Early Pleistocene river terraces of the Gediz River, Turkey

Maddy, D.; Veldkamp, A.; Demir, T.; Aytaç, A. S.; Schoorl, J. M.; Scaife, R.; Boomer, I.; Stermerdink, C.; Van Der Schriek, T.; Aksay, S.; Lievens, C.

DOI:

[10.1016/j.geomorph.2020.107102](https://doi.org/10.1016/j.geomorph.2020.107102)

License:

Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version

Peer reviewed version

Citation for published version (Harvard):

Maddy, D, Veldkamp, A, Demir, T, Aytaç, AS, Schoorl, JM, Scaife, R, Boomer, I, Stermerdink, C, Van Der Schriek, T, Aksay, S & Lievens, C 2020, 'Early Pleistocene river terraces of the Gediz River, Turkey: the role of faulting, fracturing, volcanism and travertines in their genesis', *Geomorphology*, vol. 358, 107102, pp. 1-18.
<https://doi.org/10.1016/j.geomorph.2020.107102>

[Link to publication on Research at Birmingham portal](#)

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Early Pleistocene River Terraces of the Gediz River, Turkey: The role of faulting, fracturing, volcanism and travertines in their genesis

D. Maddy, A. Veldkamp, T. Demir, A.S. Aytaç, J.M. Schoorl, R. Scaife, I. Boomer, C. Stemerink, T. van der Schriek, S. Aksay, C. Lievens

PII: S0169-555X(20)30074-X

DOI: <https://doi.org/10.1016/j.geomorph.2020.107102>

Reference: GEOMOR 107102

To appear in: *Geomorphology*

Received date: 13 June 2019

Revised date: 11 February 2020

Accepted date: 16 February 2020

Please cite this article as: D. Maddy, A. Veldkamp, T. Demir, et al., Early Pleistocene River Terraces of the Gediz River, Turkey: The role of faulting, fracturing, volcanism and travertines in their genesis, *Geomorphology*(2020), <https://doi.org/10.1016/j.geomorph.2020.107102>

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Early Pleistocene River Terraces of the Gediz River, Turkey: The role of faulting, fracturing, volcanism and travertines in their genesis.

Maddy, D.^{1*}, Veldkamp, A.², Demir, T.³, Aytaç, A.S.⁴, Schoorl, J.M.⁵, Scaife, R.⁶, Boomer, I.⁷, Stemerink, C.¹, van der Schriek, T.¹, Aksay, S.⁵ and Lievens, C.²

1. School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
2. Faculty of Geo-Information Science and Earth Observation (ITC), Twente University, Enschede, The Netherlands
3. Akdeniz University, Faculty of Letters, Geography Department, Konyaaltı-Antalya, 07058
4. Department of Geography, Harran University, 63300 Sanliurfa, Turkey
5. Soil Geography and Landscape group, Wageningen University, P.O. Box 47, NL-6700AA, Wageningen, The Netherlands.
6. School of Geography and Environment, University of Southampton, Southampton SO17 1BJ, UK.
7. School of Geography, Earth & Environmental Sciences, University of Birmingham, Edgbaston, B15 2TT.

*darrel.maddy@newcastle.ac.uk

Abstract

Reconstructing and interpreting past hydrological system changes from the Quaternary sediment-landform record presents many challenges especially when trying to establish causality. In such circumstances attempting to isolate individual drivers is perhaps unrealistic and thus inferences are made with respect to the combined influence of multiple controls and constraints. In this paper we seek to interpret the landscape responses recorded in the sediment-landform record of the Early Pleistocene Gediz valley, western Turkey, within the context of interacting geodynamic and hydrodynamic system changes.

Our earlier work on the Gediz sequence established the presence of a rich fluvial archive constrained by a comprehensive geochronology from overlying lava flows. Repeated damming of the Gediz valley floor and consequent re-routing of water flow, testifies to a direct connection between fluvial activity and volcanism. This volcanism has been linked to regional tectonic extension with regional uplift promoted as a major driver of the progressive river incision of the Gediz River over the Quaternary. This incision has been punctuated by periods of deposition dictated by sediment and water budgets controlled principally by fluctuating climate and consequent vegetation change. Recently however, the significance of more local fault movements and fracturing has been recognised and here we examine and attempt to quantify these geodynamics in greater detail. In addition, we examine and describe, for the first time, extensive associated travertine deposits. Isotopic analysis of these travertines confirms their thermogenic origin and directly links their creation to the faulting/fracturing, volcanism and the recycling of calcium-rich groundwater. The formation of mounds and sheets extend onto their contemporary valley floors, thus directly connecting the fluvial and travertine archives and allowing linkage between surface and subsurface hydrological change.

By utilising both the fluvial and travertine archives a more complex picture of landscape evolution emerges. The youngest terraces (< GT6) appear to be driven by local fault movement associated with the onset of volcanism and thus the link with fluctuating climates, as demonstrated in the higher terraces (GT7 +), is unclear. Detailed observations suggest formation of these lower terraces is also conditional on the local substrates. Here it appears that GT5-GT1 form in response to the creation of a knickpoint where the river intersects the faults in areas of hard basement rock. Hence, this response is highly localized, dependent on the immediate geometry and structure of the underlying strata. The presence of complex basement topography also plays a key role in generating ground water pressure and thus the creation of travertine mounds.

The Gediz sequence demonstrates increasing complexity. There is no reason to suggest this is unusual. Although climate and tectonics remain as key drivers the local landscape response is also conditioned by many additional factors. While it is tempting to search for global patterns ("the big picture"), such reduced complexity may be over simplistic. Recognising complexity requires detailed observation and therefore more emphasis on "the smaller picture" which can only be obtained through extensive field observation.

Early Pleistocene River Terraces of the Gediz River, Turkey:

The role of faulting, fracturing, volcanism and travertines in their genesis.

1 Introduction

Reconstructing and interpreting past hydrological system change from the Quaternary sediment-landform record presents many challenges. At a basic data level there is the uncertainty surrounding the nature of the archives themselves e.g. Is the archive complete? How reliable are the proxies? How reliable is the geochronology? More fundamentally however, there is uncertainty surrounding establishing causality i.e. how inferred changes can be linked unequivocally to one or more processes. In part this problem arises as a consequence of the complexity of process interactions, both extrinsic and intrinsic, operating at different scales and rates over time (e.g. Schumm and Lichty, 1965) making it difficult to isolate specific causal mechanisms. This challenge is highlighted for example by the debates surrounding the relative importance of climate change and tectonics in driving river terrace development (e.g. Macklin *et al.*, 2002; Vandenberghe 2003, 2015; Bridgland and Westaway, 2014;). Isolating single driving factors has proved intractable, in part because these drivers interact and, in part, because the archives reflect response to many additional drivers and constraints. Significantly, in many cases, the binary climate/tectonics choice is too simplistic and thus the search for a sole driver in such circumstances is perhaps futile. Although this conclusion may seem obvious, it remains common for the initial descriptions of large-scale river terrace sequences to be interpreted as being climate and/or tectonic controlled records. Only more elaborate, in-depth, studies provide evidence of more complex controls and drivers (Viveen *et al.*, 2014). This progression in understanding, as more observations are made, also applies to our own studies of the Gediz record.

In our previous papers concerning the Gediz River record, Western Turkey, we have suggested both climate-drivers (Maddy *et al.*, 2005; Veldkamp *et al.*, 2015) and tectonic-drivers (Maddy *et al.*, 2017) during the Early Pleistocene. As our knowledge of the sequence has improved however, even our compromise 'uplift-driven, climate-controlled system' seems to oversimplify the multitude of drivers and constraints. Elsewhere attention has

been drawn to the roles played by a number of additional factors that promote the conditions necessary for river terrace formation e.g. lithological heterogeneity; structural controls; fault movement; and local base level change due to damming events (Stokes *et al.*, 2017; Mather and Stokes, 2018; Martins *et al.*, 2017; Van Gorp *et al.*, 2016). As our work has progressed it has become clear that some, if not all, of these additional factors play some role, at least locally, in determining the Gediz river terrace sequence.

In this paper we aim to re-evaluate the drivers and controls of past Gediz River terrace formation by integrating new fluvial terrace observations with additional palaeohydrological insights gained through the investigation of associated travertine and tufa records. The river terrace archive includes hydrodynamic attributes that help us reconstruct, for example, changes in river flow characteristics in channels formed along the principal drainage lines. They also contain attributes that reflect geodynamics such as faulting (e.g. longitudinal profile offset) but there are few attributes that shed light on subsurface water sources. In the Gediz catchment the most obvious source for subsurface water data comes from the travertines and tufas archive deposited where groundwater resurgence occurs at surface springs. As these springs yield carbonized waters that rise along faults and fractures, they not only can provide insight into subsurface water recycling but also link directly to the geodynamics and geometry of faulting and fracturing. Utilising both archives provides deeper insights into how the Gediz sequence has evolved through the Early Pleistocene and highlights the complexity of natural sequences.

1.2 Geological Setting Gediz Valley

The Gediz River is the second largest river in Anatolia flowing into the Aegean Sea, with a catchment of $\sim 17500 \text{ km}^2$ flowing $\sim 400 \text{ km}$ from the mountains of the Murat Dağı in the east into the Aegean Sea north west of Izmir (Fig.1). Our current focus (Figs. 2-4) is in the Gediz valley which lies within the Kula Volcanic UNESCO Global GeoPark which, as the name suggests, is a landscape dominated by classical scoria cones and their associated lava flows formed during episodic periods of volcanism during the past $\sim 1.4 \text{ Ma}$ (Maddy *et al.*, 2017). Traversing this volcanic field is the Gediz River which has been repeatedly dammed and diverted during these volcanic episodes (Maddy *et al.*, 2017, van Gorp *et al.*, 2013, 2016).

Progressive incision of the Gediz River throughout the Quaternary leads to constantly varying available source lithologies both in space and time as the river cannibalises and erodes sediment from the complex fill of the pre-Quaternary Basin. Furthermore, this lithological complexity has direct implications for the chemical composition of the subsurface water flows and pathways. An understanding of the pre-Quaternary catchment geology is therefore fundamental to our understanding of the Quaternary sequence.

The oldest rocks in the study area are the pre-Neogene metamorphics of the Menderes Massif (gneiss, schist, quartzite and marble). These rocks outcrop predominantly in the SE quadrant of our study area (Fig. 2) and they structurally underlie Cretaceous ophiolites and ophiolitic *mélange* rocks that outcrop more extensively within this area especially north of İbrahimğa where ophiolitic hills reach over 550m a.m.s.l. (Fig. 2). The earliest deposits infilling the overlying Tertiary Selendi Basin are the conglomerates and sandstones of the Hacibekir Group (Kürtköyü and Yeniköy Formations), which is generally accepted as Early Miocene in age (Seyitoğlu, 1997, Westaway *et al.*, 2003, 2004). This Group has a restricted outcrop within the study area and comprises coarse grade and angular gravels interpreted as alluvial fan facies derived from the topographic highs of the metamorphic and ophiolitic hills of the Early Miocene (Ersoy *et al.*, 2010). These deposits, are extensively deformed, indicating an early Miocene phase of deformation (Purvis and Robertson, 2004). The İnay Group unconformably overlies the Hacibekir Group. The stratigraphic sequence of the İnay Group records progressive in-fill of the Selendi Basin. Gently inclined to sub-horizontally bedded sands and silts up to ~200 m in thickness, (Ahmetler Formation, Balçıklidere Member) are overlain by fine-grained sandstones and silts up to a few tens of metres in thickness (Ahmetler Formation, Gedikler Member). $^{40}\text{Ar}/^{39}\text{Ar}$ age estimates of 18.89 ± 0.58 Ma to 16.42 ± 0.09 Ma from intercalated tuff within the Gedikler Member in the Selendi Basin suggest an Early to early Middle Miocene age for these units (Purvis and Robertson, 2005). The İnay Group sequence is capped by up to ~300m of carbonaceous muds and silts, lacustrine facies of the Ulubey Formation, which represent the end stage of Basin fill. The age of the Ulubey Formation in the Selendi Basin can be no younger than the Late Miocene.

The Basin fill sediments are subsequently deformed during the Late Miocene as a result of tectonic extension evidenced by the formation of large numbers of NNE-SSW trending

normal faults (Yilmaz *et al.*, 2000). The throws on these faults are reported by Bunbury *et al.* (2001) to be generally less than 100m based upon the offset of the Ulubey Formation. These offsets undoubtedly created significant topography across the former Miocene lake floor, which would have promoted drainage development. A number of these NNE-SSW trending faults cut across the study area and their exhumation often appears to guide contemporary river courses (Maddy *et al.*, 2017). For a more detailed description of the Selendi Basin sequence see Ersoy *et al.*, 2010 or Maddy *et al.*, 2012a.

To help navigate the complexity of process interactions, and as a framework for discussion, Fig. 3 provides a simplified conceptual landscape model for this segment of the Gediz valley during the Early Pleistocene. This shows the key processes and constraints which exert influence on the Gediz valley environment albeit their relative importance varies in both in time and space throughout the Early Pleistocene.

The general pattern of main trunk river behaviour during this period is one of incision into the Miocene Selendi Basin fill sequence (Seyitoğlu, 1997; Ersoy *et al.*, 2010), punctuated by periods of valley widening and sedimentation (represented by the terrace sediments). This pattern requires gradient adjustment, with net incision reflecting baselevel adjustment. Thus, processes which affect baselevel are critical to understanding. Westaway *et al.* (2003, 2004, 2006) have suggested that this progressive incision is driven by regional uplift caused principally by erosional isostasy. Bunbury *et al.* (2001) however suggested that baselevel changes are driven by the fault generated subsidence in the Alaşehir Graben downstream i.e. relative uplift on the rift shoulder (Fig.1). These mechanisms focus on the regional and ignore the possibility of more local adjustments in river profile generated in response to more immediate baselevel change forced by local faulting, volcanism and, significantly, lithological constraints that vary in time as exhumation of the Miocene basin fill progresses.

During the Early Pleistocene initial river incision progresses through the relatively hard continental carbonates (limestone) of the Ulubey Formation, which cap the Miocene basin fill sequence, exploiting the weakness caused by late Miocene ~NNE-trending faults which segment the formally continuous lake sequence (Ersoy *et al.*, 2010, 2011). Once beneath the limestone the river can access the more readily erodible underlying clastic sediments of the Ahmetler and Hacibekir Formations before reaching the hard basement rocks of the

Menderes Schist and Ophiolite complex. The geometry of these units is complex, particularly the basement which reflects a buried early Cenozoic landscape deformed during the late Miocene (post 7Ma), Pliocene and Quaternary (Ersoy *et al.*, 2010). Significantly the varying substrate lithology encountered by the river channel during progressive incision exerts local constraints on both vertical and lateral erosion, limiting channel adjustment options when confined by more resistant Ulubey Formation and basement rock substrates, but allowing valley widening, and the creation of the necessary accommodation space for the subsequent sedimentation and potential preservation of the river terrace record (the fluvial archive), once on the more readily erodible Ahmetler Formation substrates.

In addition to adding complexity to the geometry of the underlying geology, faults, and associated fractures, lead to natural weakness in the substrate and thus act as foci for erosion especially in hard rocks such as the Ulubey Formation and the basement. As the basin fill is removed through downcutting and erosion, the Early Pleistocene Gediz River not only exhumes the pre-existing Miocene and Pliocene faults, but it must adjust to contemporary faulting. E-W Normal faulting during the Early Pleistocene directly affects the Gediz catchment, creating a series of shallow basins that introduce new topographic gradients that require fluvial system adjustment. The spatial pattern, magnitude and timing of repeated local crustal movements exert an immediate effect on river behaviour. This situation is complicated further by the onset of local volcanism at ~1.3Ma.

The sedimentation-incision cycles manifest in the river terrace record reflect changing water and sediment budgets, a function of river flow strength and sediment availability. Key catchment wide controls on budgets include extrinsic controls such as climate change, and its associated vegetation change, and geology (substrate lithology). Changing climate regimes govern water budgets directly through precipitation magnitude/frequency and evaporation rates but also indirectly through its constraints on vegetation and thus changes in evapotranspiration rates and subsurface water flow through the rooting zone. Substrate lithology and vegetation cover exert substantive control over sediment availability. More locally channel sediment availability is often a simple matter of slope-channel coupling i.e. whether there is sediment starvation due to decoupling or sediment exhaustion due to complete transport of the locally available stores. Available stores on the valley sides reflect the nature of slope processes. Here in the Gediz valley Ozaner (1982) mapped several

landslides albeit the age of these features is unknown and at least some of the identified landslides may have alternate explanation. Landsliding due to saturation during volcanic dammed lake phases and perhaps during seismic activity is likely however (van Gorp *et al.*, 2013). Indeed, the permutations of competing controls and constraints are numerous, especially as the local scale.

In order to simplify discussion, we will first look at the data from the key archives, fluvial (based upon previously published data and new observations) and travertine (discussed here for the very first time in the literature), separately. In addition, some data from the slope (colluvial) archive is also available (Veldkamp *et al.*, 2015).

1.3 The Gediz Fluvial Archive

The fluvial sedimentary archive of the Gediz River provides an unparalleled framework for the Early Pleistocene in Western Turkey (Maddy *et al.*, 2017). In our previous work we identified an Early Pleistocene river terrace sequence, comprising 11 terraces (GT11-1) of the Gediz Valley Formation, buried, and thus preserved, beneath capping lava flows that have helped to constrain the timing of river terrace formation. Although the frequency of terrace formation was initially thought to reflect an uplift-driven, climate-controlled system (Maddy *et al.*, 2005, 2008) later work suggested a more complex causality reflecting the interplay between climate, volcanism and neotectonics (Maddy *et al.*, 2012a, 2012b, 2015).

The terrace sequence was first recognised, and is best preserved, beneath the Burgaz and Sarnıç plateaus (Figs. 4,5). Detailed reconstruction of the buried sequence revealed an earlier, higher, sequence (GT11-7) that showed no evidence of contemporary volcanism. In places this part of the sequence is overlain by thick colluvial sediments which incorporate complex colluvial and pedogenic sequences. The complexity of these pedogenic sequences increases with terrace height and they suggest repeated wet-dry cycles interpreted as reflecting the obliquity-driven changes of the Early Pleistocene (Veldkamp *et al.*, 2015). GT6 however is overlain by thick lacustrine deposits indicating damming of Gediz drainage downstream. These lacustrine sediments incorporate thick tephra layers, a testament to the onset of volcanism. All subsequent younger terraces identified beneath the plateaus include comparatively high proportions of basalt clasts confirming their deposition after the onset of local volcanism. The GT6 terrace can be traced further downstream onto the eastern

edge of the İbrahimağa plateau where the Tavşan volcanic neck (Fig. 2, no. 2) lies directly within the projected valley path. Although attempts to obtain age estimates from this neck have so far failed, a nearby neck, Akçeşme (Fig. 2, no. 3), also lies within the projected valley floor and has an age estimate of $\sim 1.3\text{Ma}$ (Maddy *et al.*, 2017). Given that both the Tavşan and Akçeşme necks appear to emerge from the same main feeder fault, it is likely that they are close in age and hence all terraces GT5-GT1 identified upstream must be younger and thus, by inference, all higher terraces GT11-GT7 must be older. Maddy *et al.* (2017) suggest that the timing of GT5-GT1 excludes a direct climate control on terracing and thus an alternate mechanism must be sought to explain this part of the sequence. Clearly, the onset of volcanism and the recognition of active faulting during this period (Maddy *et al.*, 2017) make dynamical system response to these drivers a likely causal mechanism.

1.3.1. Terracing, volcanism and Early Pleistocene neotectonics

The lavas of the Kula Volcanic Province have been previously mapped and subdivided on the basis of their weathering characteristics and topographic expression (Erinç, 1970; Ercan, 1993; Erinç *et al.*, 1983, 1996). Conventionally four groupings are recognised ranging from $\beta 1$ (the oldest) to $\beta 4$ (the youngest). Here we are only concerned with lavas categorised as $\beta 2$ which cap the high-level Burgaz, Sarnıç and İbrahimağa volcanic plateau (Fig.2). These lavas have a comprehensive set of Early Pleistocene age estimates and associated palaeomagnetic measurements discussed in detail by Maddy *et al.* (2017).

The oldest basaltic volcanism yet recognised in this area is from the Akçeşme neck north of the İbrahimağa plateau (Fig.2) where an Ar-Ar age estimate of $1327 \pm 11 \text{ ka}$ is reported (see Maddy *et al.*, 2017, Table 1). Similar age estimates of $1325 \pm 42 \text{ ka}$, $1299 \pm 17 \text{ ka}$ and $1264 \pm 15 \text{ ka}$ from lava flows on the İbrahimağa, Burgaz and Sarnıç plateaus respectively, suggest penecontemporaneous eruptions with an onset $\sim 1.3\text{Ma}$ spanning across the area now represented by the plateau. This activity continues sporadically until $\sim 1\text{Ma}$, with the youngest age estimate of $999 \pm 21 \text{ ka}$ from a lava flow on the eastern edge of the İbrahimağa plateau. Taken collectively therefore these lavas span the MIS42 – MIS28 time interval (Lisiecki and Raymo, 2005) and constrain the age of the terrace sequence such that terraces GT11-6 must predate MIS42 and terraces GT5-1 form within this timeframe (Maddy *et al.*, 2017).

The onset of volcanism $\sim 1.3\text{Ma}$ is a direct response to rising magma. The chemical composition of this magma, as observed in the lavas, is closely allied to mantle material with little, or no, mixing with lithospheric material (e.g. Richardson-Bunbury, 1993, 1996; Ersoy *et al.*, 2008). Conventionally this volcanism has been tied to regional north-south tectonic extension (e.g. Bunbury *et al.*, 2001). Bozkurt (2001) suggests that the youngest phase of north-south extension, responsible for the high angle E-W striking normal faults that bound the Alaşehir (Gediz) graben to the south of the study area (Fig.1), began in the Pliocene $\sim 5\text{Ma}$. Similar E-W trending normal faults, but with considerably lower offsets of $\sim 20\text{m}$ and assigned a Quaternary age, have been identified in the Selendi Basin to the north of the field area (Purvis and Robertson, 2004) suggesting continuing movement during the Quaternary. Within the field area Maddy *et al.* (2017) identified movement along an E-W striking normal fault during the Early Pleistocene volcanic phase, confirming Quaternary age fault activation (or reactivation) and a close association between volcanism and fault motion. Recently however, Nikogosian *et al.* (2018) have suggested that the Kula volcanism might not result directly from local tectonics, but it may be better explained by the rise of magma through slab gaps from a mantle plume.

Whatever the precise mechanism of genesis, the rising magma has profound effect on near-surface and surface conditions. Rising magma causes surface dilation (doming), fracturing and possibly localized faulting. These structural weaknesses provide conduits for the rising magma which ultimately emerges at the land surface and forms lava flows that reshape the surface topography and modify surface drainage patterns (Maddy *et al.*, 2012b; van Gorp *et al.*, 2013, 2016). Furthermore, the rising magma acts as a subsurface heat source, warming and rerouting groundwater flow, thus reconfiguring the entire hydrological system feeding the Gediz River.

1.3.2 Gediz terrace sequence (GT5 to Gt1) and localised faulting

Based upon our extensive $^{40}\text{Ar}/^{39}\text{Ar}$ basalt age estimation dataset (see Table 2 Maddy *et al.*, 2017) our earlier work suggests that the terraces GT5-1, identified on the Burgaz and Sarnıç plateaus (Fig. 5), break the simple linkage between terrace formation and obliquity-driven climate cycles of the Early Pleistocene (Maddy *et al.*, 2017). An alternate explanation was proposed for this younger sequence based upon the recognition of contemporaneous fault

movements recognised at outcrop close to the İbrahimağa plateau. Subsequent observations and re-evaluation of existing data have provided more insight into this linkage.

The regional tectonic setting during the Neogene and Quaternary is conditioned by north-south extension and the formation of substantive ~E-W striking high-angle normal faults (Bozkurt, 2001). Although these motions have led to the creation of large-scale grabens, such as the Alaşehir (Gediz) Graben to the south of the field area (Fig.1), faulting and fracturing is not restricted to these areas. However, even small-scale fault movements can have significant impact locally on river behaviour making their identification critical to interpretation.

1.4 The Gediz Valley Travertine Archive

The subsurface fractures and faults act as conduits that serve to re-plumb the subsurface network of groundwater flow. The primary source of groundwater in the study area is from meteoric surface waters that infiltrate into the subsurface (Fig.3). The chemistry of these waters is predominantly controlled by the surface geology which in the field area is dominated by the continental carbonates of the Ulubey Formation. Dissection of these carbonates throughout the Quaternary limits their current spatial extent to outcrops along the highest plateaus but during the Early Pleistocene they would have been spatially more extensive and formed the dominant lithology flanking the Gediz valley. Dissolution of these carbonates provides calcium-rich groundwaters which subsequently route through subsurface fracture networks, enriched in CO₂ from magma sources (see Fig.3), and re-emerge at the surface at springs situated where fractures intersect the land surface. The consequent drop in CO₂ pressure as the groundwater emerges, leads to the precipitation of extensive carbonate deposits in the form of travertine.

The travertine archive not only help to locate and delimit the underlying geological structures but changing water chemistry, reflected in the chemistry of the precipitates, provides valuable insights into changing meteoric source water composition and sub-surface water cycling.

2 Methods

The investigation of the two archives (fluvial and travertine) reported here is based upon a combination of existing and new data. Fluvial archive information is drawn from our previous publications and enhanced through the utilisation of higher-resolution morphological data. The travertine archive is examined using both morphological and geochemistry data.

2.1 Morphological Data: Detailed Digital Elevation Model (DEM) processing

In order to examine the relationship between the Gediz terrace gravels, the travertines and the regional faults and fractures we must first clearly delimit both datasets in space. This requires accurate positioning of outcrops (using spot measurements), specifically the lower bounding surface of the gravel units where they directly lie on substrates of non-Gediz origin, and the use of high-resolution topographic data for the identification of key landforms based upon accurate DEMs.

Previously we created a DEM for the field area using panchromatic stereo Alos Prism satellite images, which produced a 15m cell resolution model (used as the base layer for Figs. 4,5 and 7). However, using these lower resolution, generalised, data sources makes detailed analysis challenging, especially when comparing these data against more accurate field-based spot measurements based upon conventional survey methods (see Maddy *et al.*, 2005) or more recently differential GNSS (dGNSS) positioning (accurate to sub-decimetres). High resolution topographic data is not only essential when attempting to correlate gravels over comparatively long distances, especially where terrace separation is small (i.e. in most cases <7m), but also for the identification of landscape features such as fault scarps and fractures, as these features often have subdued topographic expression. Accurate topographic data also helps to characterize travertine deposits as e.g. mounds, sheets, cascades, each of which have implications for their genesis and their relationship to the underlying palaeolandscape.

As a consequence of the need for better topographic data we have recently therefore started to obtain higher resolution topographic data using an unmanned aerial vehicle (UAV) mounted camera. Thus far UAV-mapping has targeted specific areas, but efforts are on-going to improve overall ground coverage. Nonetheless the existing UAV-based datasets

provide valuable additional data on which to base interpretation. Detailed description of our field topographic data collection method can be found in *Supplemental 1*. This increase in data resolution gives more confidence to interpretation but, even this resolution falls well short of the accuracy obtained through dGNSS positioning.

2.2 Geochemistry Data

In order to understand better how the travertine forms we present here basic elemental composition and stable isotope data ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) obtained from 75, 2.5cm-diameter, stratigraphically constrained core samples, taken from 11 substantive travertine outcrops (Fig. 4 orange circles and described below). For comparison a further 20 samples were obtained from the calcareous units of the Ulubey Formation (Fig.4. small blue triangles) together with 12 calcrete samples associated with the Gediz gravels (Fig.4 small yellow circles).

Bulk chemical composition was characterized using ICP analysis, the raw data for which, along with detailed preparation steps, are given in *Supplemental 2*. Here we use bulk chemical composition as an indicator of the original source water pathway. Water routed solely through the surficial Ulubey carbonates should closely reflect the chemical composition of that material. More deeply routed water sources have more complex pathways and interact with a greater variety of host rocks.

Stable Oxygen and Carbon isotopes were measured using a continuous-flow Isoprime (now Elementar) mass-spectrometer. The raw data and detailed preparation steps for this method are given in *Supplemental 3*. Here we use bulk stable isotopes to distinguish between thermogenic and non-thermogenic deposition and as an indication of the likely ratio of deep routed to meteoric contributing water sources. Shallow routed water may still retain attributes of the original atmospheric source water and thus, potentially, provide an insight into meteoric water composition.

3 Results

3.1 Terraces

In order to understand the generation of GT5-GT1 it is necessary to look first in the area immediately downstream of where they can no longer be identified. As much of the immediate area west of the Sarnıç plateau is heavily eroded (Fig.4) our only source of information comes from outcrops that are exposed along the perimeter of the İbrahimğa plateau. Fig.5 shows the available known gravel outcrops (most are sub-basalt) and their relationship to the wider Gediz terrace sequence is shown in the longitudinal profile (projected on the valley axis) diagram (Fig. 6). The raw data for the contact heights from the Burgaz and Sarnıç plateaus used in these figures can be found in supplementary data of Maddy *et al.* (2007) and the majority of the data used for the İbrahimğa plateau can be found in Maddy *et al.* (2012a). However, these data also include recent observations (Fig. 5, locations 216 and 217) that hint at preservation of higher, and therefore older, terraces than earlier reported. Previously, we have suggested that gravels outcropping at Şeremet (Fig 5, location 212) and west of Eriklikas (Fig 5. locations 214 and 204) may correlate with the lower terraces but gravel counts from these outcrops (see Maddy *et al.*, 2012a, Table 1) do not contain basalt. Given that the gravels of GT5-GT1 upstream all contain basalt, the property that separates them from the higher terraces, and that there are ample lavas of appropriate age in immediate juxtaposition to these sites, it seems likely that these gravels were deposited prior to the onset of volcanism. Gravels of similar composition, and correlated with GT6, do crop out on the eastern edge of the İbrahimğa plateau at site 200 (Fig.5) but these have a basal contact height ~30m above those at Şeremet, well beyond any reasonable simple correlation between the two locations given the ~0.005 suggested gradient for GT6 (Fig. 5).

3.2 Lineaments and Faulting

There are many similarly oriented structures evident in these DEM data (Fig. 4b) but most prominent are ~E-W orientated structures. In order to aid discussion, here we identify five substantive ~E-W trending lineaments, labelled f1-f5 moving northwards (Fig. 7a), although it is clear that this area should be considered as a zone rather than as a restricted number of

discrete features. Although drawn as continuous features, for much of their length the trace of the southernmost lineaments (f1-f3) are obscured by basalt flows. Below we discuss the relationship of these features to known field outcrops. In all cases it appears these lineaments reflect the surface expression of underlying fractures and/or faults.

To the west of the İbrahimağa plateau these lineaments coincide with distinct breaks in slope along a travertine-covered SSW-NNE orientated promontory (Figs. 7B, 8). Figure 7b highlights the morphology of this ridge by plotting 10m contour data. The capping travertines extend from Hanyıkığı Tepe (~667m) in the south, northwards towards the modern Gediz valley and appear to drape across a pre-existing topography (see below) where they terminate at their most northerly extent at ~490m, below which only basement rocks can be observed in the walls of the incised Gediz valley. The topography suggests there are multiple domes aligned along the ridge suggesting the presence of multiple travertine mounds. Their alignment coincides directly with the strike of a prominent NNE-SSW fault (see Ersoy *et al.*, 2010, Fig.2). However, because there is no direct contact with Quaternary volcanic deposits, the age of these deposits is unknown, and it remains possible that they are pre-Quaternary in age. Figure 7B shows that lineaments f1-f4 intersect the promontory precisely where there are discrete mounds. The internal structure of one of these travertine mounds (associated with f3) is exposed at site Mar (Figs. 7a, 10B, C., see below) where there is extensive syn- and post-depositional deformation suggestive of seismic activity associated with the faults. No trace of these lineaments can be found west of the promontory, suggesting the younger E-W striking faults terminate at the pre-existing NNE-SSW fault. The coincidence of the faults and a high basement ridge all serve to route water into the travertine mounds that form the resistant promontory. Clear scarps mark the f4 and f5 intersections with the ridge (Fig. 8). The lowest travertine outcrop lies on a distinct bench cut into the basement rocks ~490m. Further outcrops of travertine at the western perimeter of İbrahimağa close to the village of Karakoca (sites Kar and KaE, Fig. 7A) have bases at similar altitudes and travertine debris litters the fields of the incised valley that separate these outcrops from the promontory, strongly suggesting that this area was formerly covered by an extensive travertine sheet.

Moving eastwards (upstream) unequivocal evidence for faulting on f4 is clear in exposures at the foot of a prominent scarp (Fig. 10A). Maddy *et al.* (2017) report evidence of motion,

in the form of drag structures in the footwall, of a fault exposed at outcrop immediately north of the travertine outcrop at Mft (Fig. 7A). Rapid burial of the fault by basaltic volcanoclastic sediments testifies to the Quaternary age of this motion (see Fig. 9 of Maddy *et al.*, 2017). The adjacent scarp is formed in travertine (see Mft, Figs. 7, 10A) which in section displays clear sub-horizontal stratification and thus there is no indication that these deposits drape across a steep pre-existing scarp, rather it is likely that this travertine is, at least in part, cut by the fault. This scarp extends westwards towards the village of Karakoca where basalts obscure its trace. The relationship of the basalt to the fault is unclear but it is possible that the fault deforms the basalt. The basalts clearly overlie, and thus postdate, the travertine at Kar but their relationship to the travertine at KaE is currently unclear.

To the north of Mft, a further, smaller travertine deposit (Fls) intersects f5 and overlies Gediz gravels at site 204 (Figs. 5, 7A). The gravels here are deformed, but it is unclear whether this deformation results from movement associated with the lineament or whether it is due to the subsequent injection of the travertine. The base of this travertine extends ~8m below the base of the gravels and thus postdates that valley floor. Further east f5 forms the northern limit of Eriklikas (Fig. 7B), abruptly truncating the basalt there, leading to an unusually linear margin, perhaps suggesting some movement on this structure post-deposition of those basalts.

Further south, and adjacent to the Tavşan volcanic neck, is a travertine outcrop (Fig. 7A. Tav) that marks the intersection with lineament f2. There is no obvious expression of f3 on the plateau, but this lineament does directly intersect with the Akçeşme volcanic neck (Fig. 7B), the oldest basalt yet identified, suggesting this lineament may coincide with the conduit for lavas emerging from this volcanic centre.

Significantly however the gravels close to the village of Şeremet outcrop (212) north of f2 (Figs. 5, 7). Evidence for a buried scarp, associated with f2, comes from outcrops in the gulley cut between the f3 and f2 lineaments. Here lavas thicken rapidly from <15m thickness on the plateau to >70m above site 212 (see Maddy *et al.*, 2012 Fig. 6). The scarp form is, however, not evident in the upper surface of the lava which displays only a gentle slope from south to north (Fig. 9B-B').

To the east and north (Fig. 9B-B'), beyond the limits of the İbrahimağa plateau, the lineament traces are delineated through steep facets cut into ophiolitic basement rocks around Papuçlu. Here exposed ophiolitic basement forms a series of low hills, a palaeotopography exhumed from beneath the Miocene basin fill. There is considerable structural complexity to the basement here (see Ersoy *et al.*, 2014, Fig.8) but observations include the identification of E-W oriented normal faults.

3.3 *Implication of Quaternary faulting and fracturing for the Gediz Terrace sequence*

The identification of faulting and fracturing in the vicinity of the İbrahimağa plateau has profound implications for the interpretation of the Gediz terrace sequence. Figure 6 shows the longitudinal profiles of the terraces based upon correlation of our mapped gravel outcrops across the three plateaus. The anomalous composition of the lower than expected gravels at sites 212, 214, 204 can now, perhaps, be better explained and their offset position may provide the critical link between faulting and the generation of terraces GT5-1 upstream. Post-GT6 movements on f1-f5 could explain the apparent offset of sites 212, 214 and 204 relative to site 200. At present it is not possible to distinguish the composition of GT6 gravels from the older terrace gravels hence it is not possible to unequivocally attribute any of the lower (offset), non-basalt bearing, gravels (212, 214 and 204) to a specific terrace within the GT11-GT6 range on the basis of lithological composition.

In the simplest scenario we could assume that the gravels at 212 are the youngest offset gravels, preserved by the overlying basalt which entered a contemporary floodplain. As we know volcanism began during, or immediately post, the deposition of GT6, we could assume that these gravels are equivalent to the GT6 deposits at site 200. In this scenario the offset of site 212, relative to its projected altitude is ~24m (Fig 6). However, the river would pass across both f1 and f2 when flowing from site 200 to site 212 and thus this offset can be considered the accommodation of the cumulative movements across both faults. These movements would require gradient adjustments in the palaeo-Gediz upstream of the faults.

Critically, in this vicinity, the Ahmetler Formation is thin and thus it is possible that the fault offsets exposed basement rocks in the footwall. Although basement rocks cannot be observed at outcrop, due to the draping of overlying basalt, high, heavily deformed,

Hacıbekir formation rocks are observed in the footwall of f1 close to site 213 (Fig.5). Incision at the fault was thus likely constrained by the harder substrate enabling the creation of knickpoints that would propagate upstream leading to possible terrace formation upstream. Given the readily erodible Ahmetler substrate upstream, this propagation could be very rapid i.e. knickpoints could progress upstream beyond the Burgaz plateau prior to the next incremental movement.

As we already know, there are, at least, 5 additional lower terraces upstream suggesting a cumulative incision of ~35m (Fig. 6, GT67 to GT1) and thus the ~24m offset observed on f1/f2 cannot explain all of the incision. But these are not the only downstream faults. We have clearly established that there is movement on f4 and similar movements on f3 and f5 are likely. Taken collectively therefore a movement total of ~12m on these faults (f3-f5) could generate sufficient baselevel change, in association with the motion on ft1 and 2, to generate all of the upstream terraces GT5 - 1.

The timing of this faulting is clearly associated with the onset of volcanism and therefore perhaps triggered by surface doming due to the rising magma, although continuing regional extension cannot be ruled out. Closely allied to the Early Pleistocene phase of volcanism is the production of fault and fracture guided springs that lead to the deposition of travertine.

3.4.1 *Travertines at Outcrop*

Travertines crop out extensively around the İbrahimağa plateau and immediately to the west (Fig. 5 orange circles). The morphological form of these deposits suggests deposition as both sheets and mounds. Thus far 11 localities have been examined (Fig. 7A). These sites are predominantly exposed beneath basalt and therefore do not appear on surface maps but the sites Mar, Kub and Tav, which occur at the surface, have all previously been mapped as Miocene Ulubey Formation. This is not surprising given the similarity at weathered outcrop and their lower altitude has been explained as resulting from post-depositional faulting (e.g. Maddy *et al.*, 2017 use the Tav outcrop to suggest offset). However, recent commercial quarrying at Mar confirms that the carbonates that cap the promontory are indeed travertine and not continental limestones (Figs.7A, 10).

Locations Mar, Kub, Kar and KaE

While only small outcrops of travertine can be identified on the Burgaz and Sarnıç plateaus, extensive travertine outcrops can be observed to the west of the İbrahimağa plateau (Fig. 7A). As noted above the DEMs clearly delimit a series of mounds (Figs. 7B, 8A-A') capping the ridge with deposits draping across the hillside and coalescing into a larger sheet at lower elevation. Recent quarry activity around site Mar suggests a minimum thickness of 10m (Figs. 8, 9A-A', 10B) adjacent to one of the mounds along the ridge with thicker deposits recorded at Kar (~15m) at lower elevation.

The fresh travertines exposures at Mar are significant in displaying extensive syn- and post-depositional deformation. Fig. 10B shows one of the exposed faces where extensive fracturing is visible. Fig. 10C displays one of the major cracks in detail and strongly suggests offset close to 0.5m, thus implying, in this case, active post-depositional faulting. Frequent travertine brecciation also testifies to periods of intense ground instability. The fractures and faults are subject to dissolution and post-depositional infilling, often with materials rich in soil material suggesting periods of land surface stability with active soil formation.

The site of Mar lies adjacent to a mound situated at the intersection with f3 (Fig. 7A). The deformation structures could therefore relate to earthquake activity and rupture along this, and adjacent faults, both during and after deposition of the travertine at this site. There is only limited outcrop of travertine at site Kub (Fig. 7A), which lies immediately north of the f5 intersect. The weathered exposure makes identification of internal structures difficult. More extensive weathered exposures are observed at Kar, south of the village of Karakoca (Fig. 7A), where the travertine is overlain by lava. This lava has an age estimate of 1272 ± 80 ka (Maddy *et al.*, 2017, location H, table 4) thus providing a minimum age for the youngest travertine in this area. A thin exposure at KaE, which also lies immediately south of f5, is overlain by lava but it is possible this basalt is displaced.

Locations Fls, Mft and Mfl

Further east travertines crop out along f5 at Fls (up to ~12m in thickness) and along f4 at Mft (~17m) and Mfl (~8m). Exposures at Mft display sub-horizontal stratification but those at Mfl are inclined perhaps suggesting the latter has been displaced. None of these outcrops are covered by lava but the travertines at Fls are seen to form over the gravels of

site 204 and appear to extend ~8m below the terrace gravel lower bounding surface, thus these lower deposits post-date the terrace.

Location Tav

An outcrop of carbonates overlying Miocene Ahmetler Formation (sands) is seen immediately west of the Tavşan cone (Fig. 7A), reaching a maximum height of ~630m. On previous maps this outcrop is correlated with the Ulubey Formation, but it lies below the Ulubey outcrops in the scarp to the south, where the Ahmetler-Ulubey transition has been observed at ~650m. It is likely that this outcrop, which lies directly on ft2 is travertine deposited as a low mound, but its chemistry is unusual (see below). Although this mound lies adjacent to the Tavşan cone the lavas do not cover it and significantly the lava to the west, which extends onto Eriklikas (Fig. 7B), appears to flow around it. This suggests this mound formed during this volcanic phase.

Locations Kav, Bur and Ibn

Further east there is a small travertine outcrop at Kav (~5m) that intersects the trace of f1. This outcrop lies within the altitudinal range of similar travertine outcrops further east at Bur (~7m) and to the south at Ibn (~3m), both of which lie beneath basaltic lava flows. Bur and Ibn appear to intersect ~E-W lineaments north of those discussed here, suggestive of further fracture/fault traces. The lavas capping Bur are probably a lateral continuation of the lava above GT6 gravels at site 200. This lava has an age estimate of 1079 ± 16 ka (Maddy *et al.*, 2017, location M Table 4). A lateral equivalent of the lava above Ibn has an age estimate of 999 ± 21 ka (Westaway *et al.*, 2006). As these age estimates provide minimum age estimates for the underlying travertine, they confirm that their deposition falls within the post-GT6 interval during which terraces GT5-1 were deposited.

3.5 Travertine Chemistry

3.5.1 Elemental Composition

Although the three carbonate datasets (Ulubey, travertines and calcretes) share much of their basic chemistry there are notable differences. On average the travertines have lower concentrations of Mg, Si, Al, Fe, Cr, Co, K, Li and Mn but higher concentrations of Ba and Ag (Table 1). This data suggests the travertines are deposited by water derived from both

Ulubey and non-Ulubey sources i.e they are a mixture of shallow and deep water sources. Our calcrete data show greater affinity with the Ulubey Formation samples than the travertines, perhaps indicating that the soil carbonates are largely derived from the underlying tributary Ulubey Formation limestone-rich gravels (Veldkamp *et al.* 2015).

3.5.2 Stable Isotope Composition

The summary isotope data shown in Table 1 illustrates clear differences between the three datasets. The mean $\delta^{18}\text{O}$ of the travertines is lighter than both the Ulubey and Calcrete samples and heavier for $\delta^{13}\text{C}$. The calcretes are significantly different from both the travertine and the Ulubey Formation samples, especially with their considerably lighter mean $\delta^{13}\text{C}$ value.

The complexity of the data is however better illustrated in Fig. 11. Figure 11 shows the spread of stable isotope data for each of the travertine localities and the Ulubey samples (u_select shows the spread for the Ulubey samples collected from the 5 outcrops closest to the İbrahimağa plateau Fig.4A). For $\delta^{18}\text{O}$ (Fig 10a) there is considerable overlap between the travertines and the Ulubey Formation samples. The mean Ulubey Formation $\delta^{18}\text{O}$ across the field area is -7.84‰, although outcrops closest to the travertines are lighter still with a mean of -9.42‰. Mar with a mean of -10.98‰ is the site with the lightest values while Tav, with an a mean of -7.67‰, is the heaviest. For $\delta^{13}\text{C}$ (Fig 11b) a clearer pattern emerges. Most of the travertine sites are heavier, on average, than the measurements from the Ulubey Formation (mean +0.09‰ generally but +0.81‰ locally). Mfl and Kav however have similar values to those of the Ulubey Formation but Tav is significantly lighter at -1.3‰.

The majority of the travertine samples lie, particularly for $\delta^{13}\text{C}$, within ranges consistent with a thermogenic origin (Pentecost, 2005). Figure 12 plots these data within the fields identified by Teboul *et al.* (2016) who summarise published data from a wide variety of locations. In that paper the term hypogean is preferred to thermogenic.

Isotopic values have many controls and the complexity of travertine formation can lead to significant changes in values within the same outcrop dependent upon e.g. facies (see e.g. Pola *et al.*, 2013, Della Porta, 2015). Our limited dataset hints at stratigraphical differences both within and between locations but establishing causality is currently beyond the scope of our current, limited, dataset.

3.6 Travertine Interpretation

The stable isotope data from the travertine (with the exception of Tav) strongly suggest deposition from source waters with a thermogenic origin. The overlap between the travertines and the Ulubey Formation samples is not as surprising as it may first seem. The Miocene Selendi Basin sequence includes thick volcanoclastic sediments associated with the eruption of a central stratovolcano (Yağcidağ) during the Middle Miocene and thinner basalt lava flows of Late Miocene age (Ersoy *et al.*, 2010). Thus, the lake sediments of the Ulubey Formation were undoubtedly deposited within waters that comprised sources from both surficial runoff and geothermally heated groundwater. It is even possible that the Ulubey Formation also contains travertines. Today the Kula volcanic province displays some of the highest subsurface geothermal heat fluxes in Anatolia (Erkan, 2015) and surface water springs are often, but not always, warm. Holocene volcanism (Ulusoy *et al.*, 2019; Heineke *et al.*, 2016; van Gorp *et al.*, 2013) suggests this heat is closely associated with rising magma.

Heating of groundwater during the Early Pleistocene may have similarly been associated with the rising magma. The similar $\delta^{13}\text{C}$ values from Mar, Kub, Kar and KaE supports their interpretation as a sheet deposit draped across the land surface into the Gediz valley at the GT6 level. The heating of the hydrothermal fluids by the rising magma generates the most extensive travertine in the study area before emerging through the faults to form the Akçeşme neck and the lavas that cover the travertine at Kar and KaE. The rising hydrothermal fluids also permeate and alter some of the early basalt flows close to site 218 (Fig. 10D).

The travertines at Mft, Fls and Bur appear to have lighter $\delta^{13}\text{C}$ values. This could reflect changes in the source water pathways, perhaps associated with a more quiescent phase in the volcanism. The travertines at Mfl, Kav and Ibn are lighter still and match closely with the Ulubey Formation samples. It is possible that these sites relate to source waters with little or no additional geothermal heating i.e. they could principally reflect meteoric waters routed through the Ulubey Formation.

Tav has the lightest $\delta^{13}\text{C}$ values, lighter even than the Ulubey Formation samples. It is significant that the travertines at this locality have one $\delta^{13}\text{C}$ value of -6.33‰ from the middle of the sequence. This sample is consistent with our calcrete isotopic dataset

suggesting a period of active calcrete formation during deposition of this mound. Elsewhere surface calcrete developed on the Gediz terrace sequence and in overlying colluvial sediments (Veldkamp *et al.*, 2015) have been associated with aridity during Pleistocene cold stages. It is therefore intriguing to consider that the Tav mound was deposited from source waters of predominant meteoric origin and under cold climate conditions. However, the linkage of changing source water chemistry due to the changing relative contribution of meteoric waters under varying climates (see Rih *et al.*, 2000) needs considerable further exploration before unequivocal linkage can be established.

4 Discussion

It is clear that the north-south extension of the region is critical to the origins of the Gediz drainage system. Major ~E-W orientated faults in the study area may be of pre-Quaternary age but tectonic controls on river behaviour continue into the Quaternary even as the focus of regional extension moves southwards to the Alaşehir graben. This Plio-Pleistocene extension triggers volcanism in the field area, with rising magma promoting surface cracking. These fractures re-plumb subsurface drainage networks leading to the mixing of both shallow- and deep- routed water sources. These fractures also act as conduits for water to rise to the land surface where they emerge at surface water springs and deposit travertine. The bulk chemistry of these travertines reflects the mixing of shallow- and deep- routed water sources and their stable isotopic composition confirms mixing with heated, most likely more deeply routed, water sources.

By utilising both the fluvial and travertine archives a clearer picture emerges of landscape evolution in the Gediz valley during the Early Pleistocene phase of volcanism. The rising lava from the upper mantle caused the land surface to bulge in and around the three plateaus, creating an “open structure” (Ersoy *et al.*, 2010) a consequence of surface cracking. Before the lavas arrive at the surface, hydrothermal fluids are already forced through the cracks and emerge as warm water springs forming mounds from which sheets of travertine drape across the pre-existing landscape west of İbrahimağa, reaching the contemporary GT6 palaeo-Gediz valley floor. The length of time represented by these travertines is unknown but their extension onto GT6 gives a minimum age for the youngest travertines of ~1272ka. Ultimately lavas rise through these cracks and erupt at volcanic centres and block the Gediz valley leading to the formation of a large upstream lake (Maddy *et al.*, 2017). The fluvial

incision will affect the location where spring water will emerge and where associated travertines are deposited. If it becomes possible to date the travertines independently this will potentially allow us to date the incision rate of the palaeo-Gediz (Veldkamp *et al.*, 2004).

During the subsequent 300ka period sporadic eruptions spawn numerous lava flows repeatedly dilating the surface as magma rises and then falls. These motions most likely generate earthquakes and sometimes surface rupture when fractures are offset to become faults. Early in this episode, one of these events may well have triggered the collapse of the initial lava dam allowing the Gediz River to return, initially flowing across the lake floor before ultimately adjusting and recovering its pre-dam position. This time however the area in the vicinity of the block (i.e. the western İbrahimağa plateau) has become faulted and accommodation of a lower baselevel is required. As the river traverses the zone with faults it incises sending waves of erosion upstream and knickpoints generated by each progressive fault movement form lower terraces upstream (GT5-1). Meanwhile periods of volcanic quiescence are marked by travertine production at springs located along the faults. These travertines form thinner deposits than the earlier travertines. Younger basalts drape across this landscape during later volcanic activity.

Throughout this period the palaeo-Gediz struggles to accommodate the rapidly changing conditions. The apparent uplift-driven, climate-controlled system of the terrace production prior to GT6 is overwhelmed by the localized downstream changes caused by the onset of volcanism and associated crustal instability. GT5-GT1 form comparatively quickly in response to progressive downstream subsidence. The response to faulting is highly localized, dependent on the immediate geometry and structure of the underlying strata, indicating the significance of differential erosion in response to changing lithological resistance. Knickpoints form where the river intersects faults cut into the hard, underlying, basement strata. Rapid upstream migration reflects the erodibility of the Ahmetler sub-straight. The exhumation of complex basement topography also plays a key role in generating ground water pressure and thus the creation of travertine mounds.

Each of these younger terraces is buried by lava flows generated later but capping of GT1 by basalts is complete by 1256 ± 16 (Maddy *et al.*, 2017 location C, Table 4), suggesting these fault-triggered terraces form within ~ 50 ka. No lower gravels have yet been identified even

though volcanism, and most likely travertine production, continue until volcanism ceases sometime around 999 ± 21 ka.

5. Conclusions

As we observe more outcrops in detail the Gediz sequence demonstrates increasing complexity. There is no reason to suggest this is unusual. Although climate and tectonics remain as key extrinsic drivers, the local landscape response is also conditioned by many additional factors. While it is tempting to search for global patterns in such data (“the big picture”), reducing the complexity to fit over simplistic conceptual models may be misleading. Recognising complexity requires detailed observation and therefore more emphasis on “the smaller picture” based upon extensive fieldwork.

Overall this tendency, that more in-depth data and observations leads to more complex reconstructed fluvial system response dynamics, is not a surprise. Comprehensive detailed studies remain rare and many of those that are reported in the literature are still aimed at proving the climate and or tectonic controls (Hu, *et al.*, 2019; Demoulin *et al.*, 2017; Cordier *et al.*, 2014; Fuller, *et al.*, 2009). This is also partly due to the techniques used by most researchers (Stokes, *et al.*, 2012), which are often biased towards the dating of existing records with new geochronological techniques. Examples of more comprehensively studied systems with recent publications are the Rhine-Meuse system (Woolderink, *et al.*, 2019.), Allier-Loire (Pastre, 2005), Vistula (Zieliński, *et al.*, 2018), The Yellow river in China (Su, *et al.*, 2020; Gao, *et al.*, 2020) and the Colorado river in the US (Aslan *et al.*, 2019; Karlstrom, *et al.* 2017).

By combining information from our existing geomorphological and sedimentary fluvial records with an associated and newly reported travertine record we have obtained a more detailed picture of which faults were active and their surface expression, information impossible to deduce from the terrace sequence directly. This combination clearly yields more insight into the multitude of factors conditioning the formation of terraces GT5-GT1.

Combining multiple archives undoubtedly gives greater insights than using one archive in isolation. Kolb, *et al.* (2017) linked river terraces and hillslope archives for paleoenvironmental reconstruction of the Quaternary Main River, Germany, while Claessens, *et al.* (2009) combined marine and fluvial terrace records in New Zealand. Marra

et al. (2019) combined glacio-eustatic forcing and volcano-tectonic uplift as constraints on the Tiber River terraces in Italy using fluvial and volcanic archives. Lucchitta *et al.* (2000) reconstructed cyclic aggradation and downcutting using fluvial, volcanic and soil-carbonates records. Combining archives increases complexity however and thus it is probable that new methodological frameworks will need to be established in order to fully exploit these archives e.g. Briant *et al.* (2018).

Future observations will undoubtedly add to our understanding of this sequence. Here, as elsewhere, climate and tectonics have been demonstrated as key drivers of landscape evolution. Perhaps now it is time to focus more on the detail and the role played by local/intrinsic drivers and constraints.

Acknowledgements

This work was supported by the British Institute at Ankara (BIAA, 2016-2018). We would like to acknowledge the help of Mark Armstrong and David Plaice in preparing and operating the UAVs. We would also like to acknowledge the on-going help and support of the staff of the UNESCO recognised Kula Geopark and the Kula local government authorities.

References

- Aslan, A., Karlstrom, K.E., Kirby, E., Heizler, M.T., Granger, D.E., Feathers, J.K., Hanson, P.R., Mahan, S.A. 2019. Resolving time-space histories of Late Cenozoic bedrock incision along the Upper Colorado River, USA. *Geomorphology* 347, Article number 106855
- Bozkurt, E. 2001. Neotectonics of Turkey—a synthesis. *Geodinamica Acta* 14, 3–30.
- Briant, R. M., Cohen, K. M., Cordier, S., Demoulin, A. J. A. G., Macklin, M. G., Mather, A. E., Rixhon, G., Veldkamp, T., Wainwright, J., Whittaker, A., and Wittmann, H. 2018. Applying Pattern Oriented Sampling in current fieldwork practice to enable more effective model evaluation in fluvial landscape evolution research. *Earth Surface Processes and Landforms*, 43, 2964– 2980.
- Bridgland, D.R., Westaway, R. 2014. Quaternary fluvial archives and landscape evolution: a global synthesis. *Proceedings of the Geologists' Association* 125, 600-629.
- Bunbury, J.M., Hall, L., Anderson, G.J., Stannard, A., 2001. The determination of fault movement history from the interaction of local drainage with volcanic episodes. *Geological Magazine* 138, 185– 192.
- Claessens, L., Veldkamp, A., ten Broeke, E.M., Vloemans, H., 2009. A Quaternary uplift record for the Auckland region, North Island, New Zealand, based on marine and fluvial terraces. *Global and Planetary Change* 68: 383–394.
<https://doi.org/10.1016/j.gloplacha.2009.03.001>
- Cordier S, Frechen M, Harmand D. 2014. Dating fluvial erosion: fluvial response to climate change in the Moselle catchment (France, Germany) since the Late Saalian. *Boreas* 43: 450-468.
- Demoulin, A., Mather, A., Whittaker, A. 2017. Fluvial archives, a valuable record of vertical crustal deformation. *Quaternary Science Reviews* 166, pp. 10-37
- Erinc, S. 1970. The young volcanic topography of the Kula-Adala area. *Istanbul Universitesi Coğrafya Enstitüsü Dergisi* 17, 7-22
- Ercan, T. 1993. Interpretation of geochemical, radiometric and isotopic data on Kula Volcanics (Manisa-western Anatolia) *Geological Bulletin of Turkey* 36(1), 113-129
- Ercan, T., Türkecan, A., Dinçel, A. & Günay, E. 1983. Geology of Kula–Selendi (Manisa) area. *Jeoloji Mühendisliği*, 17, 3–28 [in Turkish with English abstract].

- Ercan, T., Satir, M., Steinitz, G., Dora, A., Sarıfakioğlu, E., Adis, C., Walter, H.-J., Yildirim, T. 1996. Characteristics of the Tertiary volcanics in Biga Peninsula, Gökçeada, Bozcaada and Tavşan island (NW Anatolia). MTA Bulletin, 117, 55–86 [in Turkish with English abstract].
- Ersoy, Y., Helvacı, C., Sözbilir, H., Erkül, F., Bozkurt, E. 2008. A geochemical approach to Neogene-Quaternary volcanic activity of western Anatolia: An example of episodic bimodal volcanism within the Selendi Basin, Turkey. *Chemical Geology*, 255 (1-2), pp. 265-282.
- Ersoy, Y., Helvacı, C., and Sözbilir, H., 2010. Tectono-stratigraphic evolution of the NE–SW-trending superimposed Selendi basin: Implications for late Cenozoic crustal extension in Western Anatolia, Turkey. *Tectonophysics*, 488, 210-232
- Ersoy, Y.E., Helvacı, C., Palmer, M.R. 2011. Stratigraphic, structural and geochemical features of the NE-SW trending Neogene volcano-sedimentary basins in western Anatolia: Implications for associations of supra-detachment and transtensional strike-slip basin formation in extensional tectonic setting. *Journal of Asian Earth Sciences*, 41 (2), pp. 159-183.
- Ersoy, E.Y., Çemen, T., Helvacı, C., Billor, Z. 2014. Tectono-stratigraphy of the Neogene basins in Western Turkey: Implications for tectonic evolution of the Aegean Extended Region. *Tectonophysics*, 635, pp. 33-58.
- Della Porta, G., 2015. Carbonate build-ups in lacustrine, hydrothermal and fluvial settings: comparing depositional geometry, fabric types and geochemical signature. In: Bosence, D.W.J., Gibbons, K.A., Le Heron, D.P., Morgan, W.A., Pritchard, T., Vining, B.A. (Eds.), *Microbial Carbonates in Space and Time: Implications for Global Exploration and Production*. Geological Society of London, Special Publications 418, pp. 17–68.
- Fuller, T.K., Perg, L.A., Willenbring, J.K., Lepper, K., 2009. Field evidence for climate-driven changes in sediment supply leading to strath terrace formation. *Geology* 37: 467-470. <https://doi.org/10.1130/G25487A.1>
- Gao, H., Li, Z., Liu, F., Wu, Y., Li, P., Zhao, X., Li, F., Guo, J., Liu, C., Pan, B., Jia, H., 2020 Terrace formation and river valley development along the lower Taohe River in central China. *Geomorphology* 348, Article number 106885

- Heineke, C., Niedermann, S., Hetzel, R., Akal, C. 2016. Surface exposure dating of Holocene basalt flows and cinder cones in the Kula volcanic field (Western Turkey) using cosmogenic ^3He and ^{10}Be . *Quaternary Geochronology* 34, pp. 81-91.
- Hu, X., Wen, Z., Pan, B., Guo, L., Cao, X., 2019. Constraints on deformation kinematics across the Yumu Shan, NE Tibetan Plateau, based on fluvial terraces *Global and Planetary Change* 182, Article number 103023
- Karlstrom, K.E., Crossey, L.J., Embid, E., Crow, R., Heizler, M., Hereford, R., Beard, L.S., Rickettes, J.W., Cather, S., Kelley, S., 2017. Cenozoic incision history of the Little Colorado River: Its role in carving Grand Canyon and onset of rapid incision in the past ca. 2 Ma in the Colorado River System. *Geosphere* 13: 49-81. <https://doi.org/10.1130/GES01304.1>
- Kolb, T., Fuchs, M., Moine, O., Zöller, L. 2017. Quaternary river terraces and hillslope sediments as archives for paleoenvironmental reconstruction: New insights from the headwaters of the Main River, Germany. *Zeitschrift für Geomorphologie* 61: 53-76
- Lisiecki, L. E., Raymo, M. E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography*, 20, PA1003, doi:10.1029/2004PA001071.
- Lucchitta, I., Curtis, G.H., Davis, M.E., Davis S.W., Turrin, B., 2000. Cyclic aggradation and downcutting, fluvial response to volcanic activity, and calibration of soil-carbonates stages in the Western Grand Canyon, Arizona. *Quaternary Research* 55: 23-33. <https://doi.org/10.1006/qres.1999.2098>
- Macklin, M.G., Fuller, I.C., Lewin, J., Maas, G.S., Passmore, D.G., Rose, J., Woodward, J.C., Black, S., Hamlin, R.H.B., Rowan, J.S. 2002. Correlation of fluvial sequences in the Mediterranean basin over the last 200 ka and their relationship to climate change. *Quaternary Science Reviews*, 21 (14-15), pp. 1633-1641.
- Maddy, D., Demir, T., Bridgland, D., Veldkamp, A., Stemerink, C., van der Schriek, T., Westaway, R. 2005. An obliquity-controlled Early Pleistocene river terrace record from Western Turkey? *Quaternary Research* 63, 339-346.
- Maddy D, Demir T, Bridgland D, Veldkamp A, Stemerink C, van der Schriek T, Schreve D. 2007. The Pliocene initiation and Early Pleistocene volcanic disruption of the palaeo-Gediz fluvial system, Western Turkey. *Quaternary Science Reviews*, 26(22-24), 2864-2882.

Maddy, D., Demir, T., Veldkamp, A., Bridgland, D. R., Stermerdink, C., van der Schriek, T., Schreve, D. 2012a. The obliquity-controlled early Pleistocene terrace sequence of the Gediz River, Western Turkey: a revised correlation and chronology. *Journal of the Geological Society of London* 169, 67-82

Maddy, D., Veldkamp, A., Jongmans, A.G., Candy, I., Demir, T., Schoorl, J.M., van der Schriek, T., Stermerdink, C., Scaife, R.G., van Gorp, W. 2012b. Volcanic disruption and drainage diversion of the palaeo-Hudut River, a tributary of the Early Pleistocene Gediz River, Western Turkey. *Geomorphology* 165-166, 62-77

Maddy, D., Schreve, D., Demir, T., Veldkamp, A., Wijbrans, J.R., van Gorp, W., van Hinsbergen, D.J.J., Dekkers, M.J., Scaife, R., Schoorl, J.M., Stermerdink, C., van der Schriek, T. 2015. The earliest securely-dated hominin artefact in Anatolia? *Quaternary Science Reviews* 109, 68-75

Maddy, D., Veldkamp, A., Demir, T., van Gorp, W., Wijbrans, J.R., van Hinsbergen, D.J.J., Dekkers, M.J., Schreve, D., Schoorl, J.M., Scaife, R., Stermerdink, C., van der Schriek, T., Bridgland, D.R., Aytaç, A.S. 2017. The Gediz River fluvial archive: A benchmark for Quaternary research in Western Anatolia. *Quaternary Science Reviews*, 166, pp. 289-306.

Marra, F., Costantini, L., Di Buduo, G.M., Florindo, F., Jicha, B.R., Monaco, L., Palladino, D.M., Sottili, G. 2019. Combined glacio-eustatic forcing and volcano-tectonic uplift: Geomorphological and geochronological constraints on the Tiber River terraces in the eastern Vulsini Volcanic District. *Global and Planetary Change* 182, November 2019, Article number 103009

Martins, A.A., Cabral, J., Cunha, P.P., Stokes, M., Borges, J., Caldeira, B., Martins, A.C., 2017. Tectonic and lithological controls on fluvial landscape development in central-eastern Portugal: Insights from long profile tributary stream analyses. *Geomorphology* 276, 144-163

Mather, A.E., Stokes, M. 2018. Bedrock structural control on catchment-scale connectivity and alluvial fan processes, High Atlas Mountains, Morocco. *Geological Society Special Publication*. 440, 103-128
Ozener, F.S. 1992. Detecting the polycyclic drainage evolution in Kula region (western Turkey) using aerial photographs. *ITC Journal* 1992–1993, 249–253.

Pastre, J.F., 2005. Les nappes alluviales de l'Allier en Limagne (Massif Central, France): stratigraphie et corrélations avec le volcanisme regional. (The river Allier terraces in Limagne

(France): Stratigraphy and correlation with the Massif Central volcanism). *Quaternaire* 16: 153–175. <https://doi.org/10.4000/quaternaire.383>

Pentecost, A. (2005). *Travertine*. Berlin: Springer Science & Business Media, 445 pp.

Pola, M. , Gandin, A. , Tuccimei, P. , Soligo, M. , Deiana, R. , Fabbri, P. and Zampieri, D. (2014), A multidisciplinary approach to understanding carbonate deposition under tectonically controlled hydrothermal circulation: A case study from a recent travertine mound in the Euganean hydrothermal system, northern Italy. *Sedimentology*, 61: 172-199. doi:10.1111/sed.12069

Purvis, M., Robertson, A.H.F. 2004. A pulsed extension model for the Neogene–Recent E–W trending Alaşehir Graben and the NE–SW trending Selendi and Gördes basins, western Turkey. *Tectonophysics* 391, 171–201.

Purvis, M., Robertson, A.H.F. 2005. ^{40}Ar – ^{39}Ar dating of biotite and sanidine in tuffaceous sediments and related intrusive rocks: implications for the early Miocene evolution of the Gördes and Selendi basins, W Turkey. *Geodinamica Acta* 19, 239–254.

Richardson-Bunbury, J.M., 1992. *The basalts of Kula and their relation to extension in western Turkey*. PhD thesis. Cambridge University.

Richardson-Bunbury, J.M. 1996. The Kula volcanic field, western Turkey: the development of a Holocene alkali basalt province and the adjacent normal-faulting graben. *Geological Magazine* 133, 275-83

Rihs S, Condomines M, Poidevin J-L. 2000. - Long-term behaviour of continental hydrothermal systems: U-series study of hydrothermal carbonates from the French Massif Central (Allier valley). *Geochimica et Cosmochimica Acta* 64: 3189-3199.

Schumm, S.A. and Lichty, R.W. 1965: Time, space and causality in geomorphology. *American Journal of Science* 263, 110-19.

Seyitoğlu, G. 1997. Late Cenozoic tectono-sedimentary development of the Selendi and Uşak–Güre basins: a contribution to the discussion on the development of east–west and north trending basins in western Turkey. *Journal of the Geological Society of London*, 134, 163–175.

- Stokes, M., Cunha, P.P., Martins, A.A. 2012. Techniques for analysing Late Cenozoic river terrace sequences (Editorial) *Geomorphology*. 165-166: 1-6
- Stokes, M., Mather, A.E., Belfoul, M., F, F., Bouzid, S., Geach, M.R., Cunha, P.P., Boulton, S.J., Thiel, C. 2017. Controls on dryland mountain landscape development along the NW Saharan desert margin: Insights from Quaternary river terrace sequences (Dadès River, south-central High Atlas, Morocco) *Quaternary Science Reviews* 166, 363-379.
- Su, Q., Kirby, E., Ren, Z., Zhang, P., Zhang, H., Manopkawe, P., Lei, Q., 2020. Chronology of the Yellow River terraces at Qingtong Gorge (NE Tibet): Insights into evolution of the Yellow River since the Middle Pleistocene. *Geomorphology* 349, Article number 106889
- Teboul, P.-A., Durllet, C. , Gaucher, E.C. , Virgone, A., Girard, J.-P., Curie, J. , Lopez, B., Camoin, G.F. 2016. Origins of elements building travertine and tufa: New perspectives provided by isotopic and geochemical tracers. *Sedimentary Geology* 334, 97-114,
- Ulusoy, İ., Sarıkaya, M.A., Schmitt, A.K., Şen, E., Danişık, M., Gümüş, E. 2019. Volcanic eruption eye-witnessed and recorded by prehistoric humans. *Quaternary Science Reviews* 212, pp. 187-198.
- Vandenberghe, J., 2003. Climate forcing of fluvial system development: an evolution of ideas. *Quaternary Science Reviews* 22, 2053-2060.
- Vandenberghe J., 2015. River terraces as a response to climatic forcing: Formation processes, sedimentary characteristics and sites for human occupation. *Quaternary International* 370, 3-11.
- van Gorp, W., Veldkamp, A., Temme, A. J. A. M., Maddy, D., Demir, T., van der Schriek, T., ... Schoorl, J. M. 2013. Fluvial response to Holocene volcanic damming and breaching in the Gediz and Geren rivers, western Turkey. *Geomorphology* 201, 430-448.
- Van Gorp, W., Schoorl, J. M., Temme, A. J. A. M., Reimann, T., Wijbrans, J. R., Maddy, D., ... Veldkamp, T. 2016. Catchment response to lava damming: integrating field observation, geochronology and landscape evolution modelling. *Earth Surface Processes and Landforms*, 41(11), 1629-1644.

Veldkamp A, Kroonenberg SB, Heijnis H, van den Berg van Saparoea, R. 2004. The suitability of dated travertines as a record of fluvial incision: Allier (France) floodplain dynamics during the late Quaternary. *Quaternaire* 15: 159-165.

Veldkamp, A., Candy, I., Jongmans, A.G., Maddy, D., Demir, T., Schoorl, J.M., Schreve, D., Stermerdink, C., van der Schriek, T., 2015. Reconstructing Early Pleistocene (1.3 Ma) terrestrial environmental change in western Anatolia: Did it drive fluvial terrace formation? *Palaeogeography, Palaeoclimatology, Palaeoecology* 417, pp.91-104.

DOI:10.1016/j.palaeo.2014.10.022.

Viveen W, Schoorl JM, Veldkamp A, van Balen RT. 2014. Modelling the impact of regional uplift and local tectonics on fluvial terrace preservation. *Geomorphology* 210, 119–135.

DOI:10.1016/j.geomorph.2013.12.026

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

Westaway, R., Pringle, M., Yurtmen, S., Demir, T., Bridgland, D.R., Rowbottom, G., Maddy, D. 2004. Pliocene and Quaternary regional uplift in western Turkey: The Gediz river terrace staircase and the volcanism at Kula. *Tectonophysics* 391, 121-169

Westaway, R., Guillou, H., Yurtmen, S., Beck, A., Bridgland, D.R., Demir, T., Rowbottom, G. 2006. Late Cenozoic uplift of western Turkey: Improved dating and numerical modelling of the Gediz river terrace staircase and the Kula Quaternary volcanic field. *Global and Planetary Change* 51, 131-171.

Woolderink, H.A.G., Kasse, C., Cohen, K.M., Hoek, W.Z., Van Balen, R.T., 2019. Spatial and temporal variations in river terrace formation, preservation, and morphology in the Lower Meuse Valley, the Netherlands. *Quaternary Research* 91, 570-583

Zieliński, P., Sokołowski, R.J., Jankowski, M., Standzikowski, K., Fedorowicz, S., 2018. The climatic control of sedimentary environment changes during the Weichselian – An example from the Middle Vistula Region (eastern Poland) *Quaternary International* (in press)

Figure Captions

1. General field area. Inset shows regional location within wider Mediterranean. Dashed box shows approximate location of Figure 2. Background image is the STRM30 Elevation Model with heights ranging from 0 to 2400m. Grid is in UTM Zone 35 coordinates.
2. Generalised Geology map of the field area (modified from Maddy *et al.*, 2017).
3. Conceptual landscape model for the Gediz Valley within the confines of the Kula GeoPark during the Early Pleistocene. The diagram illustrates the forcing of both intrinsic and extrinsic drivers and highlights to need to consider their interactions.
4. Area of Interest for this paper. (A) shows the general topography and principal rivers. The identified volcanic necks are shown for the Early Pleistocene volcanic plateaus. The small blue triangles and filled orange circles mark the sample points used in the geochemical analysis comprising Ulubey Formation and travertines samples respectively. B) shows selected linear structures discussed in the text. The + symbol marks UTM grid intersections.
5. Detailed buried terrace map and gravel sample locations (labelled points only for the İbrahimağa plateau, for additional point labels see Maddy *et al.*, 2017). PP is pinch point used for gradient projection (see supplemental 1). The purple shaded area is the approximate, sub-basalt, location of GT6. For additional symbols see legend Fig. 4
6. Gediz gravels longitudinal profile (terrace bases) map with suggested fault offsets. Only gravels for the İbrahimağa plateau are labelled. Pinch point (PP) is shown in Fig.5. Gravels correlated with the same terrace unit have the same fill colour.
7. Detailed map showing A) identified faults f5-f1, travertine locations with labels and the position of transects shown in Fig.8. B) Shows the detailed topography, based upon a 5m contouring of UAV-base DEM data, of the travertine promontory west of

the İbrahimağa plateau. For symbology see Figs 4 and 5.

8. Photo of travertine promontory taken looking due East. The position of the faults shown in Fig. 7 are indicated. Clear scarps associated with faults f4 and f5 are shown with offset direction indicated.
9. Cross sections (as shown in Fig. 7A) based upon multiple DEM data sources. Suggested fault positions indicated.
10. Photographs of key sections (see Fig.7A): A) Outcrop Mft, cut by fault f4, exposed at the base of the scarp. B) Outcrop in the travertine mound at MAR. C) Evidence of faulting in exposures at MAR. D) Hydrothermally altered basalt close to gravel site 218.
11. Stable isotope general composition data. A) $\delta^{18}\text{O}$ and B) $\delta^{13}\text{C}$. Box and whisker plots show site and between site variability.
12. Stable Isotope domain plot based upon groups identified in Teboul *et al.* (2016)

Table Caption

1. General chemical characteristics

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

				Main Elemental Composition									
		$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	n	Ca	Mg	Si	Al	Fe	Sr	Ba	Cr	Ag
Ulubey	Mean	-7.84	0.09	20	411982.21	19402.27	1044.42	3867.59	5065.09	527.75	27.85	22.11	0.96
	Max	-3.20	2.89		526430.91	144465.90	2051.78	14158.30	22957.97	4210.57	77.08	97.81	1.77
	Min	-	-		192391.99	1647.02	68.30	332.22	489.00	126.97	6.32	1.59	0.16
Travertine	Mean	-8.76	1.77	76	435282.47	3127.14	303.28	1263.25	1571.23	466.92	244.82	5.21	3.27
	Max	-5.29	5.96		551224.53	16723.89	2118.29	8900.91	15986.24	7438.86	477.33	44.65	47.08
	Min	-	-		104.92	871.31	2.58	8.22	5.46	104.43	39.11	0.13	0.09
*exl tufa													
Calcrete	Mean	-7.91	6.99	12	429634.29	5828.48	1004.58	3459.77	3448.26	306.86	107.63	9.35	0.52
	Max	-5.85	5.24		516445.52	10555.35	1708.70	6036.43	5322.41	593.68	149.03	24.77	2.57
	Min	-	-		413.96	0.00	228.10	755.76	22.23	110.49	22.83	1.65	0.04
Marble		-	-	1	407613.89	2090.56	40.15	122.25	1187.68	172.34		3.45	0.72

Highlights

River terrace genesis is explored by fusing fluvial, colluvial and travertine data.

Extrinsic and intrinsic fluvial terrace drivers are identified.

Fault-induced river incision on resistant substrates drives synvolcanic terrace formation.

Volcanism promotes fracturing/faulting leading to subsurface drainage reorganisation.

Travertine deposits are important surface markers of syn-tectonic/volcanic activity.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12