

Geomorphology and chronology of Late Quaternary terrace staircases of the Sakarya River, northwest Türkiye

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ABSTRACT: The Sakarya, one of the longest rivers in northwest Anatolia, has significant geomorphological units along its course including terrace systems that have potential to reveal the tectonic and geomorphological evolution of the region. The aim of this research was to identify the processes that have influenced the formation of terrace systems based on regional and local tectonic activities during the Late Quaternary and effects of global climatic changes on levels of the Black Sea. In particular along the İnhisar–Osmaneli section of the Sakarya River, the terrace systems, which are determined at four different levels, are crucial in terms of illuminating the geomorphological development of the region during the Late Quaternary. Our optically stimulated luminescence results revealed three different ages of deposition: 158.03 ± 12.93 , 150.97 ± 8.49 and 55.07 ± 4.57 ka (Middle–Late Pleistocene). This permitted calculation of a mean regional uplift rate of 0.18 ± 0.03 mm a⁻¹ since the Middle–Late Pleistocene. The younger terrace remnants correspond to Late Pleistocene Marine Isotope Stage (MIS) 3c (interstadial) and the older ones to Late Middle Pleistocene MIS 6b (interstadial). This implies that the Sakarya River accumulated floodplain sediments, now terraces, during relatively warm and humid periods. On the other hand, in cold and/or cold–warm transition periods, it created terraces by incision into the river bed. This interpretation implies that fluvial incision in the region was a response to regional uplift that has been continuing for at least the last 158 ka.

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KEYWORDS: fluvial terrace; Northwest Anatolia; OSL dating; Sakarya River

Introduction

River systems play a crucial role in shaping most of the land surface and have shown important responses to global climate changes and local/regional tectonic movements during the Quaternary (Bridgland, 2000; Schumm et al., 2000; Vandenberghe, 2002; Westaway et al., 2003; Bridgland & Westaway, 2008a; Lord et al., 2009; Vandenberghe et al., 2018). Terrace systems are exceptional natural archives where sedimentological, stratigraphic, geomorphological, climatic and hydrological records of these responses are preserved (Larson et al., 2015; Olszak, 2017; Yang et al., 2020; Ma et al., 2023). Due to their internal structures (sedimentological and stratigraphic features), elevations (morphometric features) and dating opportunities (chronology), river terrace systems have a particular importance in geomorphology. As they are spatially and temporally interrelated, terrace systems may provide important clues in understanding the geomorphological evolution of both the local valley and the region as a whole (Veldkamp, 1992).

The Anatolian peninsula was greatly affected by tectonic, climatic and hydrological changes during the Quaternary due to its unique geological and geographical location at the boundary between temperate and sub-tropical climate zones. This includes local and/or regional tectonic movements that have been ongoing since the beginning of Neotectonic activity (Bozkurt, 2001). As a consequence, widespread terrace systems have been created in the large valleys of

Türkiye (i.e. Euphrates, Tigris, Kızılırmak, Yeşilırmak, Sakarya River) with differing origins and characteristics. Quantitative studies (sedimentological analyses, morphometry and dating efforts) carried out on these terrace systems are crucial for understanding the geomorphological evolution of Türkiye's landscape during the Quaternary.

Although Anatolia offers quite rich information on fluvial geomorphology, research on this topic did not start until the middle of the 20th century. The earliest studies of the last century were aimed at describing the river systems and regimes and illustrating valley morphology. The first studies of fluvial terrace systems in this region were by İlgüz (1940) and Pfannenstiel (1941) and continued with İnandık (1955), Akkan (1970) and Erol (1973). These studies were mostly based on morphometric and stratigraphic analyses, and a geochronological dimension was added with the increased interest in terrace systems especially after the 2000s and with the use of optically stimulated luminescence (OSL) and terrestrial cosmogenic nuclide (TCN) dating methods. Among the rivers that were examined were the Kızılırmak (Doğan, 2011; Yıldırım et al., 2013b; CÇiner et al., 2015; Berndt et al., 2018; Doğan & Şenkul, 2020; Hubert-Ferrari et al., 2019, 2021), the Yeşilırmak (Altın et al., 2017; Erturaç & Kıyak, 2017), the Tigris/Dicle (Bridgland et al., 2007; Westaway et al., 2009; Karadoğan & Kuzucuoğlu, 2019), the Gediz (Westaway et al., 2003, 2006; Maddy et al., 2017, 2020), the Göksu (Aydın et al., 2019), the Melendiz (Doğan et al., 2019), the Orontes/Asi (Bridgland et al., 2012), the Filyos (McClain et al., 2019, 2021), the Murat (Demir et al., 2009; Aydın et al., 2021), the Ceyhan (Seyrek et al., 2008; Bridgland & Westaway, 2014) and the

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Sakarya (Erturaç et al., 2019a, 2019b; Erturaç, 2021; Karakoca et al., 2021; Karakoca, 2022).

The Sakarya River, 824 km long, is located on the north-western part of the Anatolian peninsula, 40 km east of the Sea of Marmara, and flows northwards into the Black Sea. A large part of northwest Anatolia is drained by the Sakarya and its tributaries. The alignment of the Sakarya valley changes frequently, mainly determined by tectonic and geomorphological factors, and it makes one of its most notable changes in direction in its middle course, near Söğüt, Bilecik. After that point, to the west of the Central Sakarya Plateau, the east–west direction of the Sakarya River shifts to a south–north direction. It reaches the Adapazarı Plain by passing through a series of gorges in the present study area. In this part of the river, there are some remarkable river terrace systems that are the subject of our study (Fig. 1).

The aim of this study was to investigate the origin and evolution of the terrace systems in the middle part of the Sakarya between İnhisar and Osmaneli districts near the city of Bilecik. There is a significant gap in the literature concerning the terrace systems within the section of the Sakarya River valley that encompasses the study area. Specifically, the role of factors influencing the formation and development of terrace levels, such as climatic changes and tectonic activities, remains unclear. This study seeks to find answers to the following research questions: (i) How have local and regional tectonic activities influenced the formation and development of terrace systems along the Sakarya River during the Quaternary? (ii) In what ways have fluctuations in Black Sea levels, driven by global climatic changes, impacted terrace formation processes along the Sakarya River valley? (iii) What is the importance of dating and elucidating the geochronological characteristic of the terrace systems in the study area? We studied the deposition and incision by the Sakarya in relation to regional and local tectonic activities and sea-level changes of the Black Sea. The section of the river mentioned above is separated by deep bedrock gorges with relatively wider valley floors in between. Our sedimentological and morphometric studies were concentrated at five different sites, namely Yakacık, Hamitabat, Gemiciköy, Küçükyenice and Selimiye. A chronostratigraphic framework was created by applying the OSL dating method to samples from three different terrace deposits (Fig. 1).

Regional setting

The study area is located in northwest Anatolia and lies within the tectonic belt known as the ‘Sakarya Continent’ which is bounded by the Intra-Pontid suture to the north and the İzmir–Ankara Suture zone to the south (Fig. 2). The Sakarya Continent consists of rock assemblages that form the fundamental units of the region, including Palaeozoic granite–granodiorites, the Söğüt metamorphics (marble and schists) and the Karakaya Formation. Overlying these units are the Mesozoic Bayırköy Formation and the Bilecik limestones (Granit & Tintant, 1960; Eroskay, 1965; Altınlı, 1973; Yılmaz, 1981), as well as the Middle Eocene–Lower Miocene Gemiciköy Formation (fluvial–lacustrine sediments) (Eroskay, 1965; Demirkol, 1977; Saner, 1980), which are unconformably overlain by Quaternary units (Fig. 3). During the Middle to Late Miocene, as a result of continental collision between the Arabian–African and Eurasian plates, Anatolia was uplifted and began moving westward, a process known as the Neotectonic period/activity (Bozkurt, 2001; Bozkurt & Mittweide, 2001; Okay et al., 2020; Şengör & Yazıcı, 2020). This resulted in the study area being subjected

to a north–south compressional tectonic regime and horizontal tectonic movements of a transform nature, placing it between two active strike-slip faults: the North Anatolian Fault Zone (NAFZ) to the north and the Eskişehir–İnönü Fault Zone (EIFZ) to the south. The presence of Mesozoic units at high mountain and plateau levels with various tilting directions indicates uplifted relief due to compression in the region. Uplifted blocks formed the Middle Sakarya Plateaus, while subsiding blocks shaped local basins such as the Hamitabat and Gemiciköy basins (Emre et al., 1998). Throughout the Quaternary, the Sakarya River and its tributaries exploited the karstic features facilitated by ongoing tectonic movements, deeply incising into the Middle Sakarya Plateaus. The resulting gorges opened the previously enclosed basins to external drainage (Emre et al., 1998; Karakoca & Uncu, 2020).

Materials and methods

Field studies and geomorphology

In this study, the terrace systems in the Sakarya valley were analysed with reference to morphometric, sedimentological, stratigraphic and chronological data. Field studies were carried out to determine the morphometric properties of the terrace systems, to establish their stratigraphy and to elaborate on their sedimentology. During the field studies, geodetic measurements were made and samples for radiometric dating were taken. In particular, a detailed geomorphology map was produced using a digital surface model with 10-m horizontal resolution and the resulting relief models obtained from General Command of Mapping of Türkiye, orthophoto images and topography maps with 10-m contour intervals. In addition, a DJI Mavic Mini Unmanned Aerial Vehicle (IHA-UAV) model and up-to-date photogrammetry method (SfM – Structure from Motion) were used to map the geomorphological features of the terrace systems. The purpose was to obtain not only a detailed and precise definition of the terraces but also spatial and temporal high-resolution topography data relating to them. These data were visualized with the help of geographic information systems (ArcMap-ESRI) and remote sensing software (Agisoft Metashape Professional).

OSL dating

To demonstrate the chronological characteristics of the terrace levels, OSL dating was used. This method for dating sediments is based on the following equation:

$$\text{OSL age (years)} = \text{equivalent dose (Gy)} / \text{dose rate (mGy a}^{-1}\text{)}$$

The magnitude of the luminescence signal from the sample is directly proportional to the natural dose. The natural dose relates to the time elapsed from the time the sample was last exposed to light or heat up to the date of measurements. The annual dose refers to the sum of the amount the sample absorbs from its setting, its embedded radioactive elements and the cosmic rays within a year. As a result, the ratio of natural dose to annual dose is equal to the age of the sample. Here, it refers to the time elapsed from the last time the sample was exposed to heat or light until the date of measurement, which is expressed as age (Şahiner, 2015).

In this study, samples were taken from silty–very fine sandy units within the river sediments. These samples were selected to provide a precise estimation of the age of sediment deposition within the river terrace levels. Sampling was carried out according to general OSL sampling procedures by hammering 6.5-cm-diameter, 4-mm-thick and 30-cm-long opaque rigid steel tubes into the pre-cleaned cross-sectional

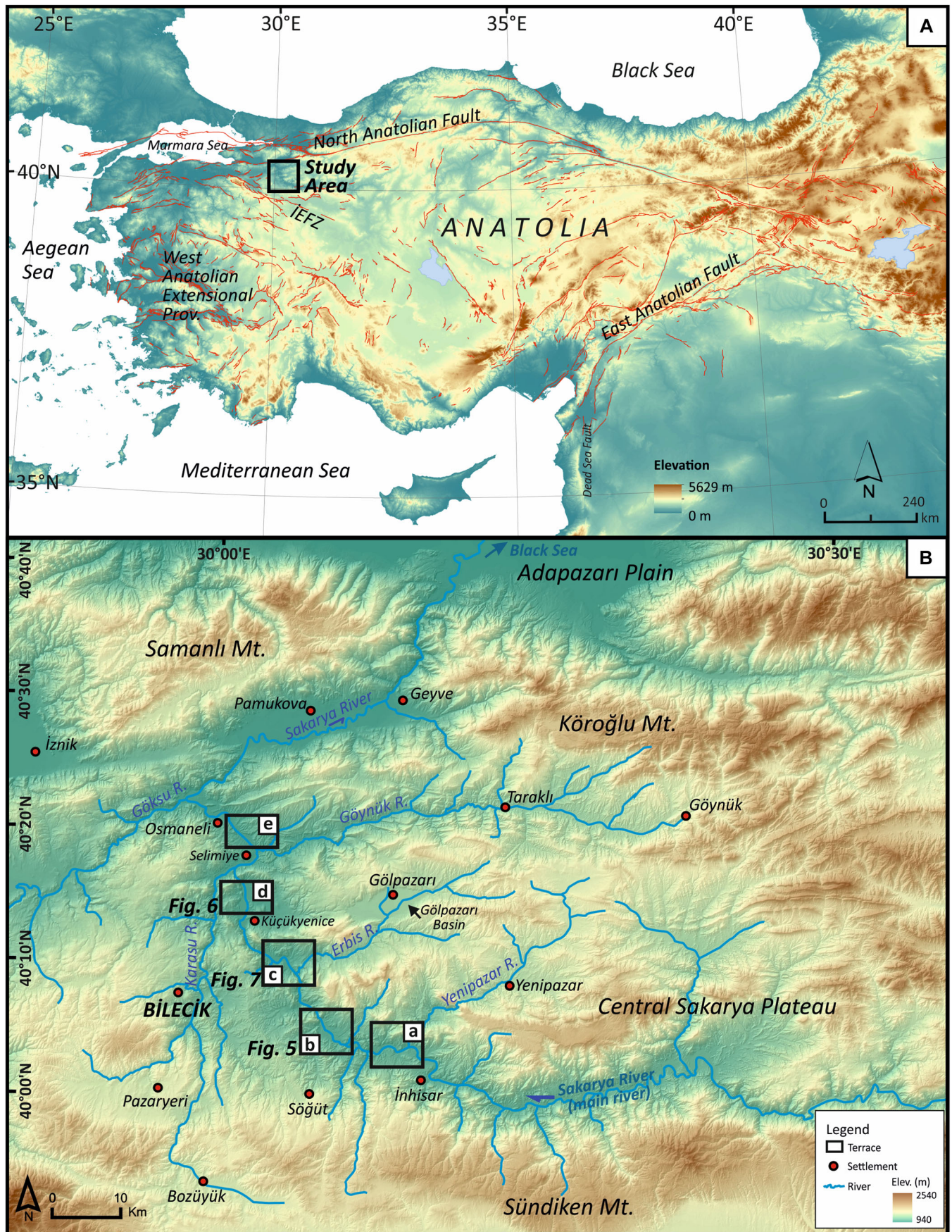


Figure 1. (A) Map showing the active faults of Anatolia and location of the study area. Red lines mark main active faults obtained from General Directorate of Mineral Exploration and Research (Emre et al., 2013). Black box shows the middle Sakarya River Basin study area. (B) Terrace systems in the Sakarya River valley. They are concentrated at five sites. (a) Site 1: Yakacık, (b) Site 2: Hamitabat, (c) Site 3: Gemiciköy, (d) Site 4: Küçükyenice and (e) Site 5: Selimiye. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

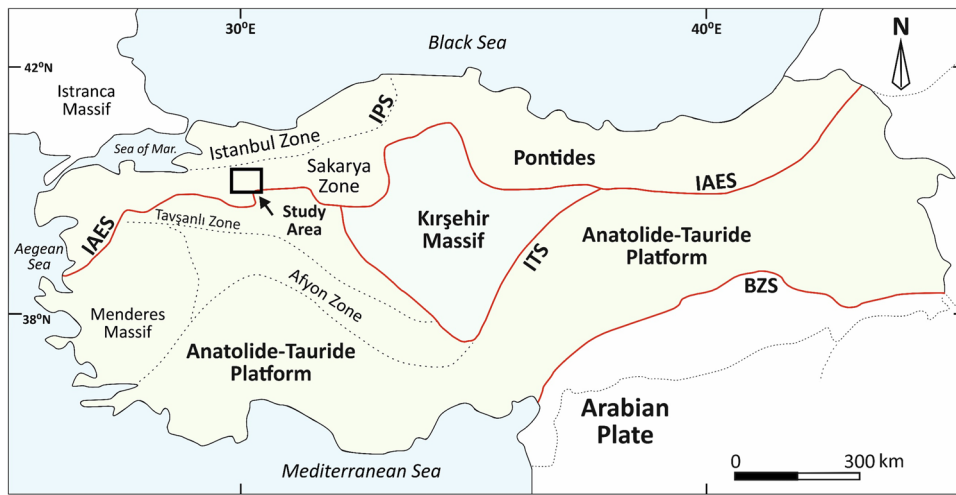


Figure 2. Generalized palaeo-tectonic map of Anatolia. IAES, Izmir–Ankara–Erzincan Suture; IPS, Intra-Pontid Suture; BZS, Bitlis–Zagros Suture (Kibici et al., 2010; Mueller et al., 2019; Okay et al., 2020; Mueller et al., 2022). [Color figure can be viewed at wileyonlinelibrary.com]

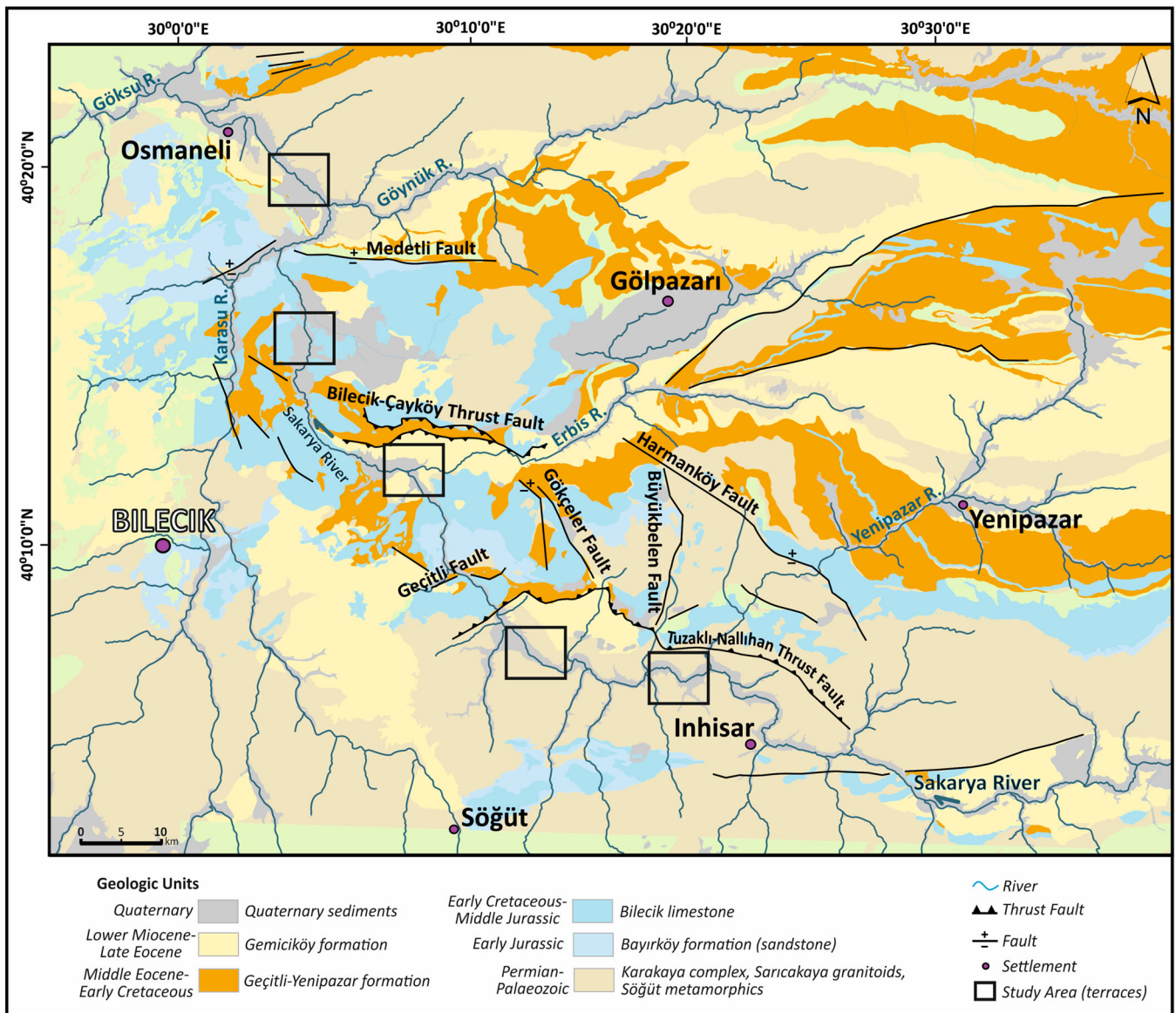


Figure 3. Geological map of the study area. The geological record is defined as two lithostratigraphic units: basic units (pre-Triassic) and cover units (post-Triassic). Fault details obtained from General Directorate of Mineral Exploration and Research (Emre et al., 2013). [Color figure can be viewed at wileyonlinelibrary.com]

surface. As a particular requirement, we ensured that light was not let into the tube during and after sampling. At the same time, at least 500 g of sediment sample was taken from the material surrounding the sample pipe to determine the environmental dose rate. The pounded pipe was sealed with a lightproof bag and tape, and compressed and packed so as not to allow shaking or moving of the sample inside the pipe during transportation. As a last step, the height of the sample location on the terrace system and the depth from the surface were noted, and the section from which the sample was taken was photographed.

All stages of OSL dating (mineral extraction and equivalent dose measurements) were implemented at Ankara University's Nuclear Sciences Institute Luminescence Dating Research Laboratories.

Results

Geomorphological features

The Sakarya drains the waters of the region known as the Central Sakarya Plateaus in its middle course. The river, together with its tributaries, deepened the valley along weakly resistant areas developed as a result of regional/local tectonic movements since its settlement in the region, and the

opportunities provided by ongoing karstification events since the Middle Miocene. Fluctuations in the level of the Black Sea due to climatic changes during the Quaternary have also undoubtedly played a role in the current geomorphological appearance. During the Quaternary, the gorges opened previously were deepened and the river also formed the terrace systems that can be followed in several steps at suitable locations along the valley (Fig. 4).

Morphometric and sedimentological characteristics of the terrace systems

Across the study area, in places the Sakarya River flows in narrow and deep gorges, whereas in others (İnhisar, Hamitabat, Gemiciköy, Küçükyenice and Selimiye Site surroundings) it flows in a relatively wide alluvial setting of basin-like character. In such alluvial reaches, in particular, it is possible to see terrace systems developed in several steps. In the study area, which covers the 72-km reach of the Sakarya River valley between İnhisar and Osmaniye, the terrace systems were studied at five sites.

Starting from the Sakarya valley floor, terrace steps were identified with varying levels at different locations. Four main terrace levels were identified (+52, +34, +18 and +10 m) around the Yakacık Site, three (+36, +24 and +12 m) around the Hamitabat Site, two (+19 and +10 m) around the

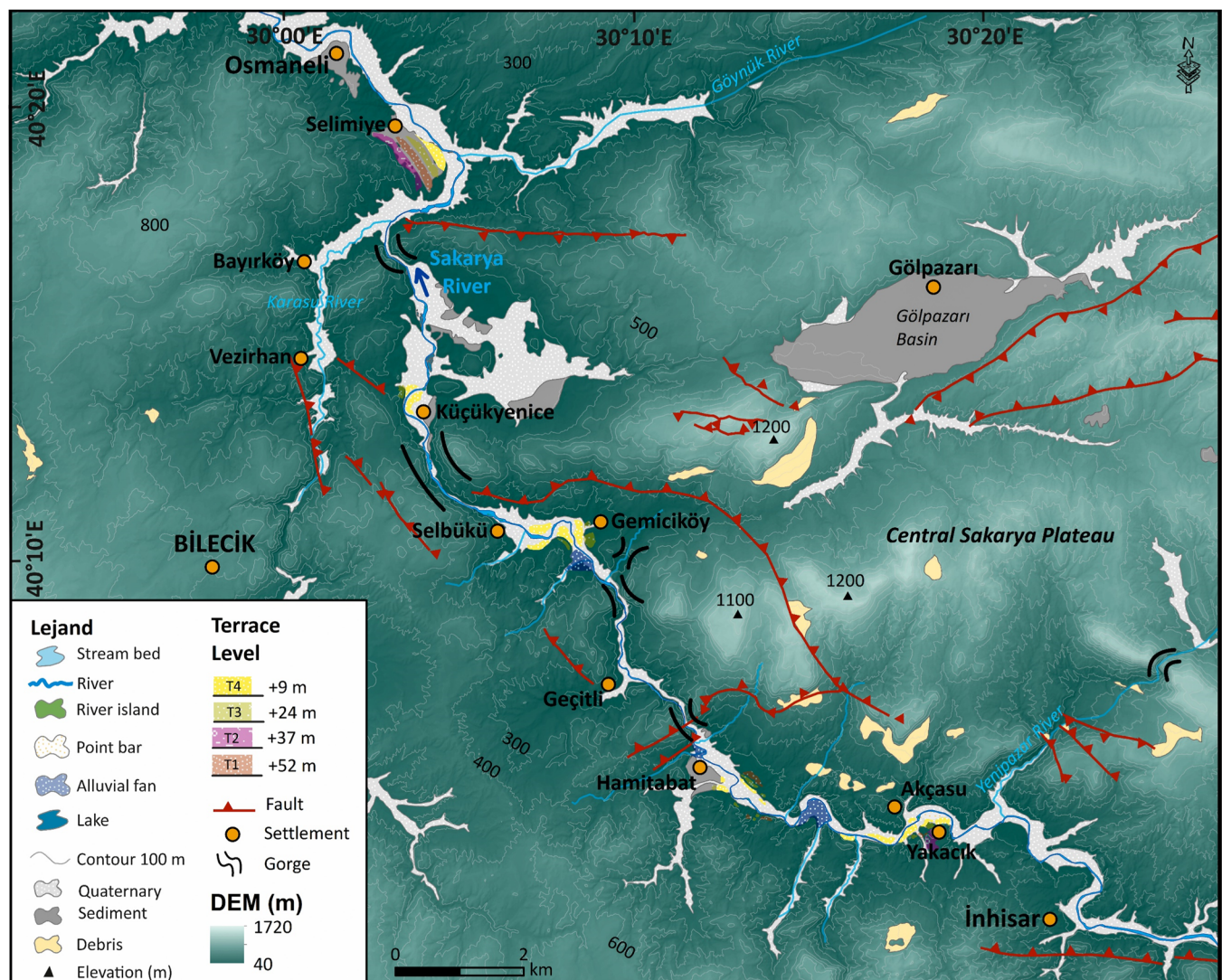


Figure 4. Geomorphological map and important fluvial morphological units in the study area. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

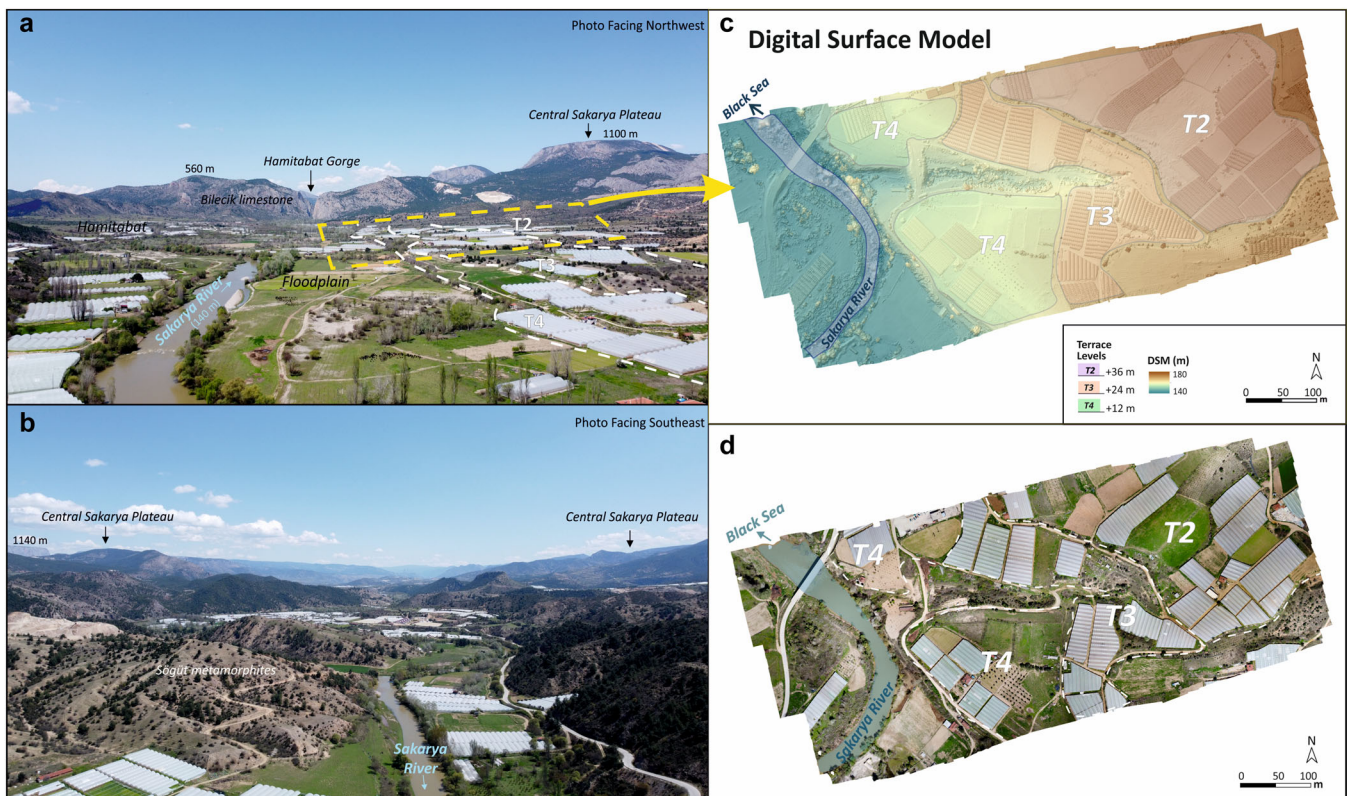


Figure 5. Aerial images showing western (a) and eastern sections (b) of the Central Sakarya Plateau. (c) High-resolution digital surface model (6.38 cm per pixel) and (d) orthomosaic image obtained using DJI Mavic Mini UAV Model of Terrace Systems (23 ha of areas T2, T3 and T4) near Hamitabat. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/jqs.3695)]

Gemiciköy Site, two (+26 and +9 m) around the Küçükyenice Site and four (+50, +37, +24 and +9 m) around the Selimiye Site (Fig. 5). At the same time, the terrace systems in this region display a regular continuity in the vertical and horizontal directions (Karakoca & Uncu, 2020).

The alluvial deposits in which the terrace systems developed consist of sections that are sedimentologically and clearly separated from each other vertically and horizontally. Among others, the terrace at +21 m (T3) height near the Küçükyenice Site has an alluvial filling of ~11–12 m. This is very important, suggesting the temporal and dynamic changes in the sedimentological processes in the region. In fact, this deposit consists of ~3-m-thick, predominantly grain-supported and well-sorted channel fillings, showing a transition from horizontal and parallel-layered fine pebbles to medium-coarse pebbles. It is followed by fluvial deposits indicating more periodic flow with planar cross-bedded sandy and semi-rounded to rounded fine-medium pebbles towards the top. Above it, there is a silty and fine sandy unit with a thickness of about 1–1.5 m and 2-m-thick horizontal and parallel laminated clay-silt floodplain sediments that continue up to the present surface. Considering the changing climatic conditions, this seems to be a sign of a gradual change in flow dynamics from flooding and high energy towards calm and low energy (Fig. 6).

Chronological characteristics of the terrace systems

The OSL dating method was applied to inorganic (clay-silt-fine sand) sediment samples taken from well-preserved terrace steps. Silty-very fine sandy sections located at three different terrace levels near the Hamitabat, Gemiciköy and Küçükyenice sites were chosen for OSL dating (Fig. 7).

According to the OSL results, the following ages were calculated from the corresponding samples: 158.03 ± 12.93 ka

at +32 m in the +36-m (T2) terrace deposit at the Hamitabat Site, 55.07 ± 4.57 ka at +5 m in the +10-m (T3) terrace near Gemiciköy, and 150.97 ± 8.49 ka at +13 m inside the +21-m-high deposit near Küçükyenice. This suggests that the deposits of the terrace systems were laid down in a period varying between roughly 160 and 50 ka (Table 1).

Discussion

There has been significant debate regarding the formation of river terraces. While there is a general consensus that climatic changes have played a crucial role in terrace formation, an increasing body of research suggests that long-term regional uplift and base-level changes are also critical factors influencing terrace development (Bridgland & Westaway, 2014). For example, records obtained from river terraces in northwest Europe (the Thames River and Hampshire Avon River) indicate that regional uplift is the primary factor influencing river incision (Maddy et al., 2000). There have been many studies related to river terrace systems in northwest Anatolia (Fig. 8). Regarding the formation and development of terrace systems in the region, these studies have revealed that the role of regional/local tectonic activity has been more effective than climatic-based sea-level changes. Our findings for the terrace systems in the middle Sakarya River valley support these results. Thus, while our dating results are similar to dates of terrace systems in various studies, their morphometric features are different.

Tectonic processes and long-term regional uplift

In a given area, the local and/or regional tectonic activity can be calculated based on the annual constant uplift rate determined from river terraces. When terrace staircases are

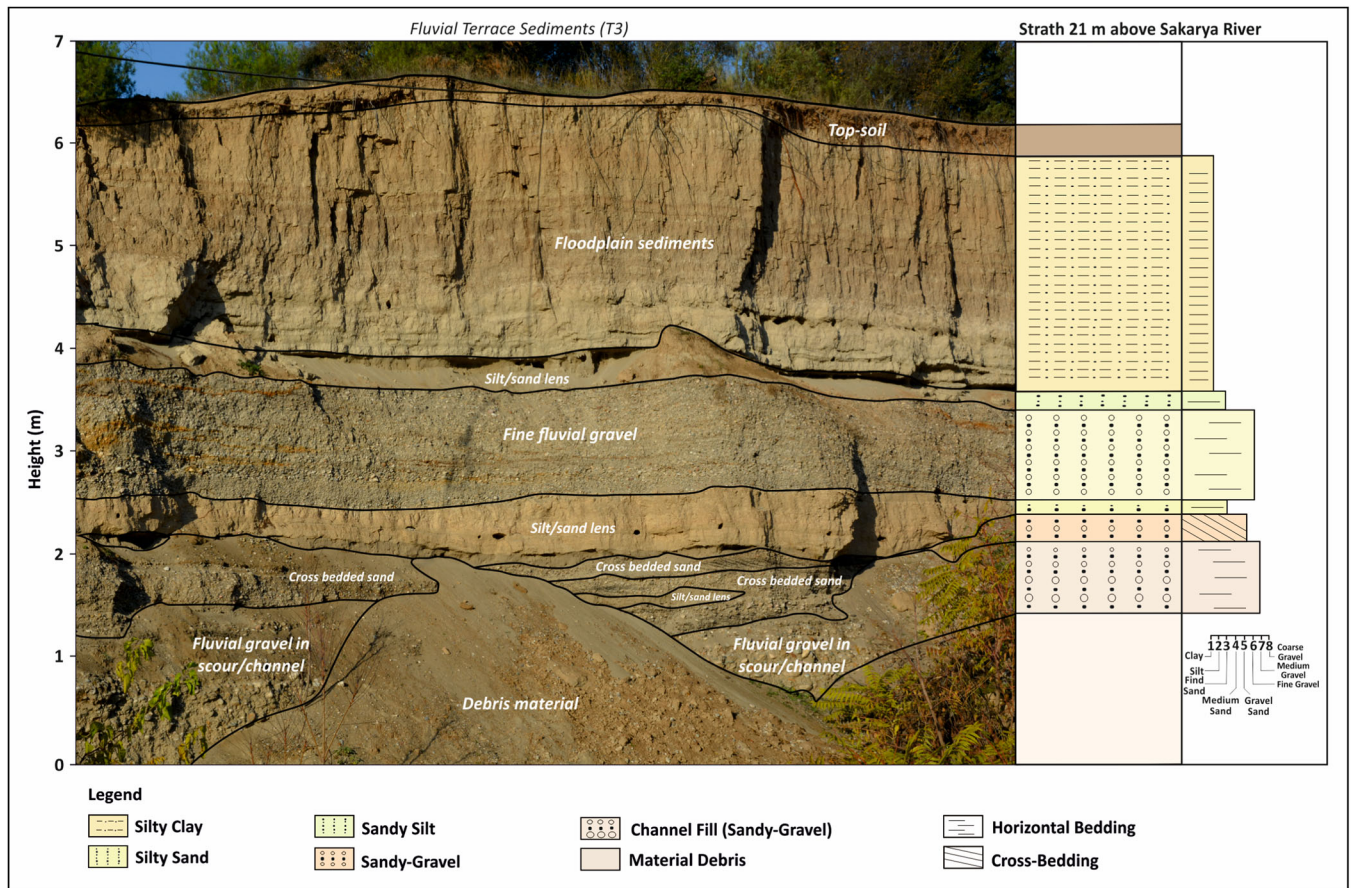


Figure 6. Stratigraphic section of T3 deposits (+21 m) near Küçüknyence (Site 4). The terrace deposit numbered T3 consists of semi-rounded to rounded, horizontally layered fine–medium sized pebbles, and in some places contains coarse pebble-sized materials. In addition, it is composed of angular stones and planar cross-bedded clay, silt and sand-sized materials [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

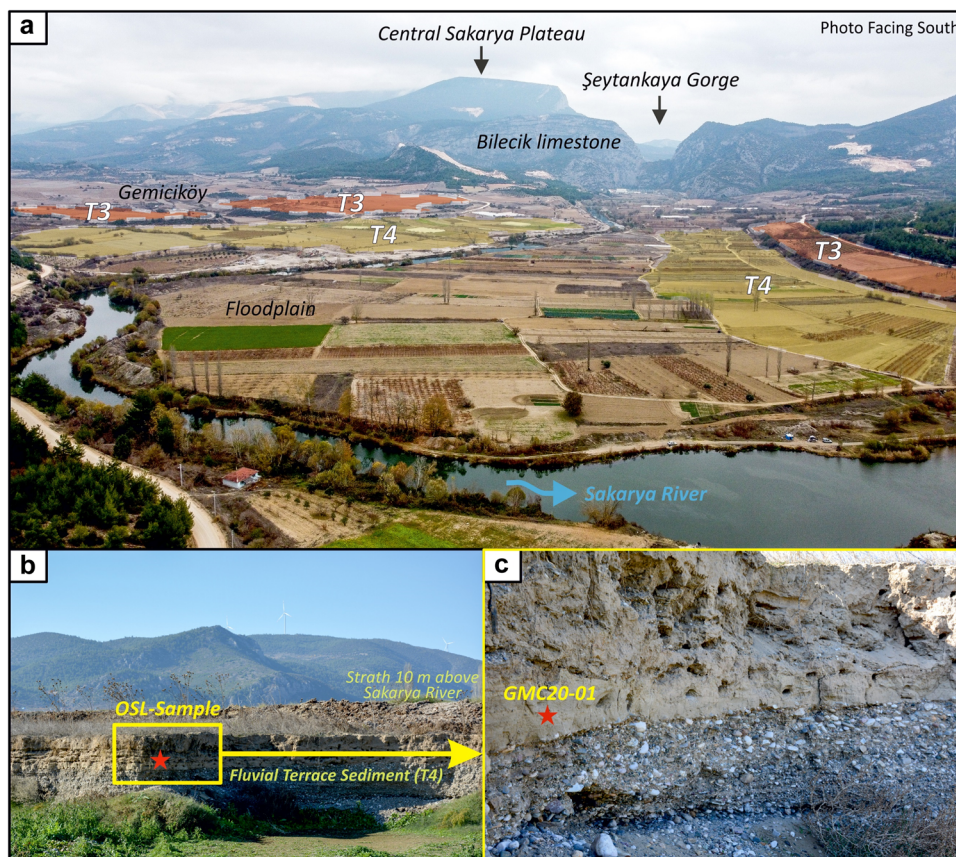


Figure 7. River terrace staircases of the Sakarya River valley. (a) Drone image showing terrace systems in the Gemiciköy Basin. (b) Strath and its deposit (T4) located 10 m above the Sakarya River. (c) Location of OSL sample within the terrace. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Table 1. Geomorphology and chronology of Late Quaternary terrace staircases of the Sakarya River, northwest Türkiye.

Sample code	Location	Altitude (m)	Depth (m)	Latitude (X°Y'Z'")	Longitude (X°Y'Z'")	Aliquots	Grain size (µm)	Equivalent dose (Gy)	OD (%)	U (ppm)	Th (ppm)	K (%)	H ₂ O (%)	Rb (ppm)	Cosmic dose (mGy a ⁻¹)	Dose rate (mGy a ⁻¹)	Age (ka)
HMT20-01	Bilecik, Söğüt, Hamitabat	178	0.3	40°05'05" N	30°14'39" E	16/16	90–140	270.58 ± 18.25	26 ± 5	1.56 ± 0.04	4.42 ± 0.66	1.31 ± 0.03	30 ± 5	40.7803 ± 1.1439	0.24 ± 0.02	1.71 ± 0.08	158.03 ± 12.93
GMC20-01	Bilecik, Merkez, Gemiciköy	126	0.3	40°11'9" N	30°08'13" E	16/16	90–140	100.73 ± 7.2	28 ± 5	1.41 ± 0.04	4.94 ± 0.57	1.47 ± 0.03	30 ± 5	46.8881 ± 1.1439	0.24 ± 0.02	1.83 ± 0.08	55.07 ± 4.57
KY20-01	Bilecik, Çölpazarı, Küçükyenice	129	0.3	40°14'08" N	30°03'86" E	16/16	90–140	265.19 ± 8.18	11 ± 2	1.48 ± 0.04	5.3 ± 0.67	1.33 ± 0.03	30 ± 5	41.5429 ± 1.1439	0.24 ± 0.02	1.76 ± 0.08	150.97 ± 8.49

well constrained by dating data, different patterns emerge in terms of height–age relationships and frequencies of terrace formation. In recent years, fluvial incision has been associated with surface uplift (Bridgland & Westaway, 2008b). One of the locations where this relationship is particularly evident is the Middle Rhine in Europe, where fluvial incision indicated by dated terraces implies surface uplift of up to ~200 m since the late Early Pleistocene, with a surface uplift rate of 0.2 mm a⁻¹ (Bridgland & Westaway, 2008b). In contrast, there have been various studies on Quaternary surface uplift in Anatolia, generally based on surface dating or fluvial terraces (e.g. Yıldırım et al., 2013a, 2013b; Çiner et al., 2015; Erturaç & Kiyak, 2017; Berndt et al., 2018; Hubert-Ferrari et al., 2021; McClain et al., 2021). The data obtained from these studies cover the last few hundred years (Okay et al., 2020). Studies indicating the regional uplift rate using the river terrace systems in Türkiye have yielded noteworthy results in relation to the proximity and distance from the NAF zone. The long-term average regional uplift rate of the Central Anatolian Plateau was determined to be 0.05–0.08 mm a⁻¹ in the central part of the Kızılırmak River (ÇÇiner et al., 2015; Doğan & Şenkul, 2020). While the regional uplift rate was measured as 0.16 mm a⁻¹ in the central part of the Gediz River in Western Anatolia (Maddy et al., 2017), this value was found to be 0.6–0.7 mm a⁻¹ in the Mut basin in Southern Anatolia, and the high uplift rate there was thought to related to mantle dynamics (Schildgen et al., 2012). These figures were recorded as 0.05 mm a⁻¹ in the Göksu River valley (Avşin et al., 2019), 0.25–0.4 mm a⁻¹ in the Ceyhan River valley (Seyrek et al., 2008; Bridgland & Westaway, 2014) and 0.5–0.6 mm a⁻¹ in the Murat River valley (Demir et al., 2009; Avşin et al., 2021). Notably, the uplift recorded in the Murat River valley (0.5 mm a⁻¹) is regarded as relatively high compared to global standards today (Bridgland & Westaway, 2007; Demir et al., 2009). The findings from Nahr el Kebir (Bridgland et al., 2024) align closely with the uplift rate (~0.4 mm a⁻¹) calculated from the terraces of the River Ceyhan by Seyrek et al. (2008). Recent research by Bridgland et al. (2024) on the Pleistocene and Palaeolithic sequences of Nahr el Kebir has led to updated interpretations that incorporate modern knowledge of climate changes and the complexity of crustal processes. In particular, revised understanding of crustal processes indicates unusually rapid uplift in this part of the Mediterranean during the Late Quaternary. It has been suggested that this effect is epeirogenic, related to crustal characteristics rather than tectonic activity, despite the proximity to major active fault zones (Bridgland et al., 2024). Furthermore, along the central NAF in the Central Pontides, transpression and crustal thickening along the northward restraining bend of the fault are thought to have produced rock uplift rates of 0.2–0.3 km Ma⁻¹ since at least 400 ka, based on Quaternary marine and river terraces (Racano et al., 2023).

Other reported regional uplift rates are as follows: 0.28 ± 0.07 mm a⁻¹ in the Kızılırmak Delta to the north of the North Anatolian Fault (Berndt et al., 2018, Berndt, 2019), 0.28 ± 0.07 mm a⁻¹ in the Gökırmak Stream, a prominent tributary of the Kızılırmak (Yıldırım et al., 2013b), and 0.15–0.20 ± 0.03 mm a⁻¹ in the Filyos Stream (McClain et al., 2021). In addition, the regional uplift rate was recorded as 1.00 mm a⁻¹ in the Kâmil Basin, where the NAF cuts the Kızılırmak (Hubert-Ferrari et al., 2021), and 0.94 ± 0.26 mm a⁻¹ (Erturaç & Kiyak, 2017) and 1.25 mm a⁻¹ (Altın et al., 2017) in the Yeşilırmak River valley, and the average value was 0.75 ± 0.06 mm a⁻¹ for the lower course of the Sakarya River just south of the first branch of the NAF (Altın et al., 2017)

In the middle course of the Sakarya River, the regional uplift rate is 0.22 ± 0.03 mm a⁻¹ in the vicinity of Hamitabat, 0.18 ± 0.03 mm a⁻¹ at Gemiciköy and 0.14 ± 0.03 mm a⁻¹ at

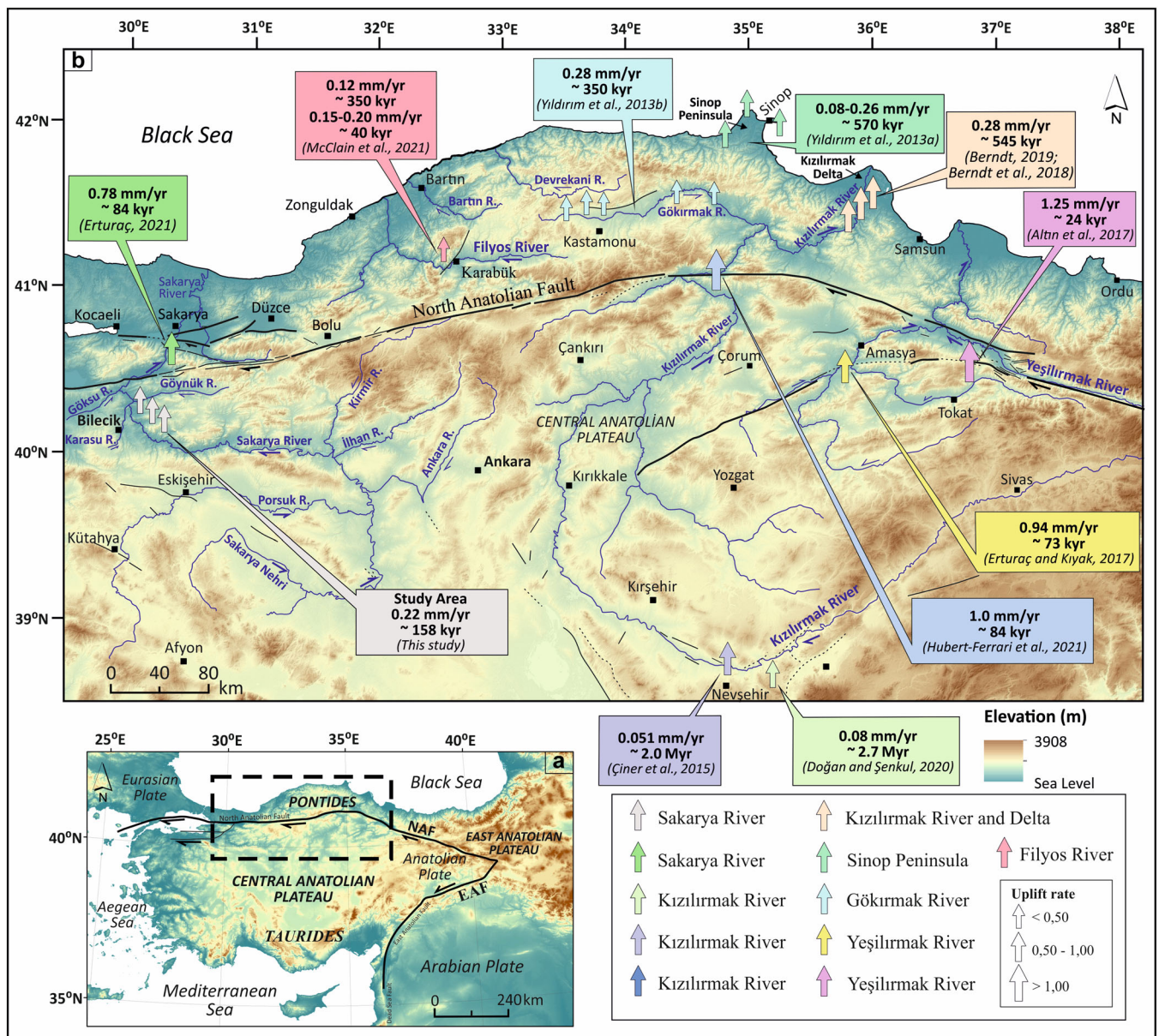


Figure 8. Maps showing the tectonic structure of Anatolia. (A) Relief map of the Central Pontides showing tectonic zones and (B) previous studies used to determine the regional uplift rate of northern Anatolia. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

Küçüknyence. Overall, the average regional uplift rate from different locations and altitudes is $0.18 \pm 0.02 \text{ mm a}^{-1}$. Thus, the OSL age results obtained here imply splitting of the river as a reaction to regional uplift that has continued for at least the last 158 ka in the area under study (Fig. 8).

When the regional uplift rates are compared, it needs to be emphasized that the values for North Anatolia are higher than those for Central Anatolia. This supports the assumption that the NAF is the main driving force dominating the pattern of uplift on the northern edge of the Central Anatolian Plateau. In particular, it can be concluded that the effects of tectonic activities superimposed on regional uplift are essentially disruptive in nature (Abou Romieh et al., 2009).

As another important result, in contrast to the hypothesis that the longitudinal profile taken along the bed of the Sakarya River between Inhisar and Osmaneli would show a regular slope within the same lithological unit, the discovery of intermittent knickpoints along the slope signals the effect of local tectonic activities (Fig. 9). Further indications of these tectonic activities include the failure to identify any gravel

orientation/imbrication in the terrace deposits, the presence of terrace steps mostly on only one side of the river valley, non-conformity of the levels of the terrace systems around Hamitabat despite appearing on both sides of the river valley, and displacements in the river bed at some locations.

Climatic processes

Previous regional tectonics studies have shown that the Sakarya River incised alluvial deposits accumulated on its valley floor in response to regional uplift during the Quaternary. In addition, climatic changes (cold–warm climate transitions) in the Quaternary both controlled the base level depending on sea-level fluctuations and shaped incision–accumulation cycles by regulating the volume of water carried by the rivers and the amount of sediment they carried (Armaş et al., 2019; Erturaç et al., 2019a, 2019b; Karakoca & Uncu, 2020; Hubert-Ferrari et al., 2021).

Our ages for the river terraces range between the Middle–Late Pleistocene (158.03 ± 12.93 and 150.97 ± 8.49

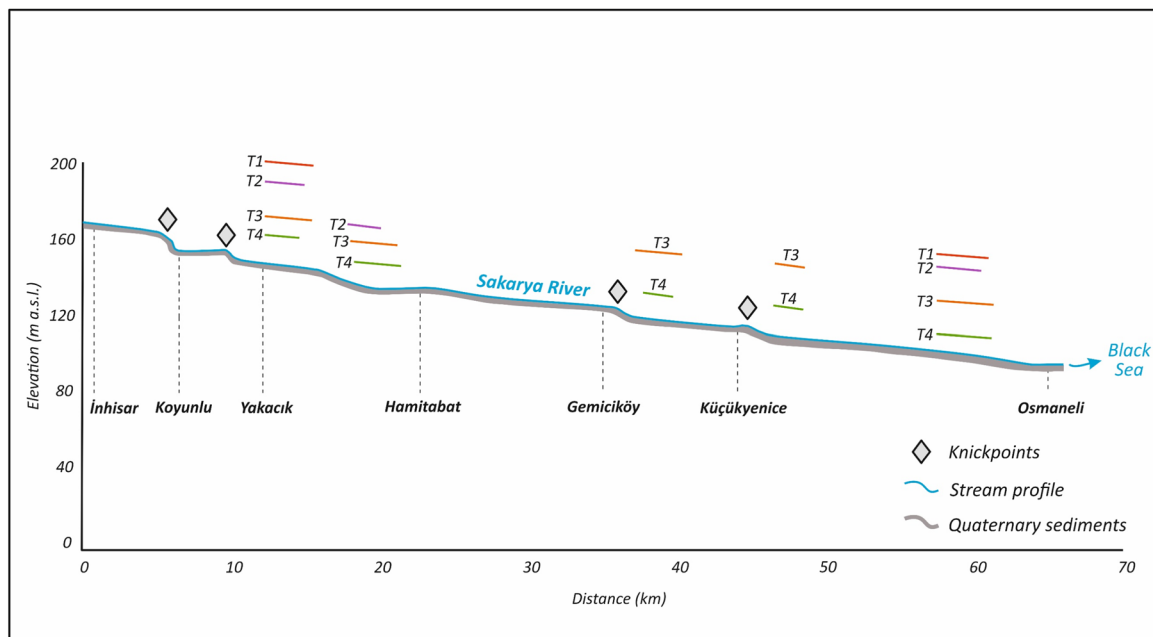


Figure 9. Longitudinal profile of the Sakarya River along the study area. Knickpoints observed within the Quaternary units indicate the local tectonic activity in the study area. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/jqs.3695)]

ka) and the Late Pleistocene (55.07 ± 4.57 ka). This implies that the deposits of the terrace systems indicate deposition between roughly 160 and 50 ka. When Marine Isotope Stages (MIS) are considered, the younger ages represent MIS 3c (Interstadial) and the older ones represent MIS 6b (Interstadial). The ages of the terrace step dating to the Late Pleistocene MIS 3 period (55.07 ± 4.57 ka) in the Sakarya River valley are almost consistent with previous dating studies on the other river valleys opening to the Black Sea, namely the Filyos Stream (52.5 ± 2.89 ka, McClain et al., 2020), Yeşilırmak River (48.5 ± 5 ka, Erturaç & Kıyak, 2017), Gökırmak Stream (68 ± 6 ka, Yıldırım et al., 2013b), Kızılırmak River–Kâmil Basin (~ 40 ka, Hubert-Ferrari et al., 2021), Develi River–Düzce Basin (~ 60 ka, Pucci et al., 2008) and Danube River (50 ± 6 ka, Armaş et al., 2019).

It can be suggested that the Sakarya River accumulated materials on its bed during the relatively warm and humid interglacial and interstadial periods when the sea level of the Black Sea was higher. Conversely, it incised its bed during the cold and cold/warm transition periods when sea level fell, forming the terrace systems. The dating results indicate the Penultimate Glacial Maximum after MIS 6b and the Last Glacial Maximum after MIS 3c for river incision (Fig. 10).

Conclusions

Türkiye, located in a highly seismically active region, exhibits significant tectonic activity (Bozkurt, 2001). In particular, Türkiye's active tectonics are characterized primarily by deformation resulting from the continental collision between the Arabian–African and Eurasian plates (Bozkurt and Mittweide, 2001). The NAFZ and the EIFZ are the products of this deformation (Bozkurt, 2001; Bozkurt and Mittweide, 2001). The EIFZ, which ruptured during the 1956 Eskişehir earthquake, is relatively less active compared with the NAFZ (Bozkurt, 2001). In contrast, the highly active NAFZ has been identified through GPS measurements as the primary driver of plate movements in the Marmara Region. These measurements indicate a slip rate of 24 mm a^{-1} on the northern branch of the

NAFZ, while right-lateral and extensional slip rates on its southern branch vary between $0.9\text{--}6.8$ and $0.8\text{--}5.5 \text{ mm a}^{-1}$, respectively (Reilinger et al., 2006; Özalp et al., 2016). The present study area is located in northwest Anatolia. Tectonically, its position is situated between the NAFZ in the north and EIFZ in the south. Therefore, it has experienced uplift under the influence of the north–south compressional tectonic regime while simultaneously being subjected to deformation.

The terrace systems developed in the middle course of the Sakarya River valley from the Middle–Late Pleistocene to the present have provided vital geomorphological and sedimentological information in terms of both revealing regional/local tectonic effects and the geomorphological development of the region.

Along the Sakarya River valley, which is the most important stream of Northwest Anatolia, terraces have been discovered that exhibit different levels starting from the valley floor. The terraces are scattered across four levels at Yakacık, three levels at Hamitabat, two each at Gemiciköy and Küçükkenice, and four at Selimiye. OSL dating was used to understand the geochronological features of these terrace systems. Our results showed ages for the terraces of 158.03 ± 12.93 ka (MIS 6b), 150.97 ± 8.49 ka (MIS 6b) and 55.07 ± 4.57 ka (MIS 3c) thus placing them within a geochronological framework. Consequently, this shows that the Sakarya has aggraded its valley floor during relatively warm climatic periods, whereas it has incised its bed during colder and/or cold–warm transition periods. In addition, according to temporal and spatial measurements of the terraces, the long-term uplift rate based on the terrace levels was $0.22 \pm 0.03 \text{ mm a}^{-1}$ near Hamitabat, $0.18 \pm 0.03 \text{ mm a}^{-1}$ near Gemiciköy and $0.14 \pm 0.03 \text{ mm a}^{-1}$ near Küçükkenice. The constant regional uplift rate of the terraces, which have disparate positions and elevations, was found to be $0.18 \pm 0.03 \text{ mm a}^{-1}$ on average. This reflects river incision occurring at different times in response to regional/local uplift across the study area, which has been continuing for at least the last 158 ± 13 ka.

This study shows that the terrace systems in the middle course of the Sakarya River valley developed within a complex system manipulated mostly by regional/local tectonic effects and partly by global climate changes.

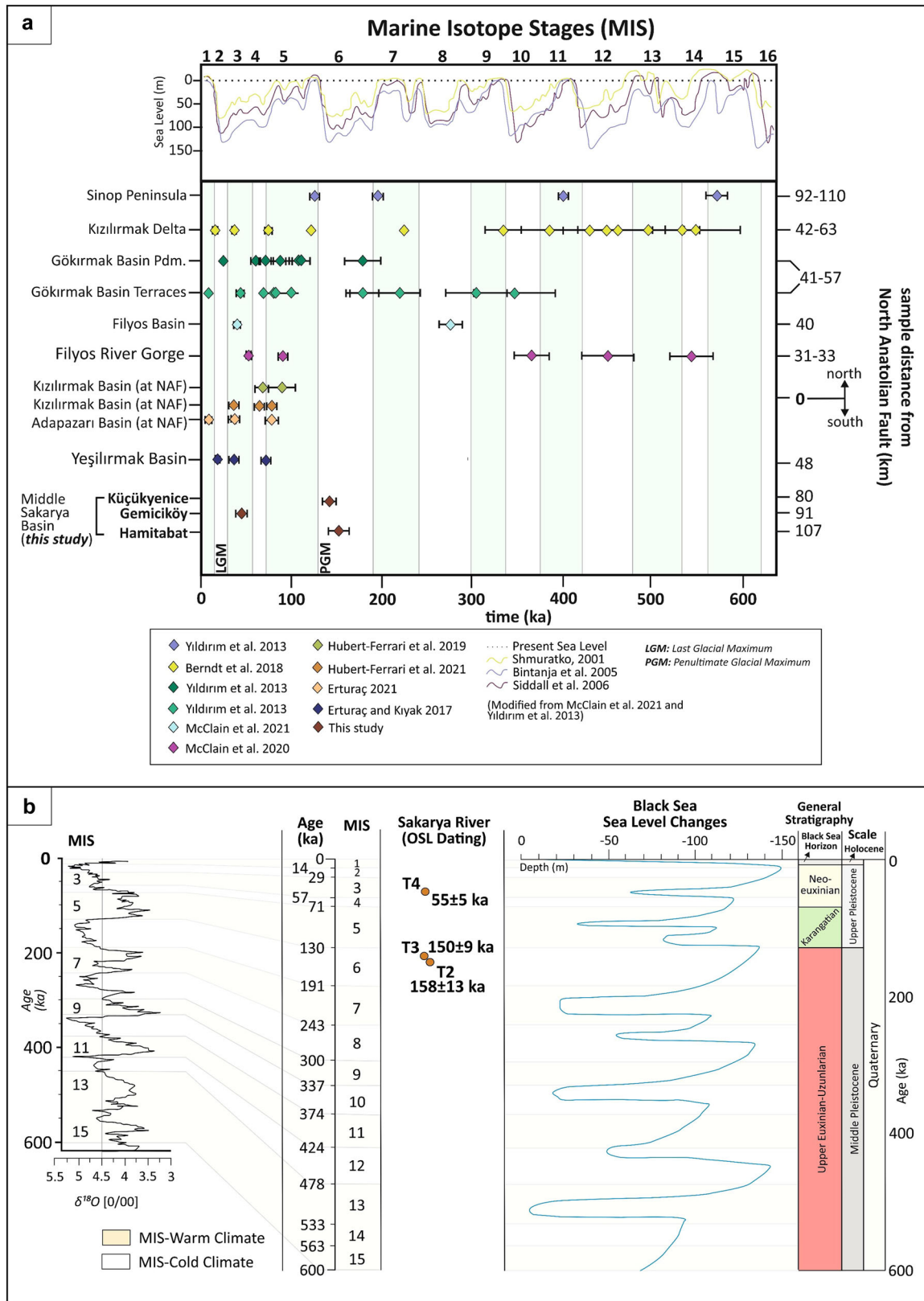


Figure 10. Middle Pleistocene–Holocene correlation of published North Anatolian terrace chronologies. Representation of international stratigraphic chart with Marine Isotope Stages, ^{18}O oxygen curve, Black Sea level changes and Black Sea chrono-stratigraphy. The locations of Sakarya River terraces with OSL ages and MIS correlations are indicated (Armaş et al., 2019; Panin & Popescu, 2007). (Above) Marine Isotope Stages (Lisiecki and Raymo, 2005) and the Black Sea level curves from MIS 16 (modified from Shmuratko, 2001; Bintanja et al., 2005; Siddall et al., 2007; Yıldırım et al., 2013b and McClain et al., 2021). Light green columns in the background represent MIS warm periods, and white columns represent cold periods. (Below) The location of studies conducted along the western and central Pontides and the obtained radiometric dating results (distances of the studies to the North Anatolian Fault Zone) are indicated on the right. Each colour represents a study area. References are given in the key. [Color figure can be viewed at wileyonlinelibrary.com]

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Abbreviations. BŞEÜ, Bilecik Şeyh Edebali University; BZS, Bitlis–Zagros Suture; DEM, Digital Elevation Model; DJI, Dà-Jiāng Innovations Science and Technology Co. Ltd; EIFZ, Eskişehir–İnönü Fault Zone; ESRI, Environmental Systems Research Institute; IAES, İzmir–Ankara–Erzincan Suture; IPS, Intra-Pontid Suture; LGM, Last Glacial Maximum; MIS, Marine Isotope Stage; NAF, North Anatolian Fault; NAFZ, North Anatolian Fault Zone; OSL, optically stimulated luminescence; PGM, Penultimate Glacial Maximum; SfM, Structure from Motion; TCN, terrestrial cosmogenic nuclide; UAV, unmanned aerial vehicle.

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