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Neolithic water management and flooding in the Lesser Caucasus (Georgia)

V. Ollivier ^{a,*}, M. Fontugne ^a, C. Hamon ^b, A. Decaix ^c, C. Hatté ^d, M. Jalabadze ^e

^a Aix Marseille Univ, CNRS, Minist Culture, LAMPEA, Aix-en-Provence, France

^b CNRS, UMR 8215 Trajectoires, Maison de l'archéologie, 21 allée de l'Université, 92023, Nanterre Cedex, France

^c UMR 7209 – Archéozoologie, Archéobotanique: Sociétés, Pratiques et Environnements, Muséum National d'Histoire Naturelle et CNRS, Paris, France

^d Laboratoire des Sciences du Climat et de l'Environnement UMR 8212 CNRS-CEA-UVSQ, Domaine du CNRS, 91198, Gif sur Yvette, France

^e Georgian National Museum, Rustaveli Av. 3, Tbilisi 5, Georgia

River management is generally thought to have started at 5500 cal. BC within the development of eastern Neolithic societies. In the Lesser Caucasus, evidence of early river management has been discovered around the famous Neolithic sites of Shulaveri, Gadachrili Gora, and Imiris Gora in Georgia. Here we report a preliminary data set indicating that river management was set up at 5900 cal. BC leading to the flooding, destruction, and local abandonment of the hydraulic infrastructures of the Gadachrili village between 5750 and 5430 cal. BC. The hydraulic infrastructures were developed during a more humid period encompassing the 8200 cal. BP (6200 cal. BC) climatic event, probably to optimize agricultural yield. It potentially led to the first prehistoric engineering accident for which there is evidence, which may have been followed by the reorganisation of the occupation and/or to architectural modifications.

1. Introduction

Despite intensive surveys, fieldwork, and excavations conducted in the last decade by international teams, cross-research between archaeology and geomorphology is limited in the Lesser Caucasus, a mountainous region at the crossroads of Europe, Asia, and Africa. Excavations within the framework of a Caucasian-European joint project encompass some of the most important Neolithic sites of the Lesser Caucasus in Armenia (Badalyan et al., 2010; Chataigner et al., 2014), Azerbaijan (Lyonnet et al., 2012, 2017; Helwing and Aliyev, 2017) and Georgia (Hamon et al., 2016; Hansen and Mirtskhulava, 2017; Hansen and Ulrich, 2017). In the last decade, understanding of the Neolithisation of the Lesser Caucasus has grown. The dates of its emergence have been defined to the turn of the 6th millennium BC, with regional specificities identified

(Badalyan et al., 2010; Guliyev and Nishiaki, 2010; Lyonnet et al., 2012; Hamon et al., 2016; Chataigner et al., 2014). The development of Neolithic societies in the Middle East and Central Asia was always closely linked to the management of water resources. This is illustrated by prehistoric water management in the Jordan Valley (Mithen, 2010; Fujii, 2007). There, the Neolithic is a key period of significant development, leading to the birth and prosperity of the first urban communities of the Early Bronze Age. The first hydraulic installations, intended, among other things, for the irrigation of cereal crops, appeared in the 6th millennium BC in Mesopotamia (Adams, 1974).

Defining clear prehistoric water management structures in the landscape and in stratigraphy is a difficult task due to their low archaeological visibility. In the Lesser Caucasus, signs of small artificial channel structures have been observed during the excavations of some Neolithic sites in Azerbaijan (Lyonnet et al., 2012, 2016; Ollivier et al., 2016) and Georgia (Hansen and Mirtskhulava, 2012), but their role has not been clearly defined as they have

* Corresponding author.

E-mail address: ollivier@msh.univ-aix.fr (V. Ollivier).

revealed limited evidence for runoff both through stratigraphy and sedimentology. With surface water management, channels vary widely in shape, size, and hydraulic characteristics (Bishop et al., 1967; Aurenche, 1982). They were frequently built to divert perennial and/or non-perennial river flows (Huckleberry et al., 2012; Huckleberry and Rittenour, 2014; Doolittle, 2011, Van Andel et al., 1990; among others). Their possible association with irrigation is also difficult to determine. The interplay between the need to respond to and to overcome certain natural constraints (climate, lithology ...), and the diversity of cultural phenomena specific to different societies, makes the links between water management structures and the need for irrigation ambiguous (Staubwasser and Weiss, 2006; Coombes and Barber, 2005; Hassan, 2011; Cauvin, 1978).

Since the 1960s, some archaeological operations have been developed in Gadachrili Gora, a Georgian Neolithic site from the Southern Caucasus Shulaveri-Shomu culture (Hamon et al., 2016). In 2013, geomorphology research was developed in the framework of archaeological investigations in a joint project between the Georgian National Museum and the French National Centre for Scientific Research (Hamon et al., 2016). Gadachrili Gora is part of the Shulaveri group sites, located close to the modern village of Imiri in Kvemo-Kartli. It is close to the sites of Shulaveri, Imiris, and Dangreuli Gora that have provided the first chronology for the area as well as most of our knowledge on the first Neolithic culture and agriculture in Georgia (Kiguradze, 1986; Hamon, 2008).

We present here our results pertaining to the discovery of a series of channels linked to a probable Neolithic water management system discovered in the vicinity of Gadachrili Gora, diverting the flow of the Shulaveri Ghele, a tributary of the Khrami river. In support of this discovery, we also briefly present an example of a Neolithic channel under study in the archaeological site of Mentesh Tepe (Middle Kura Valley, Azerbaijan).

Our results mainly raise the question of the links between climate, autocyclic phenomena, and development of water management structures in a region poorly known in this field, through a study integrating radiocarbon dating, geomorphology, archaeology, and palaeobotany of carpological remains. In spite of these different environmental, technological-typological, and topographical indicators, we carried out isotopic analyses on the seeds in order to characterise or not the occurrence of irrigation. Previous studies around the Mediterranean basin show that the carbon isotopic composition of cereal grain (mainly barley and wheat) can be used to evaluate the occurrence of irrigation practices, increasing aridity, or the impact of drought on Neolithic and Bronze Age societies (Araus et al., 1997a; b; Flohr et al., 2011; Wallace et al., 2013). In contrast, very little data of this type are available for the Lesser Caucasus where irrigation practices are not yet clearly identified for Prehistory.

Through this work we would like to highlight the possibility of the development in the Caucasus of the oldest known water management practices. In addition, we present an original focus on the potential effects of torrential palaeo-floods on Neolithic water management structures and riparian habitats.

2. Regional setting

2.1. Environmental context

Like the well-known Neolithic sites of Shulaveri Gora, Imiris Gora, and Aruchlo, Gadachrili Gora is located in the Kvemo-Kartli Plain dominating the Marneuli-Kura depression. The mountains surrounding the site show altitudes between 450 and 1080 masl and consist mainly of Cretaceous limestones, sandstones, and breccias, and of Upper Pliocene-Middle Quaternary basalts and

andesites (Fig. 1). Present-day local climate is ranked, according to the Köppen classification (Peel et al., 2007), as warm-humid continental (Dfa). The average annual temperature is 13.4 °C and about 472 mm of precipitation fall annually (Climate-Data.org). This eastern part of Georgia has the driest climate of the country (Kvinikadze et al., 2006). The vegetation mainly consists of thorn-bush steppe type present on slopes areas, where plants develop in former forest areas. The dominant plants of this type of steppe vegetation are *Paliurus spina-christi* and steppe grain species (*Bothriochloa ischaemum*, *Festuca ovina*, *Stipa pulcherrima*). Here and there separate specimens of field maple and nettle tree (*Celtis caucasica*) can also be found (Nakhutsrishvili, 2012).

2.2. The Shulaveri and Khrami hydrosystem

This mountainous and steppic landscape is also cut across by a well-developed hydrosystem consisting of the Khrami river and its local tributary, the Shulaveri river (Fig. 1). The Khrami river is a right-hand side tributary to the Kura river (Fig. 1). It originates from a spring, located on the southern slope of the Trialeti range at an altitude of 2422 masl. With a length of 201 km and a watershed of 8340 km², the Khrami river has also two main tributaries, the Debeda and the Mashavera rivers. The hydrological regime is characterised by one significant spring flood. In other periods of the year, the water level is mostly low and occasionally disrupted by summer and autumn high waters. The annual discharge rates fluctuate from 7.02 to 51.7 m³/s, depending on location (U.S. Agency for International Development & Development Alternatives Inc., 2002). The Shulaveri river originates from the joining of two springs on the northern slope of the Lokhi range at an altitude of 1190 masl and joins the Khrami from the right bank. The total length of the river is 38 km, with a catchment area of 117 km². Arriving in the plain, its average many-year discharge (0.44 m³/sec) entirely runs to irrigation channels. The Shulaveri is not currently a permanent river. Both rivers, Khrami and Shulaveri, are generally fed by rain water (40–45% of annual discharge), snow water (20–25%), and ground waters (25–30%) (United Nations, 2011).

2.3. Archaeological setting

The site of Gadachrili Gora (363 m asl., 41°23' N, 44°49' E, Fig. 2) forms part of a series of Neolithic settlements (tell) in the Kvemo-Kartli Plain (Hamon et al., 2016), distributed along a non-perennial tributary of the Khrami river, the Shulaveris Ghele (Fig. 1). It occupies a more or less central position between the sites of Shulaveris Gora, Imiris Gora, and Dangreuli Gora (totally destroyed today). The excavation of the latter in the 1970s provided the first chronological frame and knowledge of the Neolithic Shulaveri-Shomu culture in Georgia (Kiguradze, 1986). The middle part of the site is actually incised by the river Shulaveris Ghele. As a result, two thirds of the former settlement has been completely destroyed. The south-eastern side of the site and a small quantity of cultural deposits on the right bank of the river have survived. The radiocarbon dating places the first levels of this tell between 5920 and 5720 cal BC (Hamon et al., 2016). The overall archaeological stratigraphy consists of two horizons showing different types of settlement organisation. Evidence from the deepest occupation levels suggests a high-density occupation in the settlement, with complex episodes of destruction and rebuilding. The coexistence of different building techniques in the two horizons has to be noted. The high number of storage structures and the discovery of organised built spaces dedicated to storage raise many questions about the status of the site, the organisation of agricultural practices, and the relationship of these populations to the hydrographic network within the area. In addition, the spatial distribution of the

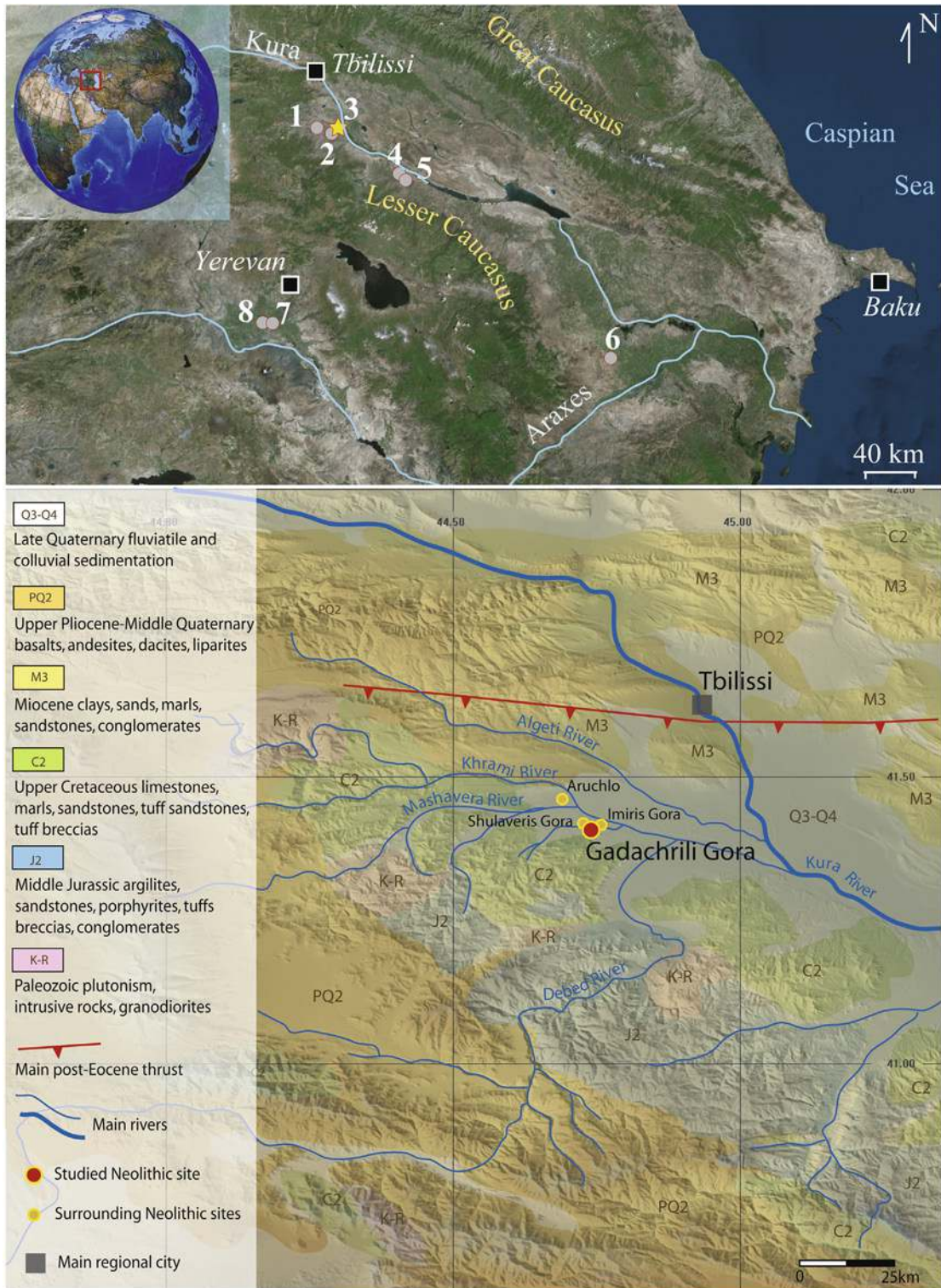


Fig. 1. General context of Gadachrili Gora archaeological site. Top panel: Numbers corresponds to the main Neolithic site recently studied in the region with: 1) Aruchlo (Hansen and Mirtskhulava, 2012); 2) Shulaveri Gora (Kiguradze, 1986); 3) Gadachrili Gora (Hamon et al., 2016); 4) Goy Tepe, (Guliyev and Nishiaki, 2010); 5) Mentesh Tepe (Lyonnet et al., 2016); 6) Kamil Tepe (Helwing and Aliyev, 2017); 7) Aratashen (Chataigner et al., 2014); 8) Aknashen (Badalyan et al., 2010). Bottom panel: Geological context and closest Neolithic sites in the vicinity of Gadachrili Gora archaeological site.



Fig. 2. a) The Neolithic site of Gadachrili Gora in the Shulvaris Ghele plain (photo T. Agapishvili); b) Building organisation in trench 1, view from the west (us 107 to us 164). First occupation horizon, destroyed by the first flood major episode (photo C. Hamon). Note the three rows of circular buildings, the concentration of storage structures in the area to the north-west and the isolated storage structures to the north. Artificial wall in the middle (Hamon et al., 2016). The US numbers represent each of the building and storage structure excavated.

settlements offers an interesting window to the study of Neolithic territories and their socio-economic organisation.

3. Materials and methods

3.1. Geomorphology

We conducted upstream-downstream research on the Shulaveri Ghele during our previous work in the Middle Kura valley defining the inland impact of the Caspian Sea relative level changes (Ollivier and Fontugne, 2012; Ollivier et al., 2015, 2016; Ollivier et al., 2015). The alluvial formation organisation was determined along the Shulaveri Ghele river. Additionally, four stratigraphic sections framing the archaeological excavation of Gadachrili (named C1 to

C4) were studied in depth. Their stratigraphic correlation and link with the archaeological site were established on an upstream-downstream longitudinal section of 300 m. Once the morphosedimentary and sedimentary sequence was recorded, the samples for radiocarbon dating were taken from the stratigraphic sequence ruptures, at the base and at key positions in the anthropic channel infilling, and at different levels of the alluvial sedimentary formations, in order to obtain an event chronology (Ollivier, 2009). The dynamics and variations of the fluvial system as well as the sediment transport energy curve were determined using macrofacies sedimentological characteristics (adapted from Hjulström, 1935, Neill, 1967, 1968, Wu et al., 1973, Miall, 1988) and a semi-quantitative analysis of the sediment facies (Bonham-Carter, 1965, Malkowski and Hoffman, 1979, McLaren and Bowles, 1985)

described in Ollivier et al. (2015). For the anthropogenic channels, the curve of erosion and deposition critical speed were defined according to the work of Hjulström (1935), Sundborg (1956), (1967), Church and Gilbert (1975), Koster (1978), Costa (1983), and Petit (1988). Their imagery was treated by chromatic filters under Adobe Photoshop CS5 extended software. The natural palaeotweg of the Shulaveri river was determined during fieldwork and by satellite images under Google Earth Pro. To avoid error with possible surficial eroded traces of modern earth channels, a series of Soviet (sheets K-38-XXI and K-38-90-G), German (sheet K38-XXI), and United States (sheet NK 38-8) topographic military maps (1: 42,000; 1:50,000; 1: 200,000 and 1:250,000) covering the years 1920-1942-1951, 1982, and 1984 were used to verify the former existence of such structures.

3.2. Radiocarbon dating

A total of thirteen radiocarbon measurements were performed on several charcoal samples (0.5–1 cm of diameter), on palaeosol organic matter and on sedimentary organic matter (Table 1). Due to the rapid sedimentation rate of the terraces, pedogenesis is greatly reduced and organic matter is buried rapidly and homogeneously without a significant turnover effect. Thus, the carbon isotopic signal of palaeosols might only be slightly altered and the measured ^{14}C activity may reflect that of the vegetation or the humus (O'Leary, 1988; Hatté et al., 1998; Hatté et al., 2001a, 2001b; Lang et al., 2003). Nevertheless, the sedimentary organic matter which was dated was a mix of sediment fluviually redeposited with remains of vegetation contemporaneous with the deposit. Consequently, these ages must be considered as slightly too old. Concerning sample SacA39133/Gif-13112, the dated organic carbon is also a mixture of sedimentary organic matter from the late Pleistocene substrate and organic matter deposited when the channel was operating. All samples were prepared following a standard procedure (Délibrias, 1985) at the LSCE Laboratory (Gif sur Yvette). Charcoal samples were treated following the ABA (Acid: Base: Acid) method. Sediments were then sieved using meshes of 250 μm to remove possible roots. The fine fraction was decarbonated with HCl 0.6 N (Gauthier and Hatté, 2008), rinsed, dried at 50 °C, and homogenised. The samples were then combusted at 900 °C in an evacuated quartz tube with copper oxide and silver foil. Radiocarbon activity was measured using AMS facilities of

LMC14 (ARTEMIS) at Saclay. Conventional ^{14}C ages are expressed in years before present (B.P.), with 1 σ error. Ages were calibrated using OxCal v4 2.3 Bronk Ramsey and Lee (2013): r5 IntCal 13 atmospheric curve (Reimer et al., 2013). Calibrated dates are given with a level of confidence of 95.4% (2 sigma range). The $\delta^{13}\text{C}$ values used for conventional age calculation are obtained from accelerator measurement and include carbon isotope fractionation due to graphitisation and ion beams during measurements. They have no palaeoenvironmental significance.

3.3. Archaeology

The archaeological data are from the fieldwork and excavations conducted over the past few years in the context of the Georgian-French collaboration (Hamon et al., 2016) in Gadachrili Gora and surrounding area. The data of the Caucasia GIS and Navigasig developed by the CNRS and the BRGM (Copyright BRGM, 2001-2009, Courcier, 2010) are used to place the archaeological sites of the Lesser Caucasus and the geomorphological evolution in the context of the regional development of the prehistoric societies.

3.4. Palaeobotany

The archaeobotanical analysis undertaken in Gadachrili Gora allowed the study of 64,300 seeds and fruit and 675 charcoal fragments. The macro-remains were extracted from the soil using a flotation machine with a sieve mesh size of 0.5 mm. Seeds and fruit were sorted out using a binocular microscope allowing $\times 10$ magnification. They were identified with the help of a reference collection of Near-Eastern seeds and comparative atlases. Charcoal fragments were studied using a reflected light microscope ($\times 50$ - $\times 1000$) (Benkova and Schweingruber, 2004, Cappers et al., 2009, Cappers and Bekker, 2013, Jacomet, 2006, Neef et al., 2011, Nesbitt and Goddard, 2006, Parsa Pajouh et al., 2001, Schweingruber, 1990, Schweingruber et al., 2011).

3.5. Isotopic analyses on carpological remains

Seed samples are carbonate-free. No chemical treatment was applied. The burnt seeds were only reduced to a homogeneous powder prior to analysis. Bulk sample C and N content were determined using an elemental analyser (Flash EA 1112) and the

Table 1
Radiocarbon dating in the studied sections of Gadachrili, Mashavera River and Mentesh Tepe.

N°-Laboratory	Section and Level	Location GPS	Nature	Age BP	Age cal. BP	Age cal. BC/AD
Gadashrili (Shulaveri River)						
SacA39135/Gif-13086	C3; 6b	41°23,453N; 44°49,242E	Sediment	1525 \pm 30	1425–1347	525–603 cal AD
SacA37799/Gif-13086	C3; 6b	41°23,453N; 44°49,242E	Sediment	1560 \pm 30	1529–1387	421–563 cal AD
SacA37091/Gif-13063	C2; 5	41°23,403N; 44°49,317E	Charcoal	4600 \pm 30	5329–5284	3380–3335
SacA37092/Gif-13064	C3; 2a	41°23,453N; 44°49,242E	Charcoal	7045 \pm 40	7954–7794	6005–5845
SacA37800/Gif-13087	C3; 2c	41°23,453N; 44°49,242E	Sediment	7745 \pm 40	8592–8433	6643–6484
SacA39136/Gif-13087	C3; 2c	41°23,453N; 44°49,242E	Sediment	7765 \pm 45	8609–8429	6660–6480
SacA37798/Gif-13085	C1; 13	41°23,422N; 44°49,334E	Sediment	8140 \pm 40	9141–9000	7192–7051
SacA39133/Gif-13112	C3; 1	41°23,453N; 44°49,242E	Sediment	8305 \pm 45	9441–9194	7492–7245
SacA37797/Gif-13084	C1; 2	41°23,422N; 44°49,334E	Sediment	11,620 \pm 50	13,564–13334	11,615–11385
Gadashrili Gora						
OS-63262	Horizon 1	41°23,436N; 44°49,258E	Charcoal	6510 \pm 110	7591–7242	5642–5293
LTL13223A	Horizon 2	41°23,436N; 44°49,258E	Charcoal	6860 \pm 45	7792–7608	5843–5659
OS-63260	Horizon 2	41°23,436N; 44°49,258E	Charcoal	6890 \pm 40	7829–7656	5880–5707
LTL13000A	Horizon 2	41°23,436N; 44°49,258E	Charcoal	6941 \pm 45	7860–7678	5911–5729
Mashavera River/Aruchlo						
SacA 33,000/Gif- 13,027	KUR GEO 12/11	41°26,764 N; 44°41,603 E	Charcoal	1930 \pm 30	1946–1820	4–130 cal AD
Mentesh Tepe						
SacA37081/Gif-13053	US 574	40°56,514N; 45°49,986E	Charcoal	6795 \pm 45	7694–7574	5745–5625

$^{13}\text{C}/^{12}\text{C}$ ratio was obtained using the online continuous EA coupled with an Isotopic Ratio Mass Spectrometer (Finigan Delta + XP). The results are expressed in $\delta^{13}\text{C}$ per mil (‰) versus the international standard V-PDB (Vienna Pee Dee Belemnite). All the analyses were performed in triplicate. Mean value is associated to uncertainty equal to the maximum between the standard deviation and the chi-square reduced error. This accounts for both measurement uncertainty and sample heterogeneity.

4. Results

4.1. Alluvial units and anthropogenic-type channels morphology

The site of Gadachrili Gora is located on a composite sedimentary fan formation locally grouping the levels T1 to T4 of the main alluvial terrace system defined in the region (Ollivier and Fontugne, 2012; Ollivier et al., 2015, 2016, Suchodoletz et al., 2016), which is forming an upstream part of the Kura river hydrosystem (Fig. 3). The torrential nature of the Shulaveri river is clearly expressed in the sedimentary facies observed in the surrounding natural sections. The studied section, named C1, C2, C3, and C4, frame the archaeological site of Gadachrili from upstream to downstream (Fig. 3). The formation reaches around seven to 8 m of thickness. The organisation of the different deposit phases shows: 1) a first Lateglacial phase dated to the beginning of the sequence around $11,620 \pm 50$ BP in C1 (13,450 cal. BP, 11,615 cal. BC, Table 1 and Figs. 3–7) with low energy sedimentation (silts and sands) punctuated by the development of hydromorphic soils and torrential detrital discharges (pebbles, gravels, and sands); 2) more pronounced torrential features (pebbles, gravels, and sand deposits with small incisions and/or erosive contact) from the beginning of the Holocene around 8140 ± 40 and 8305 ± 45 BP (9076 cal. BP, 7121 cal. BC and 9327 cal. BP, 7368 cal. BC in C1 and C3) as seen in regional studies (Ollivier and Fontugne, 2012; Ollivier et al., 2015, 2016, Suchodoletz et al., 2016) but with some short soil development; 3) a second Holocene torrential unit with pebbles, sands, and erosive contact, as well as overflow silts and the development of soils (sometimes containing bones and charcoal) laterally to the active watercourse and dated around 4600 ± 30 BP in C2 (5322 cal. BP, 3292 cal. BP); 4) a thick dark brown soil developed in the final sections of the regional stratigraphic sequences dated around 1930 ± 30 BP (1883 cal. BP, 67 cal. AD) in the Mashavera river (around the Neolithic archaeological site of Aruchlo, Fig. 8), the latter showing the same sedimentary sequence succession (Lateglacial silts and hydromorphic soils followed by pebbly Holocene torrential units covered by the brown soil) as in section C3 of the Shulaveri Ghele river with a soil dated between 1560 ± 30 BP and 1525 ± 30 BP (1466 cal. BP, 492 cal. AD, and 1410 cal. BP, 513 cal. AD).

Despite the interest concerning the Postglacial morphosedimentary organisation in this area (Suchodoletz and Faust, 2017), the most striking geoarchaeological finding concerns the existence of anthropogenic type excavations in the soft sediments of the Lateglacial - Holocene sequences (Figs. 6 and 7). The sediment at the base of these excavations contains pottery and bone debris. The local organisation of these diggings, that look like canals, is made visible in a stratigraphic section by the incision of the Shulaveri river in the site of Gadachrili (Figs. 6, 7 and 9). Covered by 2.5 m of historical period deposits, these artificial channels are not visible on the surface. Section C4 (Fig. 7), in the left bank, shows one major channel divided in three smaller well-dimensioned canals in section C3 on the right bank (Figs. 6 and 9). The preserved canal morphology of section C3 is of two distinct types, parabolic and trapezoidal, with dimensions varying between 0.75 and 1.5 m of depth and 1.5, 3, and 5.5 m width. With a unique trapezoidal morphology, the hydraulic structure observed in section C4 is of

1.5 m deep and more than 15 m wide. The radiocarbon dating obtained (Table 1) in the channels of section C3 (Figs. 6 and 9) range from 7765 ± 45 BP and 7745 ± 40 BP (8542 cal. BP and 8520 cal. BP, 6622 cal. BC and 6563 cal. BC) to 7045 ± 40 BP (7884 cal. BP, 5925 cal. BC). The oldest date, issued from a measurement on organic matter contained in the sediments (SOM), is probably too old since it represents a mix with Lateglacial sediments from the bottom of the channel (or from bank erosion). Therefore, the 7045 ± 40 BP date obtained from charcoal samples seems to be the most coherent. The hydraulic structure of section C4 remains unfortunately undated for technical reasons (poor preservation of the sampled charcoal). But the geometry, the sedimento-stratigraphy, the lithic and ceramic finds, and the stratigraphical connection with the archaeological excavation (horizon 2, Fig. 3, Fig. S1, and Hamon et al., 2016) allow us to establish these different anthropogenic channels as contemporaneous. In addition, the closeness between our stratigraphic and absolute dating results indicates that both the occupation (horizon 2 dated at 6941 ± 50 BP, 7768 cal. BP/5920 cal. BC, Fig. 3) and the hydraulic structure were probably developed during the same period. Another example of anthropogenic type channels was also found in Mentesh Tepe (Lyonnet et al., 2016; Ollivier et al., 2016). In this excavation, more modest-sized ditches than in Gadachrili were filled with alluvial material or runoff. The strongest evidence (Fig. 10) is the parabolic canal type that is chronologically framed between 5882 cal. BC (bottom of the archaeological excavation, Lyonnet et al., 2016) and 5683 cal. BC (level sealing the channel, Table 1 and Fig. 10). Despite the quality and the increasing number of excavations in recent decades, this is the first time in the Lesser Caucasus that hydraulic structures dating from the Neolithic have been clearly identified and dated in association with human settlements.

4.2. Palaeohydrology

We did not actually calculate the hydraulic components in Mentesh Tepe because the river network supplying the anthropic channel was different to today's network and needs further physiographic reconstruction (Ollivier et al., 2015, 2016). In Gadachrili, a detailed analysis of the sequences filling the channels C3 and C4 makes it possible to relatively define the flow velocities and to trace the history of their use (Fig. 11). However, it is important to note that, like the changes in the initial shape of the canals (particularly visible by the asymmetry in the right-side channel of section C3), their fill reflects only a fragmentary history of their functioning due to cleaning practices and high-energy events (Purdue and Berger, 2015). The choice of sampling the undisturbed stratigraphic decantation units was decisive in the dating of these structures. Although with different channel morphologies, the hydraulic structures of Gadachrili display the same global hydrologic, stratigraphic evolution, and morphogenic trends (Fig. 11) in their sedimentary fill. In each case, the presence of soil enriched with ash and organic matter indicates probable cleaning of vegetation and stagnant water that can be used as stratigraphic reference levels. These markers visible in the same stratigraphic position in each of the structures allow us to say that these channels have probably worked at the same time, and according to the three ^{14}C dates obtained, for a maximum period of 50–100 years. The values obtained by using the Hjulström method under natural hydrology (Fig. 11) range from $>0.1 \text{ cm s}^{-1}$ for the least dynamic flows (Lateglacial) and $>100 \text{ cm s}^{-1}$ for Holocene floods. It is generally admitted that in modern earth channels (much larger and more constantly supplied by water than those of Gadachrili), the permissible velocities are between 0.60 and 1 m s^{-1} (Soutter et al., 2007). The flow velocity must also exceed 0.5 m s^{-1} to avoid the formation of deposits in the channels and to be less than 2.5 m s^{-1}

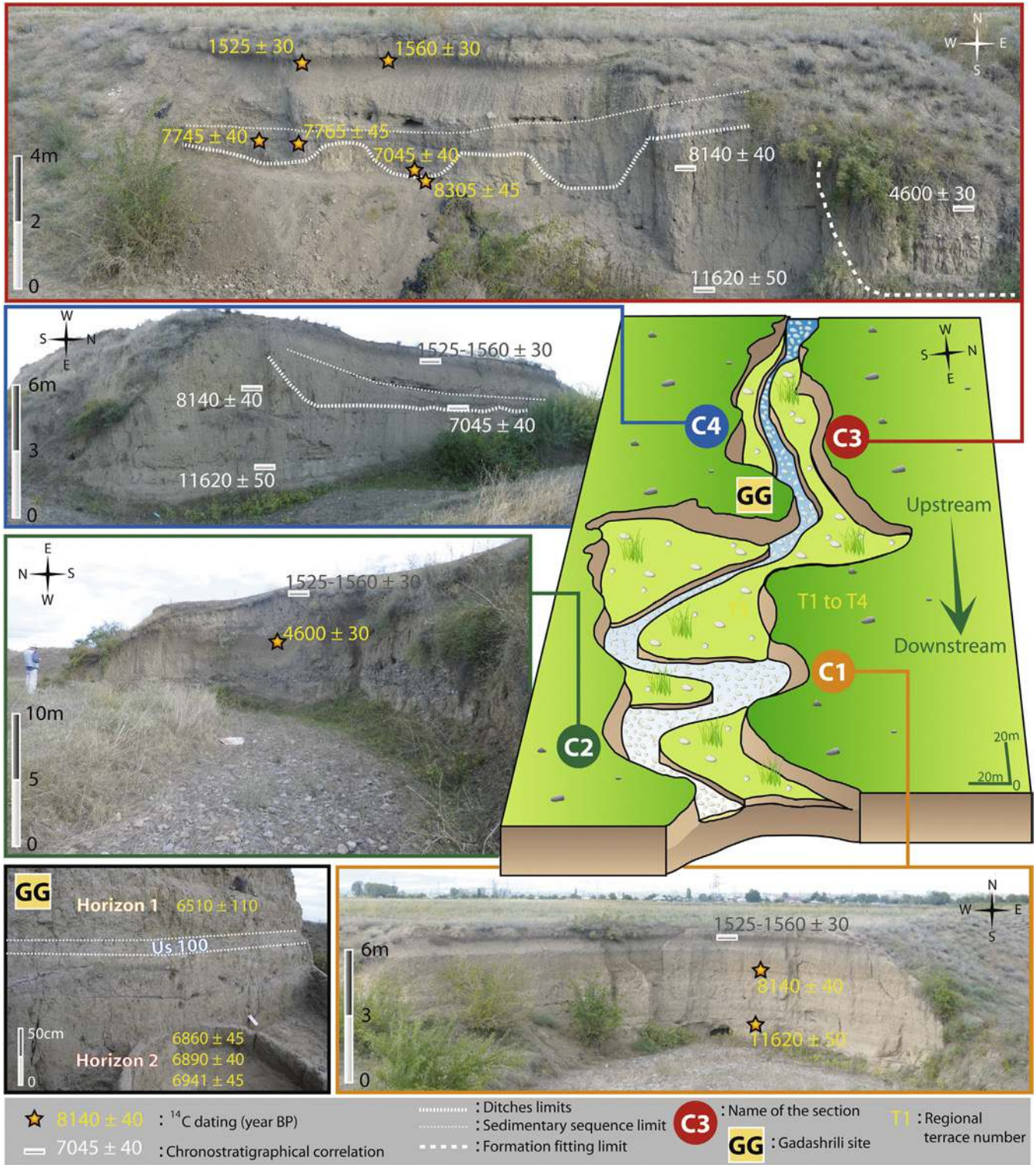


Fig. 3. Chronology, location and morphosedimentary organisation of the studied sections in and around Gadachrili site. Radiocarbon dates are reported for the different sections as well as for Horizon 1 and Horizon 2 of the excavation framing the US 100 unit.

to avoid erosion of the raft. In the small anthropogenic channels of Gadachrili (Fig. 11), the “Hjulström values” indicate flows between >10 and $>100 \text{ cm s}^{-1}$ for initial filling and >0.1 to $>1 \text{ cm s}^{-1}$ for the last flow of the structure. Integrating the section dimension of the Neolithic canals, these last estimates are confirmed by hydraulic calculations (Table S1 and Fig. S2) on a parametric section giving us

values close to around 16.5 cm s^{-1} for the average flow velocities during their conventional use. These data are incomplete and with future work (track tracing, slope measurements, reconstructions of precise channel morphologies), more precise relative velocities should be given. However, these preliminary observations indicate that the flow velocities of this type of hydraulic structure were

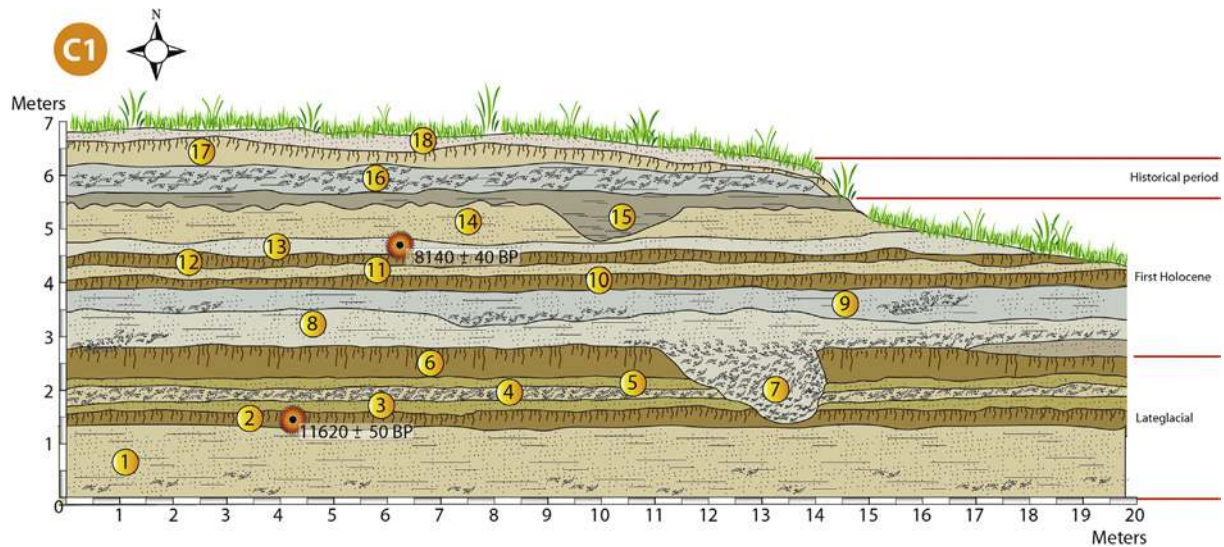


Fig. 4. Stratigraphy and radiocarbon dating of the section C1 (sedimentological description in the supplemental material). The numbers in the yellow circles are for the different stratigraphic levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

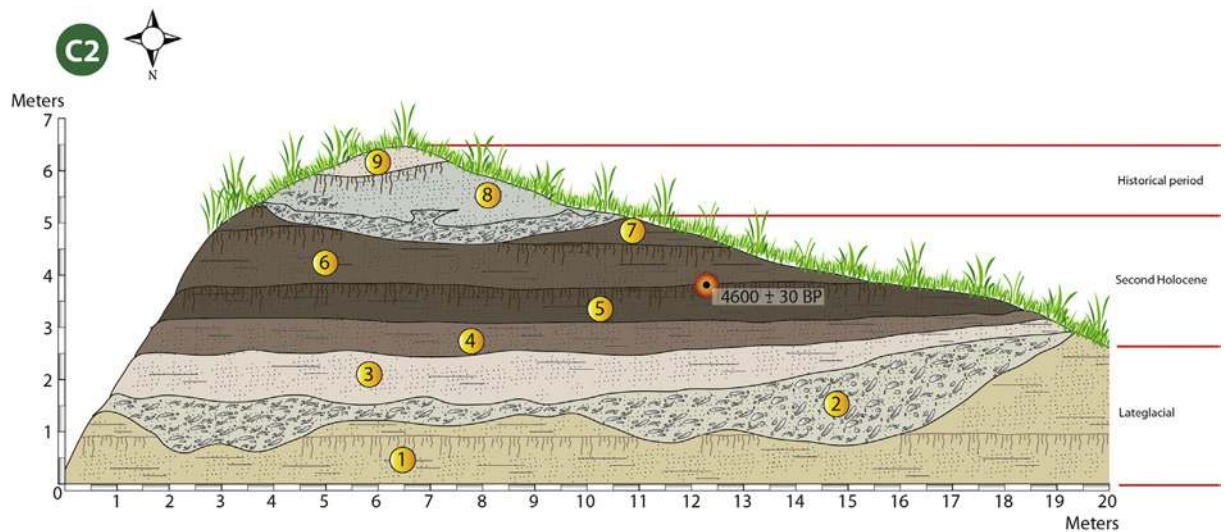


Fig. 5. Stratigraphy and radiocarbon dating of the section C2 (sedimentological description in the supplemental material). The numbers in the yellow circles are for the different stratigraphic levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

small but consistent with the current modest average flow observed for the Shulaveri river of $0.44 \text{ m}^3 \text{ s}^{-1}$. In addition, the simultaneous water filling of the three channels would provide an average relative velocity of $0.49 \text{ m}^3 \text{ s}^{-1}$ consistent with our data. As we have pointed out earlier, only part of their history is recorded in stratigraphy. The different characteristics depicted in the geometry, the feasibility, and viability of these channels, as well as the division of the main canal into three separate channels over a few meters in a soft lithological context and under a torrential regime, excludes a natural origin in their initial development.

At least two major palaeofloods are recorded in the stratigraphy of the Shulaveri river deposits surrounding the site of Gadachrili (Figs. 3–8, Figs. 11 and 12). This river of second order (Strahler, 1957) ephemeral stream has a high reactivity to hydrometeorological events (circular morphometry of the upstream basin, and numerous series of lateral drains and gullies from upstream to downstream) with water supplying the anthropic channels. Modest

but repeated during the Lateglacial period, the floods are much more marked in the Holocene (Figs. 4–8, Figs. 11 and 12) by their intensity and seem to acquire a more regional character (Ollivier et al., 2015, 2016). The stratigraphic flood sequences observed also underline the high long-term mobility and palaeohydrological variability of the Shulaveri river course (Fig. 13), especially in the sector corresponding to the alluvial fan (which flow direction, sedimentary supply, and morphology are under the control of climate changes, tectonic, and base level variations). Looking at the archaeological sequences from the Gadachrili site excavation (Hamon et al., 2016), flood deposits are visible in stratigraphic unit US 100 (silty-sandy olive green level with fine bedding and traces of oxidised rootlets, Fig. 3 and photo S1), the archaeologically sterile stratigraphic unit; a transition between anthropogenic horizons 1 and 2 respectively dated at $6941 \pm 50 \text{ BP}$ (7768 cal. BP/5856 cal. BC) and $6510 \pm 110 \text{ BP}$ (7418 cal. BP/5463 cal. BC). The US 100 stratigraphic unit is also stratigraphically, faciologically, chronologically

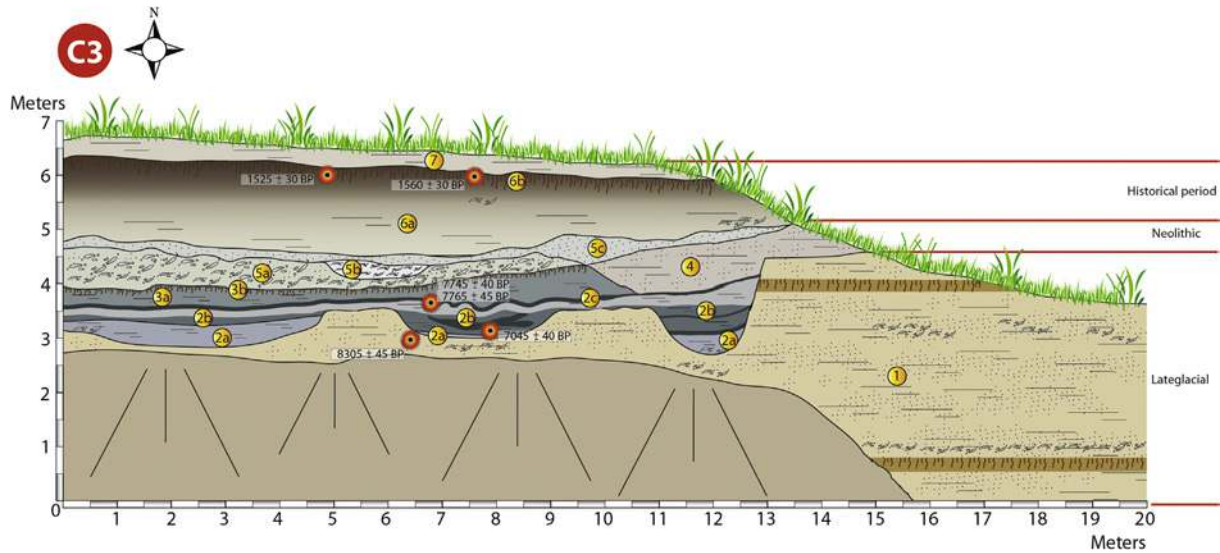


Fig. 6. Stratigraphy and radiocarbon dating of the section C3 (sedimentological description in the supplemental material). The numbers in the yellow circles are for the different stratigraphic levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

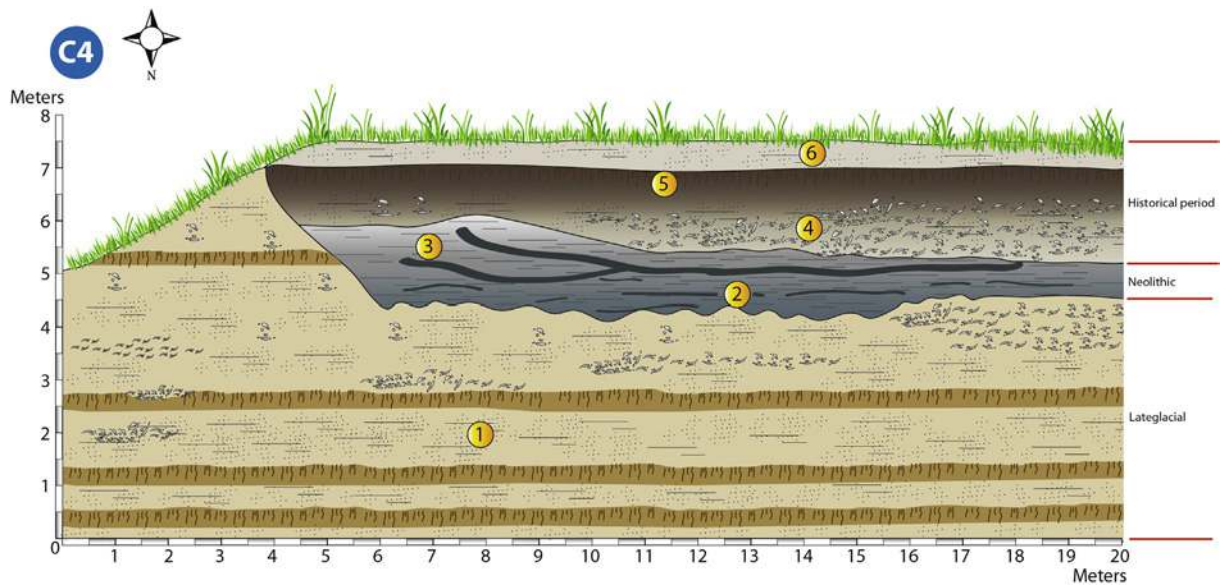


Fig. 7. Stratigraphy of the section C4 (sedimentological description in the supplemental material). The numbers in the yellow circles are for the different stratigraphic levels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(¹⁴C) and geometrically well correlated with the levels 3a and 4 of the hydraulic structures studied in sections C3 and C4 (Figs. 11 and 12 and Fig. S1), which indicates the partial destruction of the hydraulic structures and their progressive abandonment. As noticed in Hamon et al. (2016), the archaeological stratigraphy shows two horizons with different types of organisation of the settlement area. Evidence from the deepest occupation levels also suggests different building techniques between the two horizons. It is difficult to ensure that the architectonic changes are clearly the results or have been influenced by these flood episodes. But the overlap of the site between the two horizons by the US 100 stratigraphic unit (Fig. 3) with distal alluvial characteristics (probably decantation and development of a temporary quasi-wetland) clearly indicates that hydraulic structures of sections C4 and C3 have brought the floods to the site of occupation by diverting the waters of the Shulaveri

river. This dynamic has persisted over time, leading to the abandonment and destruction of hydraulic structures (Figs. 11 and 12). The impact of hydraulic equipment works (notably canals) on the spread of floods and the damage they cause is well known today. This is the case even during violent but not exceptional hydrometeorological events (Arnaud-Fassetta et al., 2002). On the Neolithic site of Gadachrili and its surroundings, the potential morphosedimentary and archaeological record of this type of phenomenon can surprisingly be found.

4.3. Components of the Shulaveri river fan

The analysis of satellite photos coupled with field investigations and laboratory analysis allowed us to trace all the different courses and to specify the development of the alluvial fan of the Shulaveri

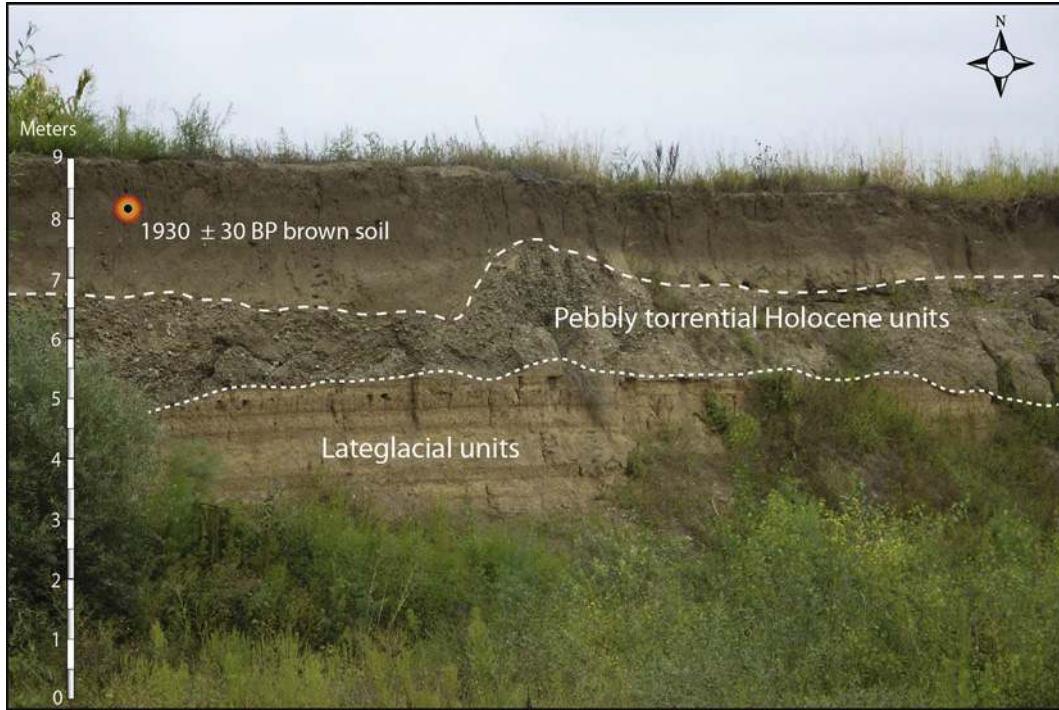


Fig. 8. The dating of the brown soil horizon in the top sedimentary sequence of the Mashavera River main terrace in the vicinity of Aruchlo archaeological site (GPS: 41°26,764 N; 44°41,603 E). Age, stratigraphical position and facies of this brown soil horizon are similar to the Gadachrili Gora sections. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

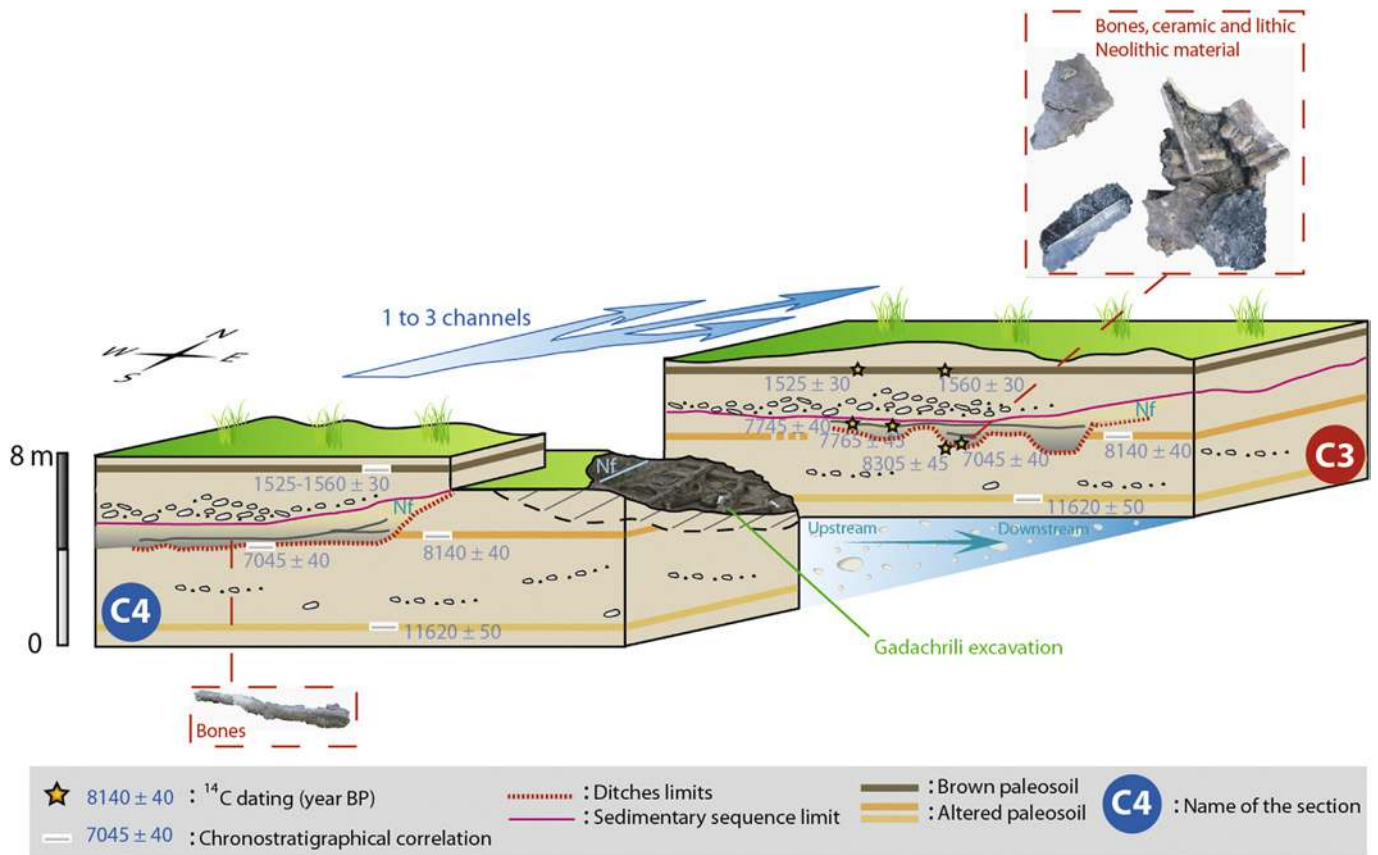


Fig. 9. Block diagram showing the organisation of anthropic channels (from one channel or pool to three diversion channels) in their archaeological and morphosedimentary context.

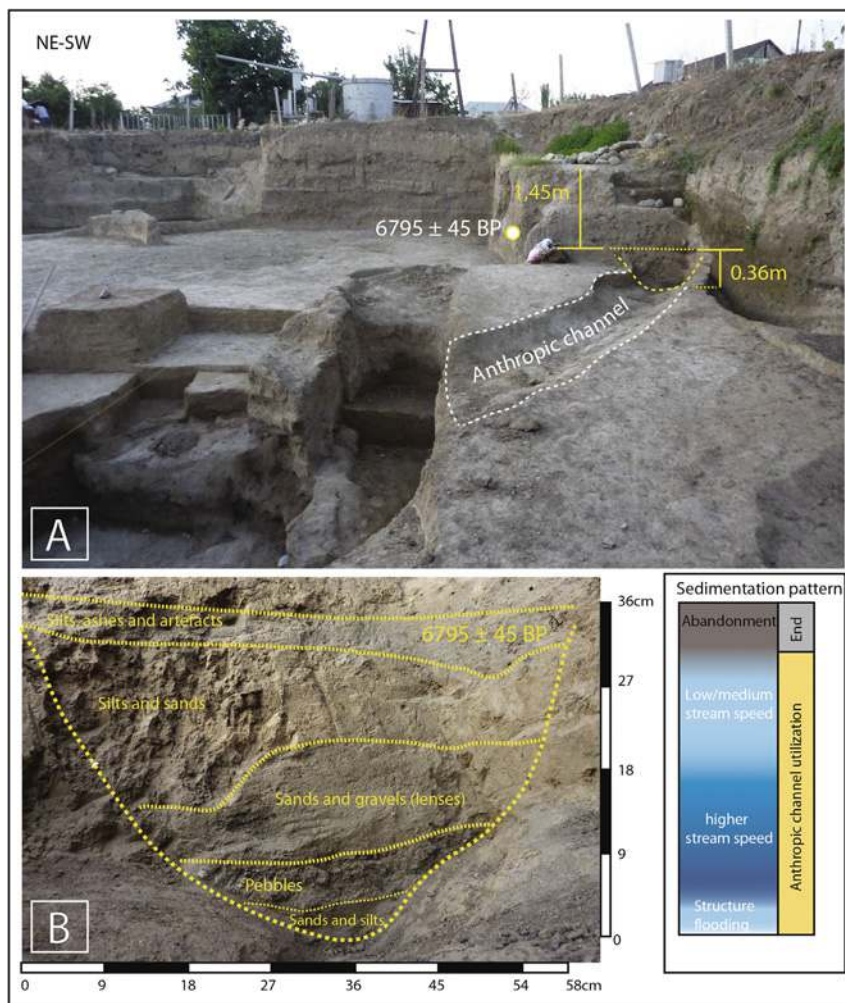


Fig. 10. Description and sedimentation pattern of the anthropic channel discovered during our preliminary geoaerchaeological studies in the excavation of Mentesh Tepe (Azerbaijan, GPS: 40°56,514N; 45°49,986E) directed by B. Lyonnet (Lyonnet et al., 2012, 2016, 2017).

river since the Lateglacial (Fig. 13).

The evolution of the alluvial fan of the Shulaveri river (Fig. 13) appears to have followed a process of global lobe migration to the east. Thus, at least seven stages marked by as many talwegs could be defined for the Shulaveri river in its eastward migration.

The physiography of the local hydrographic network is clearly influenced by tectonics (Suchodoletz et al., 2016). Nevertheless, a distal impact of the variations in the relative level of the Caspian Sea on the morphosedimentary dynamics of the regional rivers is not entirely excluded (Ollivier and Fontugne, 2012; Ollivier et al., 2015, 2016; Ollivier et al., 2015). Ongoing work attempts to precisely define the upstream spatialisation of this phenomenon for the Lesser Caucasus hydrosystems, connected in the first or second order to the Caspian Sea basin (Ollivier, in press).

4.4. Palaeobotanic and isotopic analyses on the seeds to test the possibility of irrigation practices

Several crops were identified in the samples coming from the excavations conducted in 2012 and 2013. Among the cereals, emmer (*Triticum turgidum* subsp. *dicoccum*) dominating during horizon 2, barley (*Hordeum vulgare*), a major crop during horizon 1, and, in lower numbers, naked wheat (*Triticum aestivum/durum*) were found. Among the pulses, lentil (*Lens culinaris*) and a pea-

vetches type (*Pisum-Vicia*) were recorded. Several arable plants, probably arable weeds, were also recognised (*Adonis* sp., *Aegilops* sp., *Scleranthus annuus* etc.). The study of charcoal fragments, coming probably from the use of wood as fuel, shows no clear change in the source area for wood collection. A riparian forest, with poplar and/or willow (*Populus-Salix*) or ash tree (*Fraxinus* sp.), dominates during the two horizons of the occupation, whereas other trees seem more characteristic of more open woodlands such as for example buckthorn (*Rhamnus* sp.) or maple tree (*Acer* sp.). This reconstruction of riparian, but also open vegetation cover highlights the occurrence of cultivable and irrigable areas.

Twenty-nine seed samples analysed for carbon stable isotope ratios show a data range from -25.0 to -22.7‰ ($\Delta = 2.3\text{‰}$, $n = 29$; Table 2). The $\delta^{13}\text{C}$ of the two stratigraphic zones (Fig. 14) varies within the same range (from -25.0 to -23.1‰ , med = -24.0‰ , $n = 19$, for H2 and from -24.4 to -22.7‰ , med = -23.7‰ , $n = 10$, for H1; Fig. 14). The carbon isotopic ratios of barley samples are lower for the stratigraphic zone H2 compared to the oldest zone H1 (Fig. 14). However, this result is not statistically significant (non-parametric tests performed with Statistica® 7.1; Mann-Whitney U test: $p = 0.56$; Median test: $p = 0.08$).

Fig. 14 also presents a comparison between the $\delta^{13}\text{C}$ levels of six charred seeds of Early Neolithic barley from Gadachrili and Early Bronze Age wheats from Chobareti sites also located in Georgia

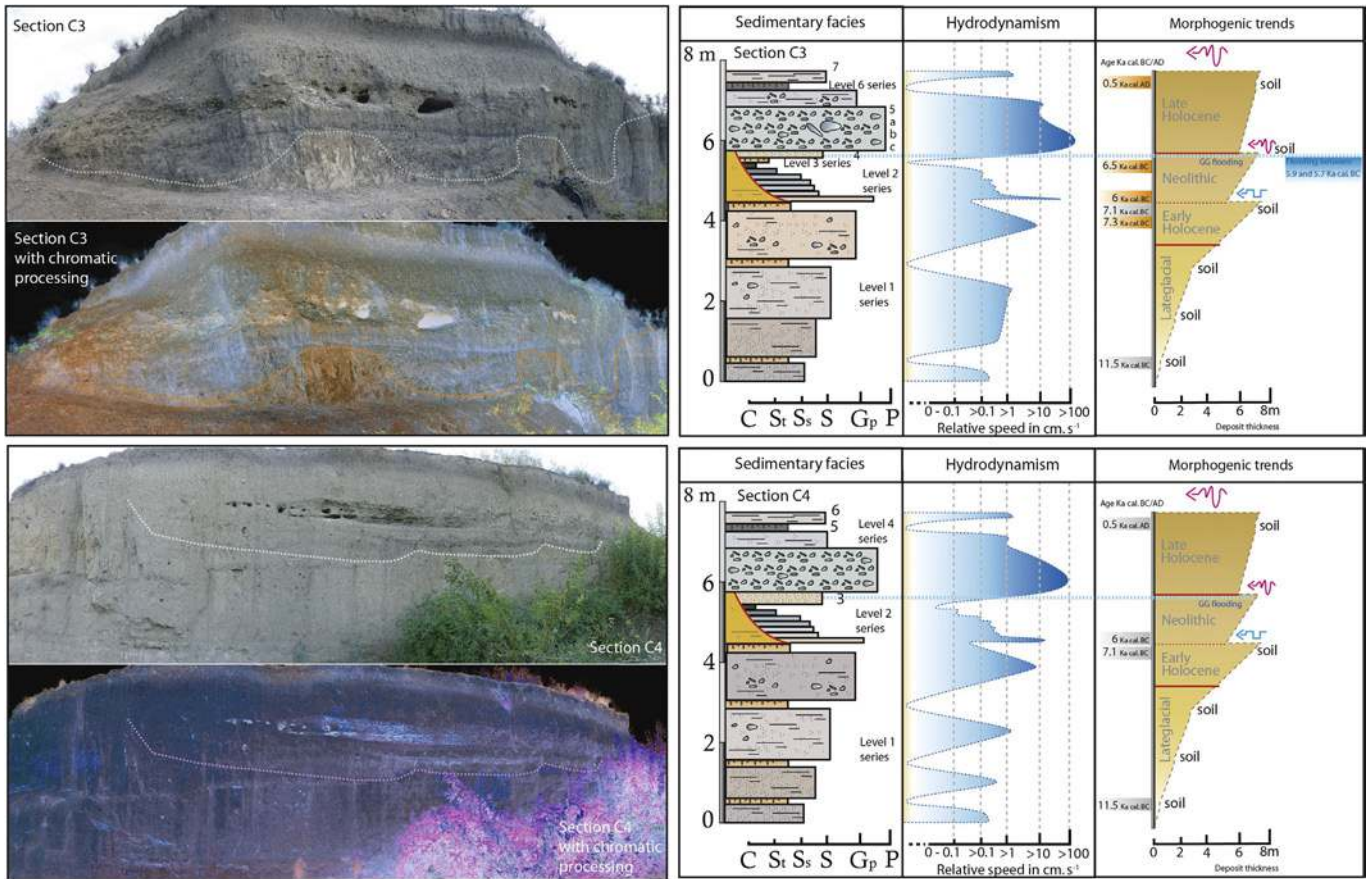


Fig. 11. Chromatic analysis, detailed stratigraphy, estimated speed flow and morphogenetic trends in the C3 and C4 sections. Legend of the sedimentary facies: C = clay; St = silts; Ss = Silts and sands; S = Sands; Gp = Gravels and pebbles; P = Pebbles (sedimentological description in the supplemental material). The numbering of sub-levels in sequences is simplified (1 series, 6 series, etc.).

(Messenger et al., 2015). This comparison of sites from different chronologies and slightly different contexts are made: 1) to attempt to discriminate irrigation practices; 2) to check the possible irrigation practices persistence in the long duration where variations in climatic humidity succeed each other between 5900 cal. BC (regionally presumed wetter) and 3000 cal. BC (regionally presumed drier); 3) and to test the palaeoclimatic results regionally obtained.

In Gadachrili, the isotopic values recorded are low and statistically homogeneous. In Chobareti (Messenger et al., 2015), the isotopic analyses are from different species and at a higher altitude compared to Gadachrili, but with weak deviations among the values, around 1.3–1.4‰. The Early Bronze age samples show much higher $\delta^{13}\text{C}$ values compared to early Neolithic ones; this result is statistically significant (Mann-Whitney U test: $p < 0.01$). The Chobareti isotopic values seem to indicate a generally drier environment.

5. Discussion

5.1. The geomorphic events kinematics

The pattern of environmental changes proposed was compared to the isotopic data from GRIP (Andersen et al., 2006), INTIMATE (Rasmussen et al., 2014), Sofular Cave (Fleitmann et al., 2009), Central Asia (Chen et al., 2008), and the Black Sea (Shumilovskikh et al., 2012) to obtain a representative analysis based on climatic

records (Ollivier et al., 2015, 2016). Local climatic and bioclimatic references are also of importance and were included in the morphodynamic reconstruction using the surrounding pollen records of Shamb (Ollivier and Fontugne, 2012), Paravani (Messenger et al., 2013), Zarishat (Joannin et al., 2014), and Nariani (Messenger et al., 2017) in Armenia and Georgia. Regional (Mosar et al., 2010) to local (Suchodoletz et al., 2016) tectonic knowledge were also included in order to determine the long-trend evolution of the hydrosystem.

Considering the numerous parameters involved (climatic, tectonic, and potentially base level changes), channel 1 (Fig. 13), incised in the alluvial Postglacial formations, could be a feedback from the hydrosystem to the Mangyshlak regression (end of the Lateglacial/early Holocene). Channels 2, 3, and 4 (Fig. 13) could be considered as an avulsion from the early Holocene highstand (Ollivier et al., 2016). Channels 5 and 6 (Fig. 13) could be the riverbed contemporary to the Neolithic occupations, and talweg 7 (Fig. 13) the one driven by the incision of the Khrami river after 603–525 cal. AD (tectonically driven? Suchodoletz et al., 2016). These different rhythms of sedimentation could be comparable to those linked to climate changes and variations in the base level highlighted further downstream (Ollivier et al., 2015, 2016). However, they mainly show that the Kura river and its tributaries form a complex system.

Considering all the data analysed, the following human occupation and postglacial landscape evolution kinematics can be proposed (Fig. 15):

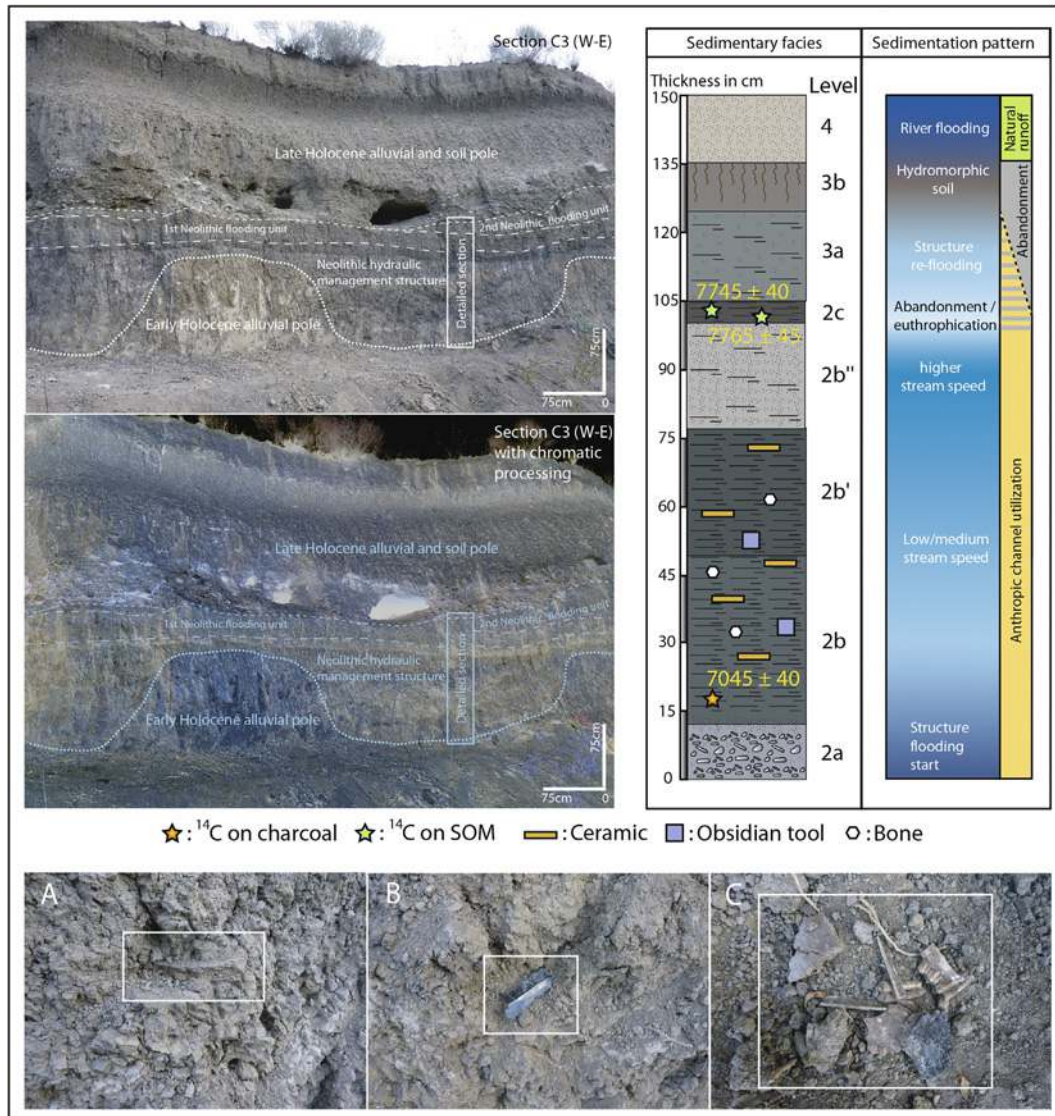


Fig. 12. Chromatic analysis, detailed stratigraphy and sedimentation pattern of the main channel of the C3 section (sedimentological description in the supplemental material).

- A) A development of the Shulaveri river alluvial fan before $11,620 \pm 50$ BP (13,450 cal BP, 11,615 BC) in a poorly drained system with multiple weakly active channels and lobes. This type of fluvial geomorphology occurred during the Greenland Interstadial 1C1 (Rasmussen et al., 2014) that is known to be regionally dry and relatively cold with an arid and steppe environment (Wright et al., 2003; Messenger et al., 2013; Leroy et al., 2013a, b). It is followed until the Early Holocene by higher sedimentation rates and the growth of torrentiality in a more temperate-humid climate (Ollivier et al., 2011, 2015, 2016; Messenger et al., 2013; Joannin et al., 2014).
- B) An incision and concentration of the Shulaveri riverbed in a steppe environment (Joannin et al., 2014; Messenger et al., 2017), around 9000- 8200 cal. BP (around 7000-6200 cal. BC). The end of this period is globally known to be a cold and dry event accompanying the expansion of the Eurasian-Siberian High (Renssen et al., 2002; Vellinga and Wood, 2002; Morrill and Jacobsen, 2005).
- C) Increased and more regular river flow in the course of a more humid climatic phase recorded around 8200-7500 cal. BP/ 6200-5500 cal. BC (Joannin et al., 2014) registering and/or succeeding to the 8200 cal. BP event (Thomas et al., 2007). In this favourable hydroclimatic context, the Gadachrili site and its hydraulic management structures are developing. A few centuries earlier, the vegetation history started to shift from open to forested vegetation (Joannin et al., 2014; Leroy et al., 2013b; Messenger et al., 2017).
- D) Development of one or several floods of the Shulaveri river around 7900-7700 cal. BP (5900-5700 cal. BC). Although the river was far away, the waters flow through the canals and flood the site of Gadachrili. The sedimentary signal is recorded by the stratigraphic unit US 100 (Fig. 3, Fig. S1, and photo S1) showing a facies (sterile silt), probably marking the spreading of the floodplain in the archaeological structures (low to medium energy flows and colonisation by herbaceous vegetation in moist environments).
- E) After 7700 cal. BP (5700 cal. BC), end of the extension of the flood episodes on the site, development of Horizon 1 around 7400 cal. BP (ca 5600 cal. BC). Possible abandonment of the channels. No evidence for visible hydraulic structures or for their reuse are registered in the sedimentary sequences.

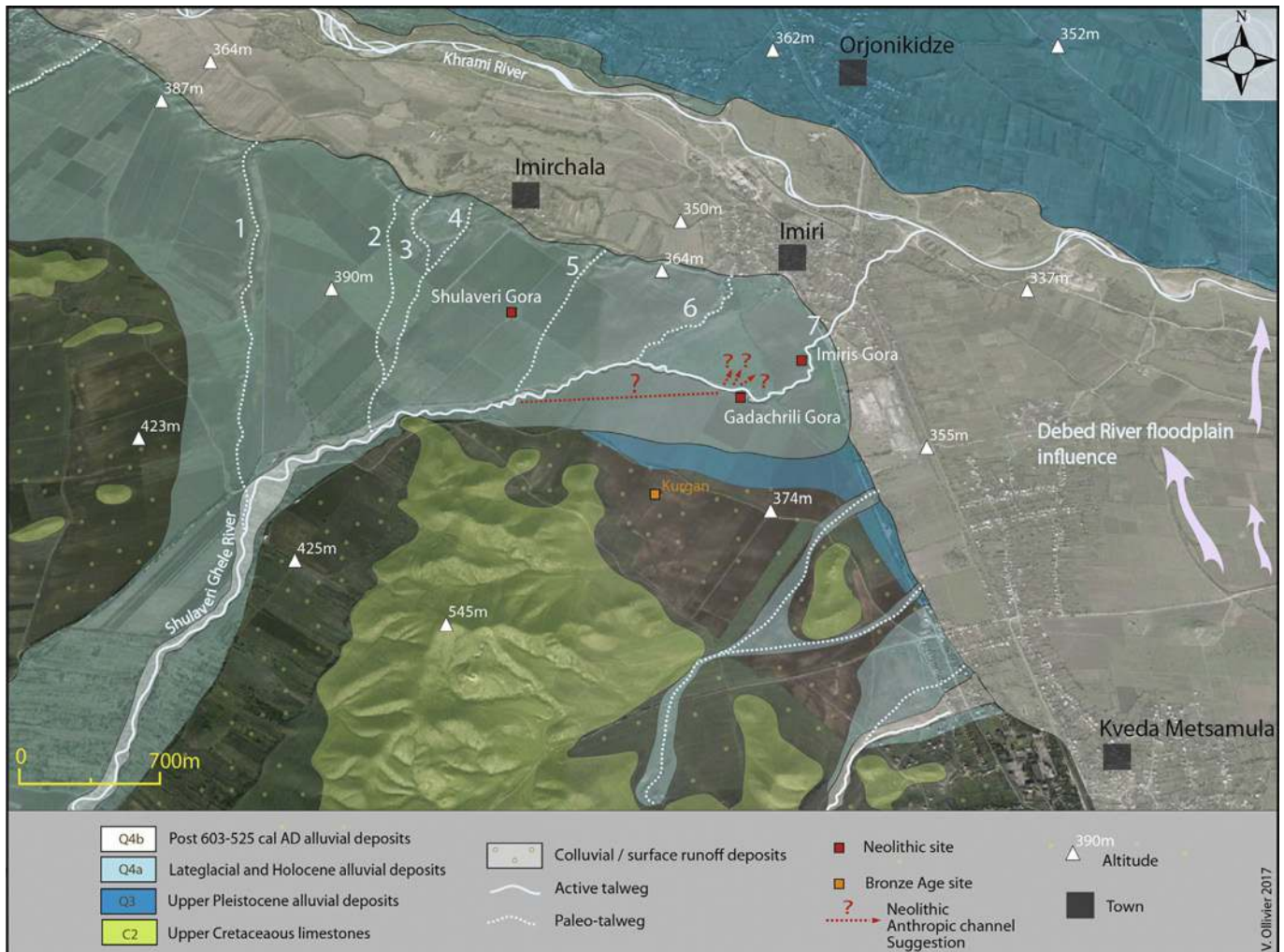


Fig. 13. The Postglacial Shulaveri River fan evolution and the surrounding archaeological sites in their geological and geomorphological context. The pale blue numbers from 1 to 7 represent the different palaeochannel of the Shulaveri River over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

- F) Around 5500–5300 cal. BP (3500–3300 cal. BC), a local reorganisation of the riverbed with a probable linear incision of the Shulaveri river and an eastward shift of its course. An increase in torrentiality and a development of soils on the riverbanks occurs. Regional climatic signals record drier phases at approximately 5300–4900 cal. BP (Joannin et al., 2014).
- G) At 1410–1466 cal. BP (ca 500 cal. AD), the Shulaveri river seems to change its course. Previously, the climate underwent a regionally drier phase around 2200–1500 cal. BP (Joannin et al., 2014). A thick brown soil horizon is developed probably due to a change in the river course. The lateral connectivity is broken resulting in a temporary disconnection of the river from its usual floodplain and in an interruption of aggradation. Later, the floodplain is reoccupied and alluvial sandy deposits cover the brown pedogenic horizon.
- H) Afterwards a lowering of the base level defined by the Khrami river (tectonically and or retroactively driven?) generates another eastward shift in the course of the Shulaveri. This is part of a linear incision dynamic that dissects the archaeological site of Gadachrili.

5.2. The Postglacial regional morphoclimatic components

For the Lateglacial, the facies and the morphosedimentary organisation observed in the alluvial deposits of Gadachrili echoes those analysed in various similar formations in the Lesser Caucasus (Ollivier et al., 2015, 2016; Montoya et al., 2013). The sedimentary bodies are representative of a weak longitudinal sedimentary transfer under the climatic characteristics of the Greenland Interstadial 1 c1 (GI-1 c1, Rasmussen et al., 2014). The competency of river sediment transport decreases and the dominant facies are silty. Alluvioils developments are frequent in relation to spasmodic, irregular, and low-energy flows but with a slight torrential component. In some mountainous areas close to Gadachrili, pollen assemblages indicate open vegetation with occasional trees developing in valley bottoms (Montoya et al., 2013). These conditions resulted from a regionally known cold and dry climate (Montoya et al., 2013; Messenger et al., 2013). The first part of the Holocene shows an increase in upstream–downstream hydrological energy and sediment transfer. As regionally seen (Ollivier et al., 2015), sandy and gravel-pebble facies are more frequent and feed the end of the alluvial fan, a sector morphologically in loss of transit energy. A more humid and warmer climate with contrasting or differently distributed rainfall regimes (Joannin et al., 2014) leads to

Table 2

Carbon isotopic ratios from archaeological seeds of Horizon 1 and Horizon 2 in Gadachrili.

Sample	N seed/sample	Horizon	US	$\delta^{13}\text{C}$ (‰)
GGBOT113	1	2	114	-24.0
GGBOT052	5.5	2	119	-23.7
GGBOT053	10	2	120	-24.3
GGBOT102	3	2	121	-23.1
GGBOT110	3	2	122	-24.9
GGBOT023	10	2	123	-24.3
GGBOT066	2	2	126	-23.5
GGBOT095	0.5	2	131	-24.6
GGBOT078	11	2	142	-23.6
GGBOT020	2	2	143	-23.9
GGBOT077	8	2	147	-24.0
GGBOT042	1	2	155	-25.0
GGBOT099	9	2	164	-24.3
GGBOT109	10	2	165	-23.3
GGBOT098	2	2	204	-25.0
GGBOT121	5	2	213	-23.8
GGBOT049	10	2	216	-24.9
GGBOT044	10	2	220	-24.3
GGBOT097	10	2	227	-24.0
GGBOT039	6	1	2006	-24.4
GGBOT009	10	1	2013	-23.5
GGBOT002	6	1	2017	-23.7
GGBOT038	10	1	2024	-24.0
GGBOT008	6	1	2025	-22.7
GGBOT037	8	1	2037	-23.5
GGBOT063	10	1	2039	-23.8
GGBOT071	2	1	2040	-23.2
GGBOT090	4	1	2040	-24.2
GGBOT065	10	1	2041	-23.8

the development of new torrential activity. The shift following the 8.2 ka event is well recorded by a marked increase in spring-summer rainfall and the forest development in the Lesser Caucasus and many regional data (Fleitmann et al., 2009, Chen et al., 2008, Shumilovskikh et al., 2012, Ollivier and Fontugne, 2012, Messenger et al., 2013, Joannin et al., 2014, Messenger et al., 2017, Fig. 16). It is also potentially linked to the Black Sea influence on the regional precipitation regimes and or its potential interactions with the monsoon mechanism (Messenger et al., 2017). The second Holocene period records a fall in the sediment transport capacity with the predominance of silt and sand facies as well as the development of thick brown soils. This could be associated with a drier climate observed in the palaeoclimatic models (Davis et al., 2003; Wanner et al., 2008). In terms of local hydrogeomorphic dynamics of the Shulaveri river, some results, mainly focused on the archaeological site of Gadachrili, are broadly in line with more recent studies on the subject (Suchodolez and Faust, 2017). Further comparisons with previous investigations, however, seem necessary.

5.3. Neolithic land use, water management, and flooding

The Gadachrili canals are probably dug to divert the waters of the Shulaveri river in order to bring this resource closer to the village. The channel characteristics shown in the section C4 (Fig. 9) would suggest a storage pond (Whitehead et al., 2008) or a large artificial arm that drives or collects some of the waters of the Shulaveri river to distribute them in the other canals in its extension as a water supply system (section C3, Fig. 9). This may be a quasi-perennial water supply without being exposed to the frequent (annual to decennial) and direct torrential floods of the Shulaveri river.

The 8.2 ka BP climatic event is frequently connected with a restructuring of prehistoric communities and the expansion of farming in the Levant, northern Mesopotamia, northeastern

Mediterranean region (e.g. Weiss and Bradley, 2001; Staubwasser and Weiss, 2006; Weninger et al., 2006; Turney and Brown, 2007; Berger and Guilaine, 2008; Pross et al., 2009). Frequently, Neolithic populations settled in areas where they could use the natural irrigation of river and lake floodplain (Van Andel and Runnels, 1995). In Gadachrili, canal construction could be motivated by the 8.2 ka climate change resulting in particular in a regional increase in humidity (Fig. 16 and Joannin et al., 2014, Messenger et al., 2013, Messenger et al., 2017). Floods spread to human occupations located on the distal part of the alluvial plain and caused by a poorly managed hydraulic system. The evidence of these hazards are rare and very precious in archaeology. Some stratigraphic evidence for uncontrolled flooding in prehistoric canals have already been studied in Arizona (Huckleberry, 1999) and in Peru (Huckleberry et al., 2012). But in Gadachrili, probably the first if not the oldest evidenced prehistoric "civil engineering disaster" occurred. Sediment source and modes of deposition within the channels vary according to the geomorphological setting and/or the climatic components. Channel fill deposits are the testimony of canal flow regulation, of the natural flooding episodes, or of the post abandonment of the structure including flooding and slopewash from the adjacent berms. They can record the impacts of natural hazards on prehistoric societies as we have assumed for Gadachrili. But it is difficult to date the construction and early use of these kind of water management structures. In addition, the hydraulic calculations show that the Neolithic hydraulic structures of Gadachrili were to be marked by strong sedimentation (due to a low flow velocity) and frequent cleaning in order to guarantee a minimal flow. This indicates that much information about the history of these channels is missing. In the case of Gadachrili, the proximity of the occupation was a determinant factor to correlate both kinds of structures and activities. However, sedimento-stratigraphic evidence remains to be found concerning the relations between agriculture and the need for such hydraulic structures.

5.4. Irrigation and the Lesser Caucasus

Surface irrigation (or gravity irrigation) uses gravity. The water is conveyed by means of channels and ditches of decreasing size. This last characteristic would fit well with what is observed in the studied sections C3 and C4. The watering itself is carried out by runoff, by submersion or by infiltration in the subsoil close to the crops. Plots with a uniform slope and low amplitude, as in the case of the alluvial fan of the Shulaveri river, lend themselves well to irrigation because they reduce the difficult earthworks. The Gadachrili's diversion system certainly consists in improving the water-efficient pattern fragily based on the regional precipitation rates and floodplain supply. It was supported by the increase in climatic humidity following the 8200 cal. BP event in the region (Fig. 16). During this wetter period, watercourses should provide a more perennial and more regular flow, partially erasing the current disadvantages inherent in the drying-up of the Shulaveri river-type torrential systems during the summer. This creates an original environmental context that makes difficult to literally use the term "irrigation", usually more dedicated to areas (with arid or semi-arid climate) where the natural rainfall and soil hygrometry are insufficient to support crops for rainfed agriculture.

The low and statistically homogeneous isotopic values recorded could underline the humidity of the climate around and after the 8.2 ka event. Irrigation practice is not ruled out, but the isotopic signals seem homogenised by this more humid environment. During the summer period, eventual irrigation would be insufficient to impact the $\delta^{13}\text{C}$ values, as grain crops mature during this season and do not require water supply (interruption of irrigation

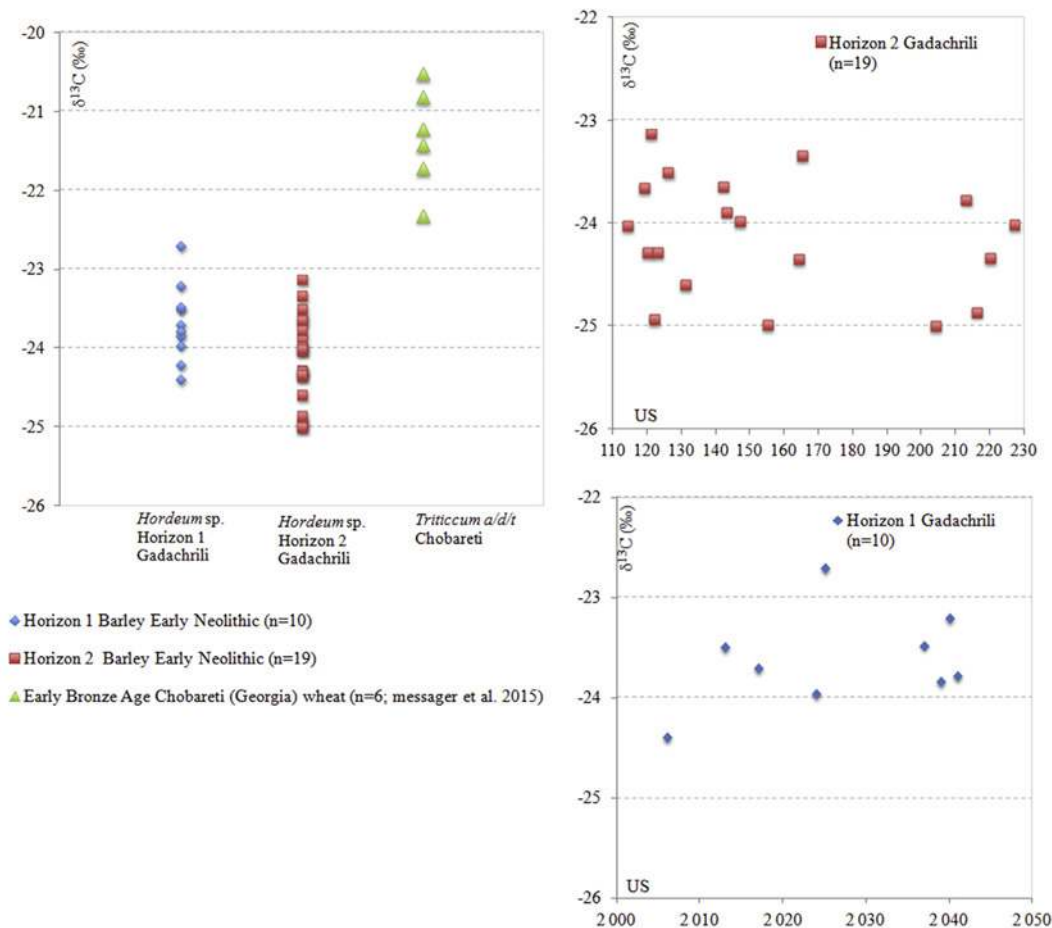


Fig. 14. Carbon isotopic ratio distribution of seed samples from the Horizon 1 and Horizon 2 in Gadachrili and from the site of Chobareti (Messenger et al., 2015). The horizontal axis is for the different US sampled.

during the run and progressive cessation during the appearance of milky grains, Reynolds et al., 1999). In contrast, no indication of irrigation has been found in Chobareti, but a drier climate between 3300 and 2900 cal. BC.

Although still insufficient evidence for a clear irrigation practice in the current specific case, the Gadachrili and Chobareti data provide additional palaeoclimatic indications consistent with the regional palynological results obtained in Paravani (Messenger et al., 2013), Zarishat (Joannin et al., 2014), and Vanevan (Leroyer et al., 2016).

The triangle between the delta of the Tigris and the Euphrates, Armenia, and the Syrian coast is the scene of the first major development of techniques in water management at least since the fourth millennium BC (Viollet, 2004). Clear evidence of early agriculture and viticulture in the Shulaveri settlements of Georgia has already been reported (Connor, 2006; McGovern et al., 2017). Although the different crops highlighted do not necessarily require a significant water supply, the question of irrigation remains unresolved. Winter cereals, mainly barley and wheat, that form a basis for the subsistence of pre and protohistoric societies, require a supply of water at the end of winter and spring (Sherratt, 1980), which nature cannot always provide. This is why the practice of artificial irrigation came probably very early to supplement the expectation of natural phenomena such as rain or floods. "Irrigation ditches" have already been identified very close to the sites of Imiris Gora and Aruchlo in former studies (Mardaleishvili and Janelidze, 1984; Connor, 2006). In each of these cases, the dating of the

formations, the nature of the sedimentary facies (see section descriptions in the supplementary material), the Hjulström values obtained and the distance from the river to the sites (Fig. 13 and Suchodoletz and Faust, 2017), allow us to exclude a possible wetland drainage function for these channels. In the case of Gadachrili or Mentesh Tepe, this is the first time that this type of hydraulic structure is studied and calibrated chronologically by absolute dating. We also assume that if the canals were used for irrigation practices it was mostly to increase and secure yields (spring watering, regular water intake limiting water stress) as part of a windfall effect related to the 8.2 ka climate change event.

Currently located in the vicinity of non-perennial streams, the sites of Gadachrili and Mentesh Tepe have nevertheless archaeological channels that have been fed by the diversion of river courses in which water circulated in the Neolithic. Through these two examples and the dating obtained on these different sites, it is attractive to consider a wet period accompanying and following the 8.2 ka climatic event (6.2 cal. BC) during almost a millennium, starting at least at 6622 cal. BC and probably ending around 5683 cal. BC. Until now, no other region of the Lesser Caucasus appears to present this type of water management structure for the Early Neolithic. Moreover, and according to the abundant international literature on this subject, the case of Gadachrili, and to a lesser extent of Mentesh Tepe, could be considered as the oldest water management structure actually discovered.

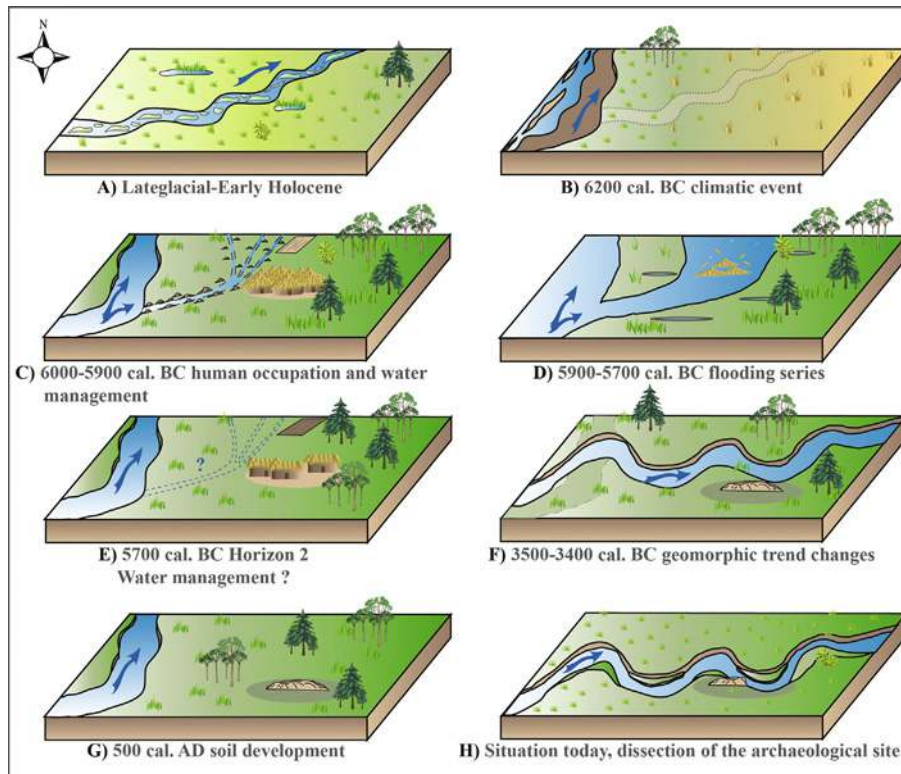


Fig. 15. Kinematics of the main Postglacial landscape evolution stages of the Gadachrili Gora site.

5.5. The potential impact of water management on the current hydrological behaviour of the Shulaveri river

As suggested in the recent geomorphological study of the lower Shulaveri Ghele by Suchodoletz and Faust (2017), lack of direct water access for the local Neolithic settlements would make possible the existence of water management structures for their water supply as formerly hypothesised for Imiris Gora and Aruchlo (Javakhishvili, 1973; Kiguradze, 1986; Hansen and Mirtskhulava, 2012). As observed in some studies, the freshwater canals could easily become new channels (Doolittle, 1980 & 2006) during high intensity flood episodes. In the case of Gadachrili, it is suggested that this type of process has occurred at least once during the use of the channel and one or more times after its abandonment. As recently supposed (Suchodoletz and Faust, 2017), the existence of water management structures in Gadachrili and possibly in the surrounding sites (Imiris Gora, Shulaveris Gora, notably) could be one of the retroactive causes of the Shulaveri river channel migration. The forcing associated with these changes could have been relatively small, implying the existence of underlying tipping points where self-propelling change - i.e. strong positive feedback - is triggered within the systems in question (Turney et al., 2016). The Shulaveri river valley seems to be, potentially, highly-sensitive to changes caused by the passing of tipping points within different components of the climate, geomorphic system, and past anthropogenic activities. In this context several aspects concerning the multiple geomorphic factors and responses in the landscape reconstruction must be investigated, especially since the incision giving rise to the current Shulaveri river seems to be recent (posterior to 1500/1900 BP, ca 500 cal. AD), indicating powerful but long retroactive phenomena in response to weak disturbances of this specific mountain hydrosystem (partly related to the Derbent lowstand of the Caspian Sea around 500 cal. AD, Sauer et al., 2013).

6. Conclusions

The interdisciplinary data involved in the study of Gadachrili deliver new results integrated into the framework of past investigations conducted in geomorphology, archaeology, and palaeoecology in the Lesser Caucasus (Ollivier et al., 2010; Joannin et al., 2010; Lyonnet et al., 2012; Messenger et al., 2013; Chataigner et al., 2014). Geomorphic response and bioclimatic changes are coupled with Neolithic land use to refine the interaction between the Caucasian societies and the evolution of their environment. Our preliminary data sets indicate that the river management was established around 5900 cal. BC and presumably led to Gadachrili village flooding as well as the destruction and local abandonment of the hydraulic infrastructures between 5750 and 5430 cal. BC. These features were developed during the more humid period following the 8200 cal. BP (6200 cal. BC) climatic event in the region. The question of the reality of irrigation practices in Gadachrili and their probable link with potential humid climatic components is complex and still needs further study. If there was irrigation, this was probably practiced to optimize agricultural yield. Important work in geoarchaeology (and in agronomy) remains to be done on all Neolithic sites studied and their environment in this region (as also shown for Mentesh Tepe in Azerbaijan). The development of water management in this area probably weakened the balance of the Shulaveri hydrosystem in the long term. This transition from the destabilisation threshold could continue to produce its effects until today. If this is the case, it would be a perfect example of the impact of the transition from a natural geosystem to an anthropised geosystem, this, since the beginning of the Neolithic. The major adjustments necessary for hydraulic farming systems (construction and maintenance of canals) require new forms of social organisation adapted to the management of an agricultural activity.

The study of these new practices accompanying the rise of the

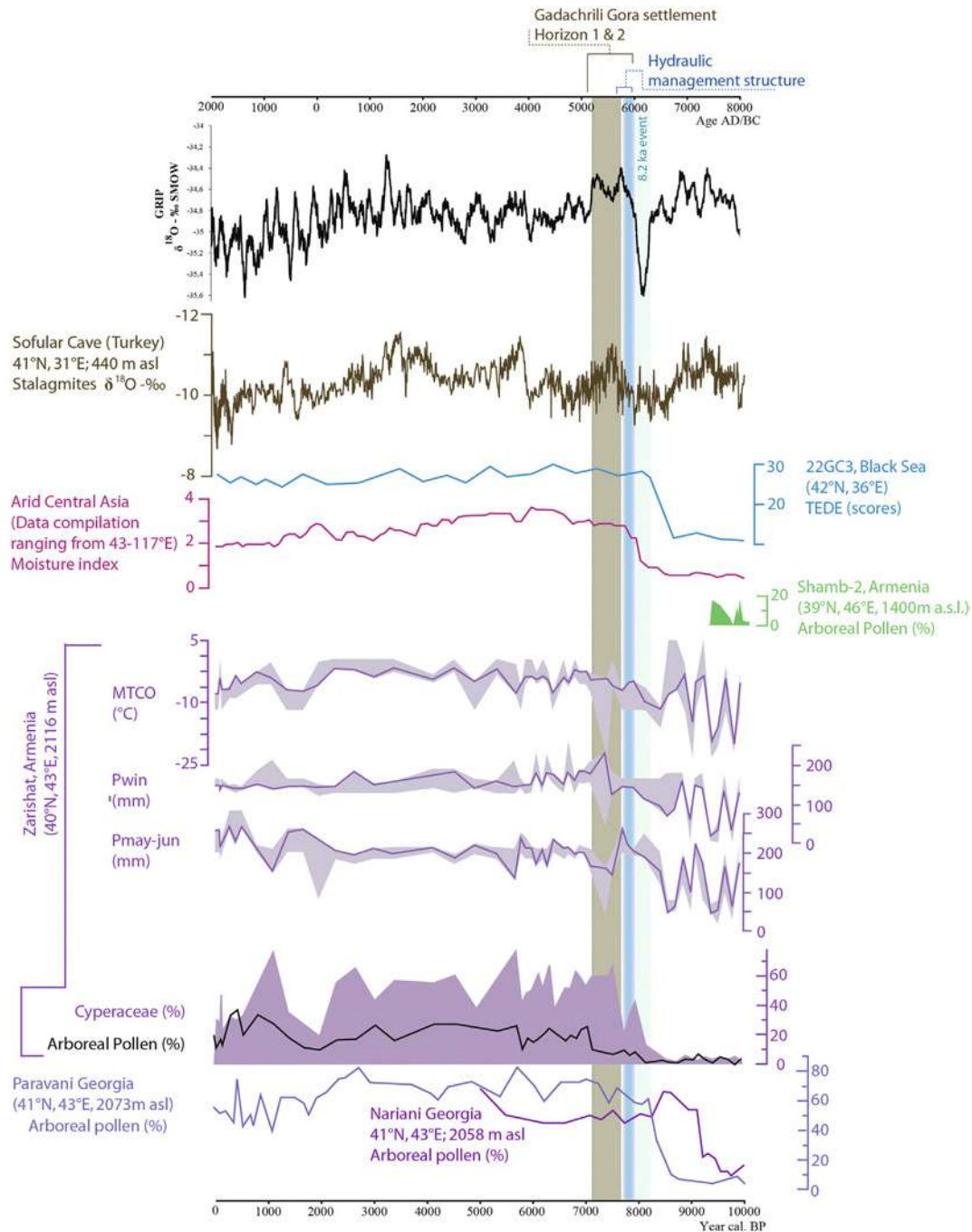


Fig. 16. Hydraulic management structure and Gadachrili Gora settlement in their global to regional Holocene bioclimatic context (GRIP: Andersen et al., 2006, Sofular Cave: Fleitmann et al., 2009, Central Asia: Chen et al., 2008, Black Sea: Shumilovskikh et al., 2012, Shamb: Ollivier and Fontugne, 2012, Paravani: Messenger et al., 2013, Zarishat: Joannin et al., 2014, and Nariani: Messenger et al., 2017).

Neolithic between Europe and Asia finds a particular echo in Gadachrili (and to a lesser extent in Mentesh Tepe). The development of multidisciplinary research on Holocene societies and environments in the Lesser Caucasus highlights the significant character of this region of Georgia in the study of recent prehistory.

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