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Late Pleistocene and Holocene alluvial archives in the Southwestern Mediterranean: Changes in fluvial dynamics and past human response

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Abstract

Cohesive floodplains from the semiarid Southwestern Mediterranean (Morocco, Tunisia) exhibit excellent preservation toward lateral erosion and present a continuous record of Late Pleistocene and Holocene flood dynamics. Holocene mean sedimentation rates and ^{14}C cumulative probability plots from cohesive Tunisian floodplain sequences reveal a coupling with North Atlantic Bond events. Short-term periods of fluvial activity match well with North Atlantic coolings. The findings indicate a strong climatic link from 4.8 ka until today. Unlike fluvial archives from the humid mid-latitudes, semiarid Southwest Mediterranean alluvial archives exhibit phases of increased fluvial dynamics under generally drier conditions.

The ^{14}C cumulative probability plot of archeological sites in Mediterranean North Africa indicates correlations with alluvial records. Therefore, prehistoric societies seemed to be very sensitive to past shifts in landscape dynamics.

1. Introduction

1.1. Southwest Mediterranean fluvial archives: records of environmental changes?

Recently, some moderate to high-resolution records of Late Quaternary archives have become available for the Western Mediterranean. Especially, speleothem and offshore records indicate a teleconnection between the North Atlantic and the West Mediterranean climatic history (e.g. Buccheri et al., 2002; Combourieu-Nebout et al., 2002; Sánchez-Goni et al., 2002; De Abreu et al., 2003; Martrat et al., 2004; Moreno et al., 2005; Hodge et al., 2007). The Western Mediterranean region was characterized by pronounced short-term climate variations during the Late Pleistocene and Holocene. In this paper, the authors discuss the potential of Southwest Mediterranean fluvial archives for paleoclimatic and paleoenvironmental reconstruction. Fluvial archives are not unequivocal climatic archives as are ice or marine cores, but they may mirror geomorphological responses to climatic oscillations and shifts. Here, subtropical geomorphic change reflects more the hygric than the thermal component of the climate. Geomorphic-sedimentological proxy data of fluvial archives, therefore, provide an opportunity to complete the highly temperature-orientated approach in research of Late Quaternary climate change through valuable information concerning humidity at a regional scale (e.g. White et al., 1996; Rose et al., 1999). Fluvial archives provide advantages for the understanding and reconstruction of Late Pleistocene and Holocene environmental changes. Fluvial archives offer information of an entire catchment. In comparison to slope deposits or colluvial archives, fluvial archives reveal environmental changes in a more regional and more representative scale. Furthermore, fluvial archives directly document processes of environmental change within the human sphere and are a reliable tool for reconstructing past human–environment interactions.

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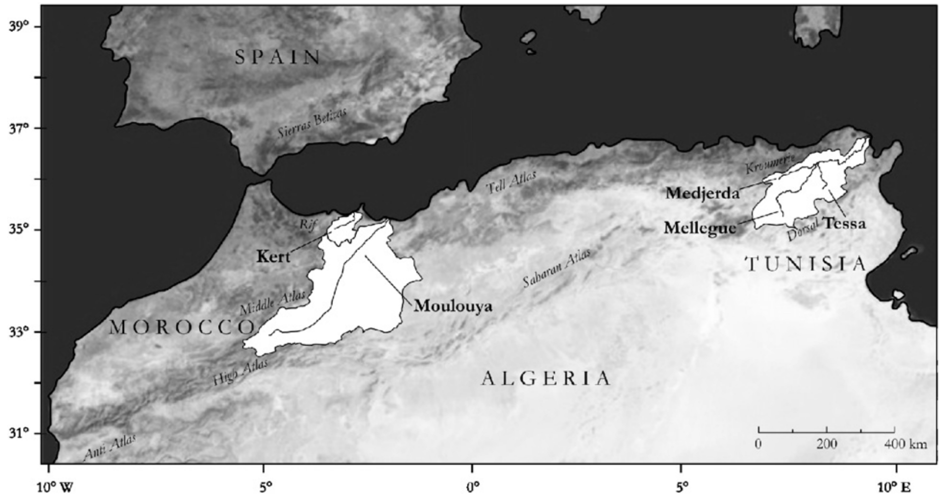

Fig. 1. Catchment areas of perennial Oued Kert, Oued Moulouya and Oued Medjerda in semiarid to semihumid Mediterranean North Africa. The lower Kert and Moulouya Rivers as well as the mid-Medjerda River exhibit cohesive floodplains.

1.2. Southwestern Mediterranean archeological archives: human response to environmental change?

Modern archeological studies emphasize paleoclimatic or paleoenvironmental history as a triggering (or a very important) cause of past human development (e.g. Weiss et al., 1993; Verschuren et al., 2000; Lamb et al., 2003; Weninger et al., 2006; Zielhofer and Linstädter, 2006). Nevertheless, a correlation of archeological data with paleoenvironmental findings often remains unsatisfactory due to a lack of well-dated and continuous sequences.

Concerning archeological reconstructions of human response to environmental change, places inhabited for several millennia like the Near Eastern and Southeast European Tells exist, but the excavated record is erratic and very much affected by natural erosion, anthropogenic disturbances, changing settlement pattern and the shifting appearances of proxies including burials, pottery or metal which follow the complexity of human societies. Regarding prehistoric settlement behavior in the Southwestern Mediterranean, especially semiarid to arid North African desert margins are generally inhabited by highly mobile societies and repeatedly used sites are rare anyway (Linstädter, 2004). More or less continuous proxies such as population density only exist for recent centuries and are therefore not available for prehistoric research.

The only chronological proxy which may be considered is a compilation of ^{14}C ages from the recently known archeological sites. The authors are aware that the existence and the frequency of radiocarbon data at a particular time depend on several factors, including the state of archeological research or the availability of datable material. Nevertheless, ^{14}C data sets from archeological sites may be used as indicators of the intensity of land use and human response to environmental changes in the prehistoric times.

1.3. Aims

This paper presents three examples of cohesive fluvial archives from the Southwest Mediterranean: fine-grained overbank sequences from the lower Kert River (NE Morocco; Fig. 1), from the lower Moulouya River (NE Morocco) and from the mid-Medjerda River (N Tunisia). The catchment areas of the three rivers are characterized by semiarid climate, and show similarities and differences in Late Pleistocene and Holocene fluvial response.

Cumulative probability plots of calibrated radiocarbon ages from alluvial archives in Tunisia are used to investigate the potential of ^{14}C data sets for 'Holocene fluvial chronologies'. The ^{14}C cumulative probabilities of archeological sites from Morocco, Algeria and Tunisia are used to find a pattern of prehistoric settlement dynamics. The focus is on rapid and distinct changes in the data curve which correspond to the shifts in the ^{14}C density plot of Tunisian fluvial archives.

2. Cohesive floodplain types with high preservation potential

According to the genetic classification of floodplains by Nanson and Croke (1992), Late Pleistocene and Holocene alluvial archives documented in this paper represent cohesive flood sequences, characterized by fine-grained clastic overbank accretion. The overbank fines are well stratified and, therefore, are markedly advantageous for chronostratigraphical reconstruction of the floodplain history. Due to the high preservation potential of cohesive overbank fines against lateral erosion, the floodplains reveal a clear spatial dichotomy. Beside cohesive flood deposits, the braided Kert River, braided Moulouya River and meandering Medjerda River feature non-cohesive coarse channel fills with strong lateral migration dynamics. However, the lateral migration and erosion are more or less limited on non-cohesive channel fills, point and braid bars.

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Consequently, the severe transition from cohesive to non-cohesive alluvial fills is characterized by exposures (10–15 m) of cohesive overbank fines, which are easily accessible for stratigraphic correlation.

2.1. *Cohesive lower Kert flood deposits (NE Morocco)*

The Kert River rises from the Eastern Rif Mountains of Northeast Morocco and flows into the Mediterranean Sea (Fig. 1). Its catchment area covers approx. 2710 km^2. Within the Kert catchment the climate is Mediterranean semiarid to semihumid with the average precipitation ranging from 300 mm in the lowlands and up to 700 mm in the Rif Mountains. According to the bioclimatic classification of Emberger (1939) and Sauvage (1963), the Kert catchment area exhibits forests of *Callitris articulata* in the drier lowlands and evergreen oak forests of *Quercus rotondifolia* in the more humid Rif Mountains.

The lower Kert is a braided river system with diverse small channels separated by temporary braid bars, consisting of coarse (gravel, sand) non-cohesive deposits. However, the edge of the braided river is flanked by the cohesive fine-grained overbank and flood basin deposits. Hence, there is a clear separation of Holocene alluvial deposits in the often redeposited inner-channel fills and clayey to silty overbank fines (Fig. 2). Barathon et al. (2000) have identified three Holocene terraces at the lower Kert River with Mid- to Late Holocene sediment sequences and isolated fluvial deposits from the Bölling/Alleröd (12,309 ± 221 BP; 14.5 ka cal BP) to Younger Dryas transition. However, chronostratigraphical study along the lower Kert River also showed Early Holocene flood deposits.

Shortly before the Kert River flows into the Mediterranean Sea, it crosses an antecedent valley and is incised in Neogene volcanic bedrock (Fig. 2). In the south of this valley the river created a basin filled with horizontally bedded cohesive overbank fines, indicating a good and representative preservation of the Holocene flood history (Figs. 3 and 4). Here, a sediment sequence 170 cm thick is striking, deposited in the entire floodplain. The upper part of Kert I profile (Fig. 3) corresponds to the grayish deposits on the opposite side of the floodplain (Fig. 4).

Two radiocarbon samples (Table 1) at the bottom and at the top of the grayish sediment sequence indicate Early Holocene Ages of 9.2 and 8.9 ka cal BP (Fig. 3). Further results have distinguished two flood processes within the grayish sequence. Grain-size analyses indicate two fining-up sequences between 205 and 290 cm as well as between 290 and 360 cm (Fig. 3). Geochemical analyses reveal additionally a separation of the grayish sequence. Aluminum (Al), zinc (Zn), magnesium (Mg), calcium (Ca) and strontium (Sr) contents between 205 and 290 cm exhibit totally different compositions than the sediments between 290 and 360 cm. In particular, the Zn and Sr signals indicate a dichotomy of the sequence. Thus, it is most likely that these sediments have a different origin.

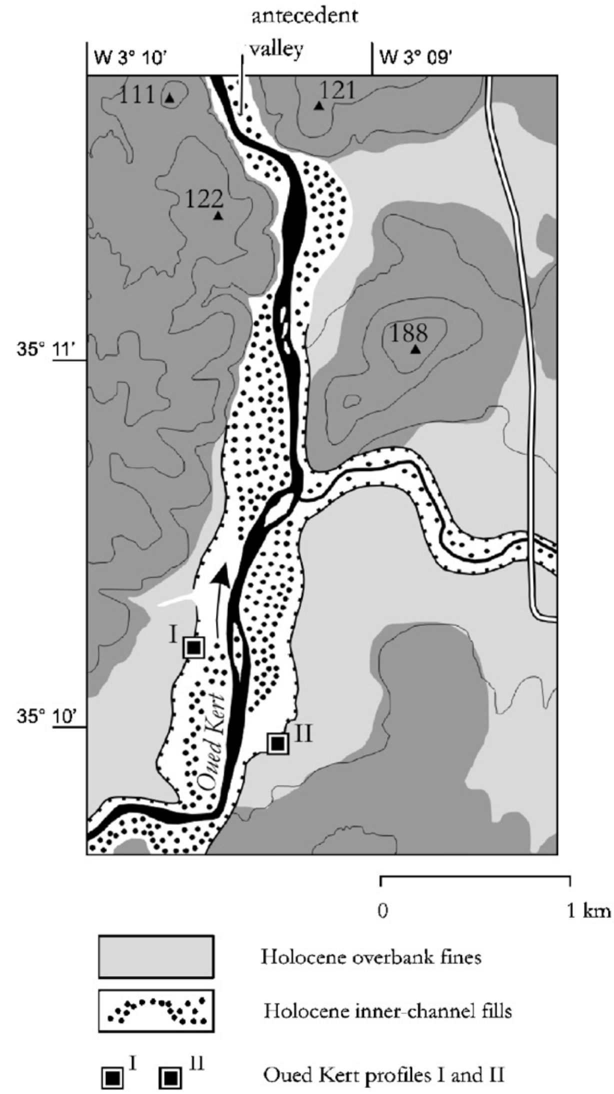

Fig. 2. Floodplain of the lower Kert River and location of Kert profiles.

The grayish sequence covers a reddish alluvial soil, probably of Late Pleistocene Age. The A horizon of the reddish soil (between 160 and 205 cm; Fig. 3) indicates a former period of floodplain stability with reduced or no flooding. At the top of the grayish flood sequence (between 320 and 360 cm), another A horizon is developed revealing equally a phase of reduced flooding.

The cohesive semiarid floodplain of the lower Kert River preserved two (mega) flood events between 9.2 and 8.9 ka. Before 9.2 and after 8.9 ka soil formation processes in the floodplain indicate phases of decreased flooding and well-balanced fluvial dynamics.

2.2. *Cohesive lower Moulouya flood deposits (NE Morocco)*

The Oued Moulouya (Fig. 1) is the main water course in Northeast Morocco. Its catchment covers approx. 53,500 km^2 (Zarki and Macaire, 1999). It rises in the Atlas Mountains at an altitude of 1770 m and flows into the

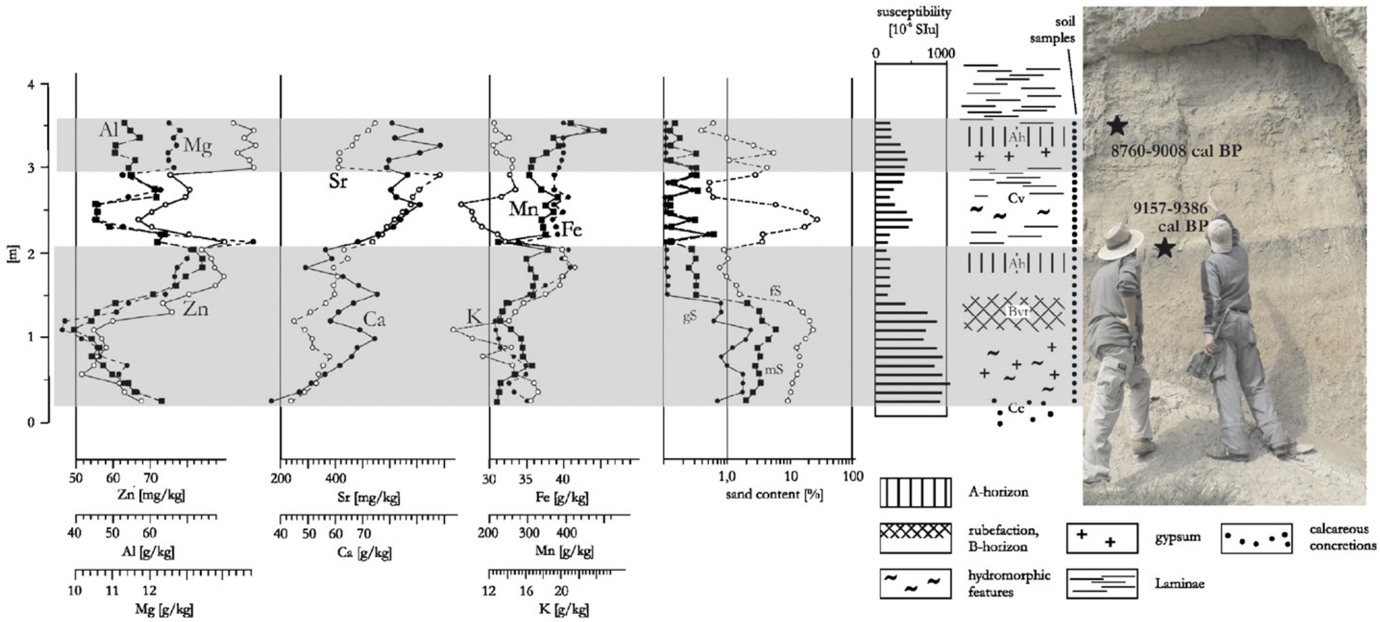

Fig. 3. Kert profile I with an Early Holocene flood sequence.

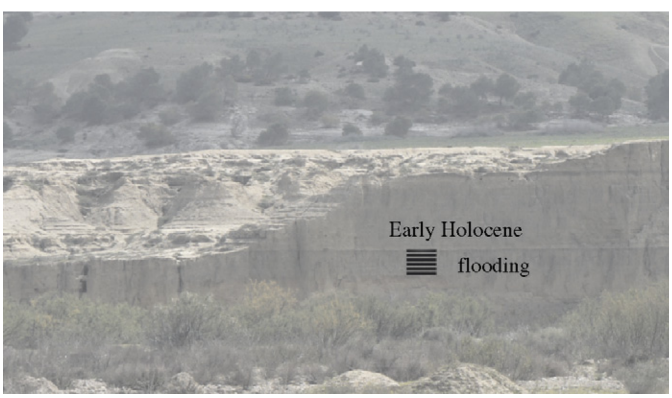

Fig. 4. Kert profile II with an Early Holocene flood sequence.

Mediterranean Sea. Within the Moulouya catchment the climate is Mediterranean arid to semiarid with the average precipitation ranging from 200 mm in the lowlands and up to 600 mm in the Atlas Mountains. Most of the rainfall is concentrated in only a few days, leading to high fluctuations in the water discharge. For example, during the 1963 flood the maximum water discharge of the Moulouya River reached 5200 $m^3 s^{-1}$, nearly 240 times greater than the mean annual discharge (Snoussi et al., 2002). According to the bioclimatic classification of Emberger (1939) and Sauvage (1963), the mid- to lower Moulouya region indicates the transition from Mediterranean arid (*Stipa tenacissima*, *Artemisia herba alba*) to semiarid (*C. articulata*) conditions.

Well-stratified cohesive Holocene overbank fines are exposed at the edge of the lower Moulouya channel bed. The Djamila stratigraphic record (Fig. 5) reveals around 15 m of Holocene overbank deposition, which may be distinguished in three characteristic sedimentation series (Fig. 6). At the bottom margin of the Djamila sequence, Series I (250–560 cm above the current river level) reveals an alternation of sandy layers with humic rich, sandy to loamy overbank fines. Weakly aggregated, humic rich overbank fines resemble buried A horizons, indicating former phases of low flood activity, soil formation and landscape stability. Neolithic open-air sites overlie buried A horizons (Fig. 6), indicating human occupation of the floodplain at that time. Neolithic sites contained undecorated ceramics and some geometric triangles. The particular types of arrowheads suggest a date of the Neolithic sites at the transition from the Early to the Middle Neolithic, around 7 ka.

Above Series I, sediment sequences of Series II become much finer (560–730 cm above the current river level). The sand content seldom exceeds 1–2%. Like Series I, the flood deposits of Series II reveal hydromorphic features, indicating an enduring high groundwater level at that time. However, some silty to clayey fining sequences end with consolidated narrow bands rich in charcoal. Ash-grayish and strong reddish (5 YR) spots ('burned' zones) point to the impact of serious fires on the former floodplain surface, indicating the onset of drier environmental conditions or increased human impact at the lower Moulouya.

Terminal sedimentation Series III (730–1540 cm above current river level) reaches the present-day floodplain surface. Series III is characterized by extremely fine laminated fining-up sequences of silty to clayey deposits. Its coloring varies from grayish (2.5 Y–10 YR) to reddish (5–7.5 YR) laminae. Equal to Series II, the sedimentation processes have been interrupted by several 'burned' zones, indicating the impact of fire. These charcoal rich bands are excellent markers for stratigraphic correlation (Fig. 6).

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Table 1
Radiocarbon samples from the lower Kert and the lower Moulouya Rivers

Site	Type	Lab no.	Material	^{14}C (BP)	^{14}C (cal BP) (1 sigma)	Sediment series	Latitude	Longitude	Above river level (m)
Oued Moulouya									
Djamila J 12.70 m	Bulk sample	KIA 30741	Humic acid	2145±25	2090–2275	Series III	N34°56′	W02°34′	12.70
Djamila J 12.34 m	Ex situ	KN 5820	Charcoal	2070±20	2011–2089	Series III	N34°56′	W02°34′	12.34
Djamila H level 9	Ex situ	KIA 30748	Charcoal	2170±20	2148–2289	Series III	N34°56′	W02°34′	11.80
Djamila H level 8	Ex situ	KIA 30747	Charcoal	3670±35	3947–4069	Series III	N34°56′	W02°34′	11.40
Djamila H level 8	Bulk sample	KIA 30747	Humic acid	3810±35	4156–4266	Series III	N34°56′	W02°34′	11.40
Djamila A 7.85–8.10	Ex situ	KN 5819	Charcoal	2994±35	3122–3250	Series III	N34°56′	W02°34′	8.00
Djamila A 4.47 m	Ex situ	KIA 30745	Charcoal	5805±35	6562–6654	Series I	N34°56′	W02°34′	4.47
Djamila A 4.47 m	Bulk sample	KIA 30745	Humic acid	5925±35	6701–6789	Series I	N34°56′	W02°34′	4.47
Djamila A 3.88 m	Ex situ	KIA 30740	Charcoal	5920±35	6697–6784	Series I	N34°56′	W02°34′	3.88
Djamila A 3.88 m	Bulk sample	KIA 30740	Humic acid	6065±30	6891–6964	Series I	N34°56′	W02°34′	3.88
Bouchih A level 1	Ex situ	KIA 30746	Charcoal	3025±35	3182–3311	Series III	N34°56′	W02°31′	8.25
Bouchih A level 1	Bulk sample	KIA 30746	Humid acid	3230±30	3413–3476	Series III	N34°56′	W02°31′	8.25
Bouchih A level 2	Ex situ	KN 5818	Charcoal	3039±59	3165–3327	Series III	N34°56′	W02°31′	8.06
Bouchih B 5.45 m	Ex situ	KIA 30742	Charcoal	3765±30	4096–4202	Series II	N34°56′	W02°31′	5.45
Metlilli 12.52 m	Ex situ	Erl-5886	Charcoal	2062±60	1961–2113	Series III	N34°56′	W02°33′	12.52
Metlilli 11.64 m	Ex situ	Erl-5887	Charcoal	2219±62	2157–2307	Series III	N34°56′	W02°33′	11.64
Metlilli 6.66 m	Ex situ	Erl-5888	Charcoal	6482±72	7327–7457	Series I	N34°56′	W02°33′	6.66
El Rhama B level 4	Ex situ	KIA 30743	Charcoal	2095±30	2024–2114	Series III	N34°57′	W02°32′	12.60
El Rhama A level 1	Ex situ	KIA 30744	Humic acid	2580±30	2714–2749	Series III	N34°57′	W02°32′	10.20
Oued Kert									
Oued Kert 3.80 m	Ex situ	Erl-8022	Charcoal	8029±77	8760–9008		N35°10′	W03°10′	
Oued Kert 2.35 m	Ex situ	Erl-802	Charcoal	8278±68	9157–9386		N35°10′	W03°10′	

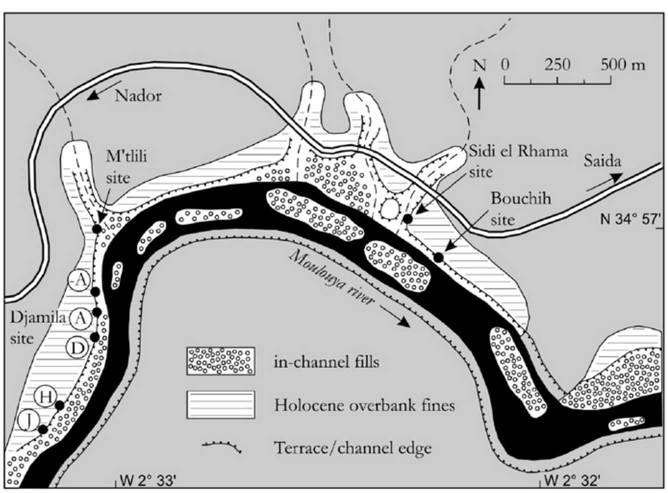

Fig. 5. Holocene overbank deposits at the lower Moulouya River (NE Morocco).

Despite the extremely narrow thickness of the laminae, the Djamila profile reveals well-stratified deposits, traceable over hundreds of meters alongside the exposure, and, therefore, embodies a quite representative archive for the Holocene alluvial history of the river. Ceramics in buried archeological sites of Series II and III show a very different pattern, resembling a sherd of a 'ceramique repousse', which has until now no parallel in Mediterranean Morocco. Other pottery founds, the so-called 'vases carenées', are well known from Bronze Age sites in Spain and date approx. 3.5 ka.

The alluvial sequences of the Djamila profile are rich in redeposited charcoal and macroremnants. Table 1 shows radiocarbon ages and calibrated ages from the Djamila exposure. Calibrated ages are also illustrated in Fig. 6. Beside radiocarbon samples from the Djamila exposure, several ^{14}C samples exist from adjacent Metlilli, Bouchih and Sidi el Rhama alluvial exposures (Fig. 5 and Table 1). Fig. 7 shows a basic model of the lower Moulouya with a synthetic documentation of sedimentation series and a composition of all the available dating results. Calibrated ^{14}C ages indicate stable and more humid environmental conditions around 6.7 ka (Series I), and an enduring change in flood dynamics somewhat before 4.1 ka with following overbank aggradation and an increase in fire frequencies (Series II and III).

2.3. Cohesive mid-Medjerda floodplain

The Oued Medjerda (Fig. 1) is the main perennial water course in Northern Tunisia and adjacent Eastern Algeria. Its catchment covers approx. 23,500 km^2. The northern catchment includes the Mediterranean sub-humid south-facing slopes of the Tunisian Tell region. The larger catchment lies to the south, drained by the main tributaries Mellègue and Tessa (Fig. 1). They drain the north-facing slopes and piedmonts of the semiarid Dorsal Mountains. The Medjerda River itself has its source in the semiarid Atlas Mountains of Eastern Algeria. In the area of the upper middle course the river passes through the Chemtou/Ghardimaou Basin (Fig. 8), a tectonic depression with

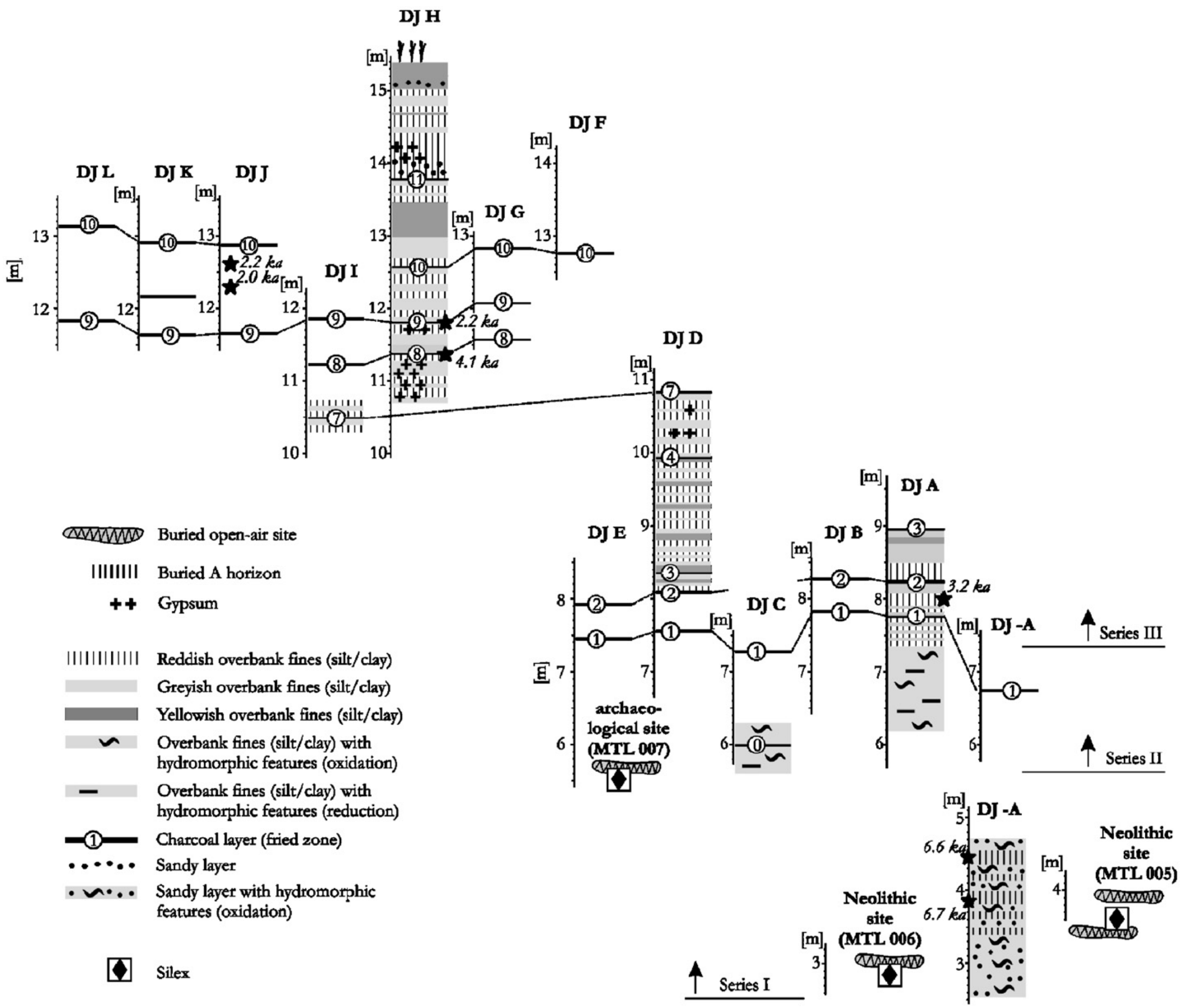

Fig. 6. Stratigraphic correlation of Djamila site (lower Moulouya, NE Morocco).

10–12 m of Holocene floodplain sediments. According to Giessner (1984), the basin is characterized by the bioclimatic transition from Mediterranean semiarid to semihumid conditions. This transition is ecologically documented by the occurrence of the Mediterranean xerophytic forest with *Pinus halepensis* and shrubs of *Quercus ilex*.

The Medjerda floodplain is subdivided into two sedimentation areas: the cohesive floodplain flat with well-stratified overbank fines and the meander belt (Fig. 9). Within the meander belt, the Medjerda is a migrating river producing predominantly non-cohesive, lateral and cross-bedding deposits. The age of the channel fills and point bars is generally very young, as modern meander development reworks older deposits. Despite internal meander migration, the meander belt as a whole is rather stable, due to the high preservation potential of the cohesive overbank fines against the lateral erosion processes. As a result, at the edge of the Medjerda meander belt, well-stratified overbank deposits enable the interpretation of sediment sequences over long distances.

The stratigraphic documentation and pedological analyses of 12 Medjerda key profiles led to the identification of five main sedimentation series (Fig. 10). Forty-two ^{14}C samples as well as paleomagnetic (declination and inclination signals) analyses have established a centennial scale Late Quaternary chronology with corresponding sedimentation rates (Faust et al., 2004; Zielhofer et al., 2004).

Alternating sediment texture, sedimentation rates and soil formation within Medjerda overbank deposits indicate short-term fluctuations in the Late Pleistocene and Holocene fluvial dynamics. Stratigraphically, the base of the composite profile shows clayey to silty fine sedimentation of the Bölling/Alleröd period. Analyses of macroremnants point to a vegetation cover indicating already contemporary Mediter-

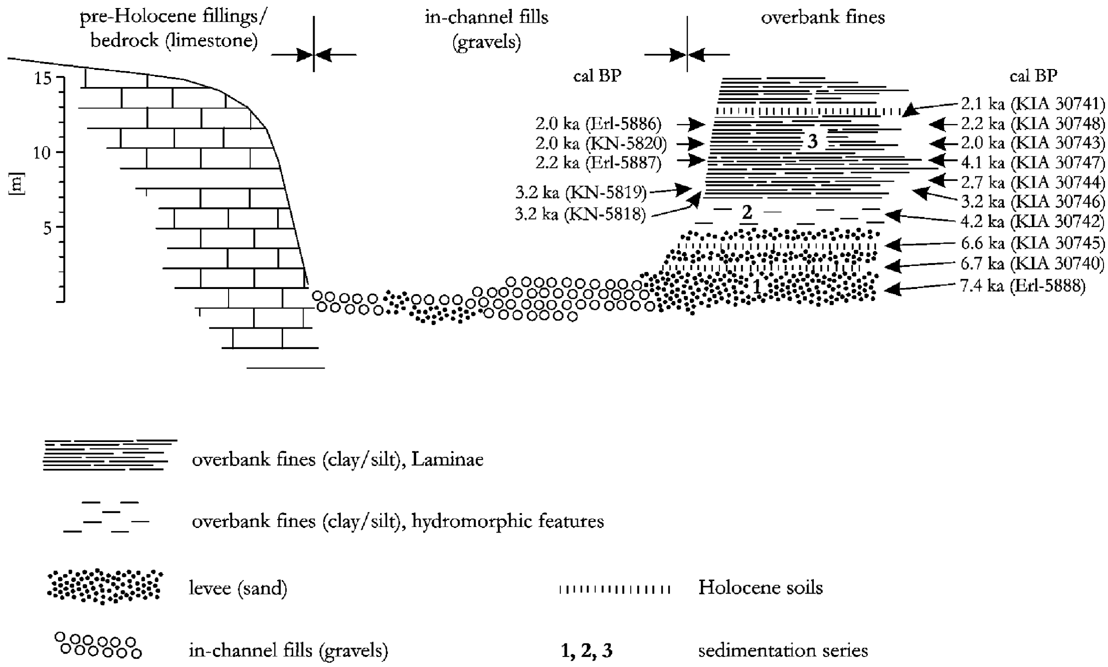

Fig. 7. Basic model of the lower Moulouya floodplain.

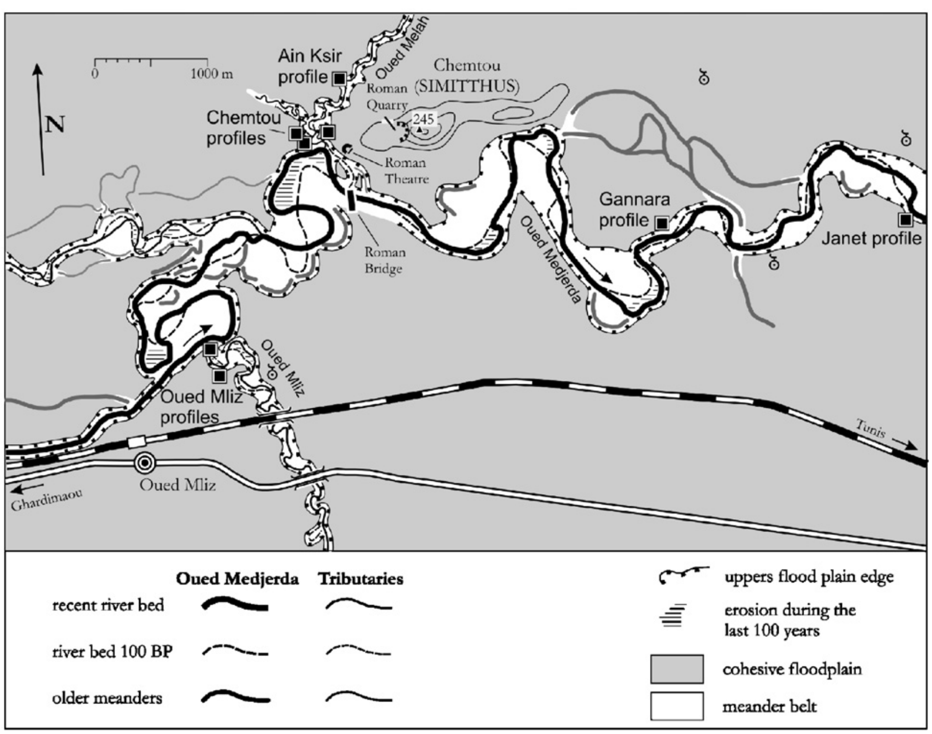

Fig. 8. Meander dynamics within the Chemtou/Ghardimaou Basin.

ranean conditions (Zielhofer and Faust, 2003; cf. Finlayson et al., 2007). This sedimentation continued until 12.4 ka. During the Younger Dryas (12.4–11.8 ka), coarse sediments and gravels were deposited. The onset of the Holocene (11.8 ka) is marked by fine sedimentation lasting until 6.6 ka. This is a long period of geomorphic stability. At 6.6 ka, the stable period is interrupted by the sedimentation of coarse material. The following time is characterized by fine sedimentation in most parts of the floodplain in which a distinct soil is formed (period of Mid-Holocene stability).

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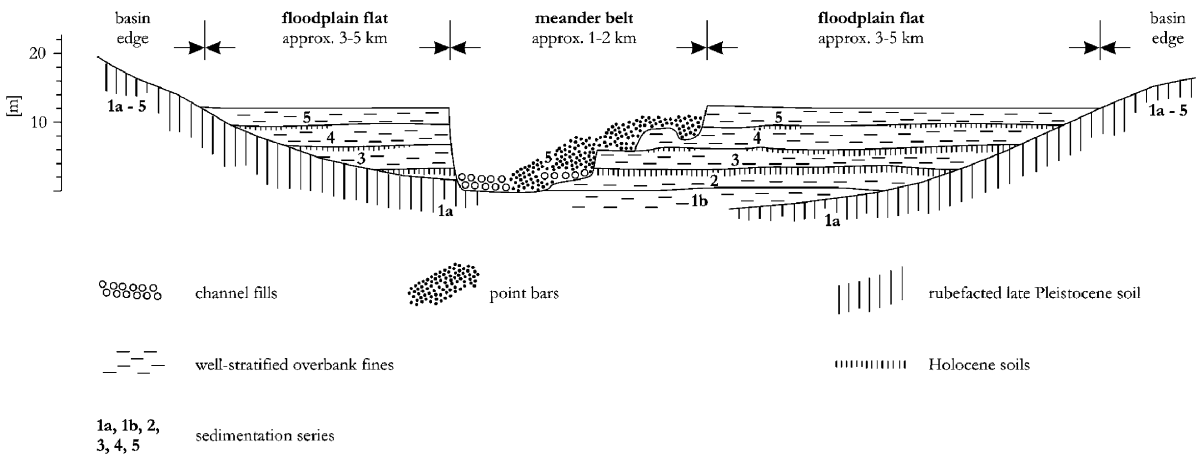

Fig. 9. Basic model of the mid-Medjerda floodplain.

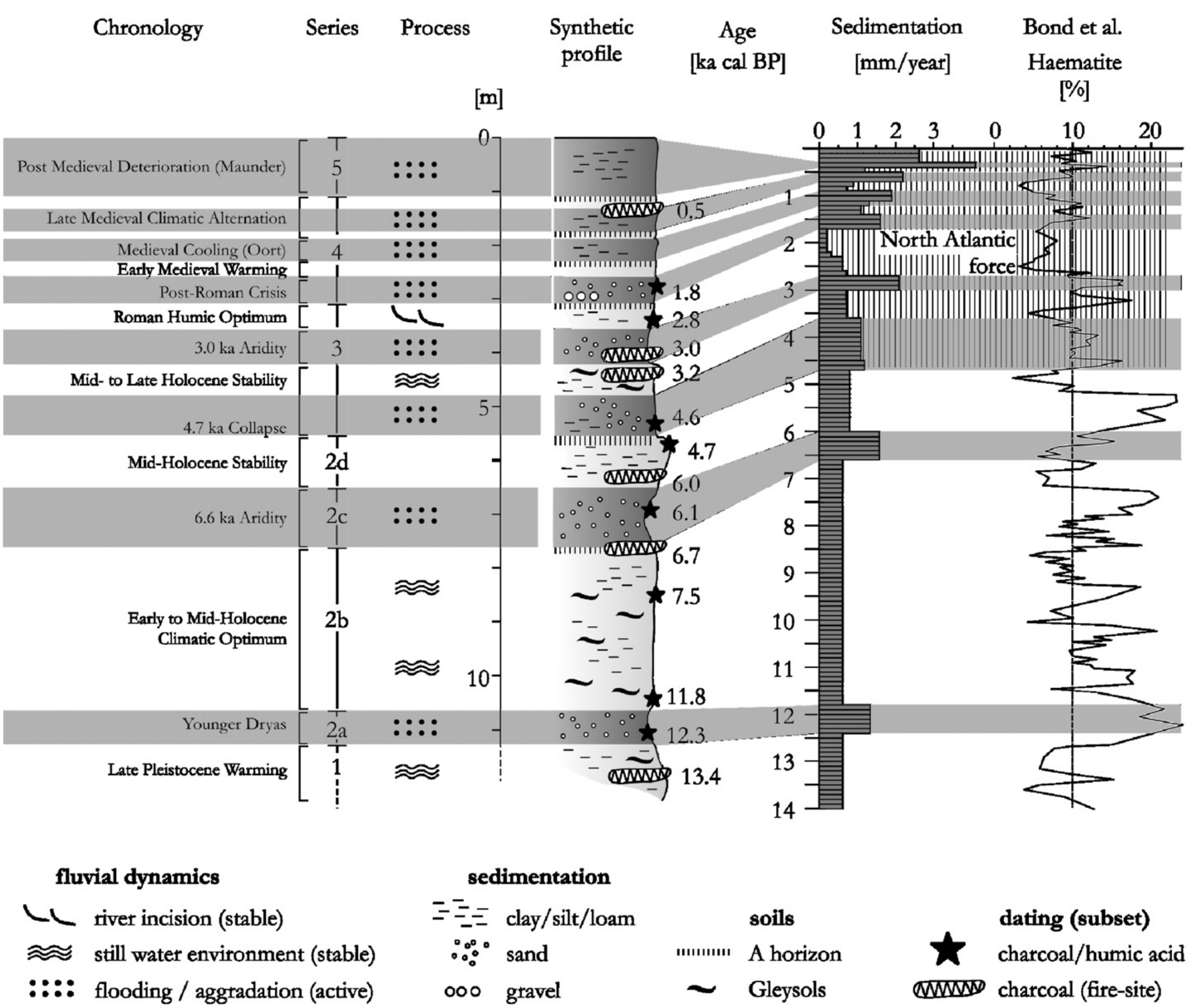

Fig. 10. Composite profile and average sedimentation rates of the mid-Medjerda floodplain, following Faust et al. (2004) and Zielhofer et al. (2004).

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Around 4.7 ka, poorly sorted sediments cover the Mid-Holocene soil. This indicates an enhancement of fluvial dynamics. Around 2.0 ka, morphodynamic stability and soil formation may be observed. At 1.6 ka, an accentuated restart of fluvial dynamics took place (Post-Roman Crisis). Certain sediment strata between 1.2 and 0.8 ka show soil formation with humic enrichment. Subsequently, some minor floods yield only fine sediments. From 0.4 to 0.3 ka, devastating floods occur in the entire Medjerda Basin, leaving thick laminated sediments (Fig. 10).

3. ^{14}C cumulative probability plots from cohesive Tunisian floodplain deposits

3.1. Previous findings, method and database

Thorndycraft and Benito (2006a, b) and Macklin et al. (2006) have used ^{14}C dates from British, Polish and Spanish fluvial sequences to gain information about Holocene flood histories in Central and Western Europe. The authors were especially focused on 'change dates', indicating ^{14}C ages which coincided with an abrupt modification in alluvial sedimentation structure or rate. Dates were calibrated and plotted as cumulative probability density functions. The research group of Macklin, Benito and colleagues demonstrated that the ^{14}C data sets of Holocene fluvial sequences in Great Britain, Poland and Spain document particularly Late Holocene ages, due to the eroding nature of most of these river systems.

The ^{14}C cumulative probability plots of cohesive floodplains from Northern and Central Tunisia document the preservation and the hydro-climatic interpretation potential of these floodplain types. The ^{14}C dates from Faust et al. (2004) and Zielhofer et al. (2004), new dates from this research (Table 2) and more than 100 dates of other research groups have been assembled into the database (Table 3). The ^{14}C dates from redeposited charcoals have been considered in the data set as representing 'activity dates', indicating processes of active fluvial dynamics. In contrast to the 'activity dates', many ^{14}C ages in Tunisian cohesive floodplains represent alluvial stability or periods of minor floods. Scharpenseel and Schiffmann (1985) collected bulk samples of autochthonous and redeposited alluvial soils in order to obtain radiocarbon data from pedogenetic organic material. The creation of pedogenetic organic material took place during periods of soil formation and landscape stability. Hence, for Tunisian semiarid floodplains two completely independent ^{14}C data sets are available. The former (73 'activity dates') represent alluvial activity; the latter (111 'stability dates') mark periods of minor floods and landscape stability.

Radiocarbon ages of both Tunisian data sets were calibrated in Calpal (www.calpal.de), the calibration program of the Cologne radiocarbon lab, and plotted as cumulative probability density functions (cf. Weninger, 1986). Fig. 11c reveals the cumulative probability plot of 'stability dates', and Fig. 11d shows the plot of the 'activity dates'.

3.2. Mid- to Late Holocene alternation of soil formation and flooding

Both cumulative probability plots of Tunisian floodplain sequences (Fig. 11c and d) show ^{14}C ages for the entire Holocene period with a Mid-Holocene maximum. The high density of ^{14}C dates during the Mid-Holocene indicates the

Table 2
First published ^{14}C dates from the Medjerda floodplain in N Tunisia

Site	Type	Lab no.	Material	^{14}C (BP)	^{14}C (cal BP) (1 sigma)	Geomorphical information	Latitude	Longitude
CH profile	Cultural layer	Erl-6339	Charcoal	11,440±50	13,233–13,480	Pedogenesis	N36°29′	E8°34′
PG profile	Fire site	KIA 20947	Charcoal	7815±40	8562–8632	Activity date	N36°29′	E8°36′
PG profile	Fire site	KIA 20948	Charcoal	5705±25	6458–6525	Activity date	N36°29′	E8°36′
SA profile	Ex situ	KIA 20940	Charcoal	3550±25	3787–3882	Activity date	N36°28′	E8°38′
SA profile	Ex situ	KIA 20941	Charcoal	3605±30	3879–3961	Activity date	N36°28′	E8°38′
SA profile	Ex situ	KIA 20942	Charcoal	4005±30	4443–4513	Activity date	N36°28′	E8°38′
SA profile	Ex situ	KIA 20939	Bone	4090±190	4325–4829	Activity date	N36°28′	E8°38′
PH profile	Ex situ	KIA 20946	Charcoal	4080±210	4284–4842	Activity date	N36°24′	E8°38′
PH profile	Bulk sample	KIA 20946	Humic acid	4050±55	4465–4692	Pedogenesis	N36°24′	E8°38′
PH profile	Nodule	KIA 20944	$CaCO_3$	12,645±50	14,717–15,285	Pedogenesis	N36°24′	E8°38′
BS profile	Bulk sample	KIA 20943	Mollusk	4640±40	5331–5447	Pedogenesis	N36°35′	E8°58′
HK profile	Ex situ	KIA 17827	Charcoal	4025±30	4451–4526	Activity date	N36°35′	E9°00′
KT profile	Ex situ	KIA 15564	Charcoal	1400±21	1301–1326	Activity date	N36°30′	E8°31′
SN profile	Ex situ	KIA 15294	Charcoal	2935±30	3039–3155	Activity date	N36°28′	E8°33′
SN profile	Ex situ	KIA 15293	Charcoal	935±25	814–903	Activity date	N36°28′	E8°33′
AK profile	Ex situ	KIA 15288	Charcoal	970±24	834–924	Activity date	N36°30′	E8°34′

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Table 3
Radiocarbon dates available from alluvial sequences in Tunisia

Secondary radiocarbon dates		Total number of ^{14}C dates	Activity dates	Stability or pedogenesis	Reference
Location	Type				
Central Tunisia	Floodplain	7	6	1	Bartels and Steinmann (1980)
Central Tunisia	Floodplain	10	7	3	Steinmann and Bartels (1982)
North and Central Tunisia	Floodplain	101	7	94	Scharpenseel and Schiffmann (1985)
Central Tunisia	Floodplain	11	9	2	Ballais and Ben Ouezdou (1992), Ballais and Benazzouz (1994), Ballais (1995)
Medjerda valley (N Tunisia)	Floodplain	9	5	4	Zielhofer et al. (2004)
Medjerda valley (N Tunisia)	Floodplain	30	27	3	Faust et al. (2004)
Medjerda valley (N Tunisia)	Floodplain	16	12	4	First published in this paper
Total		184	73	111	

high preservation potential of Holocene alluvial fills in cohesive arid to semiarid floodplains. Regarding the representativeness of the two alluvial ^{14}C data sets, 'activity dates' showing phases of fluvial activity and 'stable dates' should have been mutually exclusive. There is a good match for the Mid-Holocene with increased periods of flooding from 6.2 to 6.0, 4.7 to 4.5, 4.1 to 3.7 and 3.3 to 3.0 ka cal BP. These flood periods coincide with low soil formation signals (Fig. 11c and d).

4. ^{14}C cumulative probability plots from archeological sites

Fig. 11a shows the radiocarbon cumulative probability plot from archeological sites in Mediterranean North Africa. Two hundred and fifty ^{14}C dates from Mediterranean Morocco, Algeria and Tunisia have been considered in the database. All ^{14}C dates are derived from already published findings from excavated caves, rock shelters and/or open-air sites. Table 4 shows a compilation of corresponding archeological references. The majority of the archeological findings come from Morocco due to the very fragmentary state of research in Algeria and Tunisia. More than 110 radiocarbon findings are derived from Northeastern and Eastern Morocco, where the current excavation programs improve the state of archeological research (cf. Mikdad et al., 2000).

The ^{14}C cumulative probability density plot from the archeological sites (Fig. 11a) indicates rapid and distinct changes which correspond to known global signals of Late Quaternary climatic changes as well as to shifts in ^{14}C density plots from Tunisian fluvial archives (Fig. 11c and d). The Bölling/Alleröd warm period corresponds to an increase of archeological ^{14}C dates, whereas during the Younger Dryas the archeological ^{14}C density function reveals a noticeable decrease until 11.7 ka (Fig. 11a). A remarkable decline in the archeological radiocarbon ages is also detectable around 8.2, 7.3, 6.0, 4.8–4.4, 4.0–3.8 and 3.2–3.0 ka cal BP. With the exception of the decrease round 8.2 ka all further periods of reduced archeological ^{14}C data correspond to increased fluvial activity in Tunisia (cf. Fig. 11d).

5. Discussion

5.1. Continuous Holocene flood records within cohesive overbank sequences

The Holocene floodplains of the lower Kert, lower Moulouya as well as mid-Medjerda Rivers exhibit cohesive overbank sequences with thicknesses of 10–15 m and even more (e.g. Figs. 4, 7, 9 and 10). Cohesive Holocene flood deposits reveal well-stratified paleoenvironmental archives. Especially, fine-grained overbank deposits of the lower Kert and the lower Moulouya Rivers indicate a continuous Holocene history of flood events. With the exception of one ^{14}C sample from Djamila H8, the radiocarbon chronology reveals a good correlation with the reconstructed stratigraphic architecture of Moulouya alluvial sequences (Fig. 6). Although further investigation is necessary to ameliorate the chronological resolution of Kert and Moulouya alluvial sequences, documented ^{14}C ages show a convincing result: the distribution of radiocarbon ages is not characterized by a large peak during the Late Holocene period as shown from British, Polish and Spanish alluvial records (cf. Macklin et al., 2006). Neither the ^{14}C ages from the cohesive Kert, Moulouya or Medjerda floodplains nor the cumulative probability density plots from several cohesive Tunisian floodplains (Fig. 11c and d) point to maxima during the Late Holocene. While floodplains in more humid and temperate regions of Europe are characterized by lateral erosion processes and the redeposition of former flood sediments, cohesive floodplains in semiarid Mediterranean North Africa prove to be excellent preservation conditions against fluvial erosion and demonstrate continuous archives of Holocene floods.

5.2. Enhanced sedimentation rates during the Younger Dryas

The average sedimentation rate of the Medjerda River reacted in a sensitive way to paleoclimatic shifts. The change from landscape stability to fluvial activity with increased sedimentation rates around 12.4 ka coincides

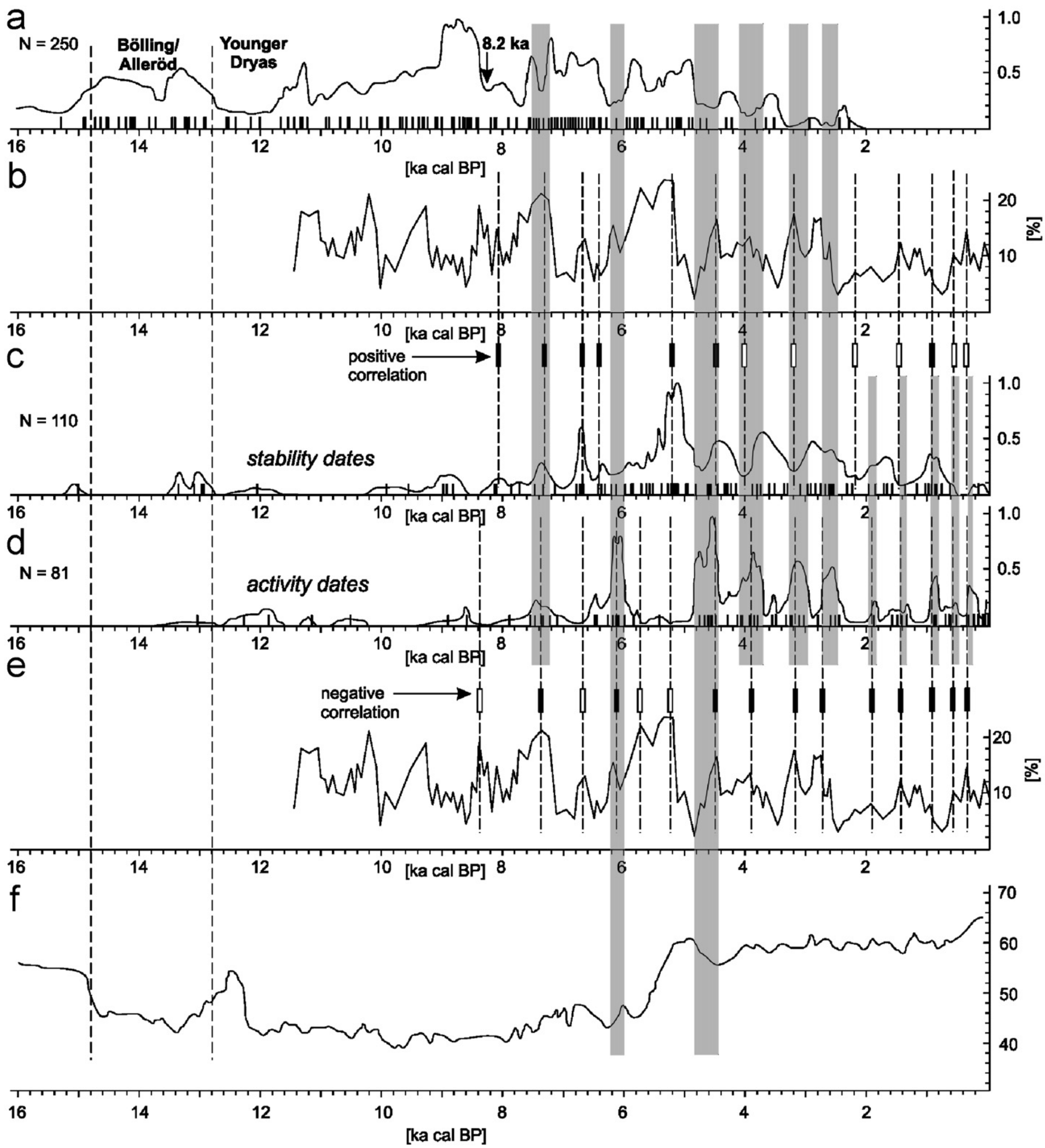

Fig. 11. (a) Radiocarbon cumulative probability density function from archeological sites (caves, rock shelters, open-air sites) from Mediterranean North Africa (Morocco, Algeria, Tunisia), (b) and (e) hematite curve (%) of Bond's North Atlantic marine core showing ice rafted debris and corresponding cooling phases (Bond et al., 2001), (c) cumulative probability density function of radiocarbon 'stability dates' from arid and semiarid Tunisian alluvial floodplain sequences, (d) cumulative probability density function of radiocarbon 'activity dates' from arid to semiarid Tunisian alluvial floodplain sequences and (f) lower latitude Saharan dust input in the Eastern Atlantic Ocean (deMenocal et al., 2000). The grayish shaded bars indicate periods of enhanced fluvial activity in Tunisia with corresponding flooding. Dashed lines show comparisons between the oscillations of the cumulative probability plots (c and d) and the hematite curve from the North Atlantic Ocean (b and e). Black rectangles mirror positive correlations between the cumulative probability plots and the hematite curve, white rectangles reveal negative correlations. The archeological data may mirror periods of lower human activity during phases of increased flooding (negative correlation between a and d).

Table 4
Radiocarbon dates available from archeological sites in Morocco, Algeria and Tunisia

Archeological radiocarbon dates		Total number of ^{14}C dates	Reference
Location	Type		
Southwestern Morocco, Atlantic coast	Open air	18	Grébénart (1975)
Western Morocco	Cave and open air	14	Débénath et al. (1983–1984), Débénath et al. (1986)
Northwestern Morocco	Cave and open air	8	Daugas et al. (1998)
Eastern Rif Mountains	Cave	56	Moser (2003), Linstädter (2004), Nami (2007)
Lower Moulouya	Open air	3	Stambouli et al. (2004)
Eastern Morocco	Cave and open air	29	Wengler and Vernet (1992)
Rassel, Tamar Hat, Taforalt, Grotte de Contrebandiers	Caves	41	Brahimi (1968), Camps et al. (1968), Saxon et al. (1974), Delibrias et al. (1982)
Miscellaneous sites, Morocco and Algeria	Cave and open air	51	Camps et al. (1973), Nehren (1992)
Tunisia (Capsian)	Cave and open air	29	Rahmani (2004)
Algeria (Capsian)	Open air	3	Lubell et al. (1976)
Chaffarinas Islands	Open air	1	Bellver Garrido and Bravo Nieto (2003)
Total		250	

with the transition from the Bölling/Alleröd to the Younger Dryas (Fig. 10). The Younger Dryas in the Central Mediterranean is considered to be induced by an aridification of the climate (Allen et al., 1999; Ramrath et al., 2000). Enhanced Medjerda fluvial activity is limited to approximately 11.8 ka (Fig. 10). These results indicate a noticeably short Younger Dryas fluvial signal in Northern Tunisia. Only 600 years appear to have been effective geomorphologically.

5.3. Missing 8.2 ka event in Southwestern Mediterranean alluvial sequences

Abrupt cold events in the Northern Hemisphere, which occurred during Holocene times, have been linked to changes in the North Atlantic circulation. One of the most important cold events occurred between 8.2 and 8.0 ka (Alley et al., 1997). Whereas the 8.2 ka event is widespread in East Mediterranean (Bar-Matthews et al., 2003; Migowski et al., 2006; Staubwasser and Weiss, 2006; Weninger et al., 2006), in Arabia (Parker et al., 2006) and in West Mediterranean (Gasse et al., 1987, 1990; Ramrath et al., 2000; Davis and Stevenson, 2007) paleoenvironmental records, Tunisian fluvial archives do not exhibit a fluvial response at that time (Figs. 10 and 11). Fluvial archives from Kert and Moulouya Rivers in NE Morocco do not indicate a clear fluvial response as well.

5.4. Increased fluvial dynamics around 6.5–6.0 ka in Tunisian alluvial sequences

Between 6.5 and 6.0 ka, enhanced floodplain aggradation is detectable in Medjerda overbank sequences (Fig. 10). The Tunisian activity dates also exhibit increased fluvial dynamics at that time (Fig. 11d). However, a period of climatic deterioration between 6.5 and 6.0 ka is not well documented from the terrestrial archives in the Western Mediterranean. Although there is some evidence of a Mid-Holocene climatic depression and an increase in geomorphic activity between ~6.5 and 6.0 ka (cf. Lamb et al., 1995; Ramrath et al., 2000; Zielhofer and Linstädter, 2006; Mäusbacher et al., 2007), the previous paleoenvironmental data sets remain somewhat inconsistent.

5.5. Strong Mid-Holocene soil formation in Tunisian alluvial sequences

Between 6.0 and 4.7 ka, the average Medjerda sedimentation rate is reduced (Fig. 10), indicating weak fluvial dynamics and favorable conditions for soil formation in the catchment. The ^{14}C cumulative probability density plots of periods of soil formations illustrate a maximum at that time (Fig. 11c). This most famous period of Holocene soil formation in Tunisian fluvial sequences occurred between 5.9 and 4.8 ka. Strong Mid-Holocene soil formation in Mediterranean North Africa has been noted (Molle, 1979; Scharpenseel and Zakosek, 1979; Zielhofer et al., 2002). Focusing on the geomorphological findings, this Mid-Holocene soil formation period was further correlated with a hygric and thermal climatic optimum in the region. However, regarding high-resolution records from the North Atlantic realm (Fig. 11b and e) and the sub-Saharan latitudes (Fig. 11f), the soil formation coincides first with a period of global climatic changes. A strong ice rafted debris signal in the North Atlantic indicates enhanced cooling (Fig. 11b), and increased dust transport from the mon-

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soonal influenced Sahara (Fig. 11f) mirrors a change to much drier conditions.

5.6. *Mid-Holocene hydro-climatic switch in Tunisian alluvial sequences*

Between 7.0 and 3.0 ka ^{14}C plots from 'activity dates' and 'stability dates' reveal a clear negative correlation (Fig. 11c and d). Before 7.0 and after 3.0 ka the signals become more blurred. However, black and white rectangles in Fig. 11 show events of negative and positive correlation between floodplain aggradation and North Atlantic cooling as well as between soil formation phases and North Atlantic cooling. Before 4.4 ka, stable soil formation phases correlate with North Atlantic cooling, but after 4.4 ka North Atlantic cooling is accompanied with decreasing soil formation. Additionally, increased flooding shows a good positive correlation with the hematite curve after 4.8 ka and a more or less opposite signal before 4.8 ka. These dynamics are also shown by Late Holocene peaks in the Medjerda average sedimentation curve (cf. 'North Atlantic force' in Fig. 10).

The strong coupling after 4.8 ka may indicate a Mid-Holocene hydro-climatic switch as has been shown recently in other paleoenvironmental records of the mid-latitudes (e.g. Leuschner et al., 2002; Magny et al., 2003; Hall et al., 2004; Roberts et al., 2004). Western Mediterranean pollen records (Yll et al., 1997; Ramrath et al., 2000) depict the Mid-Holocene hydro-climatic switch as climate deterioration with cooler and drier conditions.

Following Macklin et al. (2006), increasing Holocene flooding in Central European temperate regions and even in Spain mirrors the totally opposite matching with North Atlantic cooling phases: Before 5 ka Central European and Spanish paleoflood records match well with Holocene cooling phases, and the same authors indicate that after 5 ka the strong association of North Atlantic marine ice drift and riverine flooding becomes much weaker.

5.7. *Past human response to paleoenvironmental changes*

After the Last Glacial Maximum in Mediterranean North Africa, the Epipaleolithic period began with its early phase: the Iberomaurusian. According to numerical dating results, the approx. 10 ka long era of hunter–gatherers is well documented in several North Moroccan and Algerian cave sites, including Tamar Hat (Saxon et al., 1974), Taforalt (Delibrias et al., 1982; Lubell, 2001), Ifri N'Ammar (Moser, 2003) and Ifri el Baroud (Nami, 2007). Considering the ^{14}C cumulative probability density plot of archeological data (Fig. 11a) as an indicator of human activity, some fluctuations may be observed during the Iberomaurusian. Two peaks are visible, matching the Bölling/Alleröd warm period. The higher temperatures and increased humidity seemed to be favorable for the hunter–gather community in Mediterranean North Africa. A decrease of data during the Younger Dryas follows an increase of frequency at 11.7 ka. After the Iberomaurusian period, Late Epipaleolithic data from Mediterranean Morocco are scarce and inconspicuous. However, Late Epipaleolithic data from Capsian sites in the dry regions of Algeria and Tunisia (cf. Lubell et al., 1976; Rahmani, 2004) show a clear decline at 8.2 ka (Fig. 11a). A strong northern hemisphere cooling event (cf. Alley et al., 1997; Weninger et al., 2006) would obviously have a remarkable effect on this Pre-Saharan community.

The beginning of the Mediterranean Neolithic period does not seem to follow clear climatic or environmental shifts. Cultural processes concerning migration and acculturation determine the time schedule of the Epipaleolithic Neolithic transition in the Western Mediterranean (Linstädter, 2004). In contrast, the decline of data in the Middle Neolithic may coincide with a cooler and drier period of several centuries (Zielhofer and Linstädter, 2006). In the same way the end of the Neolithic period around 4.8 ka coincides with the increase of fluvial activity in the Tunisian river deposits (Fig. 11d). Subsequently, archeological data become too scarce to discuss in further accordance with environmental data. Nevertheless, available Post-Neolithic ^{14}C data from Mediterranean North African archeological sites reveal minima during periods of enhanced fluvial activity in the Tunisian river systems (Fig. 11a and d).

6. Conclusions

Semiarid cohesive floodplains in the Southwestern Mediterranean do not reveal a chronologically continuous Holocene archive, but they present a continuous record of flood activity. Excellent preservation conditions permit stratigraphic records of the entire Holocene.

Although fluvial archives may document single flood events, which may not necessarily correspond to a climatic signal, the record of multiple flood sequences reveals climatic signals as indicated in the Medjerda floodplain average sedimentation rate (Fig. 10) or in ^{14}C cumulative probability plots from Tunisia (Fig. 11c and d). The strong coupling between Tunisian flood histories and climatic oscillations in the North Atlantic realm points to a direct reaction of river systems to climatic shifts, even of short duration. Semiarid Mediterranean floodplains exhibit environmental archives with low retention and sensitive threshold values. Regarding current dynamics of environmental change due to global warming, abrupt shifts in the recent flood frequencies of Mediterranean river systems appear as a possible consequence.

Comparison of Holocene floodplain dynamics in semiarid Western Mediterranean with those of the temperate mid-latitudes may show Mid-Holocene hydro-climatic switches with opposite signs. North Atlantic-driven flooding in the temperate Central European regions becomes much weaker after 5 ka (Macklin et al., 2006) and in semiarid Mediterranean North Africa it becomes much stronger. This clearly indicates that fluvial archives of

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dissimilar bioclimatic zones reveal different threshold values and sedimentation patterns, and, therefore, different responses to climatic shifts. Thus, generalizations in fluvial responses are difficult to handle and must be interpreted very carefully.

Due to the high variability of precipitation with a generally high occurrence of excess rainfall, a distinguishing feature for semiarid Mediterranean regions is the extreme flood event (Giessner, 1984, 1990; Snoussi et al., 2002). Therefore, fluvial archives from the semiarid Western Mediterranean in the transition from dry North African desert margins to the sub-humid subtropics are predestined to clarify fluvial system turnovers as a response on Holocene climatic switches.

Geomorphic-sedimentological approaches from fluvial archives of Southwestern Mediterranean cohesive floodplains demonstrate the response of terrestrial archives to climate changes and even reveal a potential for mid- to high-resolution stratigraphic records. Therefore, fluvial archives are an important tool to develop Quaternary paleoclimatic and paleoprocess research, especially because of its direct influence on human sphere.

The ^{14}C plot of archeological sites in Mediterranean North Africa indicates that prehistoric societies seemed to be very sensitive to environmental shifts through time. Chronological gaps or breaks in the cave exposures often correlate with past environmental changes. Further research may show whether there are causal relations or not. Climatic impact causes environmental changes and, therefore, human responses or shifts in prehistoric land use are probable. However, the availability of archeological ^{14}C data depends on several factors, including the state of archeological research (excavations, knowledge of sites), preservation conditions of sites and changes of prehistoric settlement patterns with corresponding changes in mobility.

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