



# Geomorphological evolutionary history of the Melendiz River Valley, Cappadocia, Turkey

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Received: 25 June 2019 / Revised: 20 November 2019 / Accepted: 22 November 2019 / Published online: 6 December 2019  
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## Abstract

The Melendiz River is located at the east of Tuz Gölü Fault Zone in western Cappadocia. In the central part of Melendiz River Valley, Ihlara Canyon attracts many tourists due to its landscape, cultural and archaeological values. The Melendiz Valley also encompasses geological and geomorphological features that exemplify the evolutionary history of western Cappadocia. In this study, the late Miocene–Quaternary geomorphological evolution of the Melendiz River Valley was investigated. The results indicate that a fluvial sedimentary sequence with ignimbrite intercalation was deposited during the late Miocene and early Pliocene. This was unconformably overlain by lacustrine limestone (Kışladağ Formation) of Pliocene age. The Pliocene lake regressed westward because of the changes in the tectonic regime and geomorphological processes during the late Pliocene (~ 3 Ma ago) and the initial Melendiz River developed on the lake bottom. During the Quaternary the Melendiz River developed under the control of both the neotectonic regime and the climate. This development provoked a 160-m-deep incision into the Pliocene sediments and the early Pliocene–Miocene ignimbrites below, giving birth to the Ihlara Canyon. In the proper valley of the Melendiz River, six strath terraces and Holocene flood plain record the incision process.

**Keywords** Tuz Gölü Fault Zone · Melendiz River · Ihlara Canyon · River incision · Cappadocia

## Introduction

The Central Anatolian Plateau is a relatively small Cenozoic orogenic plateau, 400 km wide and 1200 m a.s.l (above sea level) (Çiner et al. 2015). One of the most tectonomorphologically and historically fascinating areas on the plateau is the Central Anatolian Volcanic Province (CAVP), generally known as Cappadocia (Fig. 1a). The CAVP is about 15–90 km wide, 300 km long and runs in a NE-trending continental paleo-magmatic arc (Keller 1974; Pasquaré et al. 1988; Koçyiğit and Doğan 2016). The CAVP is divided into several blocks of dissimilar size by the Tuz Gölü Fault Zone (TGFZ) (Yıldırım 2014) and the Central Anatolian Fault System (CAFS), which are major tectonic structures contributing to the evolution of the CAVP and its intracontinental

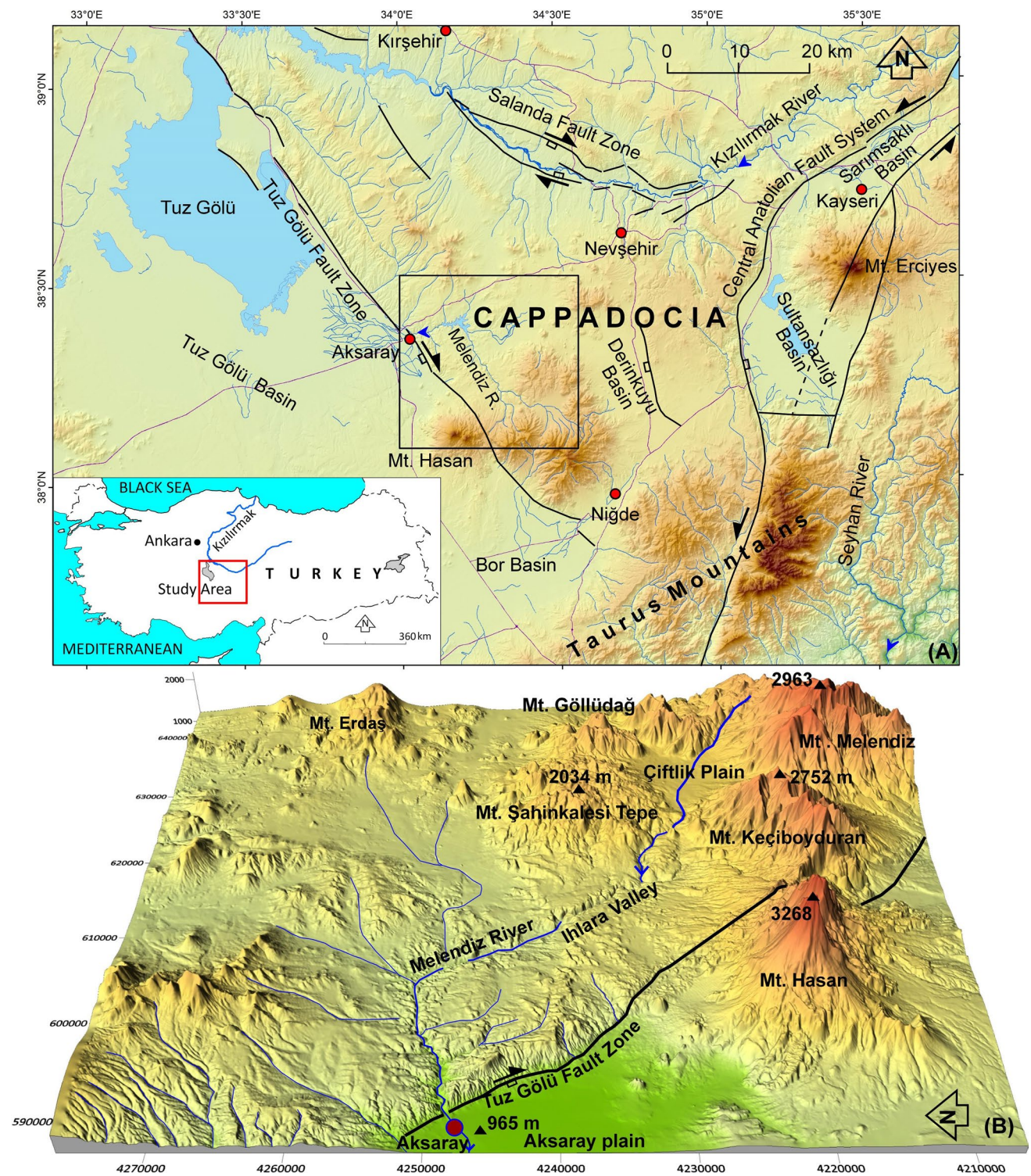
deformation (Fig. 1a; Koçyiğit and Beyhan 1998; Koçyiğit and Doğan 2016).

While streams in the western part of Cappadocia flow into the Tuz Gölü closed basin, the northern part of the Cappadocia region is drained by the Kızılırmak River (Doğan 2011; Çiner et al. 2015) that flows into the Black Sea, while the eastern reliefs are drained by short streams flowing into the Sultansazlığı closed basin. In the west, the Melendiz River is the most important stream (Fig. 1a). Born in the Melendiz Massif (2963 m) near the town of Niğde, it flows into the Çiftlik plain where it collects tributaries draining the western slopes of the Göllüdağ (2195 m), the northern slopes of the Keçiboyduran (2752 m) and the southern slopes of the Şahinkalesi (2034 m) (Kuzucuoğlu et al. 2015). The total length of the river is approximately 90 km. Its course encounters and crosses the Tuz Gölü Fault Zone (TGFZ) before ending near Aksaray city from where it enters into the Tuz Gölü closed basin (Fig. 1b). The Melendiz River incised its valley into thick ignimbrite-intercalated fluvio-lacustrine sediments (Beekman 1966; Doğan 2018; Kuzucuoğlu et al. 2018). The section where the valley becomes a narrow and deep canyon, important for its tourism potential (e.g.

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**Fig. 1** a Location of study area. b Topographic map of study area

Varnacı-Uzun and Somuncu 2015), is known as Ihlara Valley or Canyon (Fig. 1b).

The Melendiz River Valley is worth seeing for its natural beauty, ancient dwellings, churches, barns, and cellars carved

into the ignimbrites, as well as Aşıklı Höyük, a Pre-Pottery Neolithic (PPN) settlement (Özbaşaran 2011; Kuzucuoğlu 2013; Stiner et al. 2014; Kuzucuoğlu et al. 2018; Özbaşaran et al. 2018). The geological–geomorphological features on



and around the slopes of the valley reveal the geomorphological history of the SW section of the Cappadocia region, which dates back to more than 7 Ma according to the ignimbrite units (Aydar et al. 2012). Although the geological features of the valley have been partly addressed in studies of the TGFZ and Tuz Gölü basin (Fig. 1a) (Dirik and Erol 2000; Fernández-Blanco et al. 2013; Özsayın et al. 2013; Kürçer and Gökten 2012, 2014; Gürbüz and Kazancı 2014) and while volcanism was approached with detailed studies such as Le Pennec et al. (1994), Aydar and Gourgaud (1998), Temel et al. (1998), Dönmez et al. (2003, 2005), Aydar et al. (2012), Kuzucuoglu (2013) and Mouralis et al. (2019), there is a limited number of studies specifically about the geological and geomorphological features of part or whole of the Melendiz Valley (Beekman 1966; İlkışık et al. 1997; Türkecan et al. 2004; Sarı and Çömlekçiler 2007; Karabacak 2007; Kuzucuoglu 2013; Kuzucuoglu et al. 2015, 2018; Karabacak et al. 2017; Doğan 2018; Mouralis et al. 2019; Özsayın et al. 2019). In this frame, our study aims to clarify how the Melendiz River Valley was formed and the processes that controlled its geomorphological evolution. We thus investigated the geology and geomorphology of today's valley, as well as the formation of the drainage system prior to the establishment of the Melendiz River and the incision of bedrocks by the drainage system.

## Regional tectonic setting and geology of study area

The oldest rock exposed in the study area is a granitoid intrusion of late Maastrichtian–early Paleocene age (Kadioğlu 1991; İlbeyli 2005). This is overlain by a red continental sedimentary sequence from late Eocene–Oligocene deposited in a fluvio-lacustrine environment, which is exposed widely along the westerly facing steep scarp of the TGFZ southeast of Aksaray. These older rocks are overlain with angular unconformity by a volcano-sedimentary sequence of late Miocene–Quaternary age; the most diagnostic and widespread cover sequence in the CAVP. It was first recognized and introduced into the literature as the “Ürgüp Formation” by Pasquare (1968). However, the sequence was later given group ranking by Koçyiğit and Doğan (2016) as it consists of several mappable lithofacies on a scale of 1:25,000.

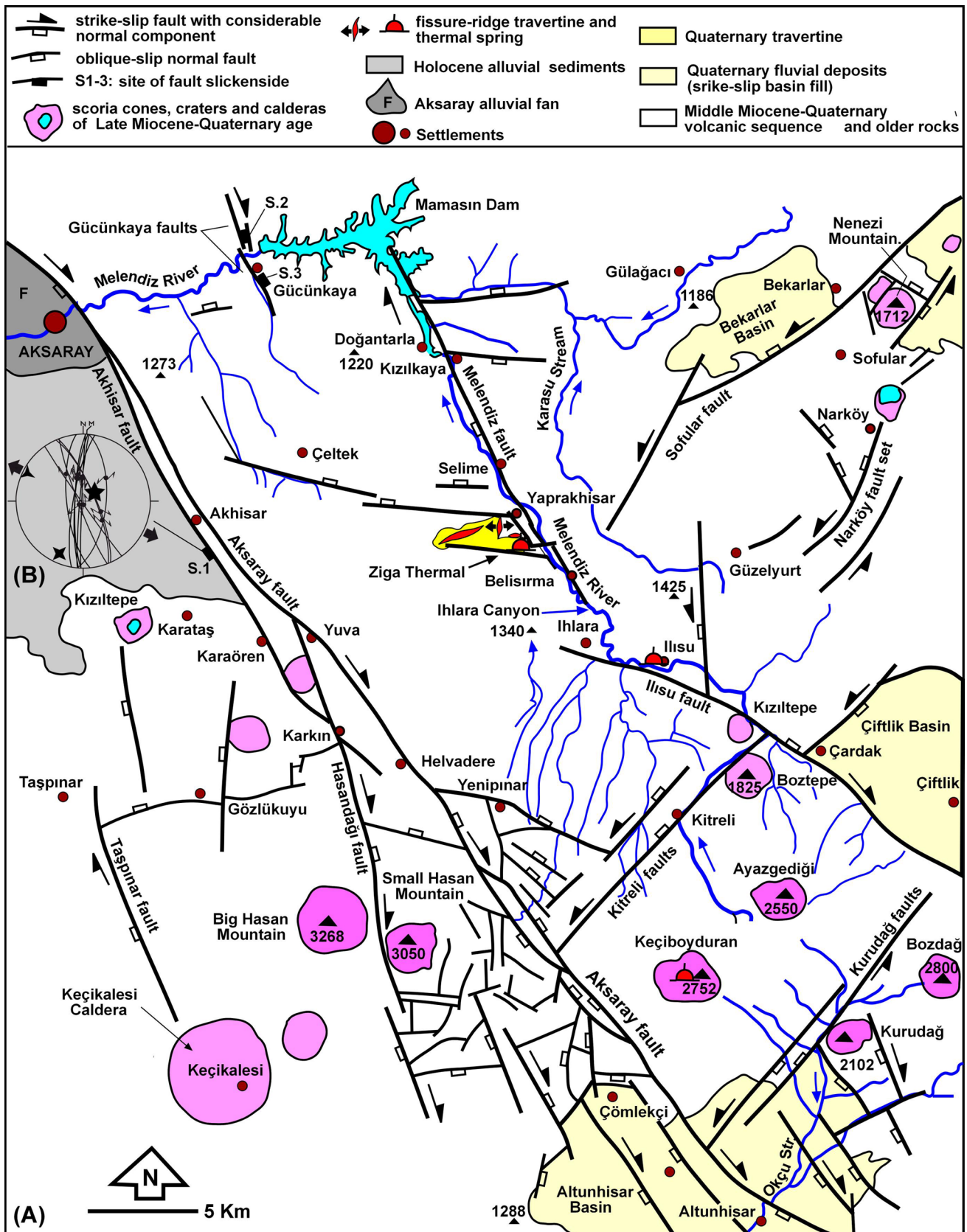
The Ürgüp Group consists mostly of lavas of dissimilar composition, ignimbrites and other pyroclastic rocks alternating with fluvio-lacustrine sedimentary facies. The oldest volcanic rocks are middle Miocene (13.7–12.4 Ma) in age and are exposed around the Keçikalesi Caldera (Besang et al. 1977; Batum 1978). Over 1 km in thickness, the Ürgüp Group is tilted to open-folded and overlain with angular unconformity by undeformed and nearly flat Quaternary

basin fill. The Ürgüp Group is penetrated by several stratovolcanoes and numerous monogenetic eruption centres, such as basaltic to felsic maars, cinder cones, calderas and silicic domes, comprising the central Anatolian Volcanic Arc (Pasquare et al. 1988). These features create an enchanting natural landscape, which makes the central CAVP very attractive for visitors.

This arc volcanism is related to continental collision (Deniel et al. 1998) between the African-Arabian and Eurasian plates. Since middle Miocene (~ 13 Ma) this collision occurs along a NE–SW orientation which is also characteristic of the alignment formed by the Hasandağ, Keçiboyduran and Melendiz volcanoes in South Cappadocia (Viereck-Goette et al. 2010). In this area, effusive activity occurs since Late–Middle Miocene (Besang et al. 1977; Pasquare et al. 1988; Aydar et al. 1995; Dhont et al. 1998). Meantime since Pliocene, explosive activity emplaced several rhyolitic to dacitic ignimbrites between 11 and 4 Ma (Le Pennec et al. 1994; Viereck-Goette et al. 2010; Aydar et al. 2012). During Quaternary, several large stratovolcanoes and a number of monogenetic igneous centres formed, that covered partly the Mio-Pliocene ignimbrites as well as the continental and lacustrine units (Keller 1974; Pasquare et al. 1988; Türkecan et al. 2004; Türkecan 2015). Early Holocene activity of the rhyodacitic lava domes around Mt Erciyes (3917 m), the largest stratovolcano of the CAVP, has been recently documented by <sup>36</sup>Cl cosmogenic surface dating (Sarıkaya et al. 2019).

The evolutionary history of the CAVP began in late middle Miocene under an extensional tectonic regime (Koçyiğit and Doğan 2016) and lasted up to late Pliocene. Starting from early Quaternary onwards, this extensional tectonic regime was interrupted and replaced by a strike–slip tectonic regime. This strike–slip neotectonic regime is still ongoing. All these events indicate that the CAVP experienced at least two phases of tectonic deformation during its development.

The Tuz Gölü Fault Zone (TGFZ) is a reactivated structure inherited from the middle Miocene–Pliocene extensional paleotectonic period. It was first recognized and named the Salt Lake Fault Zone (SLFZ) by Beekman (1966). The TGFZ is a 5- to 27-km wide, 220-km long and NW–SE trending intraplate zone of active deformation. This deformation zone is in the nature of a strike–slip fault with a considerable number of normal components, hence it was previously reported to be a normal fault zone by Kürçer and Gökten (2014). The TGFZ begins from Mt. Paşadağ to the northwest (outside the study area) then runs in a southeast direction. It follows the eastern margin of the Tuz Gölü basin up to a point southeast of Aksaray city and displays a linear trace along its western and central sections. After Aksaray, the TGFZ follows the same direction and cuts across some significant eruption centres such as the Hasandağ, Keçiboyduran and Melendiz





**Fig. 2** **a** Simplified map showing faults, strike–slip basins and significant eruption centres from late middle Miocene–Quaternary in study area. **b** Stereographic plot of slip-plane data on lower Schmidt hemisphere net (large diverging arrows indicate tension direction in late middle Miocene–Pliocene)

stratovolcanoes (Fig. 2). These eruption centres are displaced in a vertical and dextral direction of up to 13 km by the TGFZ in the area between Aksaray province and Bor county (Toprak 2000; Koçyiğit 2003). Southeast of Bor, the TGFZ changes its general trend and gains a considerable amount of reverse components. Finally, it joins the NE-trending Central Anatolian sinistral strike–slip fault system and then terminates (Koçyiğit and Beyhan 1998).

The TGFZ plays a key role in the late middle Miocene–Quaternary evolution of both the Tuz Gölü Graben and the CAVP. The 60-km-long Aksaray–Altunhisar section of the TGFZ is present in the study area (Fig. 2). In general, the Aksaray–Altunhisar section is about 12–28 km wide and 60 km long, consisting of a NNW-trending zone of active deformation made-up of numerous fault segments, each with different trends and length. However, the most prominent faults can be classified in two categories: (1) NW-trending, and (2) NE-trending. Common examples in the first category are the Aksaray, Akhisar, Hasandağ, Taşpınar, Gücünkaya, Melendiz and Iısu faults (Fig. 2). The second category is represented by the Kurudağ, Kitreli, Sofular and Narköy faults (Fig. 2).

The Aksaray Fault is also the master fault of the TGFZ. It enters the study area in the city of Aksaray and then continues in a SE direction passing through a number of settlements. It cuts both the Hasandağ and Keçiboyduran stratovolcanoes, and displaces them in a dextral direction (Toprak 2000; Koçyiğit 2003). Lastly, the fault exits the study area southeast of Altunhisar county (Fig. 2). It is made-up of a series of strike–slip complexities; such as pressure ridges, continental rift, left- and right-stepping, bifurcation, single- to double-bending and strike–slip basins, i.e. the Quaternary Altunhisar strike–slip basin. Commencing southeast of the city of Aksaray, the master fault begins to bifurcate into a series of closely spaced second-order faults, such as the Akhisar and Hasandağ faults, with west-facing steep scarps (Fig. 2).

The 20-km-long and N30E-trending Akhisar Fault displays a well-preserved fault slickenside (S.1 in Fig. 2). Kinematic analysis of the slip-plane (fault slickenside) data indicates that the Akhisar segment is an oblique-slip normal fault with a considerable amount of dextral strike–slip components (Fig. 1).

The other sub-branch of the Aksaray Fault is the Hasandağ Fault. Splaying from the Aksaray master fault around Yuva village, it then continues in a south-southeast direction for 19 km. In the Hasandağ, it cuts the twin peaks

of the stratovolcano (Küçük and Büyük Hasandağ) and displaces them in a dextral direction (Fig. 2).

The other two significant faults are Melendiz and Iısu located at ~ 13 km east of Aksaray master fault (Fig. 2). The Melendiz Fault is a 19-km-long, NNW-trending and steeply dipping structure. It cuts across the Ürgüp Group and juxtaposes the upper and younger lithofacies exposed on the downthrown western block with the lower and older lithofacies comprising the eastern uplifted block of the fault. Around Yaprakhisar village, well-developed fissure-ridge travertines are exposed on the downthrown western block. The central ridge axis strikes in directions N70E, N80W and N–S (Figs. 2, 3). Fissure-ridge travertines with axes of N70E and N80W are currently inactive; however, formation of travertines continues in a N–S direction (Fig. 3b). This still-active ridge reveals an approximately N–S contraction resulting from high compressive stress ( $\sigma_1$ ) in the study area. The deep and narrow Melendiz Canyon is developed along this zone of weakness due to vertical incision by the Melendiz River.

The 22-km-long and NW-trending Iısu Fault is exposed between İhlara town and southeast of Çiftlik village (Fig. 2). It cuts across the Quaternary volcanic products of the Keçi-boyduran stratovolcano and controls the Melendiz River along its length. The Quaternary Çiftlik basin is located on its northeastern downthrown block. Several thermal springs and local travertine outcrops are also observed along the Iısu Fault.

The lithofacies comprising the Ürgüp Group are easily erodible. For this reason, fault plane-related features might have been eroded and have now disappeared. Hence, slickensides on the Melendiz and Iısu faults could not be observed. However, around Gücünkaya village some other fault segments, namely, the Gücünkaya faults, are exposed (Fig. 2), which cut across the Ürgüp Group and underlying older granitoids. They display well-preserved slickensides with two sets of slip-lines overprinted on each other on the granitoids (S.2 and S.3 in Fig. 2). Kinematic analysis indicates that while the older set is originated from oblique-slip normal faulting (Fig. 4a, b), the younger set was caused by dextral strike–slip faulting (Fig. 4c, d). The stereographic plot of slip-plane data on the Schmidt lower hemisphere net also indicates that the extension during the middle Miocene–Pliocene paleotectonic period was NW–SE (large diverging arrows in Fig. 4b). Today the study area is under the control of N–S directed compressive stress and related dextral strike–slip faulting (Fig. 5).

This is evidenced by paleostress analysis of the second and younger set of slip-lines (Fig. 4c, d). The large converging arrows in this diagram indicate a N–S direction of the greatest principal compressive stress in the study area. This result fits well with the focal mechanism solutions of the July 30, 2005 and December 20, 2007 Bala earthquakes





**Fig. 3** General view of Akhisar section of TGFZ (view to east). *F1* Aksaray master fault, *F2* Akhisar fault

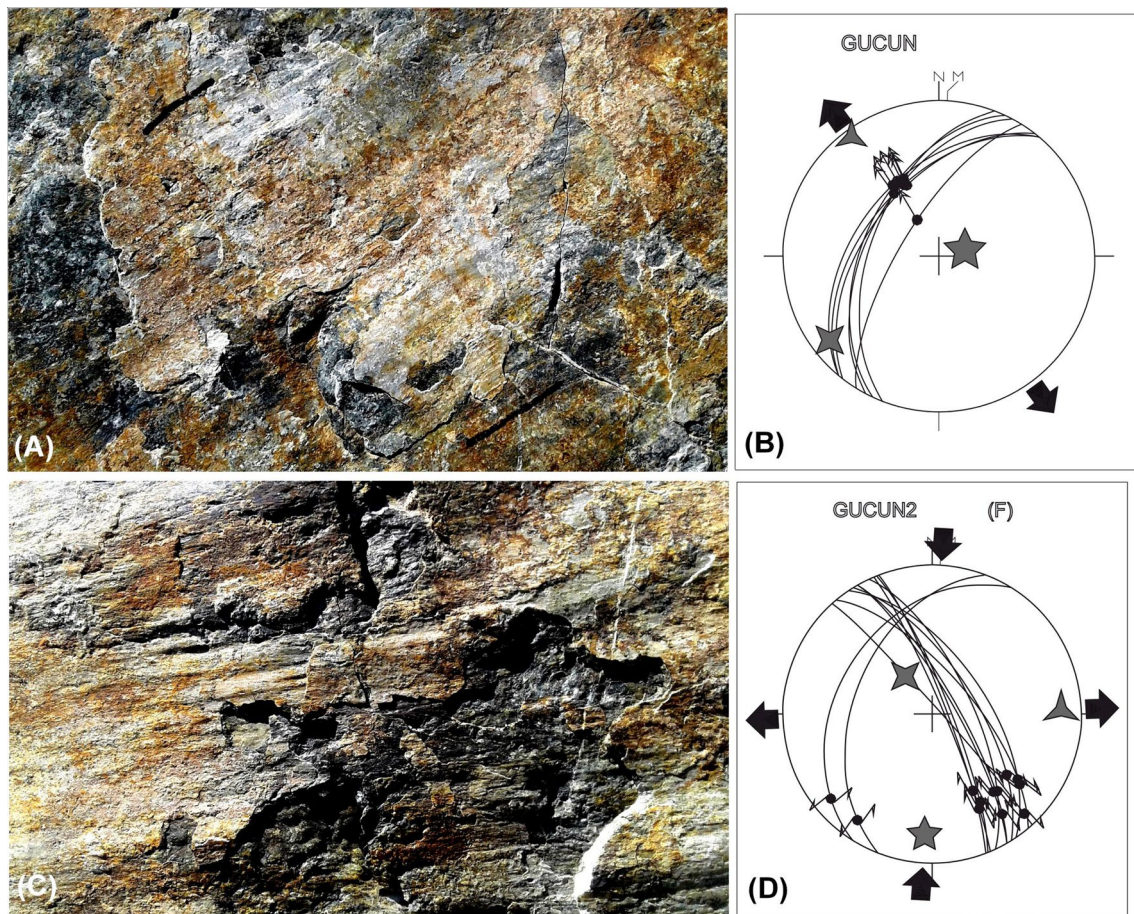
**Fig. 4** **a** Close-up of Yapra-khisar fissure-ridge travertine with central axis trending approximately N–S. **b** Close-up of active Ziga fissure-ridge travertine with N–S-trending central axis



measuring  $M_l = 5.0$  and  $5.6$ , respectively (Tan et al. 2010). These two earthquakes originated from NW- and NE-trending conjugate strike-slip faults exposed on the northwestern tip of the TGFZ, outside the study area. No moderate or large destructive earthquake has yet occurred in the TGFZ

during the instrumental period, i.e. it still retains its nature of a seismic gap. However, both the epicentre distribution of small earthquakes and the morphotectonic features caused by faulting show that the TGFZ is active (Dirik and Erol 2000; Koçyiğit 2003). The remaining NE-trending faults





**Fig. 5** **a** Close-up of older Gücünkaya oblique-slip normal fault slickenside. **b** Stereographic plot of older set of slip-data on lower Schmidt hemisphere net (large diverging arrows indicate extension direction in late middle Miocene–Pliocene). **c** Close-up of Gücünkaya

dextral strike-slip fault slickenside. **d** Stereographic plot of younger set of slip-data on lower Schmidt hemisphere net (large converging arrows indicate direction of greatest compressive stress ( $\sigma_1$ ) during Quaternary in study area)

such as Kurudağ, Kitreli, Sofular and Narköy are also active and parallel the general trend of an active regional fault system, namely, the NE-trending Central Anatolian Fault System (Koçyiğit and Beyhan 1998).

### Late Miocene–Pliocene geological context and geomorphological evolution of the Melendiz River Valley

Three ignimbrite units of late Miocene and early Pliocene age around the valley are intercalated with detritics consisting primarily of fluvial deposits (Fig. 6). These units belong to Cemilköy, Gördeles, and Kızılkaya ignimbrites in the Cappadocia region, which were previously identified, dated, and their stratigraphic relations explained (Pasquaré 1968; Pasquaré et al. 1988; Le Pennec et al. 1994, 2005; Mues-Schumacher and Schumacher 1996; Viereck-Goette et al. 2010; Aydar et al. 2012, 2013; Piper et al. 2013; Lepetit

et al. 2014). The fluvial deposits unconformably overlie granitoid rocks around Gücünkaya village in the area where the Mamasın Dam is located (Figs. 6, 7). These deposits consist of channel fill, flood plain, alluvial fan, and sheet flood deposits. The sediments are overlain by Cemilköy ignimbrite dated to  $7.20 \pm 0.09$  Ma by the Ar–Ar method (Aydar et al. 2012). The thickness of Cemilköy ignimbrite decreases from the east (from Selime village) to the north-west and west.

Late Miocene fluvial sediments also overlie the Cemilköy ignimbrite. The best place where these sediments can be observed is around Doğantarla (Göstük) village (Fig. 7). Doğantarla quarry, 1 km east of the village, contains fluvial channel deposits of Upper Miocene age. The deposits have a thickness of approximately 13 m, and the river channel fill shows lateral and vertical transitions with Gördeles ignimbrite towards the upper sections (Fig. 8a, b). Gördeles ignimbrite, dated to  $6.34 \pm 0.07$  Ma (Aydar et al. 2012), is light beige in colour and prone to erosion (Kuzucuoğlu

**Fig. 6** Sketch of stratigraphical columnar section of Melendiz Valley between Gücünkaya village and Ihlara Canyon. Ar/Ar ages adapted from Aydar et al. (2012)

Epoch	Lithology	Definition	Ar/Ar ages Ma
L. Pleistocene -recent		River terraces and floodplain deposits	
		Travertine	
Mid-Late Pleis.		Debris avalanche originating from Mt. Hasandağ	
E. Pleis.		Oldest deposits of Melendiz River drainage system (T1)	
Pliocene		Regressive clastic deposits	
		Kışladağ limestone	
Late Miocene-Early Pliocene		Fluvial (detritic) sediments	
		Kızılkaya ignimbrite	5.19 ± 0.07
		River deposits interstratified by Gördeles ignimbrite	6.34 ± 0.07
		Cemilköy ignimbrite	7.20 ± 0.09
		Fluvial (detritic) sediments	
L. Creta-E. Paleo.		Granitoid rocks	

et al. 2018). The interfingering of Gördeles ignimbrite with the channel fills in Doğantarla village and quarry shows that the ignimbrite was deposited over a large area but has been eroded except in these areas. The river deposits characterize a braided river environment (Fig. 8c), which unconformably overlies the Cemilköy ignimbrite (Fig. 8d). Almost all the river gravels originate from volcanic rocks such as basalt, and Cemilköy ignimbrite. The axis of the channels and the gravel imbrication indicate that the flow of the river was oriented from east to west-northwest. On the other hand, the gravel imbrication in the late Miocene deposits on the western slope of the valley (in Doğantarla village), shows that the river flow was towards the east. This indicates that the rivers in late Miocene were flowing towards today's Ihlara Valley. The fluvial channel fill in Doğantarla quarry is overlain by welded Kızılkaya ignimbrite, which is widely exposed over the entire Cappadocia region.

Kızılkaya ignimbrite, named after Kızılkaya village (Beekman 1966) and dated to  $5.19 \pm 0.07$  Ma (Aydar et al. 2012), is widely exposed around Melendiz Valley. The Kızılkaya ignimbrite unit is thickest in Ihlara Canyon between Belisırma village and Ihlara town. The thickness of this section shows that the source of the ignimbrite is close to Ihlara Valley. Piper et al. (2013) suggest that the Kızılkaya ignimbrite was emitted by a volcanic centre positioned in the Derinkuyu village area east of Ihlara as also suggested by Froger et al. (1998). Thin fluvial or detritic sediments overlie the Kızılkaya ignimbrite, which is also overlain by the Pliocene lacustrine Kışladağ limestone of Pliocene age (Pasquaré 1968) between Selime and Kızılkaya villages (Fig. 9a, b). The limestone contains gastropod fossils (Fig. 9c). Kışladağ limestone (between Çeltek and Uzuntarla villages) is also found over the Kızılkaya ignimbrite situated on the footwall block of the TGFZ (Figs. 7, 10). In Belisırma



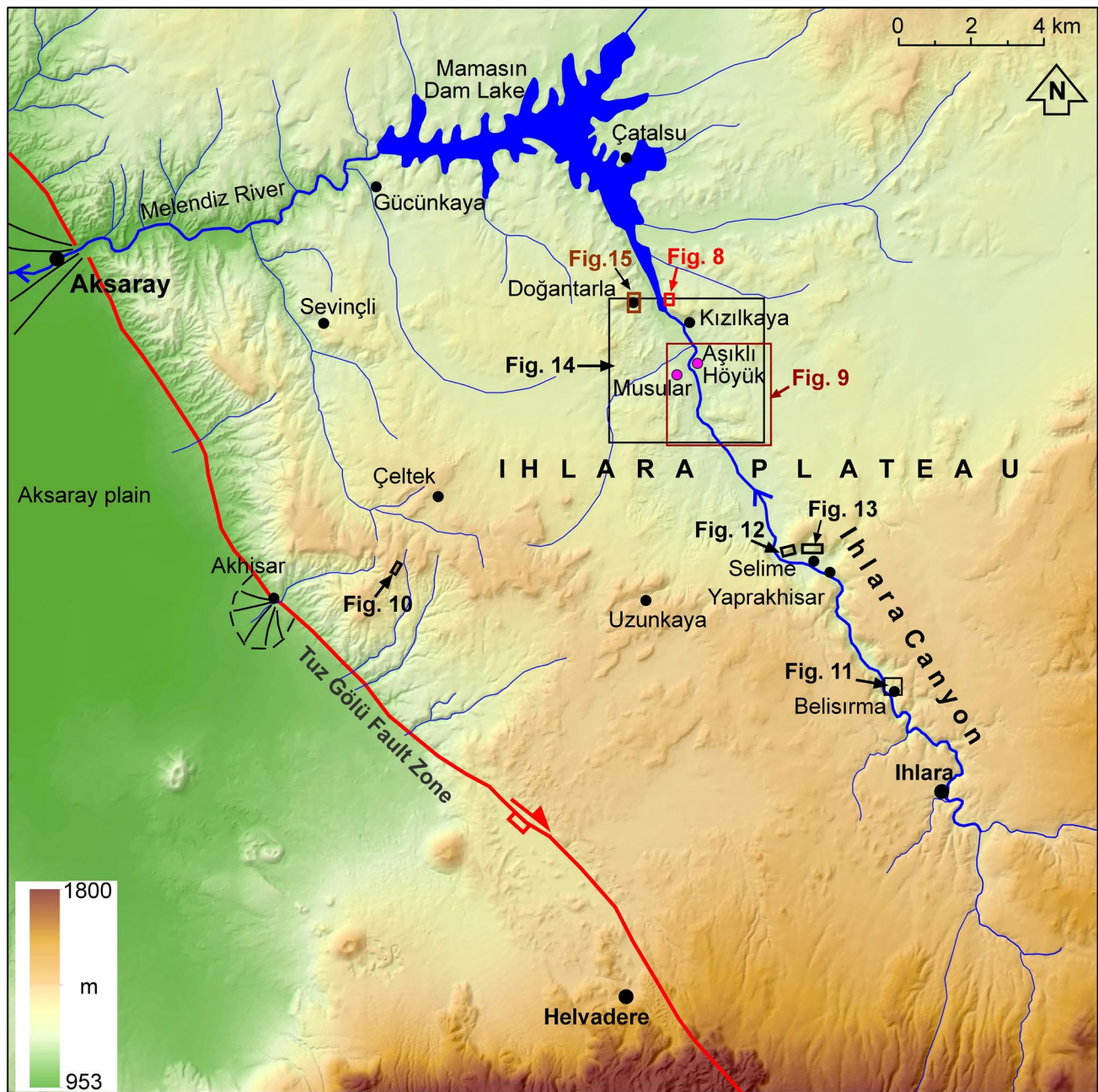


Fig. 7 Geomorphological map of study area including location of detailed geomorphological maps and photographs

village, the Kışladağ unit starts with a thick diatomite unit (Fig. 11; Gürel and Yıldız 2007).

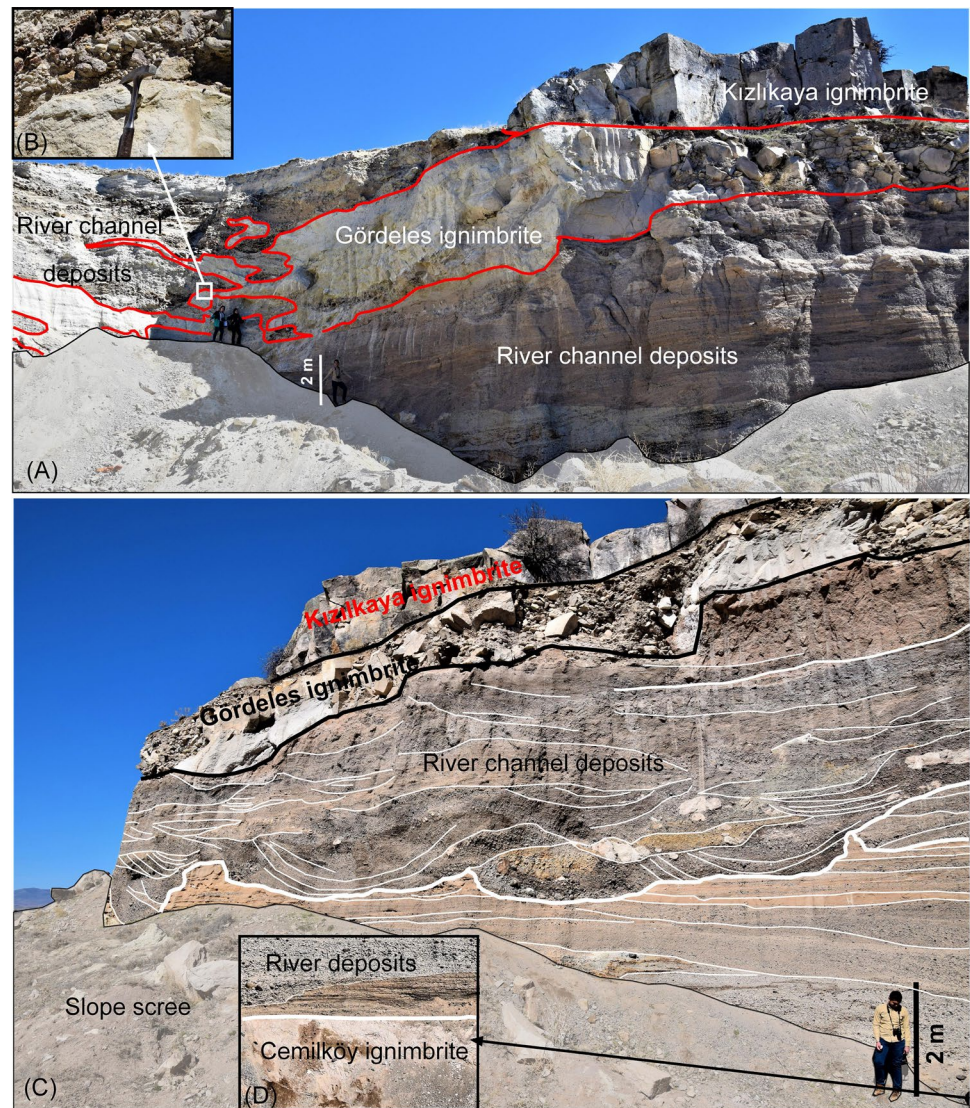
### Formation and evolution of Melendiz River Valley during Quaternary

The Melendiz River takes its source from composite volcanic mountains (Kuzucuoğlu et al. 2015, 2018; Mouralis et al. 2019). After passing through Aksaray city, the river

reaches its base level (the Tuz Gölü plain) at ~ 905 m a.s.l. (Fig. 1). In the Tuz Gölü basin, the river constructs a wide alluvial fan over and intercalating with the Pleistocene and Holocene lake deposits of Tuz Gölü (Kuzucuoğlu et al. 2018). The main trunk of the river flows northwards between Ihlara town and Doğantarla village, and then towards the west (Fig. 7). Tributaries of the river extend along a straight line and join the river almost at right angles. This organization of the river and its tributaries is controlled by faults, which developed parallel to the TGFZ (Fig. 2).



**Fig. 8** Doğanarla quarry showing cross-section from 7 to 5.2 Ma. **a** River sediments and Gördeles ignimbrite forming an intercalated deposit. **b** Close-up of boundary between ignimbrite and gravels. **c** Channel deposits indicating a braided river environment. **d** Cemilköy ignimbrite forming bedrock for river deposits



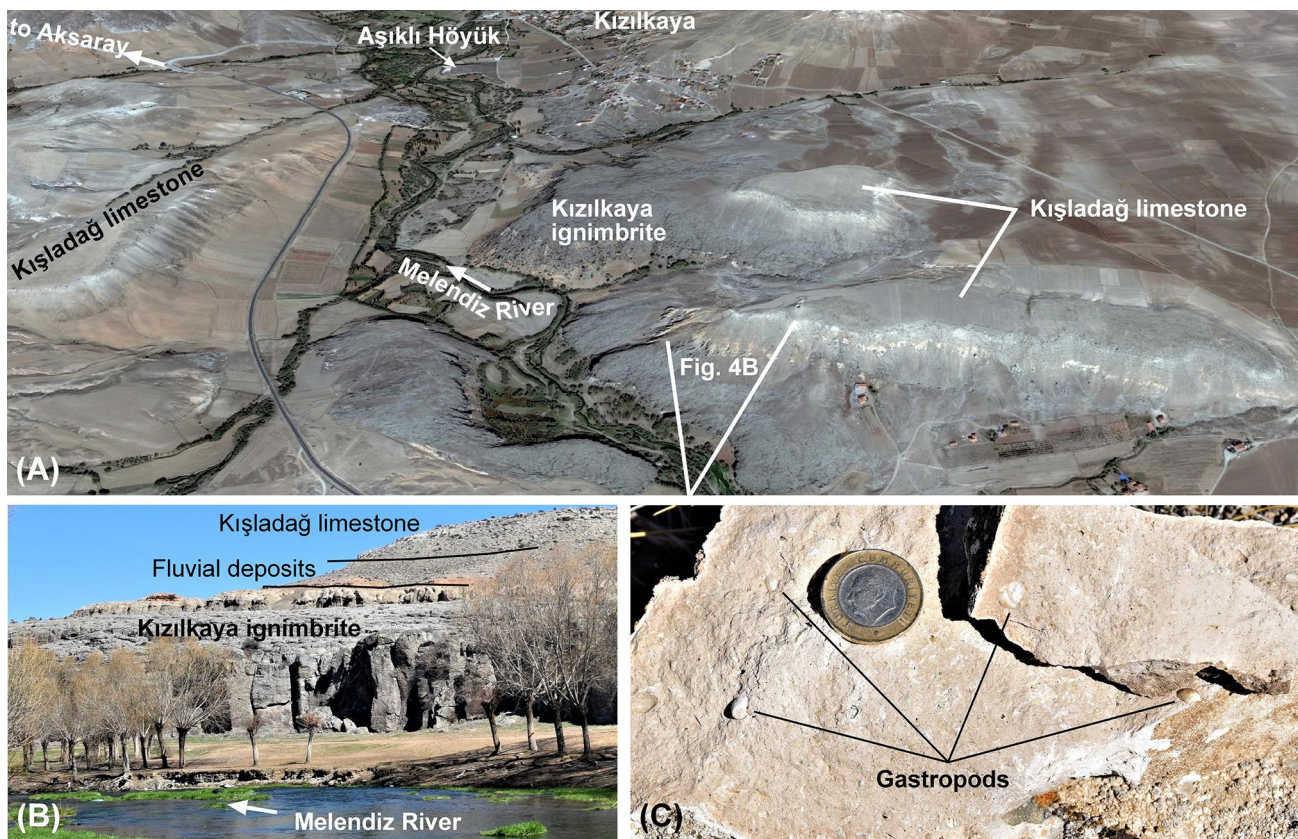
The Ihlara Canyon is part of the middle reach of the Melendiz Valley (Fig. 7). In this section, the width of the valley varies between 380 and 1270 m, reaching a maximum depth of 160 m. The data obtained from Belisırma village reveal the story of the formation of Ihlara Valley (Fig. 11). A geomorphological cross-section of the canyon at this location shows the Kızılıkaya ignimbrite at the base, overlain by the Pliocene Kışladağ limestone (Fig. 11). This latter unit is composed of diatomite, replaced upward by limestone. The whole set is unconformably covered by fluvial sediments deposited by the tributaries of the Melendiz River, and a debris avalanche originating from Mt. Hasandağ (Fig. 11).

The Belisırma section indicates that the lake environment ceased at the end of Pliocene and the river system was established in regressive lake conditions. This is evidenced by the limestone that was gradually replaced by granular and sand beach deposits in a vertical direction, recording a shoreface facies in the lake. According to these data, the

waters of the Pliocene lake east of the TGFZ must have gradually regressed towards today's Tuz Gölü basin. In the northeast of the Cappadocia region, the formation of the Kışladağ limestone was completed approximately 3 Ma ago (Le Pennec et al. 2005; Aydar et al. 2012; Lepetit et al. 2014; Doğan and Şenkul 2017; Doğan et al. 2019).

The Valibabatepe ignimbrite, dated to 2.52 - 3.0 Ma (Innocenti et al. 1975; Şen et al. 2003; Le Pennec et al. 2005; Aydar et al. 2012, 2013; Lepetit et al. 2014) caps the lacustrine Kışladağ limestone, thus dating its end ~ 3 Ma ago. Accordingly, the end of the lacustrine environment east of the Tuz Gölü fault must have occurred during late Pliocene. Fluvial deposits unconformably overlie the Pliocene lake sediments (Fig. 11a, b). These sediments, deposited in a river flowing from east to west, are composed of gravels of volcanic origin, including limestone (Fig. 11c). Such early Pleistocene fluvial deposits can be considered as the oldest deposits of the Melendiz River system. This





**Fig. 9** a Kışladağ limestone overlying Kızilkaya ignimbrite south of Kızilkaya village. b Kızilkaya ignimbrite lowered by faults to Melendiz River level. c Close-up of Kışladağ limestone



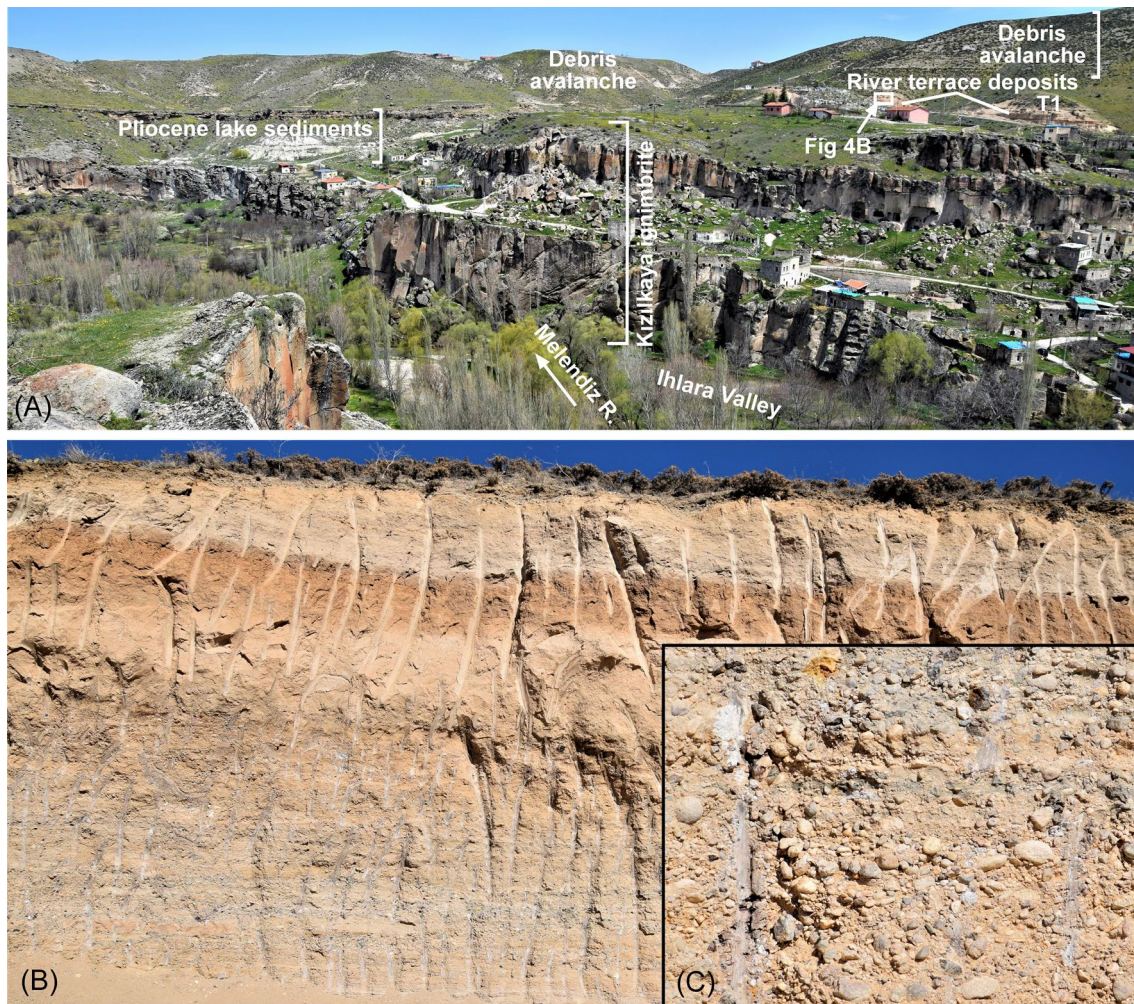
**Fig. 10** Kışladağ limestone overlying Kızilkaya ignimbrite southwest of Çelték village

indicates that the drainage system of the Melendiz River was gradually established on the bottom of the dried lake during early Pleistocene. After the fluvial deposition phase, the Melendiz River commenced its incision process during early Pleistocene and the river deposits became a

river terrace (T1). The T1 terrace is located ~ 100 m above the present river level.

The oldest terrace deposit of Melendiz River was covered by a debris avalanche (~ 40 m) from Mt. Hasandağ (Beekman 1966; Pastre et al. 1998; Aydar and Gourgaud





**Fig. 11** **a** Ihlara Valley showing detailed geological and geomorphological cross-section from 5.2 Ma to late Pleistocene with Belisırma village on rim of valley. **b** First deposits of Melendiz River system. **c** Close-up view of river deposits

1998; Mouralis et al. 2019; Kuzucuoglu et al. 2019). The debris avalanche, which consists mainly of volcanic ash and pumice, shows a wide distribution around Ihlara Canyon. The Belisırma village road cuts this debris avalanche. According to Kuzucuoglu et al. (2019) the debris avalanche entered then the Ihlara Canyon, crossed it at Belisırma, and reached the northeastern part of today's Selime village, at least ~ 22 km north of the emplacement of the collapsed Meso-Hasandağ (extension map in Pastre et al. 1998). The debris avalanche is tentatively attributed to 150–100 ka ago by Kuzucuoglu et al. (2019).

Upstream from the northern slopes of the Hasandağ, the Çiftlik basin (or plain) is drained by the Melendiz River, and surrounded by the Göllüdağ, Şahinkalesi, Melendiz and Keçiboyduran mountains (Fig. 1b). The river captured this basin by means of backward erosion during early Pleistocene. The round-shaped plain (sometimes considered as a possible Mio-Pliocene caldera; Froger et al. 1998) results

from a progressive closing due to successive volcanic events (Türkecan et al. 2004; Kuzucuoglu 2013). According to Gürel (2017), a shallow lake formed first in the basin before waters flowed into the gorge carved by the Melendiz River along the borderline between the Melendiz and Şahinkalesi massifs (Kuzucuoglu 2013; Mouralis et al. 2019).

The incision phase of Melendiz Valley during Quaternary displays a spectacular geomorphic landscape. The landscape is especially impressive in the Ihlara Canyon. Here, the main reason for the formation of the canyon is the superposition of a thick and deeply welded ignimbrite (Kızılkaya) over the softer Cemilköy ignimbrite, which is exposed only in the northern section of the canyon between Selime and Yaprakhisar villages (Fig. 7). The Kızılkaya reddish ignimbrite is very resistant to erosion, thus forming the ~ 50 m high cliffs of the Ihlara Canyon (Fig. 11) below a flat structural plateau surface. At the base of the canyon, troglodyte houses, churches, barns and cellars have been



dug into the ignimbrites (Çiner and Aydar 2019). Downstream, the Ihlara Canyon ends at Selime where Cemilköy and Kızılıkaya ignimbrites form an impressive mesa capping a badland landscape on the right bank of the river (Fig. 12). Around Selime and southward to Yaprakhisar, the Cemilköy ignimbrite is deeply incised by numerous rills and gullies forming the typical Cappadocian landscape made of “fairy chimneys” in a badland landscape (Beekman 1966; Sarıkaya

et al. 2015; Çiner and Aydar 2019; Doğan et al. 2019). The characteristic fairy chimneys are also well developed in the thick tuff wall between Selime and Yaprakhisar on the right bank of the Melendiz River (Fig. 13).

The morphology of the valley downstream from Selime settlement changes completely (Kuzucuoglu et al. 2018) where the width of the valley floor reaches 400 m and the river flows in a low sinuosity channel. The thinning and

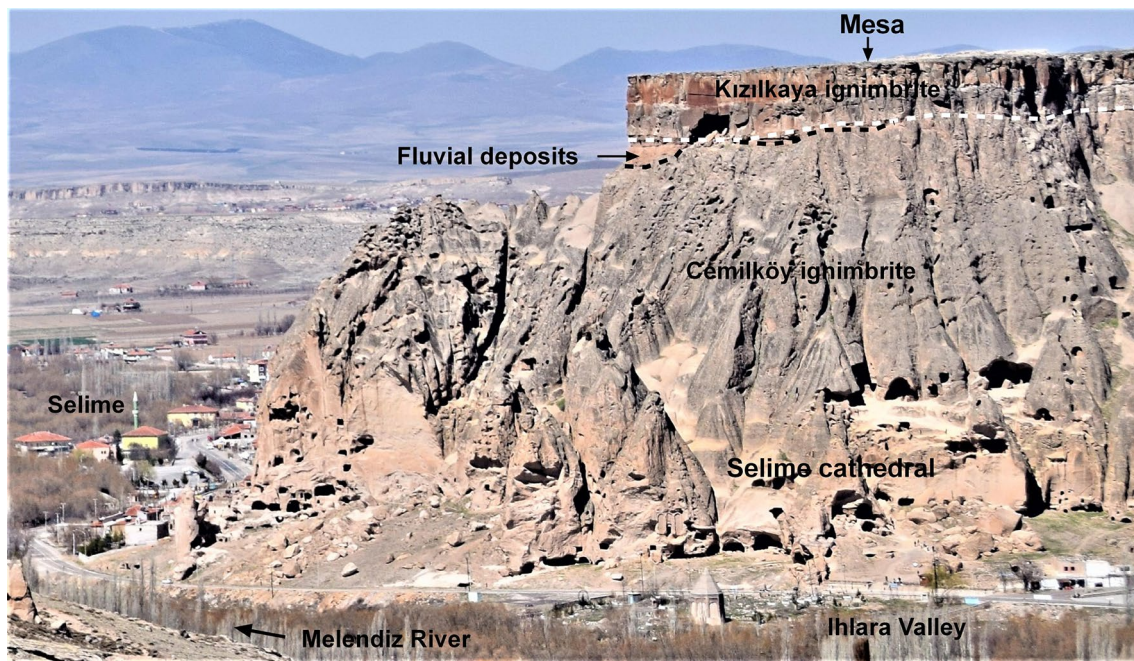


Fig. 12 Selime mesa, one of the most characteristic geomorphic features of Melendiz Valley



Fig. 13 Conical fairy chimneys formed on Cemilköy ignimbrite east of Selime village



lowering of the Kızılkaya ignimbrite to the present river level by faults during early Quaternary enlarged the valley. On the valley slopes Upper Miocene–Lower Pliocene ignimbrite-intercalated fluvial deposits (at Cemilköy, Gördeles, and Kızılkaya) are observed. Between the villages of Kızılkaya and Selime, Kışladağ limestone is exposed. The data here therefore further confirm that the Melendiz River drainage system was established between late Pliocene and Quaternary.

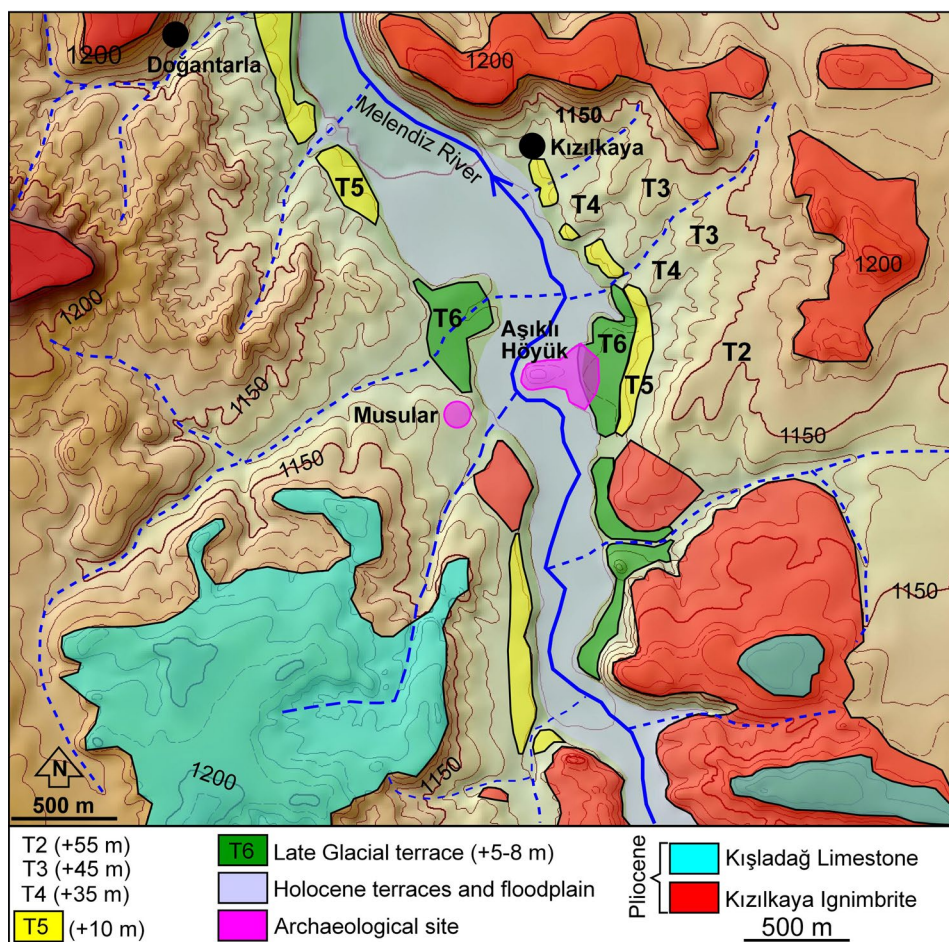
Due to the broadening width of the valley between Selime and Doğantarla villages, the river terraces are better preserved (Figs. 14, 15) than the section where Ihlara Canyon is located. In addition to the Holocene terraces, five strath terraces (T2 to T6) were mapped in the present study around Aşıklı Höyük (Fig. 14). Previously, six terrace steps were determined around Aşıklı Höyük by Doğan (2018). Kuzucuoğlu et al. (2018) found five terrace levels around Aşıklı Höyük, which are embedded within one another. The +10 m terrace was the oldest identified. The height of the terraces is +10 m (T5), +7 m (T4), +4 m (T3), +2.5 to 3 m (T2), and +1 to 2 m (T1). Among them T5, T4 and T3 are strath terraces, and T2 and T1 are embedded fill terraces. These terraces have been radiocarbon dated to from

Last Glacial Maximum up to the present (Kuzucuoğlu et al. 2018).

A Pre-Pottery Neolithic site is situated within the valley floor of the Melendiz River (Fig. 16). This site was occupied between ~ 10,500 yr and to about 9350 yr cal BP (Özbaşaran 2011; Stiner et al. 2014; Kuzucuoğlu et al. 2018; Özbaşaran et al. 2018). Part of the settlement base is ~ 4 m above today's riverbed, while another part is being eroded by today's river (Kuzucuoğlu et al. 2018). A colluvium was detected on a Late Glacial terrace by Kuzucuoğlu et al. (2018) and dated between 11.5 and 11.0 ka cal BP. After the colluvial phase, soil developed on the colluvial deposits. The early PPN population settled at Aşıklı Höyük on this soil (Kuzucuoğlu et al. 2018).

Downstream Doğantarla village, the Melendiz River intersects first granitoid rocks where Mamasın Dam has been constructed, and later the Eocene–Pliocene rocks outcropping east of the Tuz Gölü Fault Zone. At this point the width of the valley floor narrows to 400 m when intersects the TGFZ. Here, the depth of the valley does not reflect distinctly the vertical movement of the TGFZ because the Pliocene layers are largely eroded in the upper section of the valley. In the southern section of the valley, the Pliocene

**Fig. 14** Geomorphological map of Aşıklı Höyük vicinity





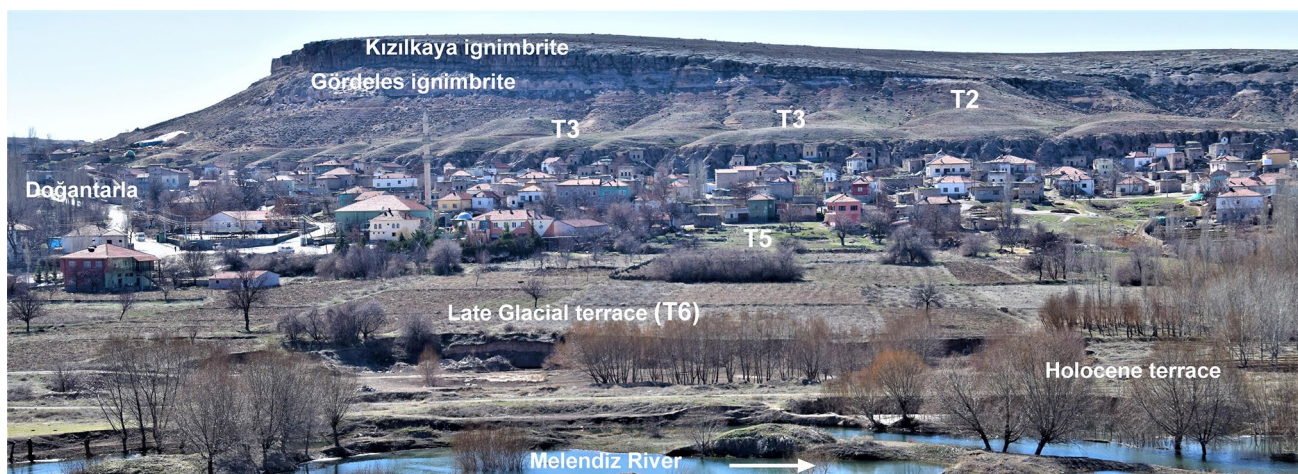


Fig. 15 River terraces at Doğantarla



Fig. 16 Location of Aşıklı Höyük on right bank of Melendiz River

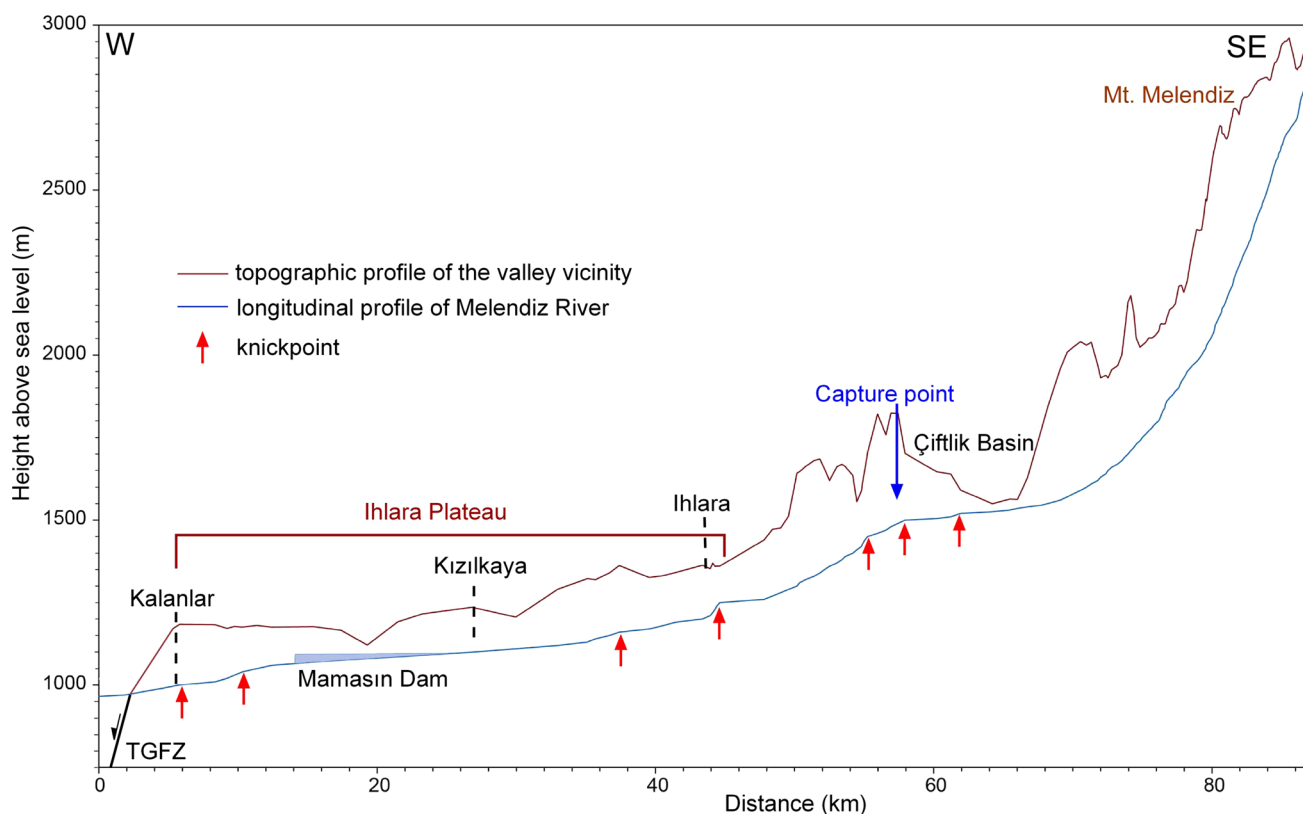
Kışladağ limestone has been preserved from erosion around Çeltek village (Fig. 10). The elevation difference between the upper level of the Pliocene limestone on the uplifted block (1331 m a.s.l) and on the downfaulted block (965 m a.s.l., west of Aksaray plain) allows to calculate a ~ 268 m vertical displacement rate of the fault in the Akhisar segment, i.e. at least 0.12 mm/year in the last ~ 3 Ma.

During the formation and evolution of the Melendiz Valley in late Pliocene-Quaternary, the vertical displacement rate of the TGFZ is significant. The graded longitudinal profile of the river also reflects the last displacement on the fault zone. There are seven knickpoints between the TGFZ and the Çiftlik basin (Fig. 17). The most downstream knickpoint is located on the TGFZ, and might reflect a former displacement on the fault. The second knickpoint between the TGFZ and Mamasın Dam, is located at the boundary of the granitoid rocks and is formed because of lithological (resistance to erosion) contrasts. The other knickpoints also appear to

be associated with lithological controls. On the other hand, on the longitudinal profile of the river, the effects of Quaternary climate and changes in level of Tuz Gölü cannot be ignored (Doğan 2018). For example, during the glacial times the Tuz Gölü lake level was higher than today (Erol 1971, 1978; Kashima 2002). According to Kashima (2002), the lake level high stand was over 15 m than its present level at 20–17 <sup>14</sup>C ka BP.

### Discussion

The findings obtained along Ihlara Valley show that a fluvial environment has been present in the late Miocene and early Pliocene (Fig. 18a). It was also found that the ignimbrites in this area are derived from three volcanic sources in the Cappadocia region. One of the last eruptions produced the Kızilkaya ignimbrite (Pasquaré et al. 1988) (Fig. 18b). The



**Fig. 17** Longitudinal profile of Melendiz River. Knickpoints and plateau surface can be seen clearly

Kışladağ diatomite (Gürel and Yıldız 2007) and limestone indicate that the study area was transformed into a lacustrine environment in Pliocene (Fig. 18c). Accordingly, stratigraphy and tectonic features present in geological cross-sections east of the Tuz Gölü Fault (Beekman 1966; Dirik and Erol 2000; Fernández-Blanco et al. 2013; Kürçer and Gökten 2012, 2014; Gürbüz and Kazancı 2014; Kuzucuoğlu et al. 2018) have been revised in this study (Fig. 6). In addition and according to our findings, Selime and Gelveri ignimbrites defined by Beekman (1966), actually belong to Cemilköy (Piper et al. 2013) and Gördeles ignimbrites.

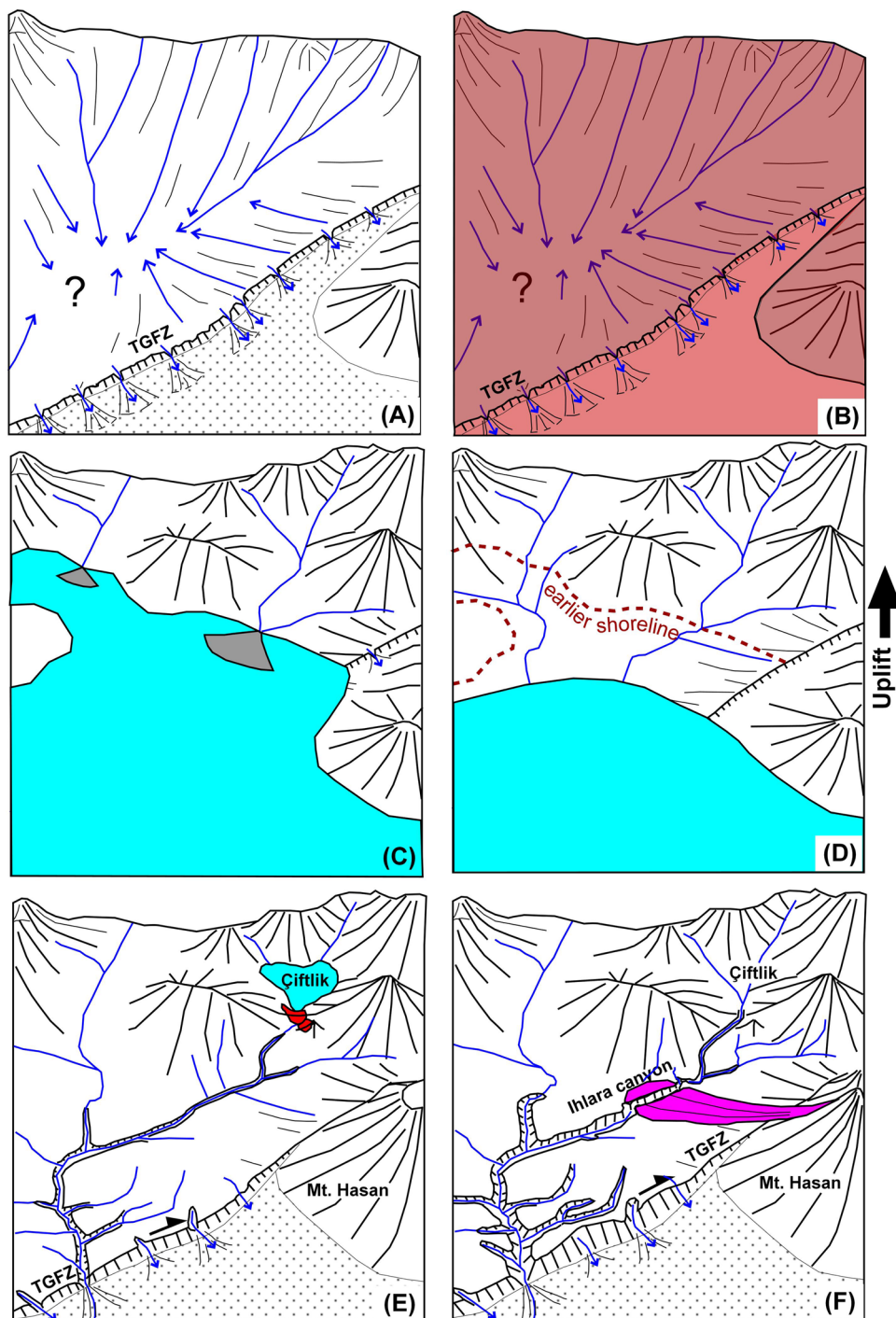
Our findings in the field have revealed that the Melendiz River drainage system was formed during the early Quaternary strike-slip neotectonic regime (Fig. 2). Therefore, the Melendiz Valley and Ihlara Canyon were incised during Quaternary (Fig. 18e, f). The fact that the oldest deposits of Melendiz River in the Ihlara Canyon are located on the Pliocene limestone confirm this conclusion (Fig. 11). The Kışladağ limestone unit was reported by Özsayın et al. (2013) and Kürçer and Gökten (2014) to be on the eastern block of TGFZ to the north of Aksaray. In fact, the Pliocene lacustrine limestone known as Kışladağ limestone in the Cappadocia region (Pasquaré 1968) can be correlated with the upper sections of the Insuyu Formation (Ulu 2009a, b) and Kuşça Member of Cihanbeyli Formation (Özsayın and

Dirik 2007, 2011), which are widely exposed to the west and south of Tuz Gölü (Dönmez et al. 2003). In the study area, lacustrine beach deposits covering the Kışladağ limestone indicate that the last period of this deposition records regression. This is most likely related to an increase in the vertical displacement rate of TGFZ, while tectonic regime was changing after late Pliocene, and perhaps the capture of western Central Anatolia closed basins during late Pliocene by Sakarya River. This change in tectonic and environmental conditions indicates that the lake regressed gradually to the west of the TGFZ, causing the development of the Melendiz River on the emerging lake bottom (Fig. 18d). After this phase, the Quaternary Melendiz River drainage system started to form under the control of neotectonic regime (Fig. 18e). This system initiated a backward erosion and incision, including the shaping of the Ihlara Canyon. A debris avalanche reached the eastern part of Melendiz Valley during the last stages of this backward erosion (Fig. 18f). It is possible that the obstacle formed by accumulation of these pyroclastites slowed-down the headward erosion of the river southward.

Six strath terraces and Holocene flood plain formed by sedimentation and incision processes in the Melendiz Valley have been preserved until today (Figs. 14, 15). One of them (oldest terrace T1) is located to the east of the Belisırma



**Fig. 18** Sketched block diagrams illustrating evolutionary history of Melendiz River Valley. **a** Fluvial environment during late Miocene. **b** Kızılıkaya ignimbrite settled on the fluvial environment 5.2 Ma ago. **c** Study area covered by Pliocene lake ~ 4.5 Ma. **d** Pliocene lake regressed and Melendiz River occupied the lake bottom ~3 Ma ago. **e** Melendiz River drainage system formed at beginning of Pleistocene. Incision began in Melendiz Valley largely due to displacement on TGFZ. During early Pleistocene, Çiftlik basin and lake formed by a volcanic barrier. **f** During the late middle and early late Pleistocene a debris avalanche reached the Ihlara Canyon from the Hasandağ. The diagram illustrating the present landscape of study area



Village. Other five terraces (T2–T6) are observed between Selime and Doğantarla villages. No age data are yet available for the higher terraces on the slopes of the valley. However, Kuzucuoğlu et al. (2018) evidence a buried strath terrace dated to Late Glacial and early Holocene, over which the PPN Aşıklı Höyük settlement was established. The Holocene terraces embedded into one another evidence erosion of the valley floor during cold phases of the Late Glacial and Holocene (Kuzucuoğlu et al. 2018 in Fig. 8).

Regarding the impact of tectonics on the geomorphology of the area since Pliocene, the present study evidences a vertical displacement rate of the Akhisar segment of the TGFZ of 0.12 mm/year since the beginning of the neotectonic period (i.e. since ~ 3 Ma). However, Kürçer and Gökten (2014), in consideration of the elevation difference between the bases of Kızılıkaya ignimbrite for this segment (268 m), determined the vertical displacement rate for the last 5 Ma to be 0.053 mm/year. The difference with our

results can be explained by the fact that Kürçer and Gökten (2014) assumed the beginning of the neotectonic period as Pliocene, hence a longer period (5 Ma), than the authors of the present study. Nevertheless, when we recalculated their vertical displacement rate on the segment for the last 3 Ma, we obtained a very close result to our findings. According to Özsayın et al. (2013), the vertical displacement rate of Kürçer and Gökten (2012) should be recalculated. They point out that Akhisar is located on a step-over zone where two segments of the TGFZ overlap and where a slip rate of 0.053 mm/year can thus be inferred for the eastern fault branch in the zone. Therefore, Özsayın et al. (2013) suggest that if the total slip was partitioned equally between both overlapping faults, then the total slip rate would have been 0.1 mm/year. This re-evaluation is largely consistent with the rate derived from our study. Özsayın et al. (2013) used also the Kışladağ limestone as a marker bed for determining relative offsets across faults around Tuz Gölü. They calculate an average relative vertical displacement rate with respect to the centre of the Tuz Gölü Basin to be 0.08–0.13 mm/year for the eastern flank from 5 to 3 Ma. This rate is also consistent with our results.

This study outlined the stages in the geomorphological evolutionary history of Melendiz River Valley. Future studies could usefully focus on dating the strath terraces and elaborating on the processes leading to the disappearance of the Pliocene lake.

## Conclusions

In the light of the field data and available literature, four main points must be underlined:

- A fluvial environment, contemporaneous with volcanism (emplacement of ignimbrites) during late Miocene–early Pliocene, was replaced by a lacustrine environment in Pliocene in the study area. ~ 3 Ma ago the lake regressed westwards because of an increase in the vertical displacement on the TGFZ, and possibly because of river captures of closed basins in western Central Anatolia by the Sakarya River. The Pliocene lake regressed and the initial Melendiz River settled on the lake bottom ~ 3 Ma ago. The drainage system of the Melendiz River was then established under the control of strike–slip neotectonic period starting from early Pleistocene.
- During Quaternary, the river continued eroding southward as well as vertically because of the (1) the vertical displacement of the TGFZ; (2) the lowering of its base level in the Tuz Gölü plain, and (3) climatic conditions. Along the river, six strath terrace and Holocene flood plain record different incision/sedimentation phases in the valley. During the southward erosion, the river even-

tually captured the Çiftlik basin, forming the Melendiz Valley and Ihlara Canyon. During late middle–early late Pleistocene, a debris avalanche reached the Ihlara Canyon and covered the oldest deposits or T1 terrace of the Melendiz River.

- The river responded to climatic changes during Late Glacial and Holocene, and a Pre-Pottery Neolithic settlement was established at Aşıklı Höyük over a Late Glacial terrace.
- On the Akhisar segment of the TGFZ, the vertical slip rate during the last ~ 3 Ma is calculated to be 0.12 mm/year.

**Acknowledgements** We would like to thank Attila Çiner, Catherine Kuzucuoğlu and anonymous reviewers for their helpful and constructive remarks that greatly improved the manuscript.

## Compliance with ethical standards

**Conflict of interest** On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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