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Holocene alluvial dynamics, soil erosion and settlement in the uplands of Macedonia (Greece): New geoarchaeological insights from Xerolakkos in Grevena

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ABSTRACT

This paper addresses the interplay between Holocene landscape evolution and human settlement dynamics, drawing new evidence from the alluvial history of Xerolakkos, a continental stream in Grevena (Western Macedonia, Greece). We developed an integrated geoarchaeological survey combining remote sensing geomorphological mapping, litho-stratigraphic analysis and radiocarbon dating with the site evidence of a new archaeological survey. Results revealed four major alluviation phases, corresponding to 1) the beginning of the Holocene until the Early Neolithic (~6300/6200 BCE), 2) the end of the Early and the Middle Neolithic (~6000–5400 BCE), 3) from the Middle Bronze Age to the Late Roman period (~1800 BCE – 500 CE), and 4) during the Byzantine and Ottoman eras (~500–1800 CE), all separated by phases of floodplain incision. Furthermore, the effects of several Holocene Rapid Climatic Changes (RCC) are traced and discussed together with potential human responses; we also provide the first alluvial sequence recording the ~6200 BCE (8.2 kyr BP) event in the Balkans. While the climate and the local geomorphological setting are considered the primary drivers behind instability and erosion during the Early and Middle Holocene, a landscape change starting in the Middle Bronze Age (after ~1800 BCE) followed by a re-organisation of the rural economy in the Roman period suggests the increasing involvement of anthropogenic forcing which, by the Ottoman period, evolved into a dynamic situation between climatic variability and adaptive land management. Finally, we demonstrate how soil erosion in the upper catchment constitutes a serious taphonomic bias when studying the regional archaeological record.

1. Introduction

The study of Holocene landscape evolution is often showcased as a complex palimpsest formed by the interaction of natural and human-induced drivers to reflect periods of environmental change, support narratives of demographic fluctuations and reconstruct past land use strategies in the Mediterranean basin (Bevan et al., 2019; Walsh et al., 2019). In the landscape archaeology of Greece, the geoarchaeological agenda has largely relied on geomorphology and soil science, which developed hand-by-hand with the rise of multidisciplinary, regional-scale systematic archaeological surveys (Yassoglou and Nobeli, 1972; Zangger, 1992, 1993; James et al., 1994; Zangger et al., 1997; Mee and James, 2000; Fuchs et al., 2004). Building on the fundamental work of Vita-Finzi (1969), natural processes were pointed as the driving force behind soil erosion and alluviation, with extreme environmental events serving as key evidence to support this view (Bintliff, 1977, 1992). On the other hand, subsequent studies emphasised the dominant role of human agency behind soil erosion and thus landscape destabilisation (van Andel et al. 1986, 1990). Nevertheless, the nature of the evidence has cautioned against single-causal interpretations, highlighting not

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only the localised impact of such phenomena but also their chronological variability from region to region (Krahtopoulou, 2000; Lespez, 2003; Glais et al., 2023).

As a result, the recursive debate over the climatic versus anthropogenic drivers –or the inadequacy of suggesting a uniform evolution pattern to interpret such a relationship– underscores the importance of regional-scale investigations to enhance data resolution and consider the extent of local landscape transformations (Dusar et al., 2011; Walsh et al., 2019). Furthermore, different sedimentary records (such as colluvial, alluvial, lacustrine and coastal deposits) exhibit diverse spatial and temporal responses to anthropogenic erosion throughout the Mediterranean (Walsh et al., 2019 citing more works). While previous case studies, for instance, in Northern Greece (e.g., the plains of Pieria, Thessaloniki and Eastern Macedonia) were developed along large alluvial environments usually adhered to the seashore (Krahtopoulou, 2000; Lespez, 2003; Ghilardi et al., 2008; Glais et al., 2023), our research shifts the focus to the continental stream of Xerolakkos in the upland region of Grevena (Fig. 1). This area features a small, mountain-bounded catchment where Holocene alluviation has a limited impact on the current physiography. Its sedimentary record, however, offers the potential to provide hydrosedimentary signals at very high spatial and temporal resolution, in a landscape where such studies are scarce (Rassios, 2004; Doyle, 2005; Doyle and Savina, 2014).

This research develops a comprehensive, catchment-based geoarchaeological approach to retrieve new local data from the sedimentary archives of the Xerolakkos aiming to reconstruct its fluvial history. The specific objectives include 1) determining the temporal distribution of alluvial dynamics between phases of stability and instability while establishing a standard chronostratigraphy for the catchment; 2) assessing the potential causality bonds between geomorphological phenomena, Holocene climatic fluctuations, human settlement and land use strategies; 3) providing taphonomic clues to better understand and interpret the archaeological record of the area; and 4) discussing long-term socio-environmental interaction and landscape transformation in Grevena and, broader, in Northern Greece from the Neolithic onwards. To reach these objectives, we combined remote sensing, geomorphological mapping, litho-stratigraphic study and pedo-sedimentary descriptions of sedimentary sequences from the Xerolakkos floodplain. The results were interpreted within a robust radiocarbon-based chronostratigraphic framework (Otto and Smith, 2013; Mayoral et al., 2018b) and were contextualised alongside the outcomes of the recent extensive archaeological survey carried out in the area of study, including parts of Ayios Georgios (Apostolou et al., 2024a,b). When available, historical sources were also employed to supplement the evidence (e.g., Kampouridis, 2014).

2. Study area

The Xerolakkos catchment is situated in the administrative region of Grevena, in Western Macedonia (Northern Greece), and forms part of the UNESCO Geopark of Grevena and Kozani.[1] It occupies a series of middle mountain ridges and plateaus, covering a surface of approximately 22.5 sq km (Fig. 1). Geologically, the area belongs to the Tertiary Mesohellenic Trough, an elongated basin stretching from SE Albania to NW Greece. Originally a marine environment within the Neo-Tethyan ocean, the Mesohellenic Trough is bounded by ophiolitic formations to the west and east, namely the Pindus and Vourinos mountain ranges, respectively (Brunn, 1956). Over time, this basin accumulated sediments up to 4 km thick (Vamvaka et al., 2006). Loose conglomerates, sandstones, marls and to a lesser degree clastic limestones constitute the main sedimentary formations of the basin and were deposited during the Miocene and the Pliocene-Pleistocene (IGME, 1972) (Fig. 1). A period of Quaternary uplift ensues to the present day, contributing to filling the valleys of Grevena with alluvial and colluvial deposits (Rassios, 2002, 2004; Doyle and Savina, 2014).

The relief of the region is characterised by continuous low ridges and well-incised valleys with an N–S direction that run for about 4 km from the southern higher part (Ayios Georgios E-W main ridge, max. 856 m asl) and drain to the northern, lower section (min. 542 m asl), where the main Xerolakkos course flows in a W-E direction, collecting all these tributaries (see Fig. 1). The northern border of the catchment forms a steep ridge that delimits it from Pramoritsa, being the largest river in the area and one of the major tributaries of Aliakmon. This renders Xerolakkos a dissymmetric catchment along the N–S axis. Finally, in its northeast corner, the course of the stream turns northward and joins the Pramoritsa.

Xerolakkos itself is a low-order ephemeral stream with an irregular hydrological regime that is common in the Mediterranean (Strahler, 1957; Peña-Monné et al., 2018). It remains dry for much of the year, experiencing notable discharge peaks only after heavy rainfall or storms. Today the active channel is incised with a flat base ranging from about 2 to 20 m wide. Its current dynamics include lateral erosion of the riverbanks due to meandering as well as coarse sediment transport and deposition in the active floodplain. Moreover, in many sections, the bed of the stream is eroding the soft underlying marls and sandstones (Fig. 2). The local climate can be described as continental Mediterranean, with cold humid winters and hot dry summers. The average annual rainfall is 700 mm, with an annual temperature of 12.2 degrees C (Fig. 1, D). Xerolakkos' location within the semi-mountainous plateaus of Grevena makes it susceptible to cold northern winds that maintain temperatures low and create the conditions for significant snowfall during the winter months (Rassios, 2004).

Modern habitation in the area comprises three small rural communities –Ayios Georgios, Klimataki and Kivotos– all located along the southern fringes of the Xerolakkos catchment. This is largely an agricultural zone of cereals, including crops along the floodplain of the stream (being out of reach of the regular floods) and the footslopes around. Only the higher ridges and the steeper slopes to the N and S of the floodplain are covered by oak tree forest. The soils are broadly classified as regosols (Misopolinos, 2015). Additionally, given the sedimentary characteristics of the floodplain, parts are nowadays subject to illegal gravel extraction. No archaeological sites or materials were discovered along the Xerolakkos floodplain. On the other hand, available survey finds from the region indicate diachronic human activity, with peaks of site numbers corresponding to the Late Bronze Age (~1700-1050 BCE) and Early Iron Age (~1050-700 BCE), as well as the Roman (~100 BCE-500 CE) and the Ottoman (~1400–1900 CE) periods (Apostolou et al., 2024a) (Fig. 3, see Table 1 for conventional periodisation). While little change can be observed in the spatial distribution of the sites until the Hellenistic period, the integration of the area into the Roman Empire was followed by the emergence of numerous small building complexes that probably belonged to the type of rural farmsteads (Evangelidis, 2022). In broader Grevena, a previous extensive survey conducted during the 1980–90s was the first systematic attempt to compile and study the surface archaeological record of the region from a long-term perspective (Wilkie, 1993). As part of that project, geoarchaeological investigations in the Leipsokouki catchment, about 12 km south of Xerolakkos, sought to determine periods of sediment deposition and soil formation related to the evolution of the human settlement (Doyle, 2005; Doyle and Savina, 2014). Their approach entailed a chronostratigraphic synthesis of both floodplain (alluvial) sediments and slope (colluvium) deposits, and therefore their analysis will serve as a comparable case study for the new research in Xerolakkos.

3. Materials and methods

The multidisciplinary reconstruction of past fluvial environments through the study of sedimentary archives holds a prominent place in geoarchaeology, as such hydrosystems provide a sensitive and reliable

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[1] https://en.unesco.org/global-geoparks/grevena-kozani.

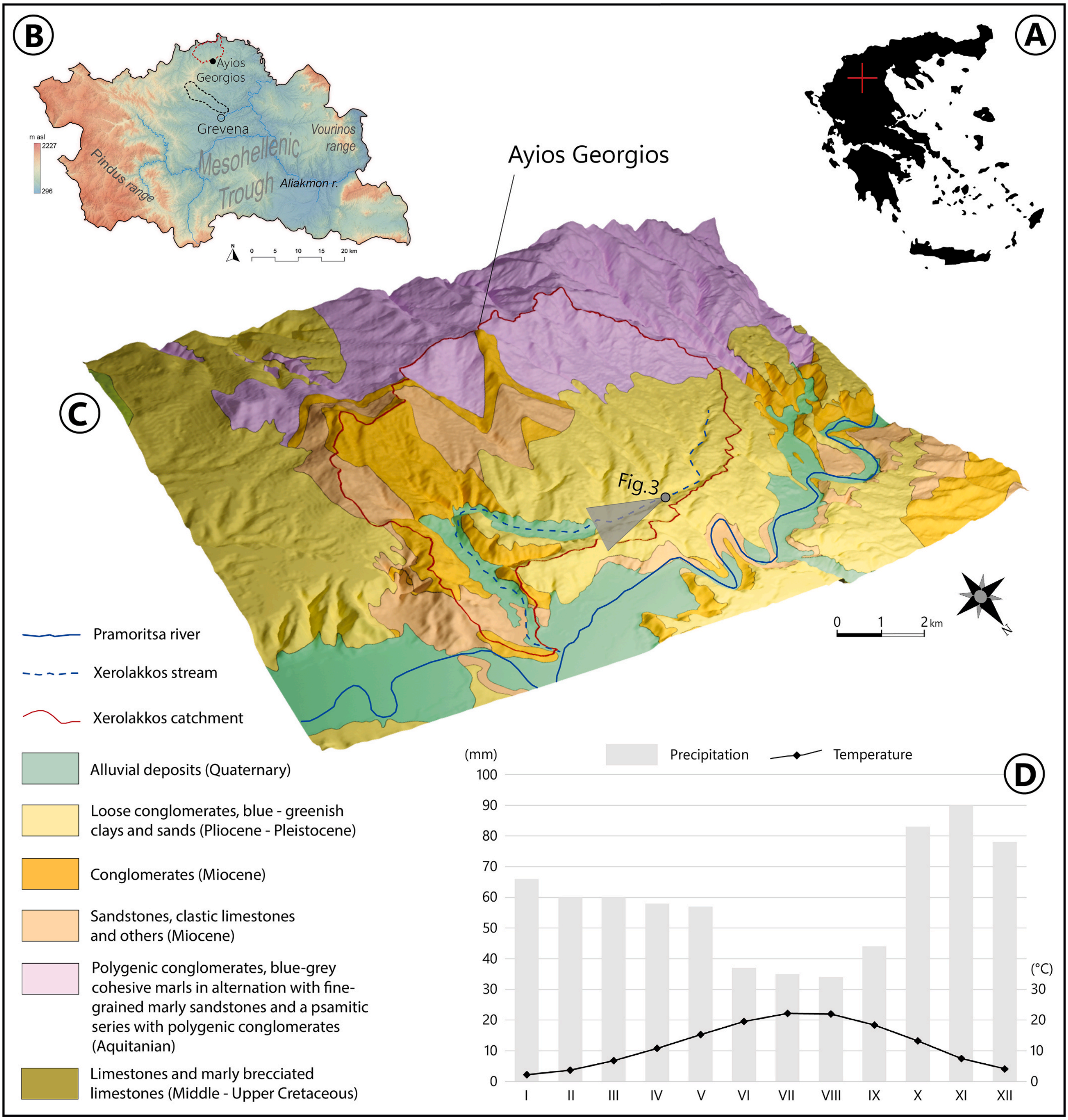

Fig. 1. A) Map of Greece with the location of area of study (red cross); B) topographic map of the administrative region of Grevena including the limits of the Xerolakkos catchment (dashed red line) and the Leipsokouki catchment (dashed black line) discussed in the text (Doyle, 2005). C) 3D geological sketch of the study area after the IGME 1:50000 sheet n∘ 84 Grevena (IGME, 1972); relief map based on the TanDEM-X Digital Surface Model (see methods). D) Climate diagram of average monthly temperature and precipitation for Xerolakkos between 1970 and 2000; spatial resolution of ~1 km^2 (after Fick and Hijmans, 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

recorder to investigate climatic variability, landscape evolution and anthropic impacts at different chronological and spatial scales throughout the Holocene (e.g. Brown, 1997, 2008; Benito et al., 2015; Wolf and Faust, 2015; Gibling, 2018; Bravard, 2020). Although developed worldwide, this approach has proven very fruitful in temperate and dryland areas (e.g. French et al., 2009; Mayoral et al., 2018a; Sampietro Vattuone et al., 2018; Wolf et al., 2021; Depreux et al., 2022). In the Mediterranean, Vita-Finzi (1969) opened the way for comprehending valley systems first on the basis of relative chronostratigraphies, i.e. of dating material culture associated spatially with the sedimentary units under examination, which was further conceptualised and expanded by many others in the following decades (e.g. Neboit-Guilhot, 1983; Bintliff, 2002; Butzer, 2008). Gradually, these projects were enriched with modern techniques such as –among others– AMS radiocarbon dating, OSL and LiDAR. (Fuchs et al., 2004; French, 2015; Evans, 2016). In this study, starting from a standard geoarchaeological perspective, we

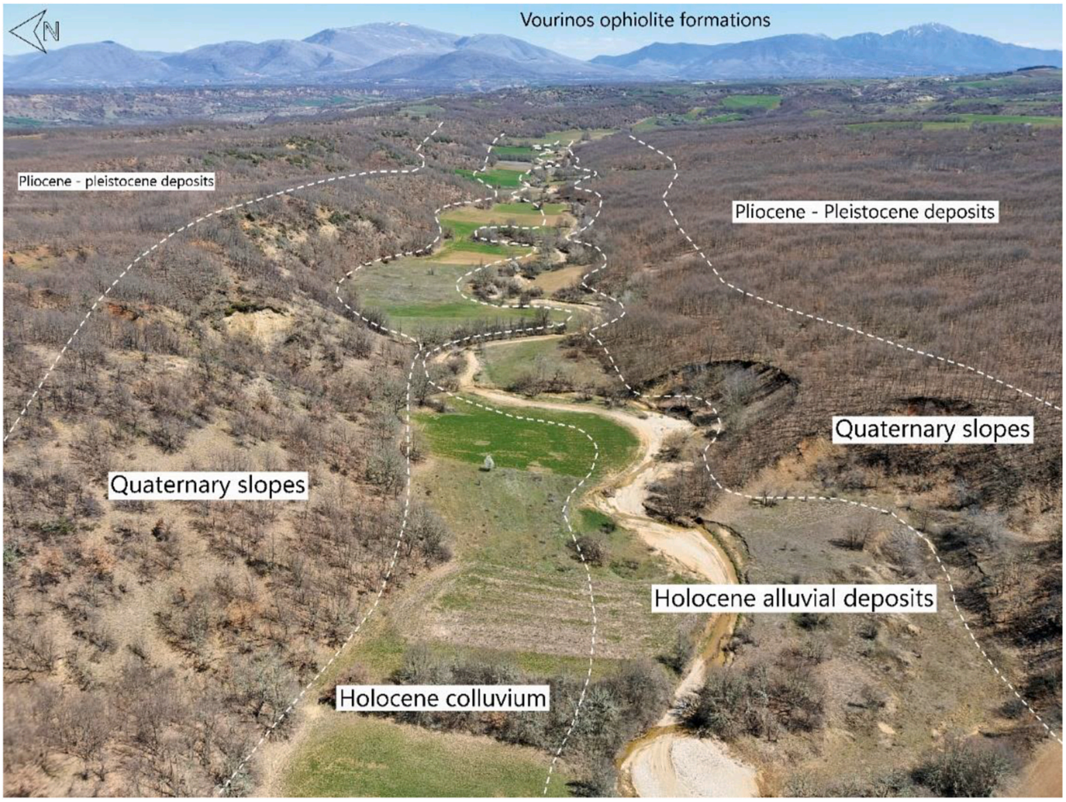

Fig. 2. Panoramic aerial view of the Xerolakkos stream and surrounding area during Spring 2022, with its main geomorphological features. Note that the Holocene colluvium in the footslopes of the N side of the stream is partly covering floodplain deposits (see Fig. 8).

tailored an integrated workflow taking advantage of state-of-the-art remote sensing techniques (mainly UAV-based imagery and DEMs). Results were combined with geomorphological mapping under GIS, thorough field-based studies of litho-stratigraphic profiles and systematic AMS 14C dating of charcoal remains, aiming to extract as much information as possible from the Xerolakkos floodplain while discussing it within an absolute chronological framework.

3.1. *Remote sensing, geomorphological mapping and longitudinal profile reconstruction*

Cartographic materials, such as the 1:50000 geological map of Grevena by the Greek Institute of Geology and Mineral Exploration (IGME) as well as historical aerial photographs of the 1944 and 1945 series by the American and British Air Forces, the 1968 series acquired from the Hellenic Military Geographical Service (HMGS) and modern satellite imagery provided by Google Earth were georeferenced and integrated using GIS. This allowed us to assess the geological and geomorphological background, whiletracing recent landscape changes in Xerolakkos, respectively (Mayoral et al., 2018b; Sampietro-Vattuone et al., 2020). Local topography was visualised using the TanDEM-X Digital Surface Models (DSMs) with a ground resolution of 12 m per pixel (Krieger et al., 2007) as well as its derivatives such as hillshade, slope and gradient maps.[2]

We generated a high-resolution Digital Elevation Model (DEM) based on UAV imagery with a ground resolution of 7.2 cm/pixel, exceeding that of most LiDAR-based geomorphological studies (Notebaert et al., 2009; Tarolli, 2014; Błaszczyk et al., 2022). Three successive drone flights with an AUTEL EVO II UAV covered 1.89 sq km over the main part of the Xerolakkos floodplain (Fig. 1C). Flights were conducted in early spring, when ground visibility conditions were optimal due to the deciduous nature of the prevailing oak trees. Photogrammetric processing of the aerial imagery with Agisoft Metashape Professional 1.8.5® facilitated the image orthorectification and the production of a merged orthophotomosaic of the area. Ground Control Points (GCPs) were then introduced into the orthomosaic for georeferencing. Finally, the DEM was generated using a dense cloud as the source data. The same approach was applied to the RAF 1944 imagery to produce a historical orthomap of Xerolakkos for comparative analysis (Orengo et al., 2015).

Geomorphological mapping of the study area (Fig. 4) was initially based on the detailed examination and identification of the landforms and geomorphic features visible in the DEMs, carried under QGIS Desktop 3.22.3 (QGIS Development Team, 2023). Basic (contour lines, slope, hillshade) and advanced (multi-hillshade and slope gradient derivatives) visualization of the DEM data using the open-source Relief Visualization Toolbox (RVT) assisted in the landform detection (Mayoral et al., 2017; Kokalj and Somrak, 2019; Chabrol et al., 2022). We prioritised the detection, characterisation and mapping of the different Holocene alluvial surfaces alongside the floodplain, being the main objective of our research. Their vertical arrangement was examined in detail using the Profile Tool plug-in (Jurgiel et al., 2012). The slopes were classified into colluvial footslopes and erosive backslopes according to their morphology and dynamics. Higher parts of the topography, corresponding to the remains of older Plio-Pleistocene alluvial surfaces (IGME, 1972), were not differentiated for this study. Finally, anthropogenic activity on the floodplain was also mapped.

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[2] Application DEM_OTHER3598 (Project MoundArch: Testing large-scale detection of mounded archaeological features and geomorphological signatures in the cultural landscapes of Northern Greece.), German Space Agency (DLR).

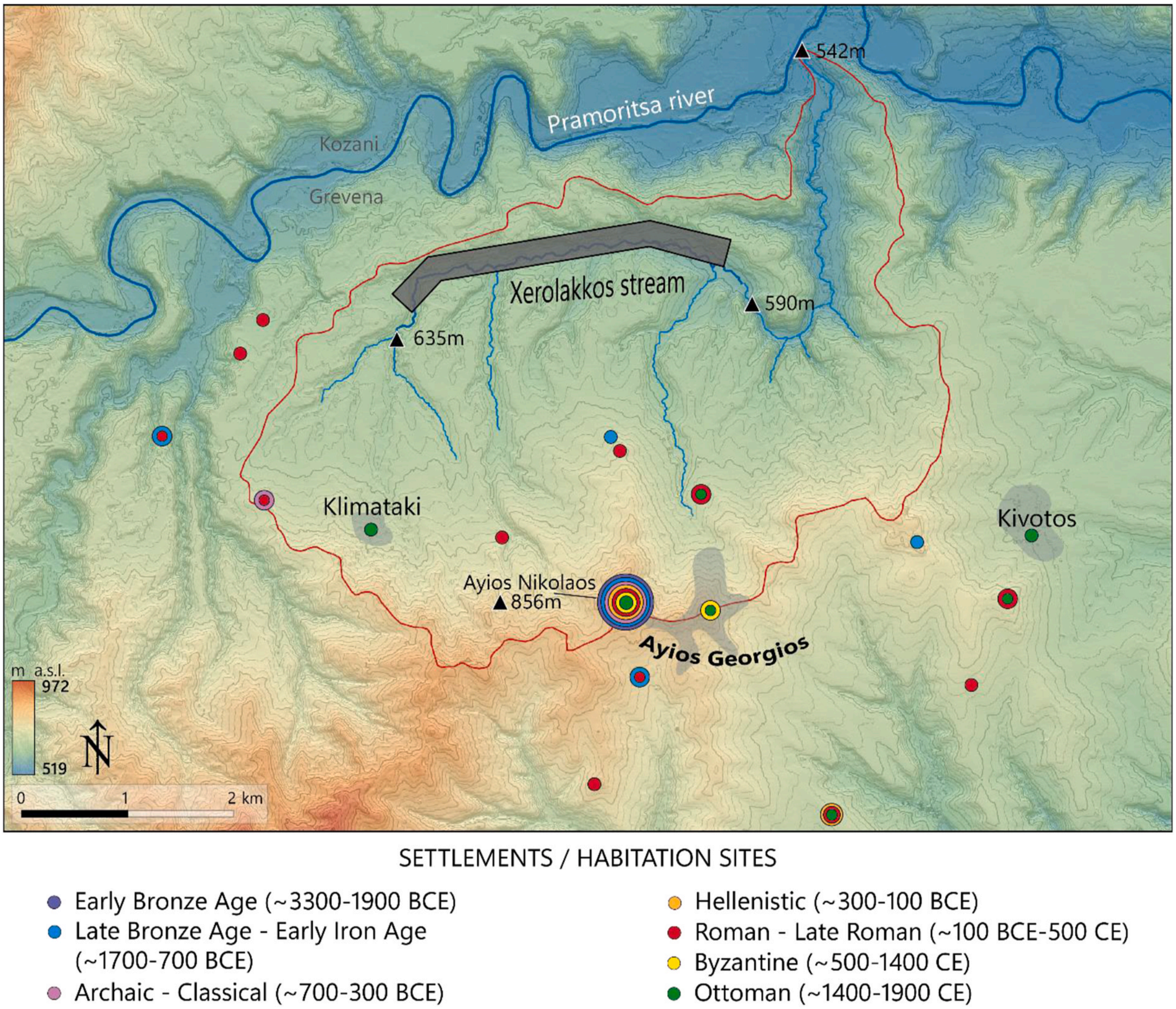

Fig. 3. Relief map of the area around Ayios Georgios, including modern settlements (labelled gray polygons) and archaeological habitation sites (colour points). Cemeteries and burial sites are not included. Red line represents the hydrological limits of the Xerolakkos catchment, whereas the dark gray box marks the studied part of the stream. Based on TanDEM-X Digital Surface Model (see methods). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Conventional chronologies of the main cultural/historical periods for Western Macedonia. After Maniatis, 2014; Weiberg et al., 2019 for the Prehistory; after Bintliff (2012); Nerantzi 2004 for the historical periods.

Early Neolithic	6600/6500–5800 BCE
Middle Neolithic	5800–5300 BCE
Late Neolithic I	5300–4600 BCE
Late Neolithic II (Final Neolithic)	4600–3300/3100 BCE
Early Bronze Age	3300/3100–1900 BCE
Middle Bronze Age	1900–1700 BCE
Late Bronze Age	1700–1050 BCE
Early Iron Age	1050–700 BCE
Archaic	700–480 BCE
Classical	480–323 BCE
Hellenistic	323–148 BCE
Roman (Early and Middle)	148 BCE – 324 CE
Late Roman	324–641 CE
Byzantine	641–1389 CE
Ottoman	1389–1912 CE

3.2. *Geomorphological ground truthing, litho-stratigraphic profile analysis and radiocarbon dating*

Geoarchaeological surveying of the main section (~4 km long) of the Xerolakkos stream (Fig. 3) was conducted to validate or correct the first geomorphological sketch based on cartographic and remotely sensed data. In-situ observations refined the landform characterisation through a more accurate morphological, topographic and taphonomic assessment of the alluvial surfaces. A mobile QGIS application (QField), supported by real-time GPS location, allowed data modifications and corrections during fieldwork. Twelve stratigraphic profiles of terraces, distributed at suitable locations along the floodplain, were selected for detailed study. After cleaning, each profile was described in pedo-sedimentary terms (grain size, Munsell colour, inclusions, sedimentary structures, pedological features, etc.), photographed and located with GPS. Simplified litho-stratigraphic logs were produced for each profile. Their interpretation followed the characterisation of general sedimentary facies and associated alluvial processes (Brown, 1997; Arche, 2010). Four synthetic litho-stratigraphic cross-sections were built and interpreted based on these data (Fig. 10).

Radiocarbon dating was carried out on 14 charcoal samples found and collected *in situ* in 8 out of the 12 studied profiles, distributed across the upper, middle, and lower sections of the stream. In all cases, the samples were disaggregated and deflocculated in water with a drop of hydrogen peroxide (H_2O_2), before sieving with a mesh of 125um to facilitate the manual extraction of the charcoal using a Carl Zeiss Stemi 2000-C W-PI 10x/23 binocular stereoscope. The samples were sent for

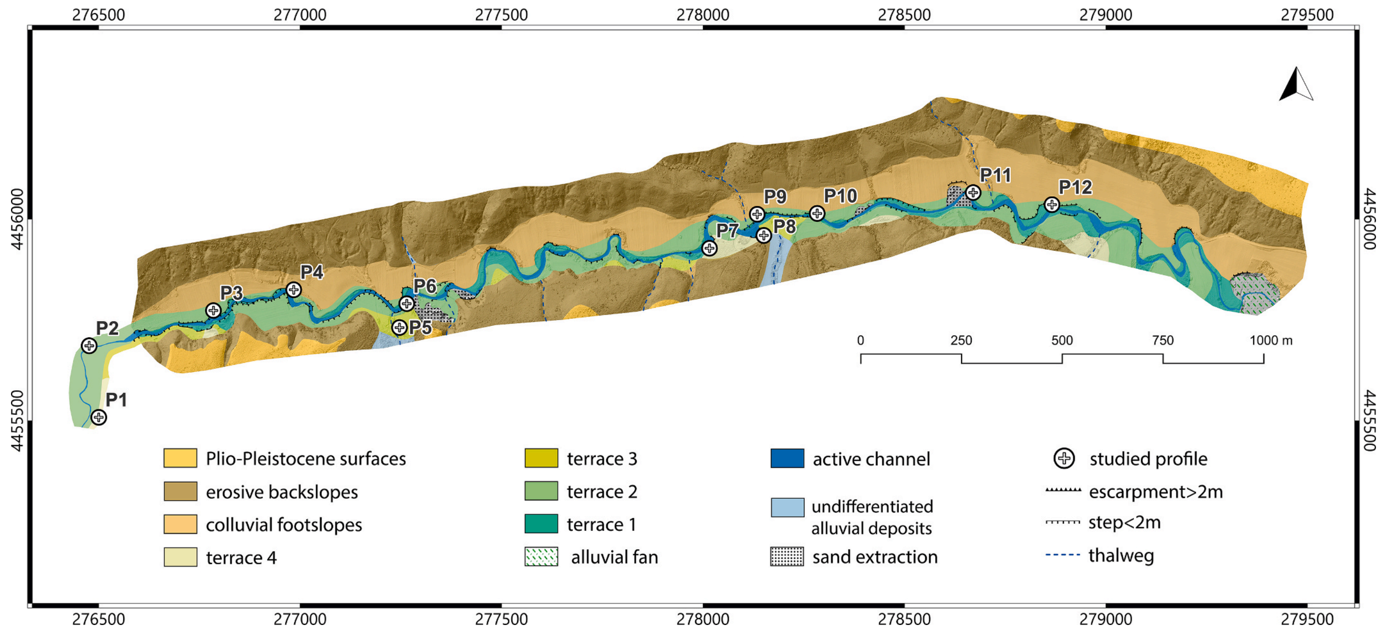

Fig. 4. Geomorphological map of the study area. The basemap is a relief model of the drone-based DEM (see methods). Coordinate Reference System (CRS): GGRS87/Greek Grid (EPSG: 2100).

AMS ^{14}C dating at the Poznan Radiocarbon Laboratory, in Poland. Results were calibrated and plotted using Oxcal 4.4.2 software (Bronk Ramsey, 2009) with the INTCAL20 curve (Reimer et al., 2020) considering two sigma ranges (Table 2).

4. Results and interpretations

4.1. Geomorphological features of the Xerolakkos valley

The two main morphological domains in the analysed section of the Xerolakkos valley are the narrow E-W floodplain and the relatively steep slopes bounding it N and S, topped by Plio-Pleistocene old alluvial surfaces. The northern slopes of the valley are characterised by steeper, short and highly erosive backslopes cut by a few ephemeral streams, and large colluvial footslopes resulting from backslope erosion. These slopes appear to extend over the alluvial landforms of the floodplain, partly fossilising them and thus making it difficult to delineate their contact (Figs. 2 and 4). The southern slopes of the valley are longer and gentler, with limited erosion and development of pedological cover – although the base of these slopes is sometimes steeper and eroded by the lateral migration of the active channel. They are cut by minor streams and some more relevant tributary valleys infilled by undifferentiated alluvial and alluvio-colluvial deposits. This dissymmetric morphological setting, with the main thalweg shifted to the south and steeper slopes with more

Table 2
Radiocarbon dating results. The 2σ ranges calibration was performed using OxCal v4.4.4 (Bronk Ramsey, 2009) and the calibration curve IntCal20 (Reimer et al., 2020).

no	Laboratory reference	14C yr BP	Calibrated yr BCE/CE (2σ ranges)	Profile	Terrace	Depth below surface (cm)	Characterisation of deposit
1	Poz-144062	7230 ± 50	6118 ± 106 cal BCE	1	4	195/200	Developed paleosol within fine alluvium
2	Poz-159543	770 ± 30	1251 ± 29 cal CE	2	2	70	Fine alluvium
3	Poz-159672	990 ± 30	1075 ± 81 cal CE	2	2	180	Fine alluvium
4	Poz-159613	380 ± 30	1540 ± 93 cal CE	4	2	165	Developed paleosol within fine alluvium with colluvial influence
5	Poz-159616	6480 ± 40	5430 ± 95 cal BCE	6	3	100	Fine alluvium
6	Poz-159617	6890 ± 50	5778 ± 110 cal BCE	6	3	230	Coarse alluvium
7	Poz-160090	7110 ± 40	5982 ± 84 cal BCE	6	3	260	Coarse alluvium
8	Poz-159619	7310 ± 50	6198 ± 138 cal BCE	7	4	70	Developed paleosol within fine alluvium
9	Poz-159620	805 ± 30	1228 ± 49 cal CE	10	2	95	Interbedded fine with coarse alluvium
10	Poz-160091	1740 ± 30	324 ± 79 cal CE	10	2	140	Fine alluvium
11	Poz-161065	3465 ± 30	1787 ± 96 cal BCE	10	2	260	Fine alluvium
12	Poz-159621	1750 ± 30	321 ± 83 cal CE	11	2	95	Developed paleosol within fine alluvium with colluvial influence
13	Poz-159615	1250 ± 30	776 ± 102 cal CE	11	2	166	Developed paleosol within fine alluvium
14	Poz-144065	1880 ± 30	159 ± 78 cal CE	12	2	155/160	Fine alluvium

footslope development in the north, is likely controlled by structural factors such as the general dipping of the underlying Miocene sedimentary formations to the North.

In the floodplain, the main landforms are a set of alluvial surfaces along the active channel. Four main terraces were recognised based on their elevation above the present stream bed. The two higher surfaces, Terrace 4 and Terrace 3, are only present on the southern side, perhaps due to the irregular evolution of the stream valley explained above. Starting with the highest, Terrace 4 (T4) surface appears between 5/5.5 and 6.5/7 m above the stream level and residual outcrops have been preserved both upstream and downstream. T4 remains are variable in size, with a length between 20 and 60 m, whereas their width does not surpass the limit of 30 m. Terrace 3 (T3) is also preserved locally across the southern floodplain and it is perched between 3/3.5 and 4.5/5 m above the channel, with remains of variable size stretching from a dozen to more than a hundred m in length. Terrace 2 (T2) refers to the most preserved surface on both the northern and southern parts of the floodplain, yet most outcrops are exposed only on the northern side. Its spatial distribution corresponds strongly to the course of the active channel today. It lies between 1.5/2 and 2.5/3.0 m above the stream, although in the downstream section it reaches occasionally up to 4 m high on the northern side (e.g., P11 and P12). T2 is the largest visible alluvial surface, with the preserved areas extending from a dozen to over hundred m in both length and width. Lastly, the youngest, Terrace 1 (T1), lies between 0.3 and 1.5 m above the modern channel and matches with its course, being in areas part of the active floodplain and in others a stabilised boulder-dominant surface but very prone to flooding.

A small alluvial fan to the end of the studied stream section has also been noted. At that point, the bed of the stream is dispersed and mixed with the current floodplain surface, creating a flat area entirely cultivated today. The active channel remains dry in most parts or carries very little water. However, heavy rainfall may provoke short-term continuous flow, including high-peak discharge events and floods. Channel mobility forms the dominant dynamic, laterally sapping the terraces and vertically incising the Plio-Pleistocene bedrock, which is often exposed at the stream bed or covered by a thin layer (<50 cm) of gravels, pebbles and cobbles mixed with clays and silts. Bank steps and escarpments are commonly found along Xerolakkos, of which only the most obvious examples were mapped for simplicity reasons. Both the higher escarpments (>2m height) and the lower steps (<2 m height) are considered to result from mass failure by lateral erosion of the channel and undercutting tree roots. Finally, recent anthropogenic interference in the form of gravel extraction was first indicated by anomalies in landform morphology and elevation values and was later validated in the field to have locally destroyed or altered the original surface of some fluvial terraces. Minor surface-level changes due to dirt road opening have also been recorded but were not included in the final geomorphological sketch since they had no significant impact on the general morphology and preservation of terraces.

4.2. *Chronostratigraphy and correlation of the alluvial sequences*

Generally, most of the studied profiles were rich in charcoal remains, spotted not only in fine, overbank deposits but also in coarser sedimentary facies corresponding to palaeochannels or small point bars. The majority of the samples dated for this analysis were collected from fine alluvial units, some of which supported more or less developed palaeosols (Table 3 & Fig. 6). All the obtained dates are considered consistent with the stratigraphic logs (Fig. 6), apart from the sample no. 12, which appears a few centuries reversed with the sample no. 13 (Profile 11), suggesting minor reworking of older charcoal. On first view, there is a chronological grouping along the distribution of dates, with Early Neolithic corresponding to Terrace 4, Early and Middle Neolithic to Terrace 3, while the rest belonging to the Roman and Byzantine/Ottoman periods are grouped with Terrace 2. The single date in the Middle Bronze Age (no. 11, 1787 ± 96 cal BCE), on the other hand, finds

Table 3
Synthetic lithological and pedo-sedimentary features of the main pedo-sedimentary facies recorded along the Xerolakkos floodplain, with an interpretation of the associated depositional environments and processes.

Sedimentary facies	Main lithological and pedo-sedimentary features	Matrix Munsell colour in dry conditions	Associated depositional environments and processes
Topsoil	Bedded silts to sandy silts, with several roots and cracks; some to many sub-angular to sub-rounded gravels (mostly granules-pebbles, very few cobbles). Deposit poorly to medium sorted. Few to several cracks, rootlets and organic remains (fauna and flora).	Mostly brown (7.5 YR 4/4) and then variations from yellowish brown (10 YR 5/4) to dark brown (7.5 YR 4/3) and rarely light olive brown (2.5Y 5/4).	Present day floodplain floor, active agricultural soil horizon, bioturbation.
Paleosol	Most commonly silts to sandy silts, including sparse to several sub-angular to rounded granules, occasionally rounded pebbles and cobbles of various size, poorly shorted. Locally several disperse Ca nodules and reddish-brown amorphous oxidation mottles, occasionally charcoal remains scattered or once arranged as a continuous *in situ* lens (size approx. 0.2–1 cm).	Three variations, a strong brown (7.5 YR 4/6-5/6), a dark grayish brown (10 YR 4/2–5/2), and a light olive/light olive brown (2.5 Y 5/3–6/4)	Both incipient and developed pedogenesis/soil formation.
Fine alluvium	Bedded silts to sandy silts, sometimes clayish silts or loams. Typically including sparse to several sub-angular to rounded granules, occasionally sparse granules and subrounded pebbles, rarely cobbles of variable size and poorly sorted. Very frequently rootlet traces.	Mostly between dark grayish brown (10 YR 4/2) and brownish yellow (10 YR 6/6), rarely light olive brown (2.5Y 5.4).	Low-energy floodplain deposits. Some bioturbation.
Coarse alluvium	Silty sands to coarse or very coarse sands, with mostly pebbles and gravels, less often cobbles, inclusions sub-rounded to rounded. Moderately to well sorted, bedded or in alternating bedded lenses of sands with fine alluvium. Occasionally very	Mostly yellowish brown (10 YR 5/6 or 10 YR 5/4), rarely strong brown (7.5 YR 4/6) or light olive brown (2.5Y 5/4).	High-energy channel migration/deposits (point bars) and channel incision. Incipient pedogenesis in some cases.

(*continued on next page*)

Table 3 (*continued*)

Sedimentary facies	Main lithological and pedo-sedimentary features	Matrix Munsell colour in dry conditions	Associated depositional environments and processes
	few scattered charcoal remains.		
Alluvium with colluvial influence	Bedded silts to sandy silts, mostly few or at times several sub-angular to sub-rounded gravels (granules, pebbles, cobbles) poorly or very poorly sorted. Locally abundant reddish and brownish amorphous oxidation mottles next or at a continuous *in situ lens* of 1–3 cm width of large charcoal remains (individual size approx. 0.2–3 cm)	Yellowish brown (10 YR 5/4 or 5/6) and light yellowish brown/light olive (2.5Y 6/4 or 5/3–5/4).	Low-energy floodplain deposits partially mixed with slope runoff deposits. Both incipient pedogenesis and developed palaeosols. Some bioturbation.
Colluvium	Bedded silty to sandy silts. Few to many disperse sub-angular to sub-rounded granules, pebbles and cobbles.	Brown (7.5 YR 4/4) or dark yellowish brown (10 YR 4./4) or light olive brown (2.5Y 5/4)	Slope deposits or alluvium reworked by rainwash and diffuse runoff, sometimes pedogenised (developed paleosol).

no parallels in the sequences of Xerolakkos. It comes from fine, silty alluvium and appears consistent with the dating of the upper part of P10, although we cannot exclude the possibility of it having been reworked. It can relate to either an unknown/non-consolidated alluvial surface or support the view that the base of Terrace 2 started to form during the Bronze Age and its deposition continued to Roman period when all the rest of the dated samples cluster. In the absence of other geomorphological or chronostratigraphic data, however, neither of these interpretations can be conclusive at this stage of the study. Regardless, the chronological lacuna between the Middle Neolithic and the Middle/Late Bronze Age remains notable and could imply either the absence of significant alluvium deposition during this period or the posterior impact of strong erosive processes in the floodplain.

Moving to the analysis of the stratigraphic logs, it revealed the dominance of fine alluvial deposits, often alternated with coarser alluvial facies or mixed with colluvium-driven inputs. Table 3 provides a descriptive overview of all the sedimentary facies recognised in Xerolakkos as well as the interpretation of their associated depositional environments and processes. Being an important part of the discussion below, the recorded palaeosols have been added as a distinct pedosedimentary class for clarity reasons, although they can be found both in fine and colluvial-influenced deposits. These interpretative keys will be used afterward to establish the chronostratigraphy of each terrace as well as to underline periods of (hydro) morphosedimentary stability and instability in the floodplain.

Terrace 4 is represented by Profiles 1, 7, and 8. P1 regards an alluvial terrace preserved very close to the slope, which must have been covered by colluvium and slope debris sealing the lower, alluvial units. On the contrary, P7 does not seem to have been affected by any post-depositional slope-driven process. Finally, P8 was also located very close to the slope, indicated both by the presence of colluvial deposits and the height of the Plio-Pleistocene bedrock. The sedimentary sequences of P1 and P7 show a certain similarity in terms of structure,

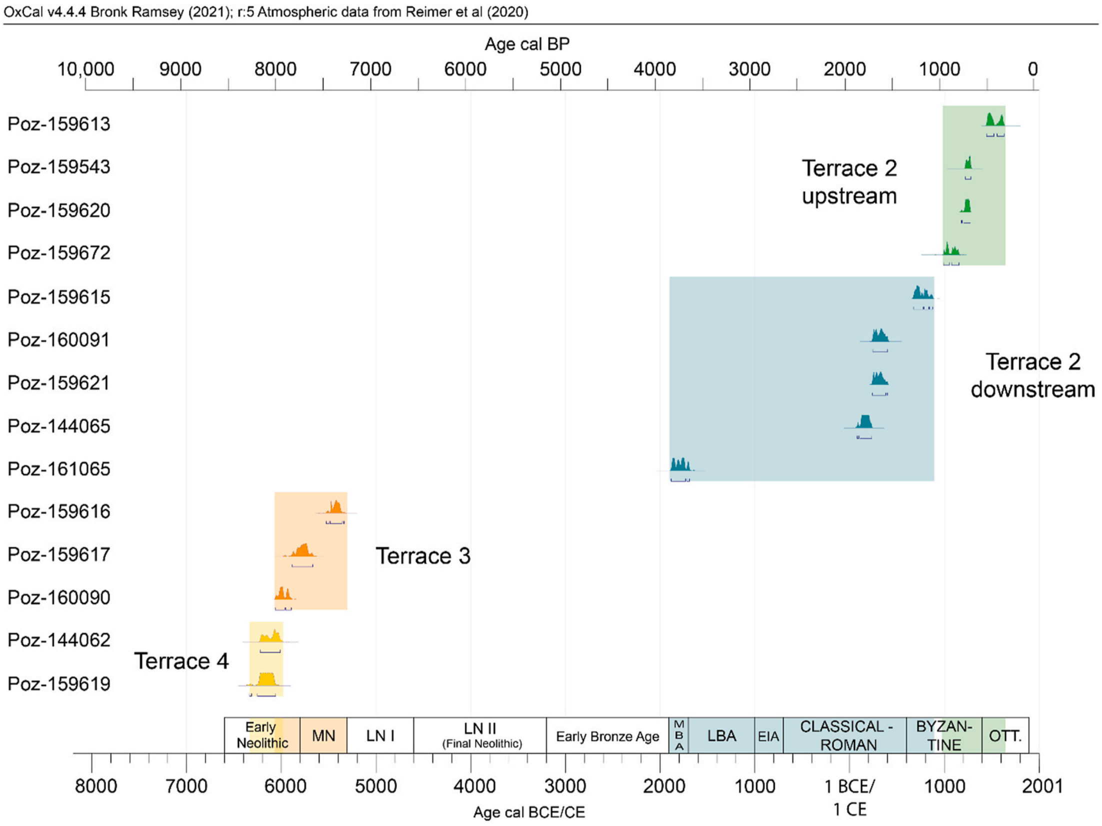

Fig. 5. Chronological diagram of the radiocarbon dates in Xerolakkos.

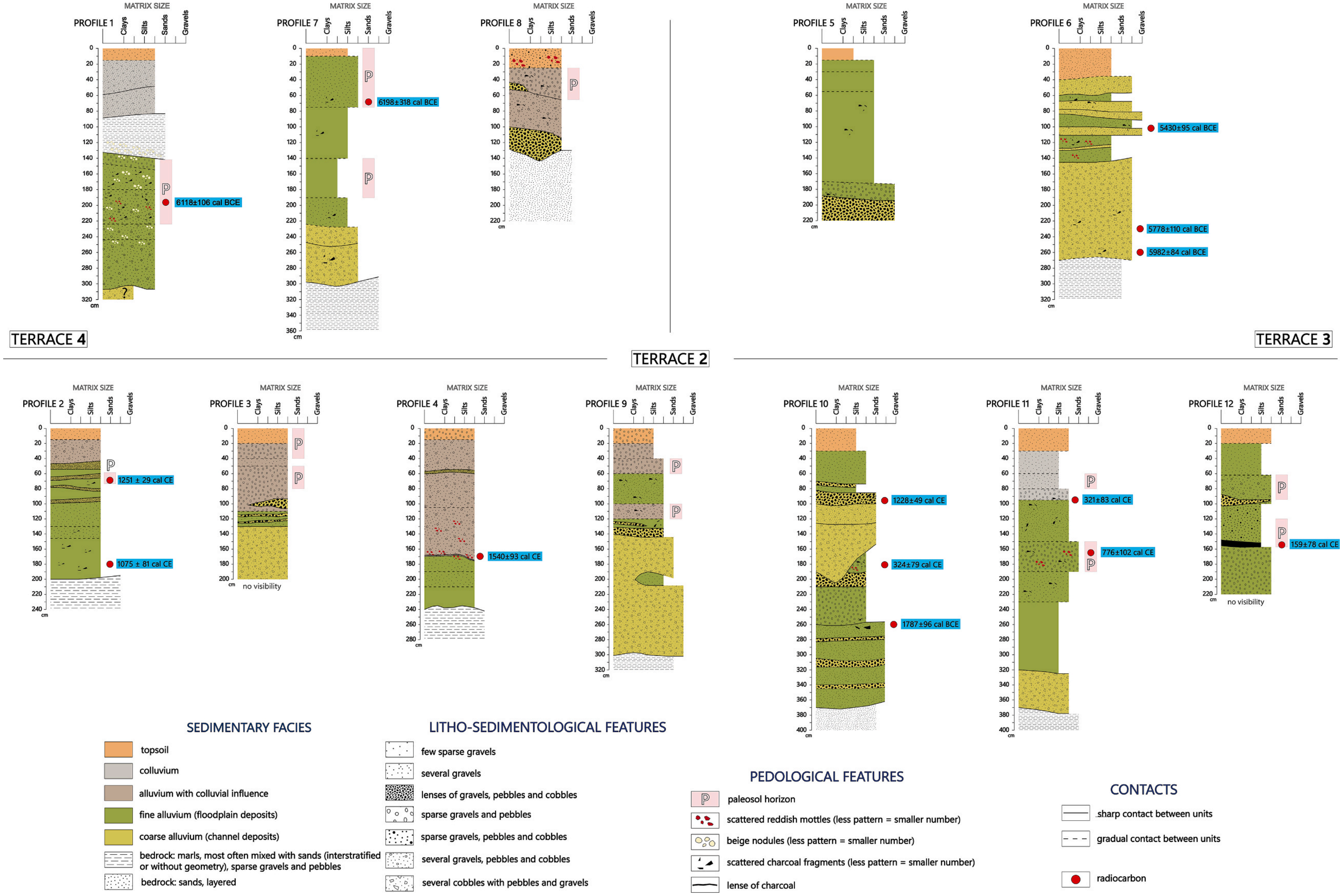

Fig. 6. Synthetic presentation of the stratigraphic logs from the studied profiles grouped per terrace.

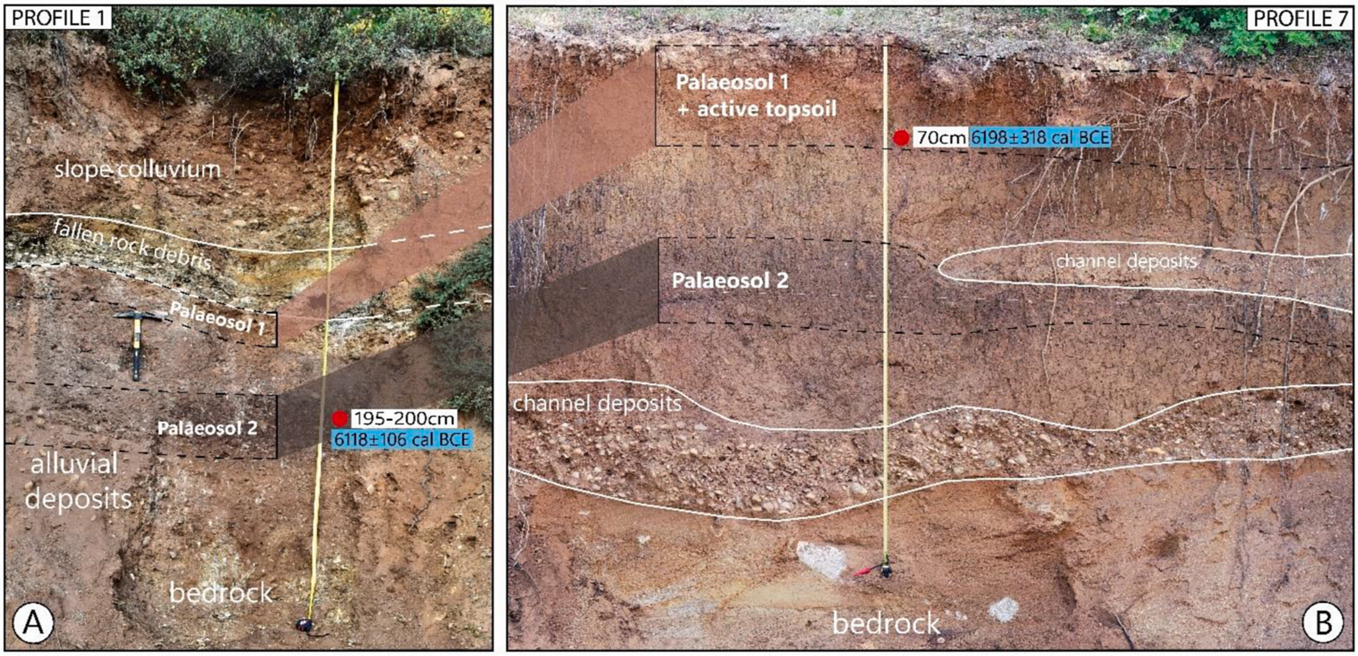

Fig. 7. Profile 1 (A) and Profile 7 (B) illustrating main units, radiocarbon dates and the correlating palaeosols.

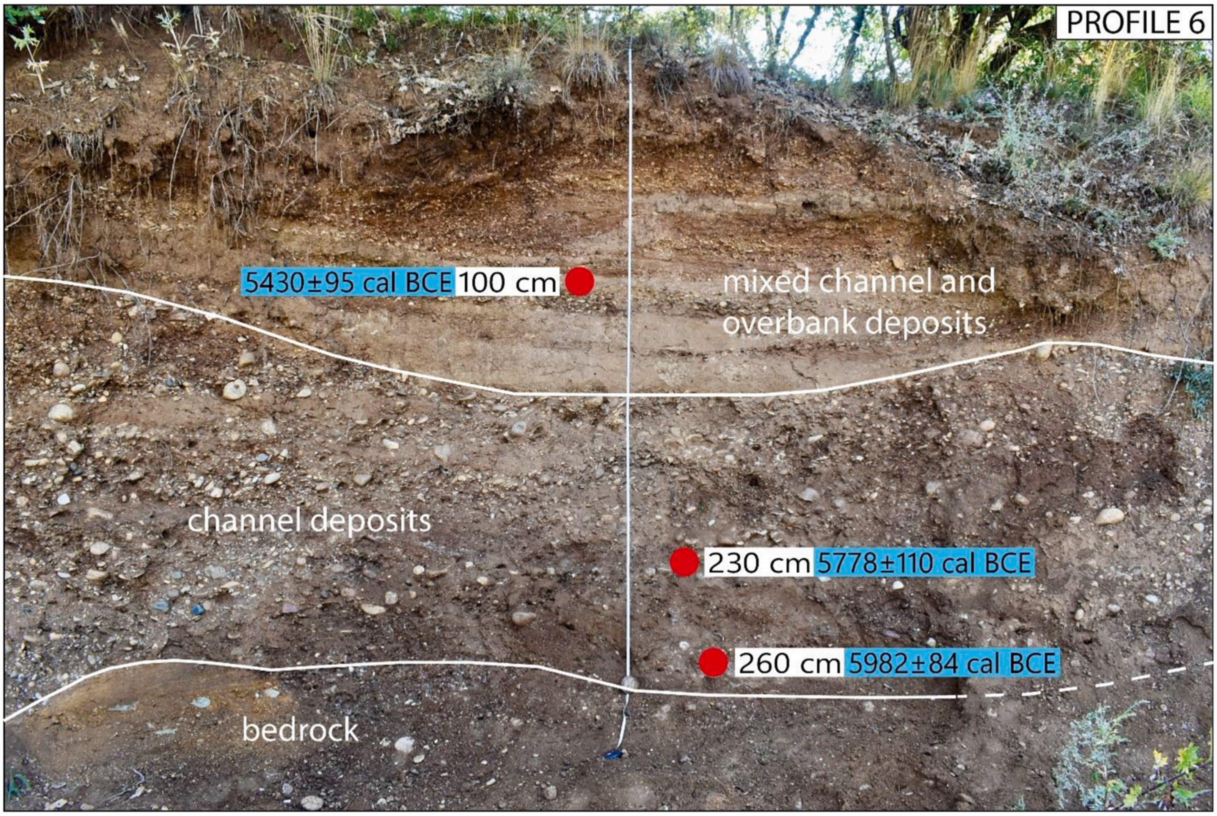

Fig. 8. Profile 6 with its main units and radiocarbon dates annotated.

processes involved and sedimentary history. They represent two of the highest alluvial surfaces in Xerolakkos, found between 6 and 7 m above the current stream bed. Their lower part, directly in contact with the bedrock, starts with coarse units of gravels, pebbles and cobbles matched as channel remains (Fig. 6, P7 and probably P1), followed by an accumulation of fine, silty-dominant overbank deposits. Within these sediments, a sequence of palaeosols provides direct evidence of parallel pedogenesis phases in P1 and P7 (Fig. 7).

Two correlated palaeosols have been recognised and have also provided radiocarbon dating. The lower is darkish brown and its incipient development suggests that it was short-lived (no. 1, 6118 ± 106 cal BCE). It is succeeded by a much more mature reddish-brown horizon at

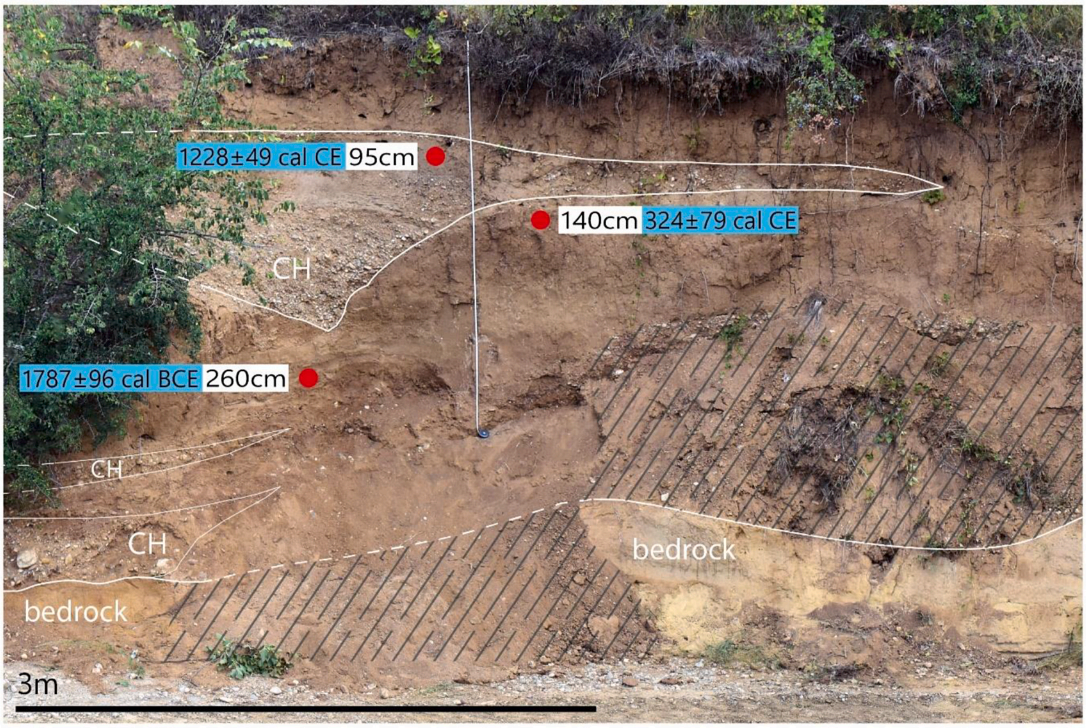

Fig. 9. Profile 10 representing its main units and the available radiocarbon dates. Diagonal black lines indicate covered parts of the profile. CH = channel deposits.

the top of the terrace that seems to have undergone a long-term pedological evolution (no. 8, 6198 ± 318 cal BCE). A very similar horizon was also recorded at the upper part of P8, matching well the above situation, but the lack of radiocarbon dating does not allow further interpretations. Accordingly, the formation of T4 must have been completed by the Early Neolithic period, around 6200 BCE, when the floodplain certainly reached relative stability as shown by the degree of pedogenesis at its top. Afterward, a phase of vertical channel incision fossilised the surface of T4, allowing perpetual pedogenesis and soil development in its upper units until nowadays. This can be seen in P7, where the reddish Neolithic paleosol coincides with the active topsoil. On the other hand, the absence of dates from the lower alluvial unit of T4 obscures definite arguments on the age of its earliest phases but it may be chronologically attributed to the Early Holocene and perhaps the Late Glacial.

The chronostratigraphy of Terrace 3 has been compiled based on the study of Profile 6, with three consistent radiocarbon dates distributed from the base to the top of the alluvial series. At the base of the sequence, successive levels of coarse gravels, pebbles and cobbles, mostly unstructured, are attributed to major channel deposits placed directly in contact with the bedrock. These channels represent events of higher hydrosedimentary energy and must have been functional between a few centuries in the early 6th millennium BCE, as indicated by two very close dates (5982 ± 84 and 5778 ± 110 cal BCE). A swift to much lower energy dynamics is illustrated at the upper part of the sequence composed of alternating lenses of finer (silts) and coarser (sands with gravels) alluvium, suggesting short episodes of fluctuating depositional energy between the streambed and the floodplain. Sediment accumulation in T3 must have ceased around or after 5430 ± 95 cal BCE, as demonstrated in the upper date of P6 (Fig. 8).

The analysis of Terrace 2 included seven stratigraphic logs and nine radiocarbon dates. Its taphonomy differs throughout the course of the stream, with the accumulated sediments reaching 2–2.5 m upstream (Profiles 1–4), whereas downstream the recorded sequences exceed 3.5 m (Profiles 9–12). This change in sediment deposition is also reflected on the relative elevation of the terraces above the current channel (see 4.1), although this distortion may have also been caused by the variability of posterior channel incision in the underlying bedrock. T2 is generally composed of finer overbank in turn with coarser channel deposits. The first are represented either by silty clays or at times loams whereas the second by lenses of gravels, pebbles and cobbles. As it already occurs with T4 and T3, the initial alluviation of T2 took place directly to the stream bedrock. Sedimentary features of the upper fine alluvial units indicate that it may have been influenced to a variable degree by colluvial influx from the footslopes (Fig. 6). This fact hampered the precise delineation of the northern limits of the T2 surface. Furthermore, the alluvial sequence seems to be characterised by a pair of incipient darkish brown palaeosoils, which can be spotted in several T2 outcrops across the Xerolakkos floodplain (P3, P9, P11 and P12). The first developed between 0.4 and 0.6 m from the top of T2, and the second in lower layers between 1.4 and 1.7 m (Fig. 6).

Radiocarbon dating in T2 provided a rather bipartite view of its depositional history and associated hydrosedimentary processes, since the available dates are placed into two separate chronological phases. Initially, the continuous layers of charcoal at the depth of ~150–160 cm in P12 and P4 seemed to indicate a single and extensive fire event. In P4, this layer was also related to the appearance of roundish reddish inclusions or mottles that most likely reflect soil erosion resulting from burning. However, the 14C results from these two layers (159 ± 78 cal CE and 1540 ± 93 cal CE, respectively) highlighted two distinct deposition phases, during the Roman and the Ottoman periods. This chronological division was also evident, for example, between P11 and P2, with the first being consolidated in the Roman/Late Roman times, whereas the latter seems to have been greatly formed between a few centuries in the Byzantine period. The stratigraphy of P10 offers insights into these distinctive aggradation episodes. A 2 m high accumulation of fine and coarse sediment must have been already happening for centuries and until a time window around 324 ± 79 cal CE, if not later, when a channel incised laterally the upper rest of these deposits, not only eroding but also burying the existing floodplain surface at that time. The finer, upper part of this channel in erosive contact has produced a 1228 ± 49 cal CE date, implying a long chronological interval

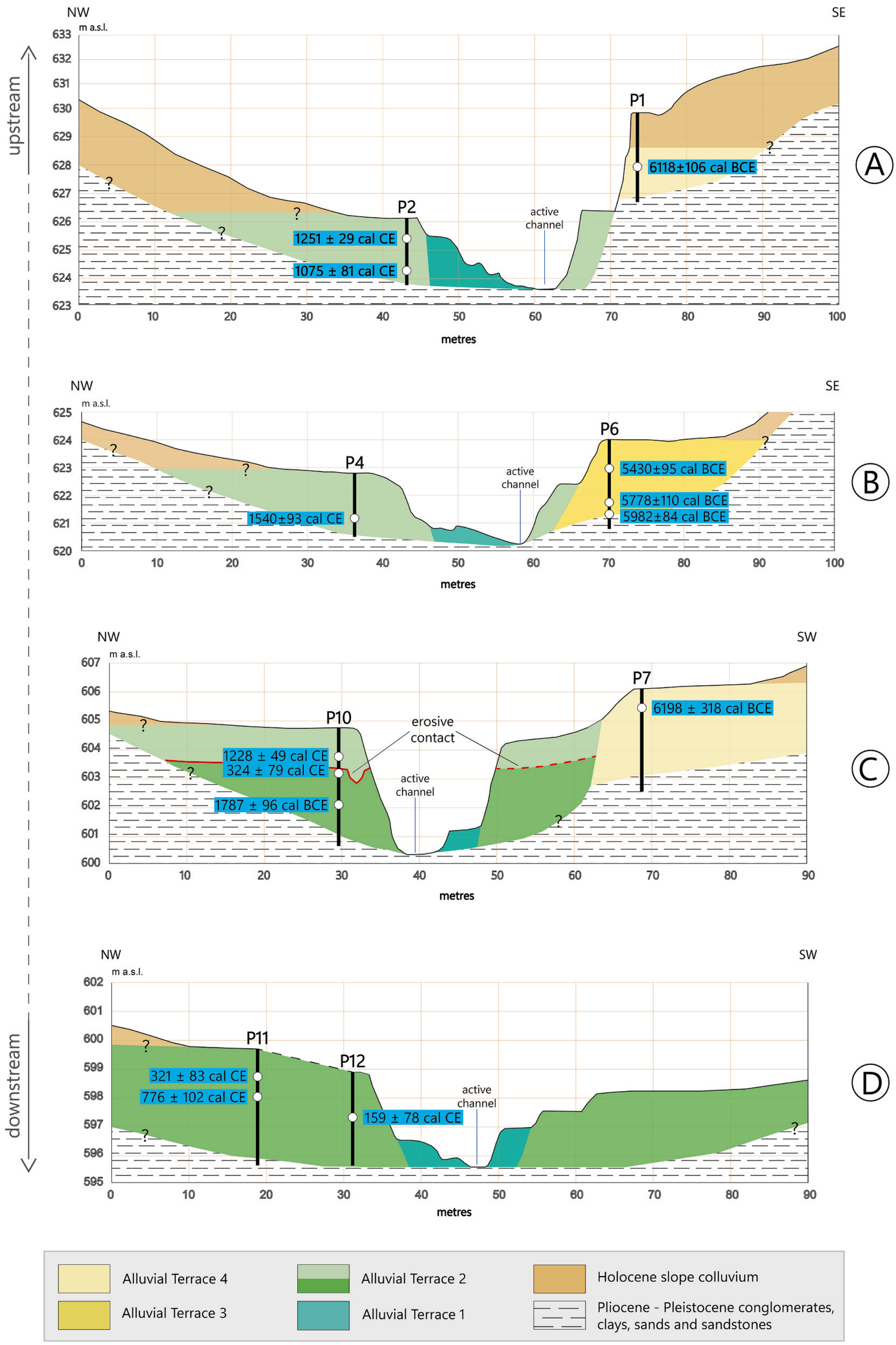

Fig. 10. Synthetic transversal sections of Xerolakkos alluvial surfaces based in geomorphological data, stratigraphic logs and radiocarbon dating. "?" indicates uncertainty in the exact contact between units.

between the older and the younger filling phases of P10 (Fig. 9).

Following the lithostratigraphic and pedosedimentary analysis of Profiles 1–12, the synthetic transversal sections of the studied outcrops point to complex and multi-phased aggradation/erosion dynamics in the floodplain evolution of Xerolakkos. The deposition of the oldest and highest terrace (T4) took place in a more or less flat valley covering homogeneously the older bedrock. The later profound channel incision through T4 not only reached the bedrock, but it also started downcutting it significantly, widening the valley floor. This phenomenon must have resulted in the formation of a strath surface, very partially preserved and only across the southern part of the floodplain (Fig. 10.A & C). From the T3 formation onwards, cut-and-fill dynamics mark the phases of aggradation and degradation in the floodplain, compiling a roughly nested geometry for T3, T2, and T1 (Fig. 10C). Furthermore, while T2 surfaces appear clearly paired upstream (Fig. 10A and B), uneven posterior erosion in the downstream (perhaps due to lateral migration of the channel) seem to have caused the formation of slightly dissymmetric terraces between the northern and the southern side of the floodplain (Fig. 10D). Finally, there is evidence to suggest the existence of at least two distinct sedimentary phases that formed T2 (Fig. 10C), despite its apparent morphological uniformity and unicity. This conclusion was only evident by the radiocarbon dates of P10, where channel deposits partially eroded and covered the sediments of a previous terrace surface formed more than a millennium before.

5. Discussion

5.1. Interpretation of alluvial dynamics and sediment behaviour in Xerolakkos

The study of the alluvial terraces in Xerolakkos has provided well-dated sedimentary sequences, shedding light on distinct hydro-sedimentary dynamics, including floodplain aggradation and degradation/incision events during the Holocene. Soil erosion and superficial formations in the slopes of the catchment, caused by both concentrated and unconcentrated runoff before being carried by a network of small ephemeral tributaries, must have been the primary source for the sedimentary materials in Xerolakkos. The generally steep relief of the catchment, coupled with the small width of the floodplain, can be indicative of a high correlation between slope erosion and floodplain aggradation. While in other parts of the Mesohellenic Trough in central Grevena gully development has been the major mechanism of sediment transport from the upper catchment to the valley floors (Doyle, 2005), it appears that currently in Xerolakkos and the adjacent Ayios Georgios area gullies are stabilised and thus this process appears less dominant. Yet this describes rather a recent phenomenon and must be attributed to the second half of the 20th century CE. For instance, the 1944 RAF imagery illustrates a series of active gullies at the time, which today has been largely covered. Local afforestation during the past decades must lie behind this development (Fig. 11A). On the other hand, slope wash by diffuse runoff may have also played a significant role in upper slopes erosion and colluvium accumulation in footslopes.

Currently, in large parts of the landscape, cultivation takes place directly on the soft marly or sandy bedrock due to the advanced state of soil degradation, particularly on hilltops and the upper slopes of the ridges (Fig. 11C). This fact should form a serious taphonomic parameter in the evaluation of the local archaeological record, since soil erosion and sediment transport towards the valley bottoms have deeply penetrated, displaced or destroyed previous levels of human activity (Fig. 11D). Only in areas where human occupation has been continuous, or cultivation was not intensively practiced, would it be more possible to identify *in situ* remains of ancient soils and undisturbed archaeological horizons. The hill of Ayios Nikolaos (Fig. 11B) represents the best example of an archaeological site to have preserved a rich, multi-period sequence of artefacts spanning from the Early Bronze Age (~3300-1900 BCE) onwards to the 20th century CE (Apostolou et al., 2024a). Although in this case Neolithic finds have yet to be discovered, locations such as Ayios Nikolaos constitute one of the few taphonomic opportunities in the landscapes of central Grevena to identify preserved strata, either anthropogenic or natural, dated back to the Early and Middle Holocene.

5.2. The Early Holocene alluvial dynamics at the advent of the Neolithic

The transition from the Late Glacial to the Early Holocene in Northern Greece is associated with profound environmental changes, including rising of the sea-level, gradual reforestation, changes in vegetation species and intensive alluvial phenomena that, coupled with the increased influx of fresh water, led to the creation of extensive coastal wetlands (for an overview see Gkouma and Karkanas, 2018). Although lacking radiocarbon dating, the presence of gravels at the base of T4 may indicate a depositional phase of very high energy that could represent locally the Late Glacial - Early Holocene transition, with torrential dynamics and less vegetal stabilisation at the slopes (Fig. 12.1). At the beginning of the Holocene, the area of Grevena likely experienced a transitional climatic regime, with prevailing fresh and humid conditions giving way to increasing seasonal contrast, marked by dry summers and severe winters (Magny et al. 2003, 2013; Berger and Guilaine, 2009; Berger, 2021). Both regional data and reviews from the wider Mediterranean context point to an expansion of open deciduous forests at intermediate altitudes, particularly *Quercus* (oak) woodlands (Lawson et al., 2005; Bordon et al., 2009; Wagner et al., 2009; Kouli and Dermitzakis, 2010; Marinova and Ntinou, 2018).

During this period at Xerolakkos, a major sedimentation phase is expressed by the fine silty alluvium of Terrace 4, illustrating that relatively stable yet aggradating dynamics must have been dominant in the floodplain certainly due to a moderately well developed vegetation in the slopes. This aligns with the regional pollen reconstructions and the idea of an open forest in Western Macedonia (Kouli and Dermitzakis, 2010; Lawson et al., 2005; Panagiotopoulos et al., 2013). By the end of the Early Holocene, parallel pedological processes of the upper part of T4, visible in both P1 and P7 (Fig. 7) marked the end of aggradation in the valley and the onset of distinct soil development under stable conditions by ~6300/6200 BCE (end of the Early Neolithic period). At this point, dark brown horizons of alluvial incipient soils were succeeded by much more weathered reddish palaeosols, indicating a shift towards greater stability within a seasonally contrasted climate. Thus, our data suggest that climatic variability did not carry a significant change in the Xerolakkos floodplain during the Early Holocene, and a progressive, long-term stabilisation of the fluvial system (and the landscape) is strongly inferred until the end of the 7th millennium BCE (Fig. 12.2). Contemporaneous pedogenesis phases has also been identified at Leipsokouki (Doyle, 2005) and Sidari (Berger et al., 2016, Fig. 13C), on the island of Corfu, during the same period.

This relative stability coincides with the life span of the Early Neolithic communities in Western Macedonia, established as early as ~6600/6500 BCE (Andreou et al., 1996; Wilkie and Savina, 1997; Maniatis, 2014; Karamitrou-Mentessidi et al., 2015; Fotiadis et al., 2019). In the region of Grevena, there are at least 23 Early Neolithic sites recorded, but only one has been partially excavated until today – thus limiting significantly our knowledge about the local Neolithisation process (Toufexis, 1994; Wilkie and Savina, 1997; Wilkie, 1999; Karamitrou-Mentessidi, 2009; Karamitrou-Mentessidi, 2016). No Early Neolithic sites have been located in Xerolakkos and Ayios Georgios (Apostolou et al., 2024a). Nevertheless, within the general context of a hydrosedimentary trend towards stabilisation noted above, local soils would have certainly developed on the loose marl and sandstone plateaus/hilltops during the last two or three millennia of the Early Holocene. This phenomenon, combined with the nature of the underlying local bedrock, must have created an attractive environmental setting for the first Neolithic farmers, characterised by relatively productive and easy to cultivate horizons. Indeed, the integration of archaeobotanical, anthracological and pollen data from Northern Greece and the Balkans reflect upon a model of mixed farming practiced by the Early Neolithic societies, probably on a limited scale around the sites and after the necessary canopy opening through the mixed oak forests (Bogaard, 2005; Marinova and Ntinou, 2018). Even though strong taphonomic biases (see 5.1) or research gaps could explain the absence of Early Neolithic sites in the area, if they existed, their pressure on the surrounding landscape e.g., by converting natural woodlands into farm and pasture lands, must have had a minimal effect on soil erosion, as we deduct from the sedimentary signals at Xerolakkos (Casana, 2008; Glais

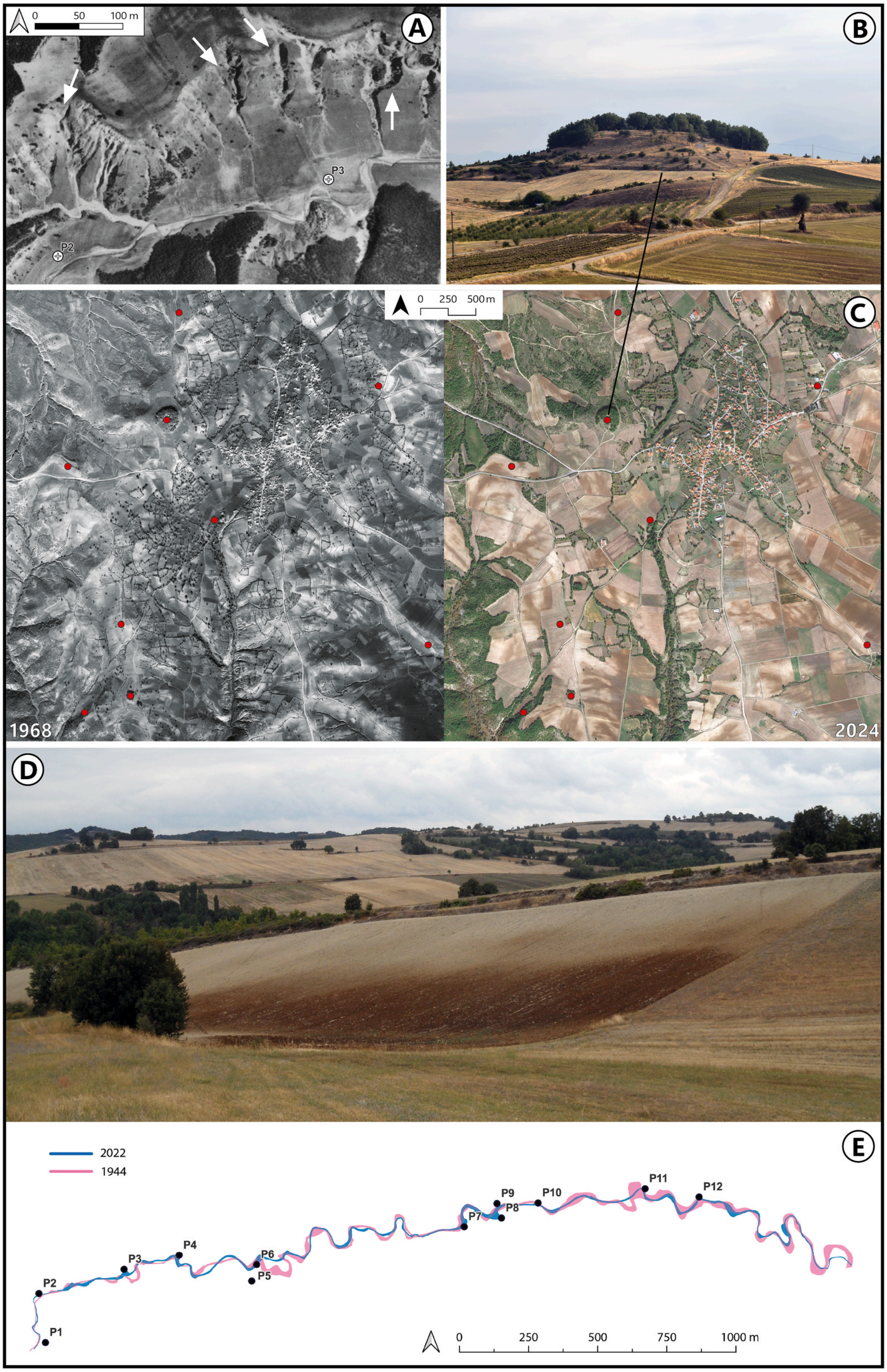

Fig. 11. A) Part of the Xerolakkos floodplain from the 1944 RAF photographs revealing active gullies at the northern side of the stream, pointed by the white arrows; labelled points correspond to the studied profiles. B) Panoramic view of the Ayios Nikolaos hill-site located at the fridges of the village of Ayios Georgios. C) Comparative analysis of the 1968 HMGS aerial imagery (left) and Google satellite data of 2024 (right) for the area of Ayios Georgios. The whitish or beige concentrations mark surfaces of exposed bedrock, denoting the degree of soil erosion at the higher parts of the topography. Red dots indicate archaeological sites. D) A ploughed field in a ridge with a clear spatial division between the exposed bedrock (marls, soft sandstones and conglomerates) due to intense erosion (beige area) at the upper side and colluvial reworking and deposition of pedogenic material -and potentially preserved palaeosoils- (darkish brown area) at the bottom. E) Recent changes in the active channel of Xerolakkos: The 1944 channel extracted from the RAF imagery compared to the channel mapped through the UAV survey conducted for the current study in 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

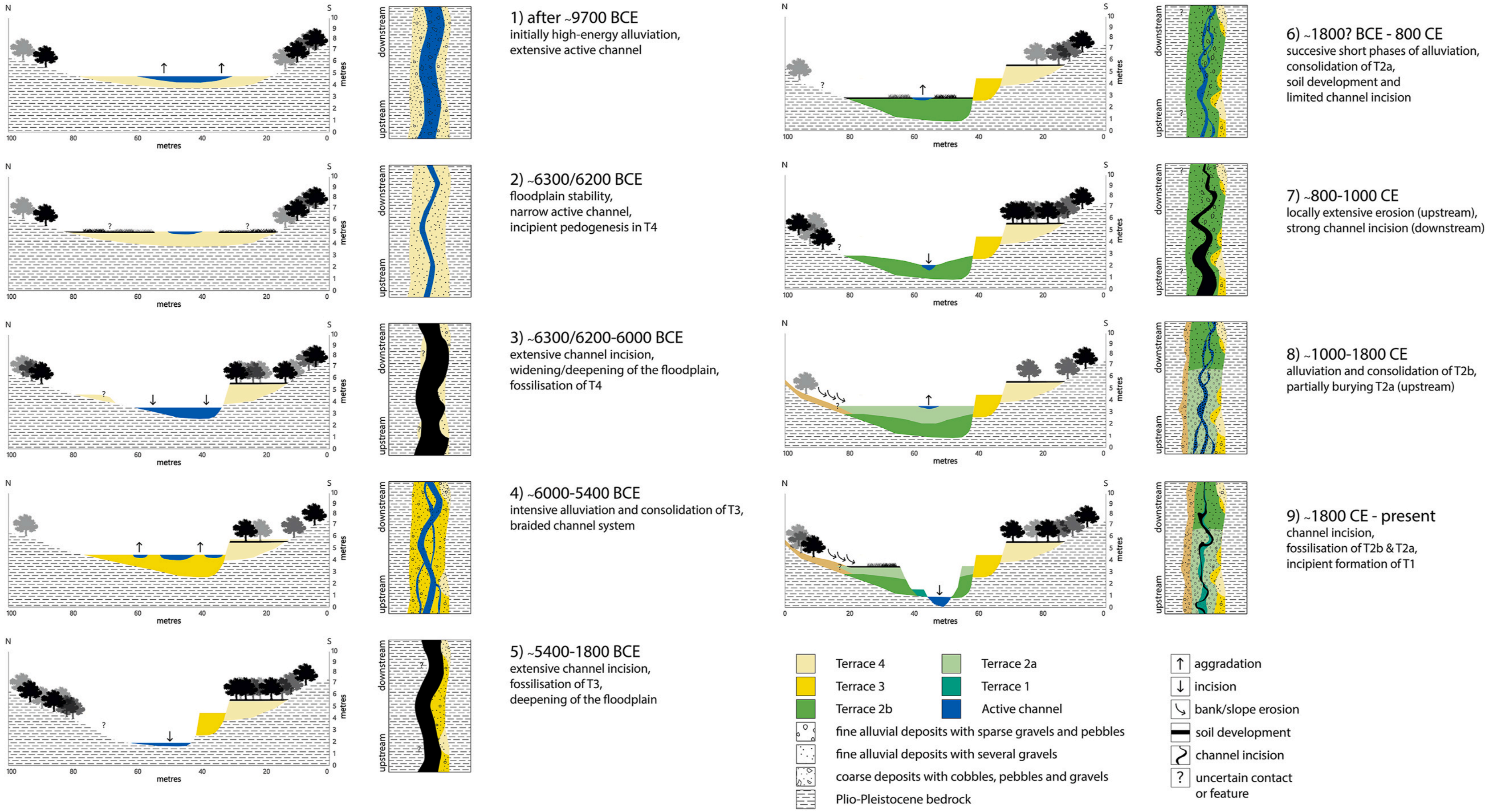

Fig. 12. Schematic evolution of the Xerolakkos floodplain during the Holocene. The tree shapes symbolise hypothetical forest or vegetation cover according to the recorded alluvial dynamics (more shapes = more coverage), while the shrub shape is used to emphasise floodplain stability and consequent soil development.

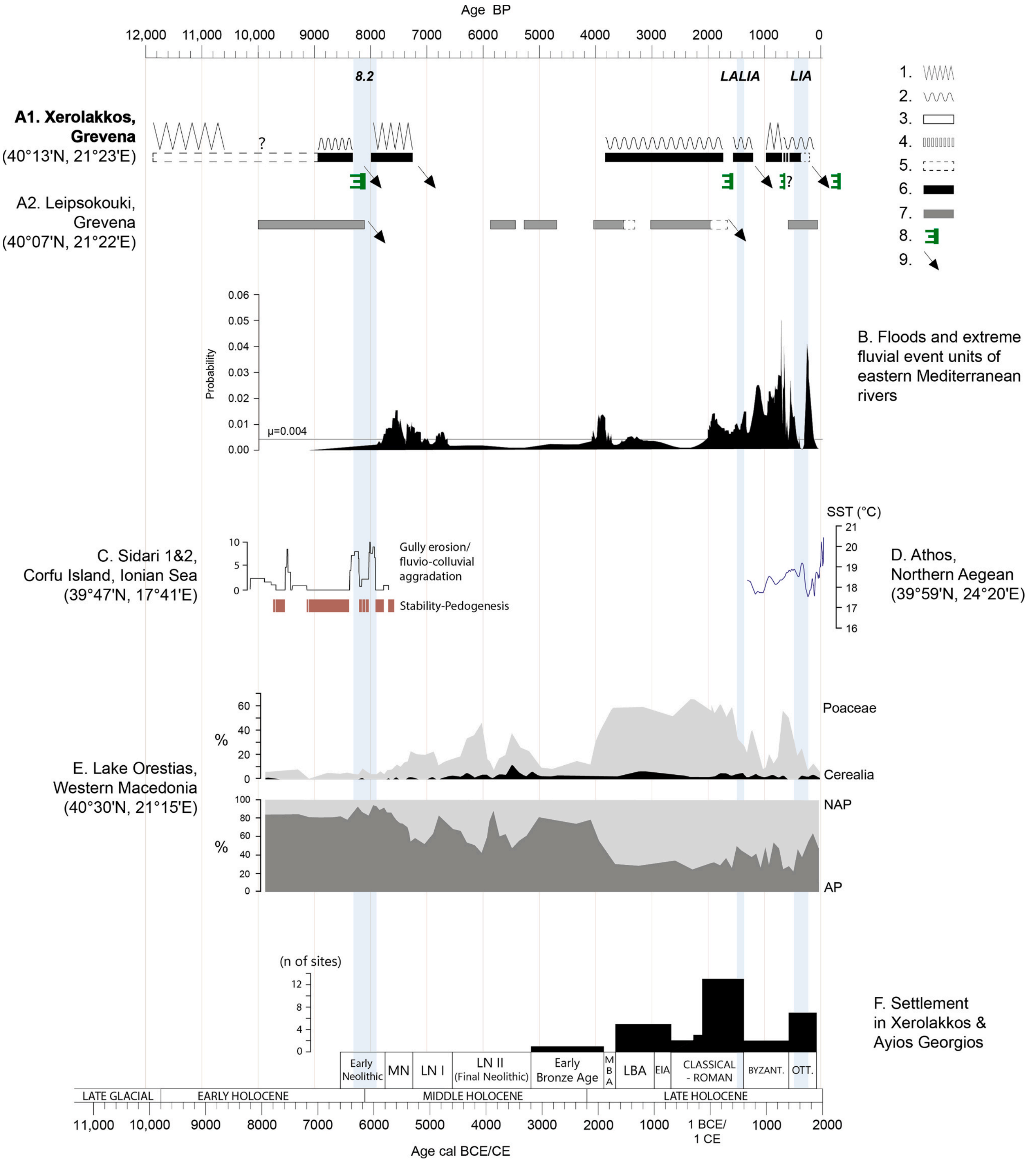

Fig. 13. Synthetic diagram comparing: A) Alluvial dynamics in this study and Leipsokouki (Doyle, 2005). LEGEND: 1. Dominant high-energy dynamics (coarse alluvium), 2. Dominant low-energy dynamics (fine alluvium), 3. Certain alluviation boundaries, 4. Intermittent/episodic alluviation boundaries, 5. Inferred alluviation or uncertain chronological boundaries, 6. Analytical dating methods only (14c), 7. Analytical dating methods (14c) and archaeological finds, 8. Soil development/pedogenesis, 9. Stream incision; B) relative CDP plots of geochronological dates from floods and extreme fluvial event units of eastern Mediterranean rivers (Benito et al., 2015); C) Cumulative Probability Density Function (CPDF) plot of Sidar 1 and 2 sites. Line represents aggradation peaks and colour box pedogenesis (Berger et al., 2016); D) Reconstructed Sea Surface Temperate (SST) curve from Athos basin, Northern Aegean (Gogou et al., 2016); E) Percentage pollen diagram from Lake Orestias. AP: arboreal pollen, NAP: Non-arboreal pollen (Kouli and Dermitzakis, 2010); F) Plot of the numbers of archaeological sites/settlements around Ayios Georgios (including the Xerolakkos catchment) divided into the main cultural periods, after Maniatis (2014) for the prehistory and after Bintliff (2012) for the historical periods. Marked light blue boxes represent the presumable duration of Holocene Rapid Climate Changes (RCC) events discussed in the text: 8.2 = 8.2 kyr BP event, LALIA = Late Antique Little Ice Age, LIA = Little Ice Age. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2016; Weiberg et al., 2019).

5.3. The 8.2 kyr BP event and the Middle Holocene

Following the alluvial stability at the end of the Early Holocene, a dramatic channel incision of more than 3 m occurred between ~6300/6200 and ~6000 BCE in Xerolakkos. This is contemporaneous and most likely related to the 8.2 kyr BP (~6200 BCE) Rapid Climate Change, one of the most abrupt climatic episodes recorded in the Northern Hemisphere during the Holocene (Alley et al., 1997). For about three to four centuries, it brought phases of hyperarid conditions on one hand, including lower temperatures during prolonged winter and at the same time phases of increased yet uneven precipitation, depending on the geographical region (Alley and Águstsdóttir, 2005; Kobashi et al., 2007; Gkouma and Karkanas, 2018). In pollen indices, this instability is bonded by a short-term setback or decline in afforestation (Fig. 13E) (Kotthoff et al., 2008; Panagiotopoulos et al., 2013).

In Xerolakkos, the river entrenchment that occurred during the core of the 8.2 kyr BP RCC could have been caused by changes in flow-sediment load ratio, either by a higher water supply because of increased rainfall or by a strong decrease of sedimentary inputs in a context of generally reduced erosion at the upper parts of the catchment. A combination involving both phenomena is also plausible, such as in the case of Sidari, where floodplain stability and deep gullying appear synchronous (Berger et al., 2016, Fig. 13C). The location of Xerolakkos on the 40th parallel north (Fig. 13.A1) deserves special attention, in this sense, and may explain the local bioclimatic conditions during the 8.2 kyr BP event. This latitude has been estimated to form the theoretical hydroclimatic boundary separating the wetter and fresher north from the more arid, but seasonally contrasting south of the Mediterranean basin. Then, the response of hydroclimatic dynamics in the Xerolakkos during the 8.2 kyr BP RCC, and during the Early to Mid-Holocene in general, may have been intermediate or shifting between these two major palaeoclimatic ensembles (Berger, 2021; Berger and Guilaine, 2009; Berger et al., 2016; Magny et al., 2003, 2013).

From ~6000 BCE, a new alluviation phase commenced to form the deposits of Terrace 3 (Figs. 12.3 and 12.4) lasting for some centuries until ~5400 BCE (end of the Early and Middle Neolithic). The well-dated stratigraphy of T3 displays mostly coarser channel and siltier flood deposits that point to fluctuating yet generally high energy processes of increased sedimentary load, implying accelerated erosion in the upper topography that would have affected the potential Neolithic settlement. Such variable hydrological conditions could be related to the sedimentary aftermaths of the 8.2 kyr BP event or of other climatic oscillations during the first half of the 6th millennium BCE. The sedimentary sequence recorded in T4 and T3 together with the intermediate incision phase may represent, to our knowledge, the first alluvial archive of the 8.2 kyr BP RCC in the Balkans, a geographical zone where such fluvial archives had remained elusive (Berger and Guilaine, 2009; Berger et al., 2016). In any case, these dynamics in the Xerolakkos seem to align well with comparative data of enhanced fluvial activity in Eastern Mediterranean, where strong alluvial dynamics and extreme floods mark the course of the 6th millennium BCE (Benito et al., 2015, Fig. 13B). Therefore, our results suggest that the area of Grevena shifted from climatic dynamics more characteristic to central Europe during the Early Holocene (until the 8.2 kyr BP RCC event), to a more Mediterranean-like hydro-climatic behaviour at the beginning of the Mid-Holocene, being consistent with proposed reconstructions of the regional climatic patterns for these periods (Berger and Guilaine, 2009, Berger et al., 2021).

The considerable chronological gap of alluvial deposits between 5430 ± 95 cal BCE and 1787 ± 96 cal BCE (Fig. 5) suggests a lack of (or very limited) alluvial aggradation episodes from the Late Neolithic to the Middle Bronze Age (Fig. 12.5). This prolonged period, which certainly involved stream incision and channel lateral migration phases contributing to largely dismantle previous alluvial surfaces in the floodplain, suggests another major stability phase in the landscape, where sediment yield was minimal –and hence soil erosion– for more than three millennia (cf. Doyle, 2005). Meanwhile, in the regional archaeological record, most of the Early Neolithic sites ceased to be inhabited in the following Middle (~5800-5300 BCE) and Late Neolithic periods (~5300-3300/3100 BCE) (Wilkie and Savina, 1997). At Ayios Georgios and Xerolakkos, however, no archaeological sites have been recovered from these periods and thus we cannot currently use settlement dynamics for further understanding this overall landscape stability. The 'earliest' evidence of occupation is found at the surface record of Ayios Nikolaos, during the Early Bronze Age (~3400-2200 BCE), which again finds no parallels in the region. Therefore, at this horizon of evidence, our geomorphological data alone could support the idea that overall human activity must have had little impact on the local soils and consequently on the slope and fluvial geomorphological dynamics before ~1800 BCE. On the contrary, drivers of environmental change and landscape evolution throughout the Middle Holocene seem to be mainly climatic, including the effects of the 8.2 kyr BP event.

5.4. Late Holocene alluviation and land-use from the Bronze Age to the end of the Roman period

This rather steady situation since ~5400 cal BCE might have started to change by 1787 ± 96 cal BCE, during the Middle Bronze Age, when the next evidence of renewed alluvial sedimentation is found at the base of Terrace 2 (Fig. 5). At around the same period (after ~2100 BCE but with a large calibration error), Doyle (2005) places the start of a major alluviation phase ('the Sirini alluvium') in the neighbouring Leipsokouki catchment. This 1787 ± 96 cal BCE date appears also synchronous with a flooding peak noted on the scale of the Eastern Mediterranean (Benito et al., 2015, Fig. 13A). Although a single 14C holds *per se* limited evidence, these regional and supraregional parallels come in favour of proposing a similar starting date for the sediment deposition in T2 of Xerolakkos.

In addition, radiocarbon results from P2, P4, P11 and P12 revealed separate aggradation and erosion phases in Terrace 2 between the upstream and the downstream. This phenomenon can be explained by the integration of stratigraphic and 14C data at P10, found in the middle part of Xerolakkos, where the entrenchment of a younger channel is noted on the top of overbank alluvial deposits of an older sedimentary filling (Figs. 6, 9, 10 and 12.7 & 12.8).Consequently, Terrace 2 can be divided into two distinct alluvial deposition phases, separated by an erosive contact. T2b corresponds to the period between the Middle Bronze Age and the Late Roman (~1800 BCE–500 CE) (Fig. 12.6), and T2a refers to the upstream, Byzantine/Ottoman fill (Fig. 12.8). This chronostratigraphic setting implies the succession of different erosional and depositional processes in the upstream and downstream sections: erosion in T2b affected the headwaters area, followed by the deposition of T2a also in the upper part of the stream with a partial overlapping of both deposits in its central part (around P10), producing a particular longitudinal geometry in an otherwise nested terrace system. (Figs. 8 and 12.8). Thus T2b and T2a show a form of time-transgressive longitudinal continuity from downstream to upstream, which could be the result of headwards migration and cut-and-fill dynamics that cannot be precisely defined from our dataset.

In detail, the formation of T2b started with the aggradation of dominantly fine alluvial material locally deposited since the Middle Bronze Age, at ~1800 BCE, onwards (Fig. 6, P10), but sedimentation must have become more rapid and abundant by the beginning of the Roman period (~100BCE-100CE). In Leipsokouki, the Sirini alluvium appears to have a very similar deposition age in two stages, between ~2100 and 1500 BCE and ~1000 BCE-100 CE, when most of its deposition occurred (Doyle, 2005). The lack of more dated 14C samples in the middle of the stratigraphic sequence of T2b does not allow further observations about the accumulation rate of the alluvium before the Roman times. By the 2nd century CE, however, this ongoing deposition exhibits signs of temporal stability or very low sediment input, shown by two short phases of pedogenesis (dark brown incipient palaeosols) dated between the 2nd and 4th centuries CE (Fig. 6, P11 & P12). In this stage, there is evidence of local and intense fire across the main thalweg in P12 (dense charcoal layer dated to 321 ± 83 cal CE), suggesting very close human activities in a likely stable floodplain. Finally, at around the 5th-6th century CE, more than 1m of fine sediment accumulation suggests a phase of renewed alluvial dynamics, which must have ended at the latest before the 11th century CE, as indicated by the date at the base of T2a (1075 ± 81 cal CE, Fig. 6, P2). In the interval, a short, perhaps centennial phase of floodplain erosion would have affected T2b in the upper part of the stream (Fig. 12.7), while the dominant process in the lower section may have been limited in the incision of the main channel. This phase ended with the partial burial of the remains of T2b by the new alluvial deposits of T2a (see 5.5).

During this first phase of alluviation in T2b, spanning approximately from the Middle Bronze Age to the Early Roman period (~1800 BCE–100 CE), the marked accumulation of fine silts describes conditions of sustained soil erosion. This sequence, extending for over 1500 years, cannot be essentially attributed to Holocene short-term hydro-climatic fluctuations, as we saw for earlier periods. For the early part of this episode, no Middle Bronze Age sites have been identified in our area of study. On the other hand, settlement evidence is more pronounced for the subsequent cultural periods, from the Late Bronze (~1700-1050 BCE) to the Hellenistic (~323-148 BCE), albeit without any notable temporal fluctuations or spatial patterns (Figs. 3 and 13F). Throughout this time, the same fine sediment yield continued to be the main alluvial dynamic expressed in Xerolakkos, which could somehowdescribe a phase of increasing, long-term anthropogenic involvement in the local landscape. Such an interpretation finds support at least in a regional scale, from the palynological record of Lake Orestias, located 35 km north of the study area in Western Macedonia. This sequence suggests a serious landscape change around ~1800-1600 BCE, when a dramatic decrease in arboreal pollen coincided with the gradual increase of *cerealia* taxa, pointing to intensifying agricultural activity around the lake until the last centuries BCE, and with a peak in cereals at ~1100 BCE (Fig. 13E) (Kouli and Dermitzakis, 2008, 2010).

Likewise, the introduction or expansion of specific land-use practices during this period could have been responsible for generating continuous soil erosion by runoff in exposed (non-forested) soils, as indeed reflected by the flow of fine sediments in Xerolakkos. Then, in line with the existing evidence, a combination of intensified agropastoral activities, for instance including the large opening of pasturelands and cultivation, may have characterised the area of Ayios Georgios. However, the limited 14C data, juxtaposed against a large chronological spectrum (~1500 years long) of apparent little change in settlement patterns, does not provide sufficient resolution to define the exact temporal relationship between human-induced erosion and alluvial dynamics in Ayios Georgios and Xerolakkos for the end of the 2nd and most of the 1st millennium BCE. This would be particularly critical for future research, if we consider that major sociopolitical developments mosty plausibly followed the incorporation of the Grevena territories into the expanding Macedonian Kingdom, by the 4th century BCE, but remain practically unexplored in terms of potential land-use impacts (Xydopoulos, 2012; Hatzopoulos, 2020).

After the annexation of Macedonia in the Roman Empire, the countryside of Grevena saw the emergence of numerous short-lived sites (~2nd-4th centuries CE), interpreted as farmsteads and established mostly in previously unexploited parts of the landscape (Alcock, 1993; Bintliff, 2012; Rizakis, 2013; Farinetti, 2018; Evangelidis, 2022; Apostolou et al., 2024a) (Fig. 3). Increasing anthropogenic exploitation can again be seen in the pollen record of the Lake Orestias (Fig. 13E), indicating that from around the 1st century CE onwards, agropastoral practices must have occupied a significant part of the landscape in Western Macedonia (Kouli and Dermitzakis, 2008, 2010). A similar picture emerges from the Prespa and Doiran Lakes, where maxima in cereal taxa were followed by large-scale recession in woodland coverage and thus the opening of the landscape, attributed to human agency through animal husbandry, vegetation clearances and of course agriculture (Panagiotopoulos et al., 2013; Masi et al., 2018).

In Ayios Georgios and Xerolakkos, the lifespan of these (Middle and early Late) Roman sites describes the busiest period of human activity, in terms of both site numbers and their spatial distribution. Paradoxically, this appears contemporaneous with a phase of soil formation and decreasing or quasi-stagnant alluvial input in the Xerolakkos floodplain. Changes in land-use or the employment of a specific strategy to limit soil erosion rate (e.g. by terracing), and consequently the runoffs and sediment fluxes ending at the floodplain, seems reasonable for understanding this phenomenon. Further indications to support intensive anthropogenic presence in this period include the fire recorded in P12 that, if deliberate, could have been part of vegetation clearance practices or other rural activities. Therefore, the Roman ‘boom’ of rural sites in Grevena must have been subject to or anyhow linked with an intensification of land-use. This does not necessarily preclude population growth but may be adhered to a re-organisation of the economic system through new land management techniques (Alcock, 1993; Butzer, 2005; Bintliff et al., 2007; Pettegrew, 2007; Bintliff, 2012; Farinetti, 2018; Mayoral et al., 2020b), perhaps to optimise crop productivity and achieve a better surplus destined not only for the local but mostly the supra-regional demands of the markets (Rizakis, 2013).

However, this economic system must have effectively ended after a couple of centuries, by the 4th-5th century CE, following the abandonment of the rural sites and, thus, parts of the agricultural landscape in Ayios Georgios. The synchronous or slightly later renewal of the alluvial deposition from the ~4th-5th century CE onwards in Xerolakkos seems very consistent with this interpretation, as it would have been driven by hastening/exacerbating soil erosion rates arriving from both the agricultural fields and agrarian structures fallen out of use. Although in a complete lack of excavation evidence related to this era, contemporary historical events, and specifically the increasing threat of Gothic and Visigothic raids from the North should have led –at least partially– to the desertion of the farmsteads in Grevena. It cannot be incidental that, after ~500 CE, cereal taxa faced an abrupt drop in pollen percentages from all the upland Western Macedonia (Izdebski et al., 2015). Under this generalised external pressure and rising econimic anxiety, settlement shifts towards more protected locations, such as walled towns and fortified hilltops, have already been claimed not only for the Grevena district (Rosser, 1999) but also for Kastoria from the late 4th century CE onwards (Tsouggaris and Tsokas, 2006; Damaskos, 2006). Many more case studies from southern Greece affirm a very similar scenario to cope with those foreign raids (e.g. Bintliff, 2012).

In addition, this last phase of alluviation in T2b is synchronous with the Late Antique Little Ice Age (LALIA), an abrupt cooling episode in the Northern Hemisphere between the 6th and 7th centuries CE characterised by anomalies in precipitation rates (Büntgen et al., 2016). Although the LALIA could have contributed to the overall erosion witnessed at the catchment, the lack of high-energy sediment flow in Xerolakkos during this period indicates that the localised effects of this RCC did not involve a serious disturbance of its hydroclimatic system, at least not due to strong fluctuations of the rainfall regime. Our suggestion might explain the low fluvial and flood activity that describes the eastern Mediterranean during the same time (Benito et al., 2015, Fig. 13B). Therefore, LALIA was not the driving force behind alluviation between the 6th and 8th centuries CE. On the contrary, social changes drawn from historical events and archaeological evidence must be sought as the main cause of soil erosion in the region.

5.5. *From the Byzantine to the modern era*

The general tendency towards aggradating conditions in Xerolakkos continued well into the Byzantine and Ottoman periods. This is represented by the deposition of T2a in the upper part of the floodplain, while overlapping with T2b at the median section (Figs. 12.7–9). More than ever before in Xerolakkos, the alluvial history of T2a reveals frequently alternating episodes between small channel and larger overbank deposits, indicative of fluctuating hydro sedimentary conditions and discharge events (e.g. Fig. 6, P2, P3 & P10). In addition, the now common appearance of colluvium-influenced inputs at the upper part of T2a (possibly starting after 1540 ± 93 cal CE, see Fig. 6, P4) demonstrates significant slope destabilisation. Phases of very incipient pedogenesis, one of which has yielded a 1251 ± 29 cal CE date, are documented next or after coarser deposits, describing short stability in the floodplain. Similar patterns have been observed in other regional sedimentary archives in Greece, starting with the works in Pieria (Krahtopoulou, 2000) and Larissa (van Andel et al., 1990), where intermittent or episodic alluviation prevailed over the last 1200 years – although with varying depositional dates from place to place (see also Wagstaff, 1981).

An increasing amount of high-temporally resolution palaeohydrological, palaeo-climatic and palaeoecological data concerning the last two millennia in Greece has also highlighted a long sequence of episodic climatic variability involving localised fluctuations in temperatures, precipitation levels and patterns, sedimentary dynamics and vegetation cover (Izdebski et al., 2015; Panajiotidis, 2015; Gogou et al., 2016; Xoplaki et al., 2016; Seguin et al., 2019; Kouli, 2020; Masci et al., 2022). Notably, a marine record from the Northern Aegean offers a window for understanding the temporal distribution of the alluvial events in Xerolakkos (Gogou et al., 2016). Enhanced continental and riverine supply attributed to higher precipitation rates and wetter/humid climatic conditions is supported for three distinct periods, between ~700 and 900 CE, ~1000–1300 CE and after ~1450 CE, all of which appear intriguingly synchronous with the last phase of alluviation in T2b and all the subsequent sedimentation phases of T2a in Xerolakkos (Fig. 13D). In T2a, the distribution of such fluvial behaviour rotates around two widespread and well-attested climatic phenomena, the warmer Medieval Climate Anomaly (MCA) with a core period between ~1000 and 1200 CE (Lüning et al., 2019) as well as the cooling and hydrologically very unstable Little Ice Age (LIA) from ~1200 to ~1850 CE but highlighted with extremes between ~1400 and 1625 CE (Luterbacher et al., 2012). The first might have been responsible for the stability and incision phase that eventually separated T2b with T2a in Xerolakkos, although the chronological match is not exact. Similarly, the effects of LIA can be advocated for the last phase of alluviation in T2a. Thus, palaeoclimatic changes seem to have influenced the hydrosedimentary dynamics of Xerolakkos throughout the Byzantine and early Ottoman times.

In terms of the historical context, successive external invasions and war expeditions followed by presumable settlement destructions characterised the region of Grevena between the 6th and the 13th century CE, but details about their effect on the local land-use are very vague (Nerantzi-Varmazi, 2004, 161). To this, the migration and subsequent establishment of Slavic communities in the area could have impacted the pre-existing land distribution and tenure (Bintliff, 2012). This new socioeconomic regime is probably reflected upon a strong hiatus in archaeological data and settlement patterns around Xerolakkos, although -as elsewhere in Greece-the latter must be partly due to the lack of systematic studies and high-resolution dating of the regional material cultures within the Byzantine Empire (Bintliff, 2012).

During the 12th century CE, clerical texts indicate a strong population decline, accompanied by the abandonment of agricultural fields that had to be left ‘unseeded and untilled’ (Nerantzi-Varmazi, 2004). In the alluvial history of Xerolakkos, this period is witnessed as high-energy sediments reaching the floodplain, complementing a view of exacerbated soil erosion due to the increasing (or persisting) land abandonment. Furthermore, pollen analysis indicate that cereal taxa reached a minimum during the same century, following a long-term decrease that started from the 5th-6th centuries onwards (Izdebski et al., 2015). Remarkably this occurred during the ‘climax’ of the Byzantine economy and within a general demographic growth in the Empire (Xoplaki et al., 2016), pointing perhaps to a reversed regional trend for Western Macedonia. However, after the supposed desertion of the countryside in Grevena, rapid expansion of cereal cultivation is advocated for all the Macedonian uplands from ~1200 CE until ~1400 (Izdebski et al., 2015). If so, in our area of study, this phenomenonis associated with low sedimentary input and, possibly, very short-term pedogenesis (Fig. 13.A1). Similarly to the Roman period, the possible re-use of the landscape in Ayios Georgios and Xerolakkos somehow assisted in lowering ongoing soil erosion.

Political stability, demographic rise and economic prosperity described the 16th century CE, when settlement in Grevena was very similar to today’s in both the location of the villages and the regional population numbers (Kampouridis, 2014). Data taken from the tax surveys conducted in 1564/65 and 1579 CE indicates that Curhli (the Ottoman-period toponym of Ayios Georgios) sustained an important wine production centre (Kampouridis, 2014). Viniculture concerns a very erosive practice but also a temperature-sensitive crop that, in Macedonia, seems to have been encouraged by the prevalence of stable climatic conditions, since marked setbacks of *vitis* in pollen records have been noted during the cooler phases of the last 1500 years (Gogou et al., 2016). This implies that, considering the presumable environmental impact of the Little Ice Age during the same period, the landscapes of Grevena allowed the regional development of vineyards. If this was the case, viniculture must be considered a major parameter behind the last alluviation in Xerolakkos, at least for the period between ~1500 and 1800 CE. Interestingly, this matches again with a rapid drop in cereal indicators for the Macedonian uplands from the 15th century onwards (Izdebski et al., 2015). Nevertheless, in the lack of any other high-resolution proxies, we cannot deduct widespread changes toward the abandonment of cereal cultivation and the preference for viticulture in Western Macedonia as a whole. Other regional geomorphological dynamics appear much more dramatic. In Leipsokouki, the youngest alluvium is strongly synchronous to Xerolakkos’ but expressed as a coarse sedimentation of abundant channel deposits accumulated typically 3–4 m above the modern flood plain (Doyle, 2005). For the last centuries of alluviation in Xerolakkos, the deposits consisted of mostly overbank silty clays and did not exceed 1–2 m of accumulation. Such a contrasting view in Leipsokouki leads to the locally prevailing impact of a climatic change (in this case of the Little Ice Age) perhaps due to ineffective land management and very limited natural vegetation coverage.

Today, an ongoing phase of stream incision takes place at the streambed (Fig. 12.9). Although the stream does not regularly hold continuous water flow, unless heavy rainfall, its discharge peaks have still the power to modify rapidly the active channel but also the preservation of the surrounding terraces. A comparison between the aerial imagery of 1944 and the present view, for example, shows strong meander mobility (and thus hydrological dynamism) as well as a significant reduction in the width of the active channel today (Fig. 11E). In fact, large parts of the 1944 channel constitute now the semi-active T1, while continuous incision has eventually made the current channel deeper and narrower. Overall, this indicates a loss of energy, probably resulting from a combination of climatic variables, involving decreased precipitation, with less hydro-sedimentary inputs arriving at the stream due to afforestation and slope stabilisation (e.g., gullies, see 5.1). The former phenomenon is common in Greece and has emerged progressively from the middle 20th century CE to the present day (Gerasimidis et al., 2008). Particularly in Xerolakkos, forest expansion to the slopes and next to the floodplain has certainly minimised the sedimentary supply and runoff.

This remarkable variability of fluvial activity in Xerolakkos over the past two millennia, which may take place within a very local scale and for relevantly short timespans, tends to point to a human catalyst as the main agent behind landscape changes. However, this occurs in a land already under stress, due to a conglomeration of a generally strong background of anthropogenic pressure and cumulative impacts on soils (especially during the Roman period), while the effects of climatic oscillations, even if relatively modest, were inevitably becoming more and more evident across less resilient fluvial systems, such as in Xerolakkos. Such conditions may be reflected by the fact that, although the sedimentary dynamics of Xerolakkos and Leipsokouki appear well coupled for most of the Holocene, they show different sedimentary responses over the last two thousand years, underlining the dominance of very localised anthropogenic dynamics and landscape destabilisation processes. We thus agree with Lespez's (2003) assumption about the plains of Eastern Macedonia, that changes in land use management (farming and grazing) and not simply an intensification of agriculture or demographic trends were the driving force behind the accelerated rates of alluvial aggradation for the last ~1500 years. Then, as we further demonstrate through the example of Grevena, more emphasis should be placed on the detailed study of the land-use cycles, before determining the real part of climate changes in shaping natural morphogenic systems (Lespez, 2003; Lespez and Ghilardi, 2024).

6. Conclusions

We conducted a geoarchaeological study to investigate the interplay between hydro-climatic variability, soil erosion and settlement histories in the landscapes of Grevena during the Holocene. Radiocarbon dating has provided a robust chronostratigraphy of the alluvial terraces in the Xerolakkos stream, enabling their discussion alongside other Holocene palaeoenvironmental records at local and regional scales. Archaeological data complimented the suggested hypotheses.

Initially, Xerolakkos must have experienced an intense sedimentation in the transition from the Late Glacial to the Holocene, gradually giving its place to a stability phase in both the floodplain and the upper landscape, which climaxed by the middle of the 7th millennium BCE. In this paper we present what may be the first detailed alluvial sequence recording the 8.2 kyr BP (~6200 BCE) event in the Balkans, an area previously lacking such fluvial archives. The 8.2 kyr BP RCC in Xerolakkos is witnessed as a dramatic episode of channel incision by ~6300-6000 BCE. The nature of this climatic event seems associated with anomalies in the hydrological system of the stream, likely revealed as a combination of enhanced precipitation and low soil erosion in the catchment.

At this stage of research, anthropogenic impacts from the first Neolithic communities and subsequent activity in the landscape are not evident at all until ~1800 BCE. In principle, climatic variability seems to have driven landscape changes and alluviation episodes in Xerolakkos during the Early and Middle Holocene. However, the alluvial phase during the 6th millennium BCE and later human settlement from the 2nd millennium BCE onwards must have affected the preservation of older sites in the area, leading to the virtual disappearance of the Early and Middle Holocene archaeological record. Except for very particular settings (e.g. Ayios Nikolaos), post-depositional processes in the upper parts of the topography (e.g. hilltops, ridges) describe a strong taphonomic bias in the evaluation of the regional settlement patterns.

Our data suggests that the continuous alluviation in Xerolakkos commencing during the Middle Bronze Age (~1800 BCE) involved human-induced erosion that was gradually intensified within a timeframe of relative climatic optimum and under specific political contexts (Roman Empire), building upon a narrative of widespread landscape exploitation. However, the character of this anthropogenic intervention remains elusive for the earlier periods (~1800-100 BCE), due to data resolution limitations. During the Roman and early Late Roman times (~2nd-4th centuries CE) sedimentary dynamics are stabilised in the floodplain. This balancing may describe the introduction of a land management strategy to minimise the ongoing soil erosion and improve crop productivity. The emergence of farmsteads, in the same period, must be therefore connected with the above hypothesis. Then, by the Roman times, the local communities had developed a very adaptive behaviour against an already degradating landscape, being capable of regulating soil erosion on a large scale. External raids were presumably responsible for the end of this regime, which was followed by an almost simultaneous re-initiation of alluvium input in Xerolakkos after the 5th century CE, illustrating the potential geomorphological dimension to such historical events and developments.

Over the last ~1500 years, the combination of anthropo-climatic causality appears as the dominant driver of landscape destabilisation. On one hand, regional palaeoclimatic variations align closely with the temporal distribution of alluvial episodes in Xerolakkos that cover the Byzantine through the Ottoman periods (~600–1800 CE). However, a strong background of persisting anthropisation on the soils must have amplified or reduced the effects of climatic instability. This makes long-term human decision-making the main catalyst behind erosional processes, bringing variable outputs. For example, during the 16th century CE, the local effects of the Little Ice Age might have encouraged viticulture instead of cereal crops, producing enhanced soil erosion. Conversely, the present-day management of land-use results in a phase of channel incision in Xerolakkos, under the effects of recent afforestation and climate change.

To conclude, this study showcases the importance of integrating local geomorphological data with regional palaeoenvironmental proxies and archaeology to gain valuable insights into the complex dynamics of long-term socio-environmental interaction. By doing so, we can waive comprehensive narratives of past human societies and their environment, particularly in lesser-studied parts of Greece, where the reconstructed settlement patterns alone could not help to define the causal relationship between land-use strategies and geomorphology (e.g., for the periods before and after the Roman Empire). In this part of Grevena, soil erosion constitutes a continuous challenge in the efficient management of the local landscapes. More than anything, this underscores a diachronic process of human adaptation and resilience. Future multidisciplinary work in the Xerolakkos and the broader area will further contribute to understanding how climate, environmental change, and the local socioeconomic systems shaped the landscapes of upland Macedonia over the *longue durée*.

CRediT authorship contribution statement

Giannis Apostolou: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alfredo Mayoral:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Konstantina Venieri:** Writing – review & editing, Validation, Resources, Investigation, Funding acquisition, Data curation, Conceptualization. **Sofia Dimaki:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Arnau Garcia-Molsosa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mercourios Georgiadis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hector A. Orengo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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