CATASTROPHIC BADLAND FORMATION IN W ANATOLIA TRIGGERED BY BYZANTINE LAND-USE CHANGES?

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Abstract

Mediterranean badlands are commonly thought to be of Pleistocene origin, reflecting periods of increased erosion driven by climate or tectonic change. Firm evidence for historical badland formation is absent. However, reliable records of Mediterranean landscape erosion types and rates remain scarce. This paper presents the first results from ongoing investigations into the origins of the badland landscape in the Gediz River Basin near Kula (Western Turkey). These active badlands are developed in Tertiary deposits that are locally capped by Quaternary fluvial and lacustrine sediments. Near the basin edge, gullies expose metamorphic basement. The badlands contain fluvial benches, colluvial and gully fill sediments that merge downstream into terrace, lacustrine and tufa deposits. These landform-sediment archives have good sediment exposure and are placed within a reliable chrono-stratigraphic framework, allowing reconstruction of badland evolution.

Preliminary data suggest that the badland landscape formed recently, most probably around 800 AD, after a period of prolonged (~1 Ma) landscape stability. The data suggest that badland formation does not occur under conditions of natural climate variability in the area. Badland formation is probably caused by human agricultural activities. The incision ages may correspond to a profound change in land use during the mid-late Byzantine period, with more reliance on livestock and abandonment of arboriculture. We suggest – for the first time - that badland formation is triggered by human land-use change, and in particular by intensive livestock holding which increased runoff and infiltration.

Key words: Badlands, Mediterranean, Gullying, Land-use, Byzantine

1. Introduction

Badlands present some of the most dramatic examples of Mediterranean erosion: areas dissected by a dense gully network with narrow ridges and steep slopes which are non-vegetated and unsuitable for agriculture (Woodward, 1995). They generally occur in poorly consolidated strata of Tertiary age, but they are not confined to the regions of lowest rainfall. The causes for badland formation are poorly understood (Bull and Kirkby, 1997). Mediterranean badlands are commonly thought to be created by Pleistocene base-level or climate changes (e.g. Bintliff, 2002; Bull and Kirkby, 1997), while human land-use changes are largely disregarded as a mechanism controlling their initiation. This view is based on a handful of primary investigations of badlands with limited dating control (e.g. Gilman and Thornes, 1985; Brain and Yair, 1982). It has been suggested that Mediterranean badlands are generally natural, geologically conditioned landforms, with no documented Mediterranean record of rapid badland formation in historic landscapes (Grove and Rackham, 2001).

However, there appears to be no natural factor accounting for the bare character of many Mediterranean badlands under prevailing Quaternary climates prior to human impacts on the natural vegetation (e.g. Regues *et al*., 2000). It appears unlikely that past climatic oscillations in the Mediterranean were responsible for creating bare surfaces as long-term vegetation records indicate that the region supported, prior to human interference, steppe to (open) forest environments during the Quaternary period (Frogley *et al*., 2001; Tzedakis, 1993). Recent investigations in other climatic settings have revealed that the initiation of gullying and badland formation is often associated with the introduction of intensive agricultural practices. In Germany, for example, gullying and a marked increase in lacustrine/fluvial sedimentation rates followed large-scale vegetation clearances from the late Neolithic period onwards (Dotterweich, 2005; 2008). Badland formation in the African savannah (Eriksson *et al*., 2000; Boardman *et al*., 2003) coincided with the introduction of intensive agriculture during the late Holocene. The connection between intensive gullying and agricultural practices has lately also been suggested for badlands in SE Spain (Mather *et al*., 2002).

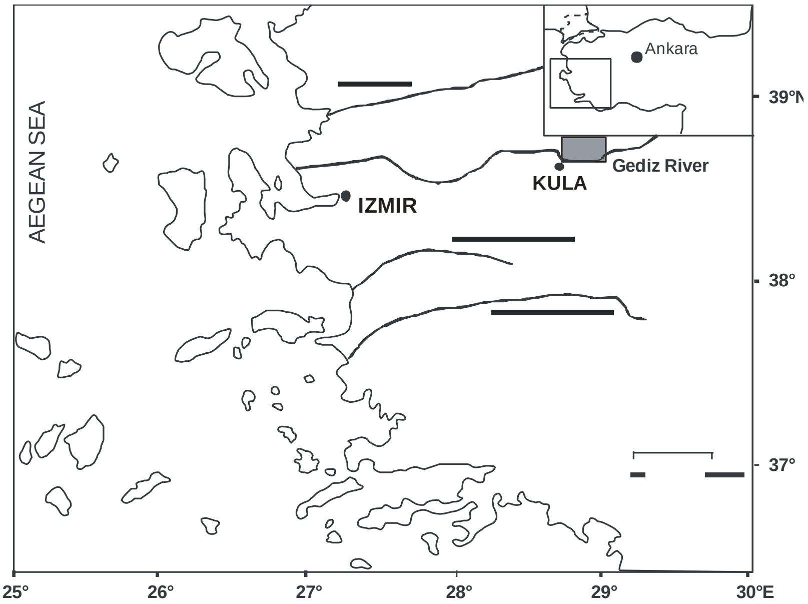

Figure 1: Location of the Study Area

It remains of crucial importance to establish the various controls on Mediterranean badland formation in order to inform modern land-use policies on best practise and promoting sustainability. This paper presents the preliminary findings of ongoing investigations of Mediterranean badland evolution near Kula, Western Turkey (Fig. 1) and aims to establish the timing and causes of regional badland formation.

2. Study Area

The landscape record near Kula (Fig. 1) offers a unique opportunity to establish whether badlands were present in this area throughout the Quaternary period. The study area contains active badlands and extensive records of earlier styles of landscape erosion, base-level changes and human occupation. Therefore, the full range of controls (i.e. climate, base-level and human) proposed to cause badland formation may be studied.

The present climate of the area is Mediterranean in character with pronounced winter precipitation and summer dryness (National institute of Meteorological affairs, 1984). Active badlands are developed in sandy-silty, near-horizontally bedded Tertiary basin fill deposits of the fluvial-lacustrine Ahmetler Formation (Seyitoğlu, 1997) which are partially capped by a thin veneer of slope-, fluvial and/or lacustrine sediments of Quaternary age (Maddy *et al*., 2005, 2007, 2008) (Fig. 2). The badlands contain a variety of landform-sediment archives including benches, colluvium and gully fill sediments that merge downstream into fluvial terrace, lacustrine and tufa deposits. These archives have extensive exposure. Observations suggest that gullying and piping, allied to mass movements such as bank- and pipe-collapse, are the major erosion mechanisms in badland formation.

The study area also contains a multiple-period archive of earlier styles of erosion, as Pleistocene landscapes are fortuitously preserved beneath a sequence of basaltic lava flows (Figs. 2 and 3). These flows caused instant landscape burial and fossilisation, thus preserving the underlying topography. The buried landscapes are well-exposed around the edges of the lava plateaus. Associated fluvial, lacustrine and land-slide deposits inform on base level changes and valley floor geometry. This exceptional sequence of Pleistocene landforms and deposits has been placed within a relatively well-constrained chronostratigraphic framework.

Finally, archaeological evidence and historical records provide information on the past topography and land-use of the study area. Individual finds suggest occupation since the Pleistocene, but throughout the study area there are remains indicating intensive settlement from the Lydian (~6th century BC) to the end of the Byzantine period (~12th century AD) in the region. The following Ottoman period is characterised by continuous – albeit less intensive – occupation of the area, while agricultural intensification typifies the modern period.

3. Methodology

Geomorphological mapping was achieved using aerial photographs, geological and topographical maps and field survey. Lithostratigraphic field description was conducted on sediment exposures in natural cliff- and bank sections. Selected sediment exposures were sampled in the field for sedimentary analyses. Absolute dating control is provided by three range-finding ^{14}C dates on charcoal samples from gully fills. Throughout this paper, analysed dates are expressed as calibrated calendar ages (cal BC/AD). Calibrated ages were calculated with the OxCal 3.1 program (Bronk Ramsey, 2005), using the terrestrial calibration data set (INTCAL98; Stuiver *et al*., 1998) and atmospheric data from Reimer *et al*. (2004). Additional (relative) age estimates are provided by archaeological data.

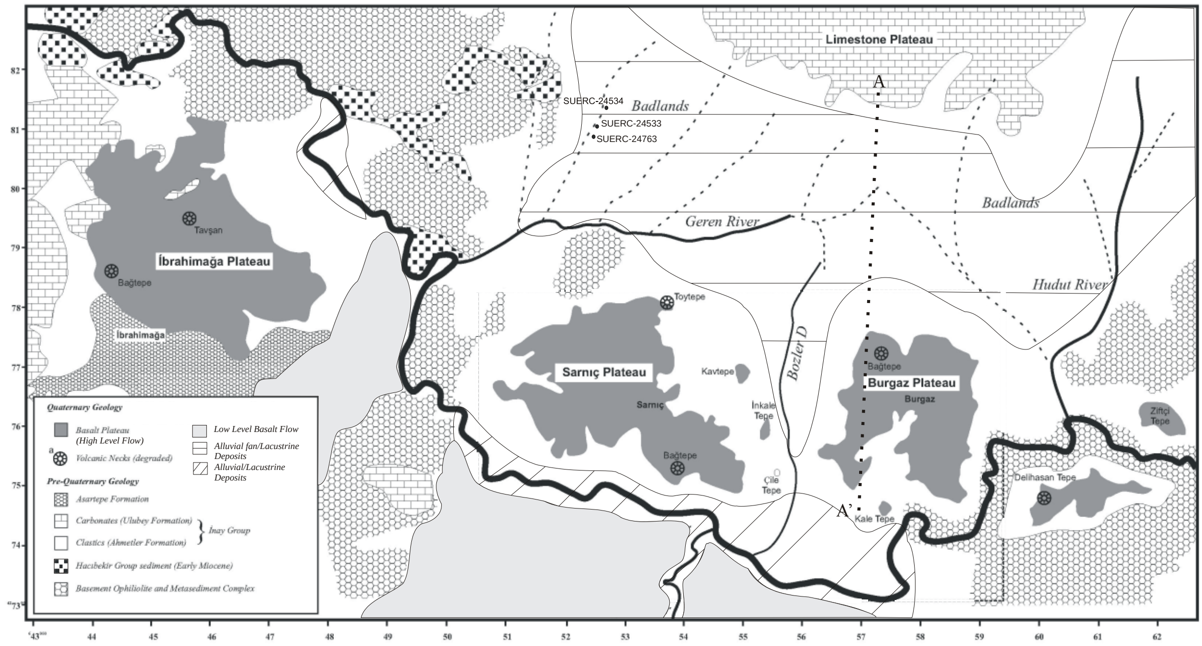

Figure 2: Simplified geological map of the study area (after Maddy et al., 2007)

4. Long-term Landscape Development

The high-level lava plateaus were formed ~1.2 to 1Ma (Westaway *et al*., 2003, 2006). Lava flows repeatedly dammed the contemporary Gediz valley floor thus creating multiple lakes over time which left a suite of deposits between 500m – 650m in the landscape (Maddy *et al*., 2007, 2008). Large-scale landscape incision was followed by a phase of renewed volcanic activity that started ~236ka and probably ended in the Holocene (Westaway *et al*., 2003, 2006; Yilmaz, 1990). Observations confirm that low-level lava flows related to this period repeatedly blocked the Gediz valley at the Geren confluence (Fig. 2). The corresponding suite of lacustrine, deltaic and fluvial deposits related to these lava dams is found at altitudes between 440-380m. The youngest absolute age-estimate for a lava flow damming the valley floor just downstream of the badland area yielded an age of ~7ka. Badland gullies are incised into the Ahmetler formation through the surfaces of fluvial limestone gravel bodies and lacustrine deposits that are inset behind the high-level lava plateaus (Figs. 2 and 3). These landforms and deposits are associated with different generations of lakes, created by the repeated blocking of the Gediz River valley by lava flows.

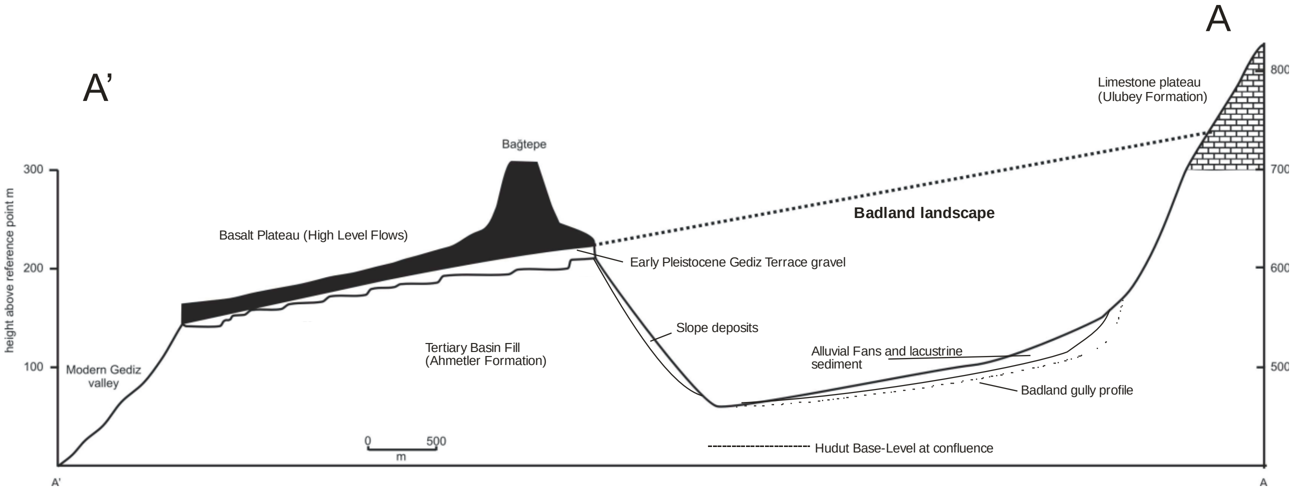

Figure 3: Schematic cross-profile of the Badland area (for location see Figure 2)

4.1 Sediments and landforms in the Badland area

Stacked, coarse limestone gravels are found in linear, 10-16m thick, sediment bodies between 560-510m in the badland landscape (Fig 4), flanking the limestone escarpment in the Ulubey formation (Figs. 2 and 3). These fluvial deposits consist of multiple fining-upward cycles that are each 2-3m thick. The stacked valley fill bodies are 200-250m wide and 1.2-1.5km long. Downstream these limestone gravel bodies interfinger with fine-grained, up to 15m thick, lacustrine sediment bodies that form distinct bench levels in the landscape, at ~500-515m. Individual lacustrine sediment bodies are linear in shape and up to 200m wide with lengths of up to 1km. These levels and sediment assemblages cluster around the same height bands as the lava dam sequences. Deposition of the high stacked limestone fills (560-510m) and lake sediments (500-515m) are associated with (lacustrine) base-level forced deposition in valleys. Given the altitude of the deposits, these lakes can only be associated with dams created by the oldest (highest) lava flows. The youngest of these flows blocked the Gediz River near the Geren confluence ~1Ma ago (Maddy et al. 2007, 2008; Westaway et al. 2003, 2006), when the bed of the Gediz was at ~496m (Fig 4).

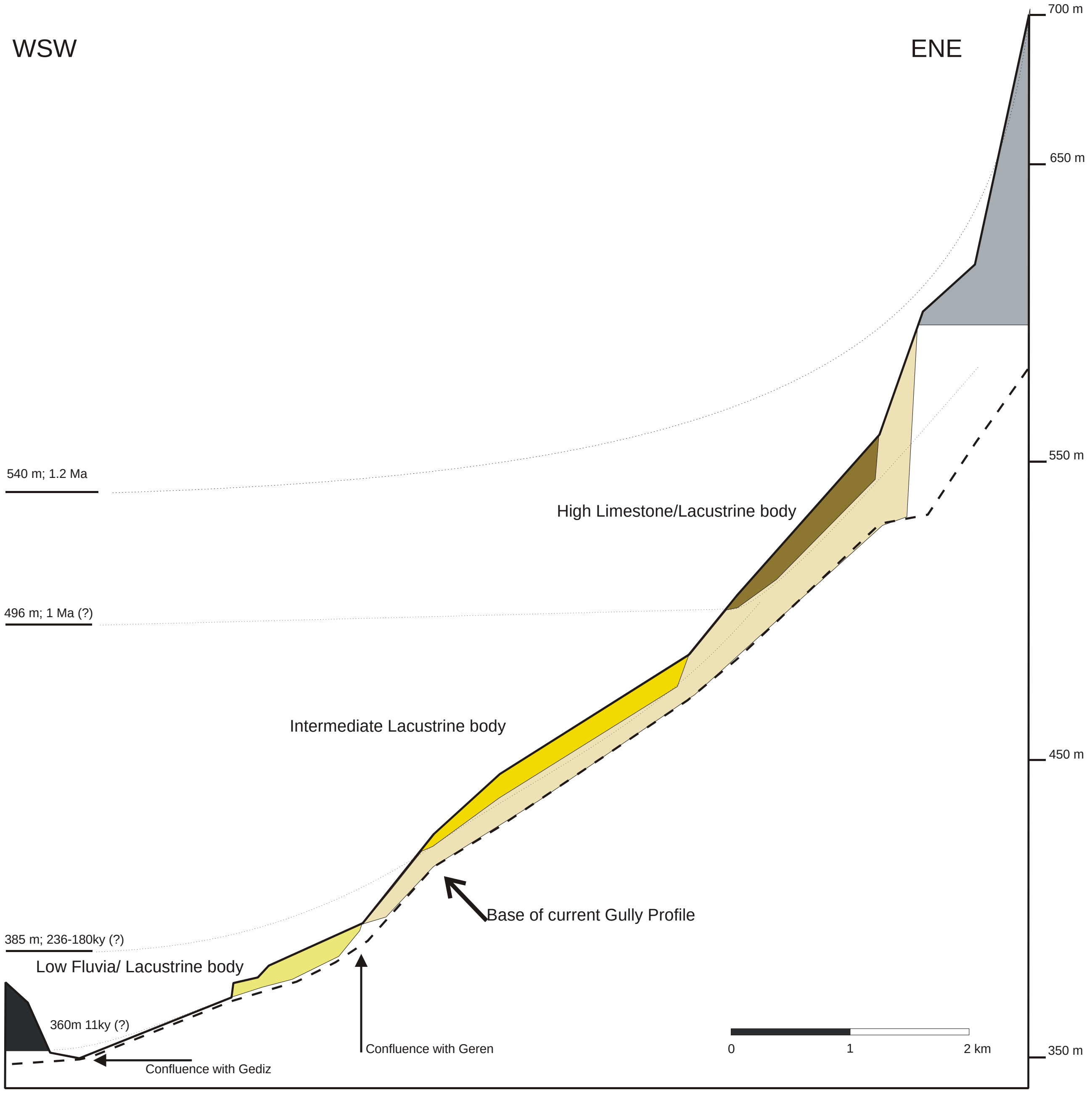

Figure 4: Elevation model of landform-sediment assemblages along the Geren Tributary

The second distinct topographic level in the landscape, around ~430-465m, is underlain by up to 15m of fine-grained lacustrine, linear sediment bodies (Fig 4) of up to 100m wide by 1km long. Deposition of these intermediate level lacustrine sediments is again related to deposition in lakes that drowned tributary valleys. These lakes are associated with lava dams which are dated to 236-180ky BP, when the contemporary level of the Gediz River at the Geren confluence was at 385m (Fig 4). Finally, distinct bench levels are found at ~375-390m. These levels are underlain by a mix of deltaic and fine-grained floodplain sediments and are up to 15m thick; the individual width of these assemblages is up to 50m by a length of up to 500m. This lowest level of sediment assemblages is associated with the youngest lava dam at the mouth of the Geren confluence. This dam is dated to ~11-7ky BP, when the level of the Gediz at the Geren confluence was located at about 360m; at present the Gediz River bed at this location is at about 258m.

The geometry and sedimentology of the inset badland gullies is distinctly different from the landforms and deposits described above. Gullies and gully fills occupy up to 100m wide zones, inset within the above deposits and the Ahmetler formation. Individual gully fills are up to 20m wide, 5-6m thick and some 10s of meters long: they are deep relative to their width and show evidence of lateral activity. Their gravel content is limited to limestone lag deposits of decimetre thickness, while the limestone gravel is much finer than that in the higher limestone bodies described above. In addition, the gully fills contain mass-waste deposits, decimetre thick cross-bedded sands and colluvial beds as well as much charcoal.

5. Timing of gully incision

Preliminary age estimates are available for gully fills exposed between 6.0-6.45km upstream from the Gediz confluence along the Geren tributary (Figs. 2 and 4). The highest level gully fill at 6km upstream is inset between high level linear limestone bodies that run parallel at either side of the gully complex. The active gully base is ~15m below the top of this level; however, a recent anti-erosion dam has caused aggradation in the present gully floor. The highest gully fill contains ~5m of sediments, including a ~10cm thick layer of colluvium (1.5m above the fill base) that can be traced up the contemporary valley slope. Charcoal particles from this layer yielded ages between 780-990 AD at the 2-sigma level of confidence (SUERC-24763; Fig. 2). These age estimates are dating the infill of the gully; incision must have pre-dated the infill.

The highest level gully fill at 6.45km is again inset between high level limestone bodies. The top of the ~15m thick stacked limestone fill is ~25m above the active gully channel. The base of the highest inset gully fill at this location is ~7m above the active gully channel, and the fill reaches a thickness of up to 5m. The gully fill contains a colluvial layer with abundant charcoal ~2m above the basal lag; this layer can be traced up the contemporary valley sides. Charcoal particles from this layer yielded ages between 980-1160 AD at the 2-sigma level of confidence (SUERC-24534; Fig. 2).

A low level gully fill at 6.1km is up to 2.5m thick, with the basal lag ~1.6m above the present gully base. The exposure is up to 30m wide and the staircase-shaped basal lag deposits testify to lateral migration and concurrent incision of the gully. A colluvial layer at ~1m above the fill base contains abundant charcoal that has been dated to 1450-1640 AD at the 2-sigma level of confidence (SUERC-24533; Fig. 2). In all of these cases, dated samples came from colluvial layers that could be traced up the valley side. This suggests that the samples are contemporary with the gully infill (i.e. these are not particles reworked from further upstream). Even if the particles are reworked, this would give an over-estimation of the gully fill ages.

5.1 Incision rates

The stratigraphic context of age-estimate SUERC-24534 provides the basic data to calculate vertical incision rates. The limestone gravel body – which now forms a flat interfluve between the gullies of the badlands – formed latest about 1Ma ago. The height difference from the top of this limestone level to the base of the highest (dated) gully fill is about 18m. Thus the incision rate is: 18m/1Ma = 0.0018 cm/year. This rate is likely to be an overestimation: the limestone body was probably rapidly incised to its base upon lake drainage ~1Ma ago, followed by a long period of stability. The base of the limestone body is at most 4m above the base of the highest gully fill body thus giving a likely incision rate of 0.0004 cm/year.

From the base of the highest channel fill to the bottom of the active gully there is a height difference of 7m. Thus the incision rate is: 7m/1000yr = 0.7 cm/year. This estimate is likely an under-estimate: incision of the gully started at a level about 10m above the present gully channel thus giving a vertical incision rate of 1cm/year. Whichever rate is used, they do illustrate the enormous increase in the rate of incision over the last 1000 years.

Knickpoint incision rates are more difficult to establish, but an approximation can be given by comparing the timing of infill of the highest gully levels which are located about 450m apart (age-estimates SUERC-24763 and SUERC-24534). The infill of the gully is assumed to have taken place immediately after incision (which is reasonable given present-day processes); therefore, the age-difference between the sites will give an estimate of the rate of knickpoint progression in the gully. The age-estimates overlap at the 2-sigma confidence level, incision at both sites could be (near) instantaneous. If the midpoint of the dates is taken, the wave of incision moved upstream at a rate of ~2.65m/year, while comparing the maximum age-difference between the two dates gives a rate of ~1.18m/year.

5.2 Timing of badland formation

Gully formation at one location is not necessarily proof for wider badland formation. There are, however, additional lines of evidence suggestion a similar timing of gully formation in different parts of the study area. Prior to the Holocene there is no geomorphic-sedimentological evidence for gullies anywhere in the study area. The pre-incision, pre-badland topography has been preserved in areas of stream capture. Stream power after the capture events was limited thus preserving the pre-capture topography and limiting gully formation. The presence of thick (2-3m) red soils suggests the long term stability of these areas: their topography consists of gently sloping surfaces that are connected to wide, shallow valleys (of the captured streams) which are underlain by 1-2m of bedded fluvial sediments (mainly limestone gravel and sand).

Archaeological evidence throughout the landscape indicates that incision took place during the Holocene. The most persuasive evidence comes from an archaeological site in the Kerran tributary, which flows into the Selendi River (Fig. 2). This site shows evidence of Roman occupation (bones, pottery – esp. Terra Sigilata – and house structures) over a wide area of at least 200 by 400m. However, this entire occupation area is currently deeply dissected by gullies. The archaeological remains are found scattered on interfluves at elevations of 530-540m (sometimes of less than 1 m wide) that are separated by gullies with their base at 480-475m. There must have been at least 40m of post-Roman incision at this site.

Gullies in the flanks of the Burgaz lava plateau (Fig 2) also dissect Roman to Byzantine era structures. Again, minimum ages for incision here are post-Roman to post Byzantine (12th century in this area). Archaeological data from the wider badland area, in the adjacent Bozler and Hudut tributaries, also support a post-Mesolithic incision phase. Sites containing pottery (of undetermined age) have been incised by the badlands, while gully fills contain also pottery (again of undetermined age). Although the exact age for incision cannot be more firmly established, these data indicate a Holocene date for the widespread incision of the landscape.

6. Discussion & Conclusions

Despite substantial changes in climate and vegetation cover over the past 1Ma years in the study area, there is no evidence for widespread gullying and badland formation prior to the Holocene period. This suggests that natural climate variability and associated vegetation changes did not cause badland formation. Furthermore, past base level changes associated with the formation of lava dams and lakes appear not to have triggered badland formation. The base-level changes seem to have had mainly a local effect: damming and lake formation led to local deposition of lacustrine and fluvial sediments. Upon drainage of the lake, these deposits were incised, and the pre-dam stream profile was again occupied. Incision did not extent much beyond the dam-related sediments. For example, ~2km up the mouth of the Geren is a Roman site next to the river. Archaeological structures show that the river bed during Roman times was practically at the same level of pre-11ky BP river, i.e. the deposits associated with the youngest lake were incised up to the pre-dam river level by Roman times. Finally, badland gullying seems to have been triggered around the same time in the Holocene, while base-level histories for the tributary catchments are very different in space and time.

The preliminary age-estimates and the archaeological evidence place the incision period firmly in the Holocene period, most likely between Roman times and ~800 AD. In the Geren, gullying and deep incision started 3-4km upstream from the Gediz confluence in the tributaries bordering the trunk (Geren) river. The Geren River at the Roman site ~ 2km upstream from the Gediz confluence has incised up to 2m since Roman occupation and has substantially widened its channel through lateral erosion. Knickpoint erosion rate estimates allow for a rough estimation of the initial timing of erosion of the Geren tributaries (see 5.1). Given that the dated gully fills are ~3km upstream of the trunk river, ages for the start of incision at the trunk river confluence range from near instantaneous (i.e. ~700-800 AD) to ~300-100 BC (3km at 2.65m/year; based on mid-point of dates) and earliest around ~1700-1500 BC (3km at 1.18m/year; based on maximum age-difference). Archaeological evidence and observed rates of gully formation (<10 years) favour a late Roman to early-mid Byzantine age (i.e. ~300-700 AD) for the badland formation.

The Holocene age for badland formation suggests that it was caused by the new and major environmental change of this period, namely the introduction and development of agriculture. Intensive land-use started ~1500 BC according to pollen sequences throughout SW Turkey (e.g. Eastwood *et al*., 1999; Vermoere *et al*., 2002) during the so-called Beyshehir Occupation (BO) Phase. This phase is characterised by increased erosion throughout Turkey. Land-use is characterised by mixed cereal cultivation, livestock holding and arboriculture. However, the study area shows no positive evidence for gully erosion during this period, despite evidence suggesting intensive occupation. The BO occupation phase ended around 500-700 AD and was followed by reforestation. Renewed rapid and widespread clearance took place around 800-900 years AD. Land use changed significantly: arboriculture was virtually absent, while the dependency on livestock increased notably. Pollen diagrams show the continuation of this land-use up to the 19th century (England *et al*., 2008).

Preliminary data suggest that gully erosion and badland formation were associated with the change in land-use around 800 AD. Intensive livestock holding lead to a major change in runoff-infiltration mechanisms. Clearance, overgrazing and path erosion around drainage lines lead to i) higher runoff, ii) concentration of runoff along specific pathways, iii) increased infiltration near pathways through piping, and iv) higher peak flows. The combination of these factors triggered incision and piping leading to gully erosion. Evidence for increased (peak) discharges comes from the lower Geren River, where the channel bed near the Roman site testifies to both incision and widening through lateral erosion, suggesting higher stream power.

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