scale, asymmetry factor (AF), basin shape index (Bs), hypsometric integral (HI), and hypsometric curve (HC) analyses were performed (Schumm, 1956; Strahler, 1952; Keller and Pinter, 2002). The AF index provides information about basin tilting and tectonic asymmetry, while the Bs index reflects basin elongation and structural control. HI and HC analyses were used to assess erosional maturity and geomorphic evolution of the drainage basins.

Channel-Scale Analyses

The normalized channel steepness index (ksn) and χ analyses were used to evaluate channel response to tectonic forcing (Wobus et al., 2006; Perron and Royden, 2013). The ksn index is sensitive to spatial variations in uplift and incision, whereas χ analyses provide information about drainage equilibrium, divide stability, and potential drainage reorganization processes (Table 1; Figure 3).

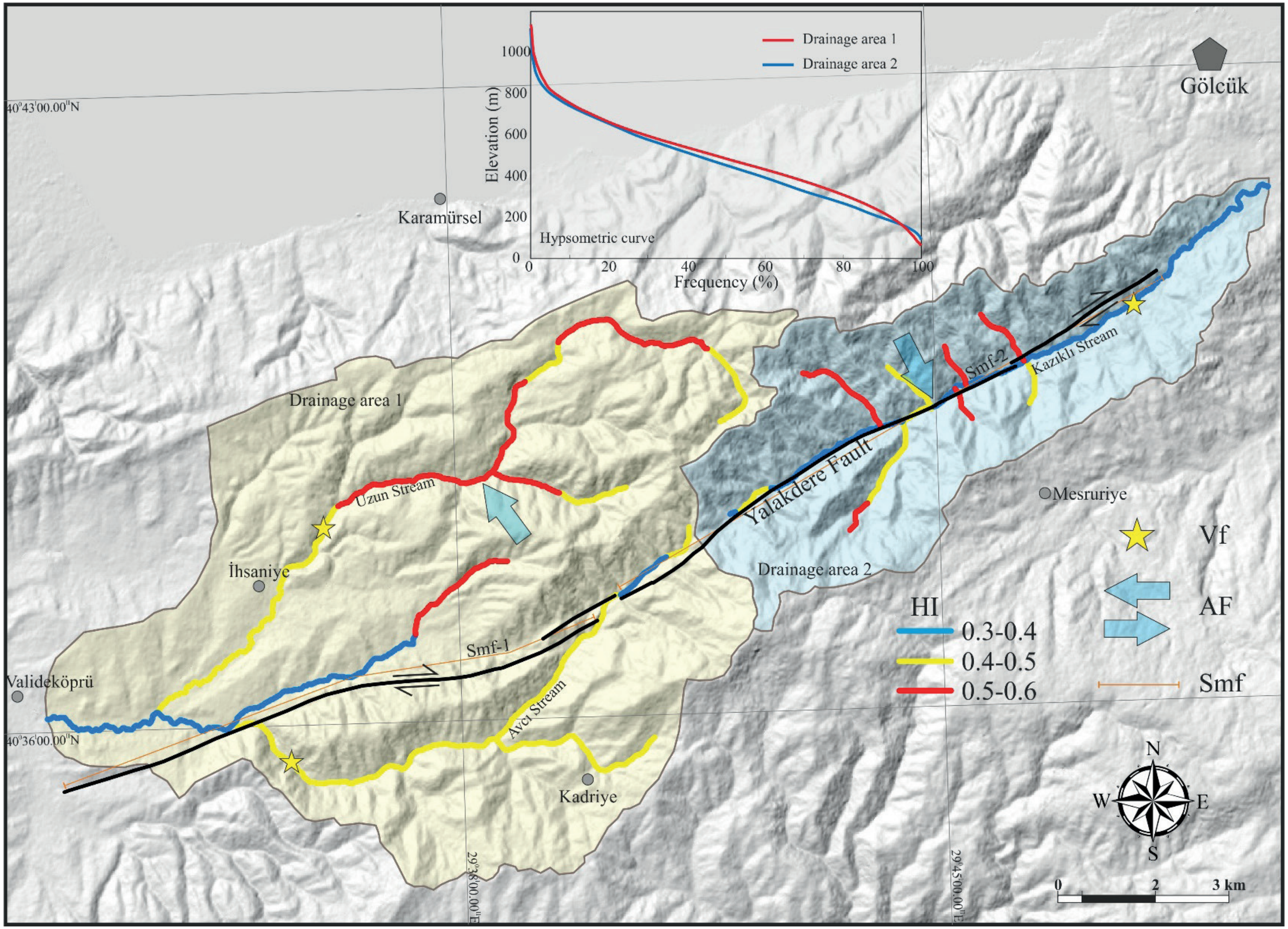


Figure 3. Geomorphic indices calculated on the Yalakdere Fault controlled mountain front and drainage areas (Smf and Vf calculation sites, tilting directions determined by AF index).

Şekil 3. *Yalakdere Fayı kontrollü dağ cephesi ve drenaj alanlarında hesaplanan jeomorfik indeksler (Smf ve Vf hesaplama sahaları, AF indeksi ile belirlenen eğim yönleri).*

River Profile Inversion Model

River profile inversion modelling was applied to longitudinal stream profiles to reconstruct the temporal evolution of uplift along the Yalakdere Fault following the stream-power based inversion framework of Goren et al. (2014). The inversion approach follows the detachment-limited stream power incision framework proposed by Goren et al. (2014), in which river profiles preserve information about transient uplift histories through upstream-migrating knickpoints. Longitudinal river profiles were transformed into χ-space, and uplift histories were reconstructed through linear inversion of χ–elevation profiles. The inversion model assumes that erosional parameters remain spatially uniform through time and that knickpoint retreat follows stream-power scaling relationships. The inversion model adopts a spatially uniform effective erodibility coefficient (K), following the original formulation of Goren et al. (2014). Consequently, lithology-dependent variations in rock erodibility are not explicitly represented. Spatial variations in lithology may locally influence incision efficiency and knickpoint retreat rates; therefore, uncertainty in K mainly affects the absolute timing of reconstructed uplift events rather than the relative shape of the inferred uplift histories. Accordingly, the inversion results are interpreted as first-order approximations of long-term tectonic forcing. Observed and modelled χ–elevation profiles were compared in order to evaluate model performance and goodness of fit. The reconstructed uplift histories were interpreted in terms of temporal and spatial variations in tectonic activity along different fault segments (Table 1). The inversion results should be interpreted within the assumptions of detachment-limited stream power incision models and spatially uniform erosional parameters. The time coordinate (τ) produced by the inversion represents model time derived from χ-space rather than a directly dated geological timescale. Consequently, the τ axis should be interpreted as a relative temporal framework. References to geological ages (e.g., the Early Pleistocene or approximate Ma ranges) are intended only as approximate correlations based on the adopted inversion parameters and the regional geological framework, rather than independently constrained numerical ages. Accordingly, the inversion is primarily designed to reconstruct the relative temporal evolution of uplift rather than to establish absolute chronologies of uplift events. Lithological heterogeneity, localized sediment cover, drainage reorganization, and transient climatic variations may locally influence river profile geometry and knickpoint migration rates. Therefore, reconstructed uplift histories are interpreted as first-order approximations of long-term tectonic forcing rather than absolute uplift histories.

RESULTS OF MORPHOMETRIC ANALYSES

Morphometric analyses conducted along the Yalakdere Fault were evaluated comprehensively by differentiating between drainage basins and considering the southwestern and northeastern segments of the fault (Table 2).

Table 2. Morphometric indices calculated for the drainage basins along the Yalakdere Fault.
Çizelge ***2.*** *Yalakdere Fay Hattı boyunca uzanan drenaj havzaları için hesaplanan morfometrik indeksler.*

Drainage area	Geomorphic indices					
	Smf	Vf	HI	AF	Bs	ksn (mean)
1	1.57	0.17 0.25	0.45	0.72	2.12	46
2	1.32	0.12	0.44	0.45	3.98	50

Mountain Front Morphometry (Smf, Vf)

In the southwestern segment of the fault, the calculated Smf values fall within a low range, indicating that the mountain front parallel to the fault trace exhibits a largely linear morphology with limited irregularities. In the same segment, Vf values are also low, particularly along Uzun Dere and its tributaries, corresponding to narrow and deeply incised valleys characterized by steep slopes and limited valley floor width. In contrast, in the northeastern segment of the fault, Smf values are consistently higher than those observed in the southwestern segment, suggesting a more irregular mountain-front morphology. In this area, Vf values increase along Kazıklı and its surrounding drainage network, indicating broader valley floors and more open valley cross-sectional geometries.

Basin-Scale Indices (AF, Bs, HI, HC)

For Drainage Basin 1 (southwestern segment), AF values indicate a distinctly asymmetric basin form, with the drainage network systematically deflected relative to the main channel axis. The calculated Bs values indicate an elongated basin, reflecting strong structural control on basin development. HI values indicate moderate topographic dissection, and the corresponding hypsometric curve exhibits a slightly more convex profile.

In contrast, Drainage Basin 2 (northeastern segment) displays a different asymmetry pattern, reflecting a distinct drainage orientation relative to the main channel. Lower Bs values indicate a shorter and wider basin, whereas HI values are slightly lower than those of Drainage Basin 1. The corresponding hypsometric curve is slightly smoother and less convex. Overall, the hypsometric curves of both drainage basins are broadly similar, differing only subtly in curvature (Figure 3).

RESULTS OF CHANNEL-SCALE ANALYSES

Normalized Channel Steepness (ksn)

Channel-scale analyses along the Yalakdere Fault reveal pronounced spatial variability in normalized channel steepness (ksn) between the two drainage basins. In Drainage Basin 1 (southwestern segment), low ksn values (<30) are mainly confined to tributaries connected to the main channel and to the western part of the basin. Moderate ksn values (31–60) become more common in the central sector and closer to the fault trace, whereas high ksn values (>60) are concentrated in short, steep tributaries adjacent to the fault trace. Around Uzun Dere, the drainage network exhibits a heterogeneous distribution of ksn values, with low, moderate, and high values occurring along neighbouring channel reaches. Overall, moderate and high ksn values are more widespread in Drainage Basin 1, indicating greater spatial variability in channel steepness.

In Drainage Basin 2 (northeastern segment), ksn values are represented by fewer stream segments. Low ksn values occur mainly along the main channel and several tributaries, whereas moderate and high ksn values are restricted to short channel reaches in the central and northern parts of the basin. High ksn values are less extensive and occur in fewer channels than in Drainage Basin 1, indicating that elevated channel steepness is more localized within the drainage network (Figure 4).

χ Analysis and Drainage Divide Position

Evaluation of χ distribution together with the topographic profile shows that the drainage divide is located in the central part of the study area and corresponds to the highest elevation along the profile. χ values increase progressively towards the divide, reaching their highest values near the ridge crest. The χ distribution is asymmetric across the divide, with consistently higher values in Drainage Basin 2 (eastern side) and lower values in Drainage Basin 1 (western side). In map view, the divide forms a sinuous and irregular boundary rather than a linear geometry, particularly in its central and northern sectors. The inferred divide migration is from east to west.

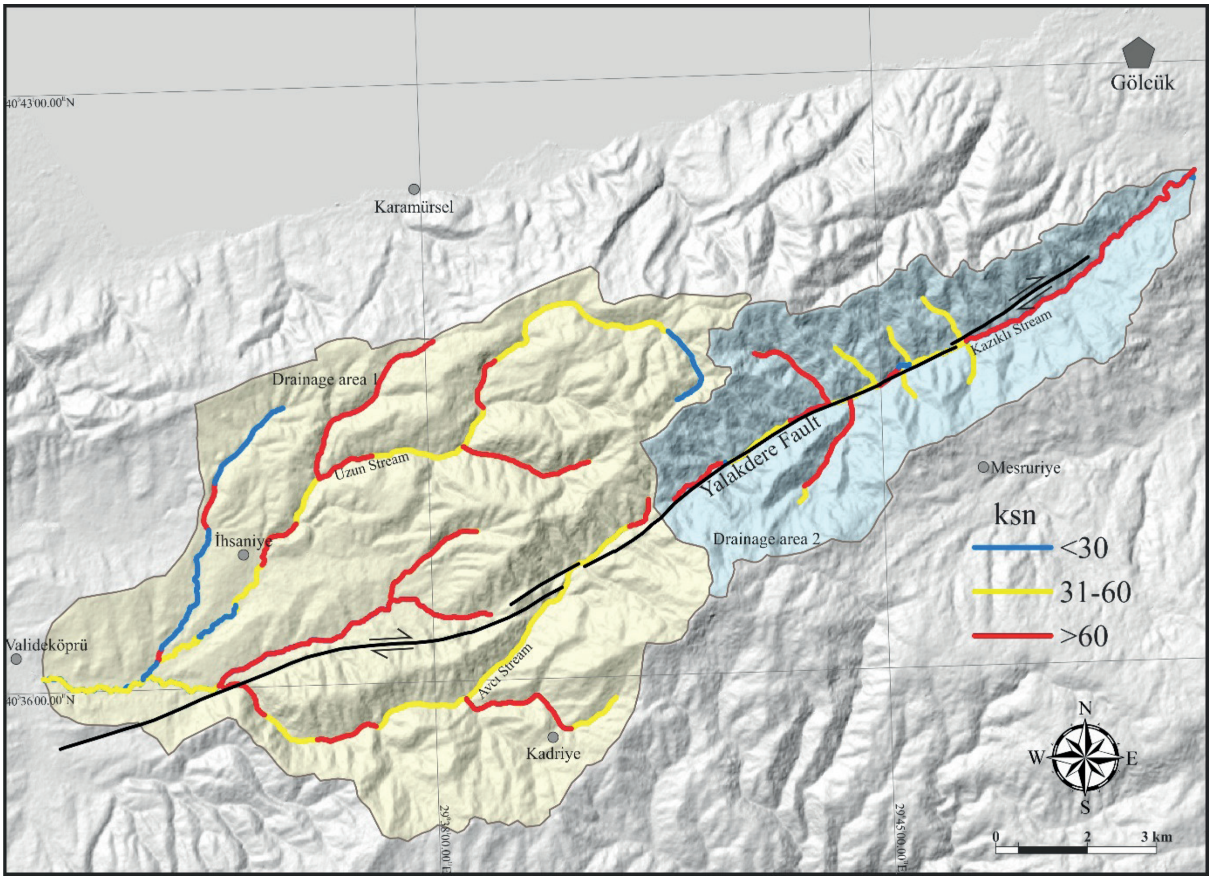


Figure 4. Spatial distribution of normalized channel steepness (ksn) values along the Yalakdere Fault.

Şekil 4. *Yalakdere Fayı boyunca normalize edilmiş kanal dikliği (ksn) değerlerinin mekansal dağılımı.*

Drainage-divide stability was evaluated by comparing χ values between neighbouring channel heads immediately adjacent to the divide, following the approach of Willett et al. (2014) and Forte and Whipple (2018). Accordingly, the aggressor–victim interpretation is based on these local χ contrasts rather than on the longitudinal χ profile, which is included only to illustrate the overall spatial variation in χ (Figure 5).

RESULTS FOR RIVER PROFILE INVERSION

River-profile inversion results were evaluated separately for Drainage Basins 1 and 2. The reconstructed uplift histories are presented using the inversion timescale, with the corresponding geological ages representing approximate temporal correlations based on the adopted model parameters.

For Drainage Basin 1, reconstructed uplift rates during the Late Pliocene–Early Pleistocene (~2.5–1.8 Ma) are relatively low (~0.18–0.22 mm/yr). During the Early Pleistocene (~1.8–1.2 Ma), uplift rates increase gradually to ~0.25–0.35 mm/yr, reaching a maximum of approximately 0.35 mm/yr at ~1.2–1.0 Ma. During the Middle Pleistocene (~1.0–0.5 Ma), uplift rates decrease to ~0.14–0.20 mm/yr before increasing slightly during the Late Pleistocene (~0.5–0.1 Ma), when they range between ~0.18 and 0.22 mm/yr.

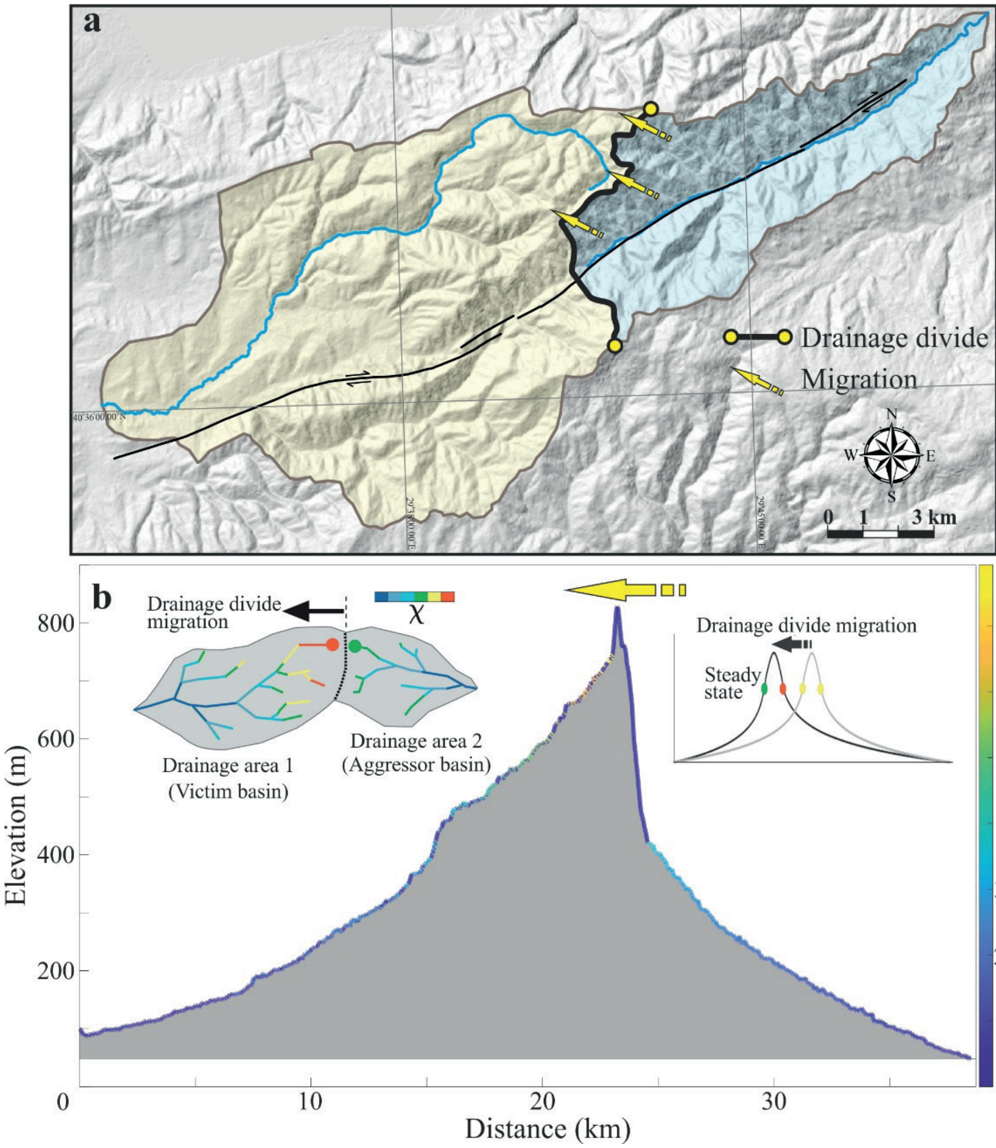


Figure 5. a) Spatial distribution of χ values and drainage-divide geometry. **b)** Longitudinal χ profile extracted along the transect shown in panel (a). The profile illustrates the overall variation of χ along the selected transect and is not intended as the primary basis for evaluating drainage-divide disequilibrium. The aggressor–victim interpretation is derived from χ contrasts between neighbouring channel heads immediately adjacent to the drainage divide.

Şekil 5. a) *χ değerlerinin mekânsal dağılımı ve drenaj bölümü geometrisi.* ***b)*** *(a) panelinde gösterilen kesit boyunca elde edilen boyuna χ profili. Bu profil, seçilen kesit boyunca χ değerlerinin genel değişimini göstermek amacıyla sunulmuş olup, drenaj bölümü dengesizliğinin değerlendirilmesinde birincil dayanak olarak kullanılmamaktadır. Saldırgan–kurban (aggressor–victim) havza yorumu, drenaj bölümüne doğrudan komşu kanal başları arasındaki χ karşıtlıklarına dayanmaktadır.*

For Drainage Basin 2, reconstructed uplift rates during the Late Pliocene–Early Pleistocene (~1.8–1.5 Ma) range from ~0.20 to 0.26 mm/yr. During the Early Pleistocene (~1.5–1.0 Ma), uplift rates increase to ~0.30–0.38 mm/yr. In the Middle Pleistocene (~1.0–0.6 Ma), they fluctuate between ~0.24 and 0.30 mm/yr before decreasing slightly during the Late Pleistocene (~0.6–0.2 Ma) to ~0.18–0.25 mm/yr.

Comparison of the observed and modelled χ–elevation (χ–z) profiles shows good agreement for both drainage basins, indicating that the inversion model reproduces the observed river profiles reasonably well. The agreement is stronger for Drainage Basin 2, whereas Drainage Basin 1 has greater scatter between the observed and reconstructed χ–z profiles (Figure 6).

DISCUSSION and CONCLUSION

Basin-scale morphometric indices reveal clear morphotectonic contrasts between the southwestern and northeastern segments of the Yalakdere Fault. Low Smf and Vf values in the southwestern segment indicate a relatively straight mountain front and narrow, deeply incised valleys, consistent with stronger tectonic control (Bull and McFadden, 1977; Silva et al., 2003). In contrast, the northeastern segment is characterized by higher Smf and Vf values, reflecting a more irregular mountain-front morphology and broader valleys.

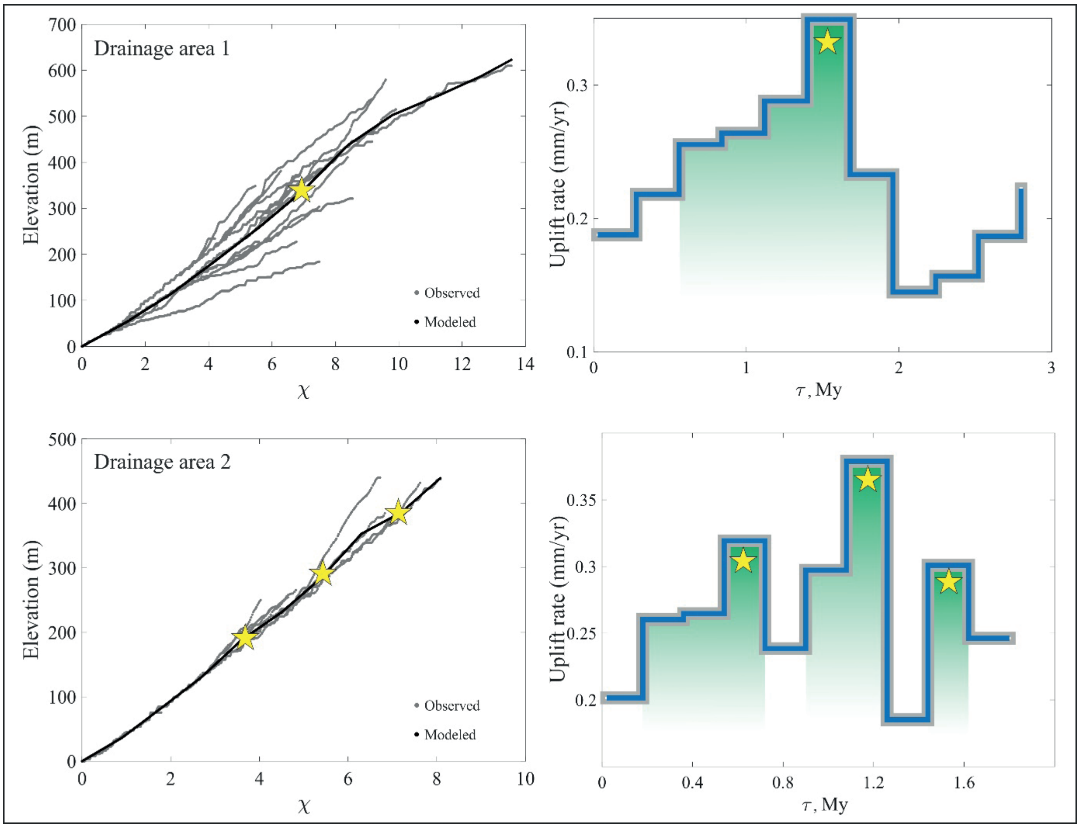


Figure 6. Observed and modelled χ–elevation profiles (left panels) and reconstructed uplift histories (right panels) for Drainage Basins 1 and 2. The horizontal axis (τ) represents inversion model time derived from χ-space rather than independently-dated geological time. Geological age assignments discussed in the text are therefore approximate correlations intended to facilitate regional geological interpretation.

Şekil 6. *1 ve 2 numaralı drenaj havzaları için gözlemlenen ve modellenen χ-yükseklik profilleri (sol) ve yeniden oluşturulan yükselme geçmişleri (sağ). Yatay eksen (τ), bağımsız olarak tarihlendirilmiş jeolojik zamandan ziyade χ-uzayından türetilen tersine çevirme modeli zamanını temsil eder. Bu nedenle metinde tartışılan jeolojik yaş atamaları, bölgesel jeolojik yorumlamayı kolaylaştırmak amacıyla yaklaşık korelasyonlardır.*

The AF, Bs, and HI indices further indicate stronger structural control and more heterogeneous deformation within Drainage Basin 1, consistent with localized differential block tilting (Keller and Pinter, 2002; Topal, 2012). Although the hypsometric curves for the two drainage basins are broadly similar, the slightly higher HI values in Drainage Basin 1 indicate a relatively less eroded landscape, while the subtly more convex hypsometric curve provides supporting evidence. Overall, these basin-scale morphometric indices suggest that landscape evolution along the southwestern segment of the Yalakdere Fault was more strongly influenced by tectonic processes than along the northeastern segment.

The spatial distribution of normalized channel steepness (ksn) is consistent with the morphotectonic contrast between the two segments of the Yalakdere Fault. The more widespread and heterogeneous distribution of ksn values in the southwestern segment reflects greater spatial variability in channel gradients, particularly near the fault trace where the highest ksn values are concentrated (Topal and Irfan, 2025). Elevated ksn values are commonly interpreted as indicators of enhanced rock uplift and transient channel adjustment in actively deforming landscapes (Wobus et al., 2006; Kirby and Whipple, 2012; Topal, 2024). Accordingly, the concentration of high ksn values in the southwestern segment suggests stronger tectonic control than in the northeastern segment, where elevated ksn values are more localized and channel gradients are comparatively uniform. Together with the basin-scale morphometric indices, these observations indicate that tectonic deformation is the primary control on fluvial adjustment along the Yalakdere Fault.

χ-based analyses provide important insights into drainage equilibrium and divide stability (Willett et al., 2014; Forte and Whipple, 2018; Topal, 2019; Topal et al., 2025). Along the Yalakdere Fault, the asymmetric distribution of χ values indicates pronounced disequilibrium between the adjacent drainage basins, suggesting that the drainage divide is actively evolving rather than stable. The irregular and sinuous geometry of the divide, particularly in its central and northern sectors, further supports ongoing drainage reorganization. Higher χ values in Drainage Basin 2 and lower values in Drainage Basin 1 indicate a persistent imbalance in erosional potential between the two basins. Following the framework of Willett et al. (2014) and Forte and Whipple (2018), these χ contrasts identify Drainage Basin 2 as the aggressor basin and Drainage Basin 1 as the victim basin. This interpretation is based on local χ contrasts between neighbouring channel heads immediately adjacent to the divide rather than on the longitudinal χ profile shown in Figure 5. The inferred east-to-west migration of the divide, together with its irregular geometry, suggests that divide migration is locally influenced by differential tectonic uplift associated with fault segmentation rather than occurring uniformly along the fault. These observations are consistent with drainage-basin reorganization in tectonically active regions, where spatial variations in uplift promote divide migration through headward erosion (Willett et al., 2014).

River-profile inversion results indicate that uplift rates along the Yalakdere Fault have varied through time. Because the reconstructed uplift histories are expressed in inversion-model time (τ), the corresponding geological ages should be regarded as approximate temporal correlations rather than absolute numerical ages. Accordingly, the results are interpreted primarily in terms of the relative timing and evolution of uplift. In both drainage basins, uplift rates fluctuate throughout the Pleistocene, indicating that uplift was not constant. Drainage Basin 1 records a pronounced uplift peak during the Early Pleistocene followed by a gradual decline, whereas Drainage Basin 2 exhibits more frequent fluctuations, with peak uplift occurring over shorter intervals. These contrasting uplift histories are consistent with previous studies showing that river-profile inversion can resolve along-strike variations in uplift associated with fault segmentation and differential block motion (Goren et al., 2014).

The geological framework of the study area indicates that the two drainage basins contain different proportions of resistant metamorphic rocks and younger sedimentary units, suggesting spatial variations in bedrock erodibility (K). These lithological contrasts may influence local incision efficiency and introduce uncertainty into the conversion of χ-space to geological time, although no independent constraints on spatial variations in K are available. Therefore, the inversion was performed using a single effective erodibility coefficient, following Goren et al. (2014). The reconstructed uplift histories should therefore be interpreted as relative temporal trends rather than precise geological chronologies. Furthermore, the longer temporal record reconstructed for Drainage Basin 1 most likely reflects the larger χmax and greater basin extent, which increase the recoverable inversion window, rather than being evidence for an older phase of tectonic activity.

The along-strike morphotectonic contrasts observed along the Yalakdere Fault may reflect progressive localization of deformation within the eastern Marmara region. Based on integrated geomorphological, geophysical, and sedimentological evidence, Forte et al. (2014) proposed that tectonic deformation has evolved since the Late Pleistocene from a broad deformation zone characterized by large step-overs and en echelon fault systems to a more localized principal deformation zone. The morphotectonic patterns documented in this study, including higher channel steepness (ksn), greater drainage disequilibrium (χ), and spatial variations in reconstructed uplift histories, are consistent with this regional model of tectonic evolution. In particular, the southwestern segment of the Yalakdere Fault appears to represent a more localized zone of active deformation, where fault geometry and differential uplift exert stronger influence on landscape evolution than in the northeastern segment. The geomorphic characteristics documented in this study are consistent with regional observations reported by Tarı and Tüysüz (2016), who showed that active deformation along the eastern Marmara sector of the North Anatolian Fault has produced fault-controlled drainage networks, asymmetric drainage basins, straight mountain fronts, and deeply incised valleys. Similar geomorphic characteristics are observed along the Yalakdere Fault, particularly in the southwestern segment where lower Smf values, higher channel steepness (ksn), and greater drainage disequilibrium (χ) indicate stronger tectonic control than in the northeastern segment. The integrated multi-scale morphometric analyses presented here further show that tectonic deformation varies significantly along strike, reflecting the combined influence of fault segmentation and differential uplift on geomorphic development.

The morphotectonic evolution of the Yalakdere Fault reflects the combined influence of lithological heterogeneity, fault segmentation, and long-term tectonic deformation. The spatial patterns of morphometric indices, normalized channel steepness (ksn), χ anomalies, and reconstructed uplift histories indicate that the observed topography cannot be explained by climatic forcing alone but instead records dominant tectonic influence modified by local geological conditions. Although minor lithological heterogeneities are present, both drainage basins are predominantly underlain by resistant crystalline basement rocks, including metagranite and high-grade metamorphic units with younger sedimentary deposits confined to limited local exposures. Consequently, variations in rock strength alone are unlikely to explain the pronounced morphotectonic contrasts across the study area. Instead, these contrasts primarily reflect differential uplift associated with the segmented geometry of the Yalakdere Fault. The discontinuous step-over geometry of the fault, particularly between Senaiye and Akçat, likely promotes localized variations in uplift and strain accumulation, which are expressed by spatial variations in channel steepness, χ disequilibrium, and reconstructed uplift histories. Together, these observations indicate that the drainage network is actively adjusting to differential uplift and evolving base-level conditions. The temporal variability in reconstructed uplift rates further suggests that deformation has changed through time, most likely in response to variations in slip distribution among individual fault segments within the broader North Anatolian Fault system.

This study presents a comprehensive multi-scale morphometric analysis of the Yalakdere Fault by integrating mountain-front morphometry, basin-scale indices, normalized channel steepness (ksn), χ-based analyses, and river-profile inversion to evaluate the tectonic controls on landscape evolution. The results reveal distinct morphotectonic differences between the southwestern and northeastern fault segments. The southwestern segment is characterized by straighter mountain fronts, narrower and more deeply incised valleys, greater spatial variability in channel steepness, and stronger drainage disequilibrium, whereas the northeastern segment exhibits more subdued geomorphic development and less variable morphometric characteristics. χ-based analyses indicate that the drainage divide is not in equilibrium and is migrating from Drainage Basin 2 towards Drainage Basin 1, reflecting ongoing drainage reorganization driven by differential uplift. River-profile inversion reveals temporally variable uplift histories, indicating that deformation has evolved differently along individual fault segments through time. Overall, the results show that the geomorphic evolution of the Yalakdere Fault is primarily controlled by fault segmentation and differential tectonic uplift, whereas lithological heterogeneity exerts a secondary influence on landscape development. More broadly, this study demonstrates the value of integrating multi-scale morphometric analyses with river-profile inversion to investigate the long-term evolution of active strike-slip fault systems and provide a quantitative framework for comparable tectonically active regions.

GENİŞLETİLMİŞ ÖZET

Kuzeybatı Anadolu, aktif deformasyonun yoğun olduğu ve yüksek sismotektonik aktiviteye sahip doğrultu atımlı fay sistemlerinin geliştiği önemli bir tektonik kuşaktır. Bölgenin güncel tektoniğini kontrol eden Kuzey Anadolu Fay Zonu, yalnızca yatay yer değiştirmeler değil, aynı zamanda topoğrafik değişimi doğrudan etkileyen düşey bileşenli deformasyonlar da sergilemektedir. Yalakdere Fayı, sağ yönlü doğrultu atımlı fay karakteri, segmentli geometrisi ve belirgin topoğrafik izi ile Doğu Marmara bölgesindeki neotektonik süreçlerin anlaşılması açısından önemli yapılardan biridir. Bununla birlikte, fay boyunca gelişen yükselme tarihçesi, segment ölçeğindeki deformasyon farklılıkları ve drenaj sistemlerinin tektonik kontrollü evrimi henüz ayrıntılı biçimde ortaya konulamamıştır. Bu çalışma, Yalakdere Fayı boyunca topoğrafyanın tektonik denetimini çok ölçekli morfometrik analizler ve akarsu profili ters çözümleme modeli kullanarak değerlendirmeyi amaçlamaktadır.

Çalışma kapsamında topoğrafik analizler üç temel ölçekte gerçekleştirilmiştir: (i) dağ önü morfolojisi, (ii) havza ölçekli morfometri ve (iii) kanal ağı ile akarsu profili analizleri. Analizlerde Sayısal Yükseklik Modeli (SYM) verileri kullanılmış; drenaj ağları ve havza sınırları CBS tabanlı yöntemlerle otomatik olarak türetilmiştir. Dağ önü morfolojisinin değerlendirilmesi amacıyla dağ önü eğriselliği (Smf) ve vadi tabanı genişlik/yükseklik oranı (Vf) indisleri hesaplanmıştır. Havza ölçeğinde asimetri faktörü

(AF), havza şekli (Bs), hipsometrik integral (HI) ve hipsometrik eğri (HC) analizleri uygulanmıştır. Kanal ölçeğinde ise normalize kanal diklik indisi (ksn) ile χ (chi) tabanlı drenaj bölümü kararlılığı analizleri gerçekleştirilmiştir. Ayrıca, akarsu boyu profillerine uygulanan ters çözümleme modeli yardımıyla yükselme oranlarının zamansal değişimi nicel olarak değerlendirilmiştir.

Dağ önü morfometrisi sonuçları, fayın güneybatı segmentinde düşük Smf değerlerinin baskın olduğunu ve dağ önü çizgisinin belirgin biçimde doğrusal karakter sunduğunu göstermektedir. Aynı segmentte düşük Vf değerleri, dar ve derine yarılmış vadilerin geliştiğini ortaya koymaktadır. Bu durum aktif yükselme ve güçlü tektonik kontrol ile uyumludur. Buna karşılık kuzeydoğu segmentinde daha yüksek Smf ve Vf değerleri hesaplanmış olup, burada daha düzensiz dağ önü geometrisi ve geniş vadi tabanları gözlenmektedir. Havza ölçekli analizlerde güneybatı segmentindeki havzaların belirgin asimetrik karakter sunduğu belirlenmiştir. AF değerleri drenaj ağının sistematik biçimde eğimlendiğini gösterirken, yüksek Bs değerleri yapısal kontrollü uzamış havza geometrisini işaret etmektedir. HI değerlerinin orta-yüksek aralıkta olması ve hipsometrik eğrilerin çoğunlukla konveks karakter göstermesi, topoğrafyanın genç ve aşınım açısından tam olgunlaşmamış olduğunu ortaya koymaktadır. Kuzeydoğu segmentinde ise daha düşük HI değerleri ve konkav hipsometrik eğriler daha ileri aşınım evresini göstermektedir.

Kanal ölçekli analizler boyunca hesaplanan ksn dağılımları, fay segmentleri arasında belirgin mekânsal farklılıklar olduğunu göstermektedir. Güneybatı segmentinde yüksek ksn anomalileri özellikle fay izine yakın kısa ve dik yan kollarda yoğunlaşmaktadır. Bu durum, kanal eğimlerinin aktif yükselme süreçlerine duyarlı olduğunu göstermektedir. Aynı havza içerisinde düşük, orta ve yüksek ksn değerlerinin ardışık biçimde gözlenmesi, kanal profillerinin mekânsal olarak heterojen deformasyona yanıt verdiğini ortaya koymaktadır. Kuzeydoğu segmentinde ise yüksek ksn değerleri daha sınırlı alanlarda gözlenmekte ve kanal ağı genelinde daha homojen bir dağılım sergilemektedir.

χ analizleri, drenaj bölümlerinin dinamik denge durumundan sapmış olduğunu göstermektedir. Topoğrafik bölünme çizgisi çalışma alanının merkezi kesiminde yer almakta ve maksimum yükseltiye karşılık gelmektedir. χ değerleri bölünmeye doğru artmakta, ancak bölünmenin doğu ve batı taraflarında belirgin asimetri sunmaktadır. Özellikle doğu havzasında daha yüksek χ değerleri gözlenirken, batı havzasında daha düşük değerler hâkimdir. Bu durum iki havza arasında enerji dengesizliği bulunduğunu göstermektedir. Harita görünümünde drenaj bölümü doğrusal bir geometri sunmamakta; özellikle orta ve kuzey kesimlerde sinüzoidal ve düzensiz bir karakter sergilemektedir. χ dağılımları, drenaj bölümü göçünün genel olarak doğudan batıya doğru gerçekleştiğini göstermekte olup, bu durum diferansiyel yükselme ve aktif topoğrafyanın yeniden şekillenmesiyle ilişkilendirilmiştir.

Akarsu profili ters çözümleme sonuçları, Yalakdere Fayı boyunca yükselme oranlarının zaman içerisinde önemli değişimler gösterdiğini ortaya koymaktadır. Güneybatı havzasında Geç Pliyosen–Erken Pleyistosen döneminde görece düşük yükselme oranları belirlenmiş, Erken Pleyistosen boyunca yükselme hızlarının arttığı ve yaklaşık Erken-Orta Pleyistosen geçişinde maksimum değerlere ulaştığı saptanmıştır. Orta Pleyistosen'de yükselme oranlarında azalma gözlenirken, Geç Pleyistosen boyunca yeniden artış meydana gelmiştir. Kuzeydoğu havzasında ise yükselme oranları daha kısa zaman aralıklarında dalgalı değişim göstermektedir. Her iki havza için gözlenen yükselme tarihçeleri, fay segmentasyonu ve diferansiyel blok hareketleriyle uyumlu sonuçlar sunmaktadır. Gözlenen ve modellenen χ-yükseklik profilleri arasındaki yüksek uyum, uygulanan ters *çözümleme modelinin topoğrafik gelişimi başarılı biçimde temsil ettiğini göstermektedir.*

Elde edilen tüm morfometrik ve zamansal veriler birlikte değerlendirildiğinde, Yalakdere Fayı boyunca topoğrafik evrimin litolojik heterojenite, segmentli fay geometrisi ve uzun dönemli tektonik aktivitenin ortak etkisi altında geliştiği anlaşılmaktadır. Güneybatı segmentinde gözlenen yüksek morfotektonik aktivite, daha dirençli metamorfik kayaçların varlığı ve fay geometrisinin lokal deformasyonu yoğunlaştırması ile ilişkilendirilmiştir. Kuzeydoğu segmentinde ise daha zayıf litolojiler ve daha düşük topoğrafik enerji koşulları baskındır. χ tabanlı analizlerin ortaya koyduğu drenaj bölümü kararsızlığı, topoğrafyanın hâlen denge durumuna ulaşmadığını ve aktif olarak yeniden organize olduğunu göstermektedir.

Sonuç olarak bu çalışma, çok ölçekli morfometrik analizlerin doğrultu atımlı fay sistemlerinin topoğrafik etkilerini ortaya koymada yüksek duyarlılığa sahip olduğunu göstermektedir. Yalakdere Fayı boyunca belirlenen morfometrik anomaliler ve zamansal yükselme değişimleri, fayın aktif neotektonik karakterini açık biçimde ortaya koymaktadır. Çalışma ayrıca, Doğu Marmara bölgesindeki doğrultu atımlı fay sistemlerinin jeomorfolojik evriminin anlaşılması açısından nicel morfotektonik yöntemlerin etkinliğini vurgulamakta ve bölgedeki uzun dönemli tektonik süreçlere ilişkin yeni veriler sunmaktadır.

ACKNOWLEDGMENT

This study was carried out within the scope of TÜBİTAK KAMAG 1007 project number 123G013 for MTA (General Directorate of Mineral Research and Exploration in Türkiye), the client institution. We thank the Editor and reviewers who evaluated the article for their valuable contributions and TÜBİTAK for their contribution. This article is also derived from a section of the PhD thesis work of Seray ÇINAR YILDIZ, a student at ÇOMÜ School of Graduate Studies.

ORCID

Seray Çınar Yıldız https://orcid.org/0009-0005-7048-8456

Süha Özden https://orcid.org/0000-0001-6321-0812

Savaş Topal https://orcid.org/0000-0001-7451-6606

REFERENCES / *KAYNAKLAR*

Alpar, B. & Yaltırak, C. (2002). Characteristic features of the North Anatolian Fault in the eastern Marmara region and its tectonic evolution. *Marine Geology, 190*(1-2), 329-350. https://doi.org/10.1016/S0025-3227(02)00353-5

Bargu, S. ve Sakınç, M. (1984). *Armutlu Yarımadası'nda Karamürsel ile İznik Gölü Arasındaki Kesimin Doğal Agrega Potansiyelinin Araştırılması ve Değerlendirilmesi* (Rapor no: TBAG-587). TÜBİTAK.

Bargu, S. & Sakınç, M. (1989). Geology and structural properties of the region between the İzmit Gulf and İznik Lake. *İstanbul Üniversitesi Mühendislik Fakültesi Yerbilimleri Dergisi, 6*(1–2) 45-76.

Bull, W. B. & McFadden, L. D. (1977). Tectonic geomorphology North and south of the Garlock fault, California. In: Doehring, D.O. (Eds.), *Geomorphology in Arid Regions. Proceedings of the Eighth Annual Geomorphology Symposium* (pp.: 115-138). State University of New York, Binghamton. https://doi.org/10.4324/9780429299230

Elmas, A. & Yiğitbaş, E. (2005). Comment on "Tectonic evolution of the Intra-Pontide suture zone in the Armutlu Peninsula, NW Turkey" by Robertson and Ustaömer. Discussion. *Tectonophysics, 405*(1-4), 213-221. https://doi.org/10.1016/j.tecto.2005.05.007

Emre, Ö., Erkal, T., Tchepalyga, A., Kazancı, N., Keçer, M. & Ünay, E. (1998). Neogene-Quaternary evolution of the eastern Marmara region, northwest Turkey. *Bulletin of the Mineral Research and Exploration, 120*, 119-145. https://izlik.org/JA66NT78JL

Emre, Ö., Duman, T. Y., Özalp, S., Şaroğlu, F., Olgun, Ş., Elmacı, H. & Çan, T. (2018). *Active fault database of Turkey. Bulletin of Earthquake Engineering*, *16*(8), 3229-3275. https://doi.org/10.1007/s10518-016-0041-2

Forte, A. M. & Whipple, K. X. (2018). Criteria and tools for determining drainage divide stability. *Earth and Planetary Science Letters, 493*, 102-117. https://doi.org/10.1016/j.epsl.2018.04.026

Forte, E., Sugan, M., Del Ben, A., Pipan, M., Gasperini, L. & Kurt, H. (2014). Multidisciplinary analyses to understand the tectonic activity and the evolution of the North Anatolian Fault in the Hersek Peninsula (Izmit Gulf, Turkey). *Bollettino Di Geofisica Teorica e Applicata, 55*(3), 589-616. https://doi.org/10.4430/bgta0122

Gökten, E., Havzoğlu, T. & Şan, Ö. (2001). Tertiary evolution of the central Menderes Massif based on structural investigations of metamorphics and sedimentary cover rocks between Salihli and Kiraz (western Turkey*). International Journal of Earth Sciences, 89*(4), 745-756. https://doi.org/10.1007/s005310000099

Göncüoğlu, M. C., Erendil, M., Tekeli, O., Ürgün, B.M., Aksay, A. ve Kuşçu, İ. (1986). *Armutlu Yarımadasının doğu kesiminin jeolojisi* (Rapor No.: 7786). MTA (Unpublished), Ankara.

Goren, L., Fox, M. & Willett, S.D. (2014). Tectonics from fluvial topography using formal linear inversion: Theory and applications to the Inyo Mountains, California. *Journal of Geophysical Research: Earth Surface, 119*(8), 1651-1681. https://doi.org/10.1002/2014JF003079

Hare, P. W. & Gardner, T.W. (1985). Geomorphic indicators of vertical neotectonism along converging plate margins, Nicoya Peninsula, Costa Rica. In M. Morisawa & J. T. Hack (Eds.), *Tectonic Geomorphology: Proceedings of the 15 Annual Binghamton Geomorphology Symposium* (pp.: 75-104), September 1984. Boston. Allen and Unwin.

Keller, E. A. & Pinter, N. (2002). *Active tectonics, Earthquakes, Uplift and Landscape*. 2nd Edition, Prentice Hall, Upper Saddle River, 362.

Ketin, İ. (1957). Kuzey Anadolu deprem fayı. *I.T.Ü. Bull., 15*(2).

Kirby, E. & Whipple, K. X. (2012). Expression of active tectonics in erosional landscapes. *Journal of Structural Geology, 44*, 54-75. https://doi.org/10.1016/j.jsg.2012.07.009

Okay, A. & Görür, N. (1995). Time and space relations in the formation of the West Black Sea and Thrace Basins. *Proc Symp on the Geology of the Thrace Basin*, 9–10.

Özalp, S., Emre, Ö. & Doğan, A. (2013). The segment structure of southern branch of the North Anatolian Fault and paleoseismological behaviour of the Gemlik Fault, NW Anatolia. *Bulletin of the Mineral Research and Exploration, 147*, 1-17. https://izlik.org/JA97CD39KS

Özcan, Z., Okay, A., Özcan, E., Hakyemez, A. & Altıner, S. (2012). Late Cretaceous-Eocene geological evolution of the Pontides based on new stratigraphic and palaeontologic data between the Black Sea coast and Bursa (NW Turkey). *Turkish Journal of Earth Sciences, 21*(6), 933-960. https://doi.org/10.3906/yer-1102-8

Perron, J. T. & Royden, L. (2013). An integral approach to bedrock river profile analysis. *Earth Surface Processes and Landforms, 38*(6), 570-576. https://doi.org/10.1002/esp.3302

Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geological Society of America Bulletin, 67*(5), 597-646. https://doi.org/10.1130/0016-7606(1956)67[597:EODSAS]2.0.CO;2

Schwanghart, W. & Scherler, D. (2014). TopoToolbox 2–MATLAB-based software for topographic analysis and modeling in Earth surface sciences. *Earth Surface Dynamics, 2*(1), 1-7. https://doi.org/10.5194/esurf-2-1-2014

Silva, P. G., Goy, J. L., Zazo, C. & Bardaji, T. (2003). Fault-generated mountain fronts in southeast Spain: geomorphologic assessment of tectonic and seismic activity. *Geomorphology, 50*(1-3), 203-225. https://doi.org/10.1016/S0169-555X(02)00215-5

Strahler, A. N. (1952). Dynamic basis of geomorphology. *Geological Society of America Bulletin, 63*(9), 923-938. https://doi.org/10.1130/0016-7606(1952)63[923:DBOG]2.0.CO;2

Şengör, A. M. C. (1979). The North Anatolian transform fault: its age, offset and tectonic significance. *Journal of the Geological Society, 136*(3), 269-282. https://doi.org/10.1144/gsjgs.136.3.0269

Şengör, A. M. C. & Yılmaz, Y. (1981). Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics, 75*(3-4), 181-241. https://doi.org/10.1016/0040-1951(81)90275-4

Tarı, U. & Tüysüz, O. (2016). The effects of the North Anatolian fault on the geomorphology in the Eastern Marmara region, northwestern Turkey. *Geodinamica Acta, 28*(3), 139-159. https://doi.org/10.1080/09853111.2015.1065308

Topal, S. (2012). *Denizli Havzasındaki fayların tektonik jeomorfolojisi* [Unpublished PhD thesis]. Pamukkale University, Türkiye, 145 pp. (in Turkish with English abstract).

Topal, S. (2019). Evaluation of relative tectonic activity along the Priene-Sazlı Fault (Söke Basin, southwest Anatolia): Insights from geomorphic indices and drainage analysis. *Journal of Mountain Science, 16*(4), 909–923. https://doi.org/10.1007/s11629-018-5274-x

Topal, S. (2024). Geomorphological responses of rivers to active tectonics along the Karahayıt Fault, Western Türkiye. *Journal of Mountain Science, 21*(5), 1464-1474. https://doi.org/10.1007/s11629-024-8649-1

Topal, S. & Irfan, M. (2025). Normal faulting and its role in the drainage divide migration in the Karıncalıdağ region, Menderes Massif, Western Türkiye. *Journal of Mountain Science, 22*(1),312–323. https://doi.org/10.1007/s11629-024-9132-8

Topal, S., Çınar Yıldız, S. & Özden, S. (2025). Orhangazi ve Yalova Fayları arasında kalan horst boyunca su bölüm hattının göçü: Aktif tektonik yönünden çıkarımlar. *Türk Coğrafya Dergisi, (87)*, 67-77. https://doi.org/10.17211/tcd.1638374

Willett, S. D., McCoy, S. W., Perron, J. T., Goren, L. & Chen, C. Y. (2014). Dynamic reorganization of river basins. *Science, 343*(6175), Article 1248765. https://doi.org/10.1126/science.1248765

Wobus, C., Whipple, K. X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B. & Sheehan, D. (2006). Tectonics from topography: Procedures, promise, and pitfalls. In S. D. Willett, N. Hovius, M. T. Brandon, D. M. Fisher (Eds.), Tectonics, Climate, and Landscape Evolution (pp.: 55–74). https://doi.org/10.1130/2006.2398(04)

Yılmaz, Y., Genç, Ş. C., Yiğitbaş, E., Bozcu, M. & Yılmaz, K. (1995). Geological evolution of the late Mesozoic continental margin of Northwestern Anatolia. *Tectonophysics, 243*(1-2), 155-171. https://doi.org/10.1016/0040-1951(94)00196-G

Yiğitbaş, E., Elmas, A. & Yılmaz, Y. (1999). Pre-Cenozoic tectono-stratigraphic components of the western pontides and their geological evolution. *Geological Journal, 34*(1-2), 55-74. https://doi.org/10.1002/(SICI)1099-1034(199901/06)34:1/2%3C55::AID-GJ814%3E3.0.CO;2-0

Yiğitbaş, E., Elmas, A., Sefunç, A. & Özer, N. (2004). Major neotectonic features of eastern Marmara region, Turkey: development of the Adapazarı–Karasu corridor and its tectonic significance. Geological Journal, 39(2), 179-198. https://doi.org/10.1002/gj.962