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Hydrosedimentary records and Holocene environmental dynamics in the Yamé Valley (Mali, Sudano-Sahelian West Africa)

Enregistrements hydrosédimentaires et dynamiques environnementales holocènes dans la vallée du Yamé (Mali, Afrique de l'Ouest soudano-sahélienne)

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ABSTRACT

Research conducted in the Yamé Valley (Dogon Country, Mali) provides valuable information about the river systems and their Holocene evolution in Sudano-Sahelian West Africa. Past research in the region has relied primarily on marine and lacustrine records. The new results confirm correlation between palaeoclimatic fluctuations recorded in both the river system and in tropical African lakes. They offer a new continental milestone for understanding of the environmental repercussions of Holocene monsoon oscillations. These studies demonstrate the value of river systems as a palaeoenvironmental record and the role of palaeoclimatic and anthropogenic factors in the Holocene dynamics of Sudano-Sahelian hydrosystems.

RÉSUMÉ

Les recherches effectuées dans la vallée du Yamé (Pays dogon, Mali) apportent des renseignements originaux sur les systèmes fluviaux et leur évolution holocène en Afrique de l'Ouest. Jusqu'à présent, les recherches paléo-environnementales dans la région s'appuyaient essentiellement sur des enregistrements marins et lacustres. Les nouveaux travaux confirment la transcription, dans un système fluvial, des fluctuations paléoclimatiques enregistrées ailleurs en Afrique tropicale. Ils offrent un nouveau jalon continental pour la connaissance des répercussions environnementales des oscillations holocènes de la mousson. Ces études montrent l'intérêt des systèmes fluviaux comme enregistreurs des changements paléo-environnementaux et le rôle des facteurs anthropiques et paléoclimatiques dans la dynamique des hydrosystèmes soudano-sahéliens.

1. Introduction

The increase in palaeoclimatic and palaeoenvironmental research in Africa over the last two decades (Gasse, 2000; Gasse, 2005) has relied primarily on the marine

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(DeMenocal et al., 2000; Haslett and Smart, 2006; Hooghiemstra et al., 2006; Lézine et al., 2005; Marret et al., 2006) and lacustrine (Garcin et al., 2007; Gasse, 2000; Leblanc et al., 2006; Lézine, 1998; Shanahan et al., 2006; Shanahan et al., 2006; Salzmann et al., 2002) records. Relatively little information is known concerning the response of river systems to palaeoenvironmental change. With rare exceptions (Gumnior and Thiemeyer, 2003; Runge, 2002), research has mainly focused on the larger river systems, particularly the Nile, Congo and Niger (Lézine, 1998; Makaske, 1998; Marret et al., 2006; Saïd, 1993; Williams et al., 2000). Preceding research in the Yamé Valley (a tributary on the right bank of the Niger) and the site of Ounjougou in particular showed the potential of this region for the reconstruction of Holocene river system dynamic in Sudano-Sahelian West Africa (Lespez et al., 2008; Rasse et al., 2004; Rasse et al., 2006). Initial results of new investigations make it possible to propose an overall chronostratigraphy for the Yamé Valley deposits and to reconstruct the general evolution of hydrosedimentary dynamics over the last ten thousand years.

2. Location and context of the study

The spring of the Yamé River is on the Bandiagara Plateau (Daveau, 1959), Upper Precambrian sandstone that forms the heart of the Dogon Country, and joins the Niger River 107 km west, in the east-central zone of the Inner Niger Delta, north of Mopti (Fig. 1). The section analyzed is located upstream from Bandiagara in the middle region of the valley, a steep valley 20 m deep cutting through the sandstone. The Yamé then drains most often in the base of a sandy valley, 30 m wide, except when it cuts through sandstone banks and becomes a narrow rocky riverbed. The river is characterized by continuous flow marked by strong seasonal irregularity, due to the monthly rainfall distribution. The Sudano-Sahelian climate has a nine-month-long dry season (October to June) that explains the severity of the lowest water levels. By contrast, the wet season (June to September), associated with the return of the monsoon to the north, contributes significant precipitation (a mean of 563 mm/yr at Bandiagara). Rainfall occurs most commonly as intense showers that cause active runoff and meandering flow charged with sediment, throughout the base of the valley. Nevertheless, the aquifer of the deeply diaclased sandstone plateau absorbs the flood flow and, by slow restoration, maintains an active channel with temporary pools until the middle of the dry season. In this hydroclimatic context, the vegetation is a Sahelo-Sudanian savanna strongly altered by humans (Le Drézen, 2008; Le Drézen and Ballouche, 2009). The dominant crop of millet fields alternating with rare fallow fields characterizes the agrosystems. Some tree species (acacia, African fan palm and shea butter tree) are kept for their dietary usefulness. Marginally, some wooded areas persist in ravine bottoms while the Yamé Valley, rich in water resources, is intensively cultivated (market gardening and specialized crops such as onions).

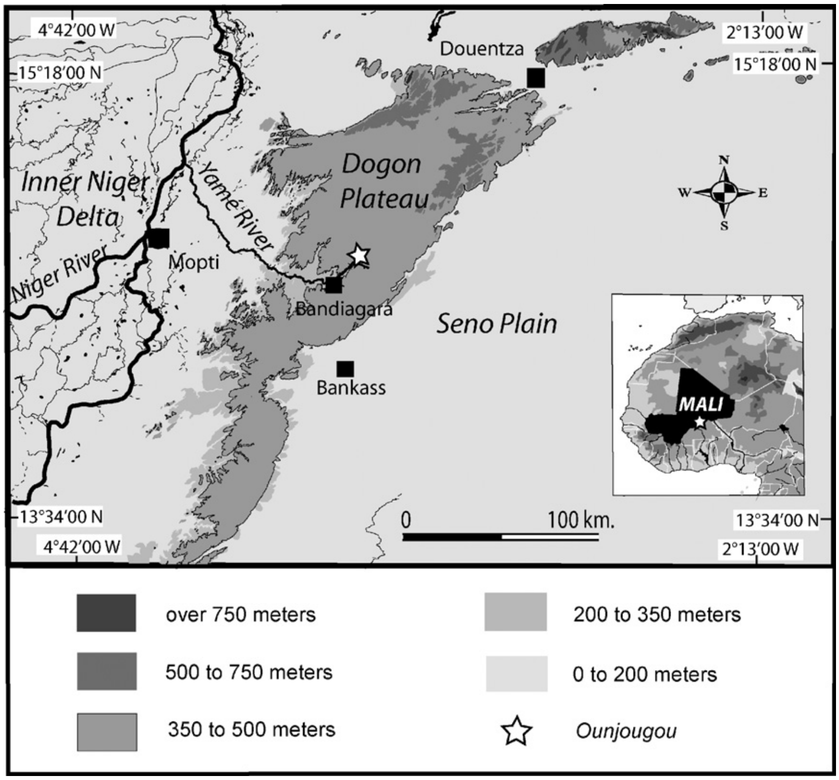

Fig. 1. Location map of the study area.

Fig. 1. Carte le localisation de la zone d'étude.

The sites of Ounjougou (14°24′ N; 3°30′ E) are spread along a 10 km-long section where the Holocene sedimentary deposits are trapped in irregularities in the sandstone. Discovered in 1993 as a result of intense erosion exposing abundant archaeological material and several stratigraphic profiles, they have been subject to ongoing analysis since this date (Huysecom et al., 2004; Huysecom et al., in press; Lespez et al., 2008; Rasse et al., 2006). In Sub-Saharan West Africa, evidence of Early Holocene occupation is sparse and more recent occupations are generally sites with only a limited chronological sequence. Ounjougou thus offers exceptional conditions for the study of the history of the Sudano-Sahelian ecosystem in West Africa.

3. Material and methods

Since 1936, the influence of the Yamé after self-capture (Rasse et al., 2004) accounts for the generalized incision of Holocene and Pleistocene formations and allows their observation in profile. After the establishment of a general outline of the geomorphological and palaeoenvironmental evolution of the valley over 40 ka (Lespez et al., 2008; Rasse et al., 2006), more recent investigations have focused on the systematic analysis, over more than one kilometer, of the stratigraphic limits of Holocene fluvio-paludal formations and the precise drawing of more than 50 profiles. This work led to identification of a succession of 17 sedimentary Holocene sequences, which recently obtained 84 dates (Huysecom et al., 2008; Ozainne et al., 2009; Rasse et al., 2006) situate with precision.

The analysis of the sedimentary facies is based on the study of the stratigraphic sequences observable in the field. Analysis of the sediments is also based on particle size analysis done using a laser granulometer and micromorphological observations of undisturbed blocks of sediment sampled directly from the profiles studied. Fifty-two oversized thin sections were analyzed using classic method (Courty et al., 1989). These yielded data on the internal organization of the sediments and led to description of the macro- and micro-facies. Altogether, these analyses reveal the internal organization of the fluvio-paludal formation of the Yamé riverbanks.

Results of stratigraphic observations in the field (Fig. 2 a and b), and particle size and micromorphological analyses

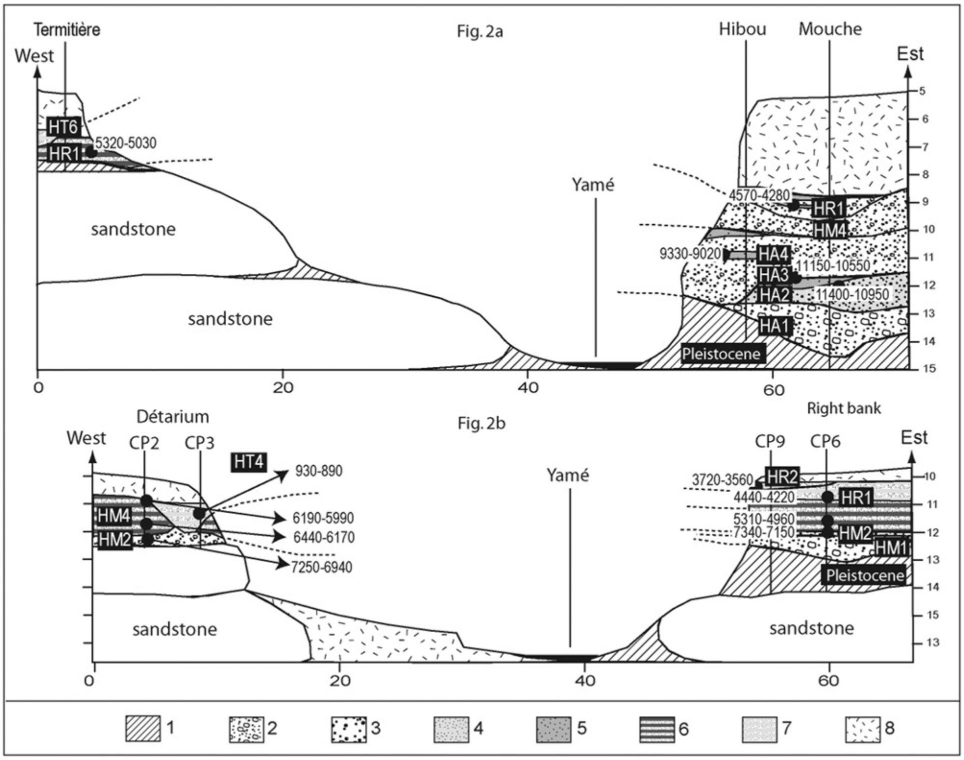

Fig. 2. Cross-sections of alluvial filling at Ounjougou. 2a: Cross-section downstream (Mouche-Termitière). 2b: Cross-section upstream (Balanites-Detarium).

Pleistocene silty-sandy sediments; 2. Sand to gravel and pebbles; 3. Coarse sand; 4. Fine to medium sand very rich in organic matter; 5. Laminated sediments rich in charcoals; 6. Seasonal laminated sediments; 7. 20–21st deposits; 8. pedogenesis.

The dates are obtained by the radiocarbon method and are expressed in calibrated years BP with two standard deviations.

Fig. 2. Coupes chronostratigraphiques du remplissage sédimentaire du site d'Ounjougou. 2a : coupe avale (de la Mouche et termitère ; 2b : coupe amont (Balanites-Detarium).

1. sédiments sablo-silteux pléistocène ; 2. sables grossiers et galets ; 3. sables grossiers ; 4. sables fins à moyens très riches en matière organique ; 5. sédiments laminés riches en particules charbonneuses ; 6. sédiments saisonniers laminés ; 7. dépôts du 20–21è siècle ; 8. pédogénèse.

Les datations ont été obtenues par radiocarbone et sont présentées en années calibrées BP, avec deux déviations standard.

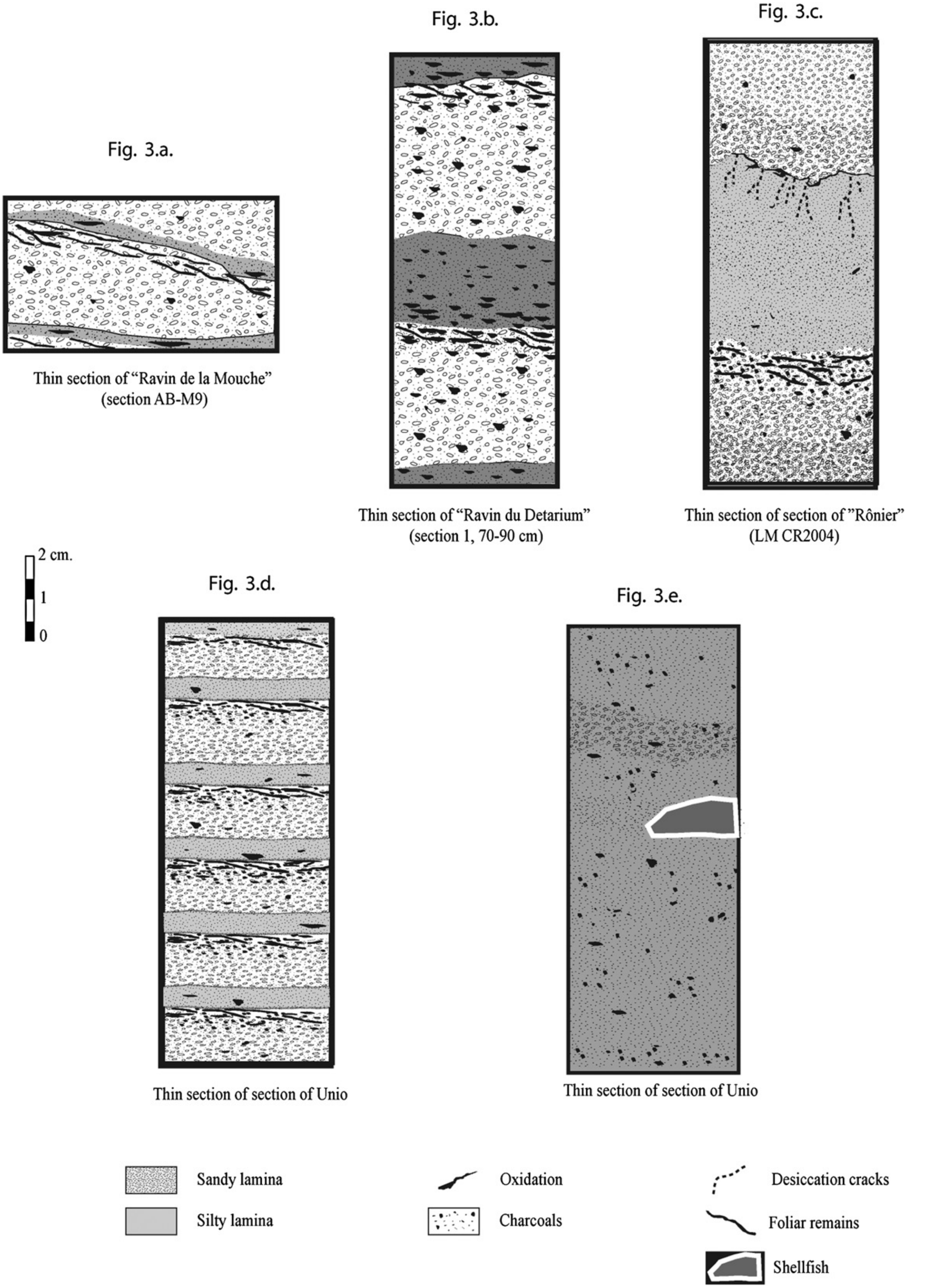

Fig. 3. Thin-sections of alluvial deposits: 3a: Early Holocene (Ha4, 8115 ± 50 BP). 3b: Middle Holocene (HM4, 6187 ± 58 BP). 3c: Recent Holocene (HR2, between 2641 ± 36 & 2400 ± 50 BP). 3d: Final Holocene (HT4, between 935 ± 33 & 870 ± 30 BP). 3e: Final Holocene (HT6, between 255 ± 45 & 155 ± 30 BP).

Fig. 3. Lames minces des dépôts alluviaux. 3a : holocène précoce (Ha4 : 8115 ± 50 BP) ; 3b : holocène moyen (HM4 : 6187 ± 58 BP) ; 3c : holocène récent (HR2 : entre 2641 ± 36 et 2400 ± 50 BP) ; 3d : holocène final (HT4 : entre 935 ± 33 et 870 ± 30 BP) ; 3e : holocène final (HT6 : entre 255 ± 45 et 155 ± 30 BP).

are presented in the context of the chronological basis established through the preceding archaeological and stratigraphic research (Huysecom et al., 2004; Huysecom et al., 2008; Huysecom et al., in press; Lespez et al., 2008; Rasse et al., 2006). The sedimentary sequences are grouped into 11 terms divided into four broad periods, fairly uniform with respect to the operation of the river system, and can be described by the specific organization of the macro- and micro-sedimentary facies (Fig. 4). These initial results permit proposal of a general interpretation of the hydrosedimentary record of the Yamé Valley, which has then been compared with the palaeoenvironmental data available for North Tropical Africa (Fig. 5).

4. The beginning of the African Humid period: 11.5-8.5 ka cal BP (Early Holocene)

Following a still poorly understood vigorous incision phase between the Pleistocene and Holocene formations (Lespez et al., 2008), sedimentation begins with the Early Holocene. It is dominated by bedded and detritic alluvial formations, ochre-red or gray, formed by medium to coarse sands and centimetric gravels with oblique and sometimes intersecting sedimentation (HA1, HA4). These formations are interrupted twice (HA2-HA3, HA4) by finer sedimentation characterized by the alternation of sandy-gravel beds (1–3 cm thick) and thin layers of fine sands and gray sandy silts (around 0.5 mm thick) containing abundant organic material (leaf remains, charcoal) in sub-horizontal position. Micromorphological analysis of the fine sequences indicates the absence or weak development of oxidation bands and desiccation cracks affecting the thinnest laminae while the charcoal particles are rare and very small (Fig. 3Fig. 3a).

Coarse detritric formations and their sedimentary organization indicate a wide bed with sandy gravel banks and strong competence and mobility (Neumann et al., 2009). This braided bed was established during most of the Early Holocene and follows a phase of weak morphogenesis that typifies the end of the Pleistocene and shows a spectacular period of channel incision more than 10 m deep into the Pleistocene formations (Rasse et al., 2006). This succession demonstrates the transition from a period of hydrological abundance promoting the increase of the liquid rates of discharge and the incision, during a period of stabilization of these rates while runoff continued to contain an elevated solid component. Taking account of the available chronological limits (*ante* 10.3 ka cal BP), this succession could be interpreted as reflecting the establishment of humid climatic conditions at the beginning of the Holocene due to a rapid reactivation of the monsoon in Northwest Africa after the Late Dryas (Garcin et al., 2007; Gasse, 2000; Lézine, 1998). Over this period, the rhythmic sediments that typify certain phases of HA2-3 and HA4 evidence a temporary slowing of the alluvial morphodynamics (11.4–10.6 ka cal BP then after 9.3 ka cal BP). The Yamé Valley was next followed by a rambling bed with minor competence within a fairly wide flood plain, characterized by a seasonal pattern of sedimentation. The rainy season contributed to rambling flow with strong competence in a wide sandy gravel bed while the dry season led to decantation deposits in permanent pools as shown by the absence of desiccation evidence at the top of the fine deposits attributable to the dry season. Moreover, for the first time in the sedimentation, the abundance and nature of organic material evidences the importance of the vegetal cover in the valley base (riverain) and slopes (Eichhorn and Neumann, 2007; Neumann et al., 2009). This indicates the transition to a calmer river system that can be explained by the reconquest of vegetation on the slopes and in the base of the valley, limiting the sedimentary contribution to the talweg. This change typifies the entire Sahelian zone, which saw the rapid development of tree species with Guinean and Sudanian affinities in the open savannas persisting from the preceding periods (Lézine, 1989; Maley, 1981; Salzmann et al., 2002).

5. Hydrosedimentary change and its significance during the African Humid period: 8.5 to 4 ka cal BP (Middle Holocene and Late Holocene 1)

A break in sedimentation is first observed for more than a thousand years (8.8–7.4 ka cal BP). This sedimentary hiatus is one of the key phenomena in the Holocene chronostratigraphy of the Yamé Valley. It follows a period of affirmation of the seasonality and slowing of the hydrosedimentary dynamics (post 9.3 ka cal BP). The lack of evidence of sedimentation must be put into relation with the weakness of the available flow since sedimentary stock that could be mobilized was present on the valley slope. These observations, that indicate a significant change in the hydrological history, should be combined with the rapid and generalized lowering of the level of many African lakes affected by the monsoon climate (Gasse, 2000). This is interpreted as a dry event recorded more or less synchronously in most African lakes between 9 and 8 ka cal BP, but remains poorly understood (Shanahan et al., 2006).

During the next phase (7.4–4 ka cal BP), bedded and detritic alluvial formation were deposited in the base of the valley, formed of medium to coarse sands and centrimetric gravels, systematically interrupted by more complex gray to black formations with or without a strong charred organic material component. These formations correspond to the alternation of detritic beds of fine to medium-grained white to gray sands (1–5 cm) including a higher quantity of charcoal particles of larger size (>1 cm) and beds of fine sands and silts (1–2 cm) containing abundant charcoal particles and macro-vegetal material (leaves, seeds). Despite much post-depositional bioturbation (termite action), micromorphological analysis confirms the rhythmic structure of the sediments (Fig. 3b). It also shows a strong concentration of organic material, charred or not, in sub-horizontal position at the top of sandy laminae before thinner sandy silt laminae. At the top of the latter, oxidation bands are quite rare while desiccation cracks are generally absent. The structure of the sediments, the nature and importance of the macro-vegetal material indicates the infilling of narrow channels within an alluvial plain and slopes characterized by a dense gallery forest with Guinean affinities (Eichhorn and Neumann, 2007; Le Drézen, 2008). A channel with a discharge of strong competence and a sandy sedimentation then characterized the rainy season while the competence of discharge decreased during the dry season, leading to low energy deposits in permanent pools. These formations evidence a hydrological abundance that typifies the wet period recorded across tropical West Africa until around 5 ka cal BP (DeMenocal et al., 2000; Gasse, 2000; Lézine, 1998; Servant, 1983). Across most of the Sudano-Sahelian region of West Africa, this corresponds to the affirmation of humid zones characterized by hygrophilous vegetation with Guinean affinities within a dense savanna with trees (Ballouche and Neumann, 1995; Salzmann et al., 2002). This equilibrium appears to have been upset during a short period with a new sedimentary hiatus (6.7–6.5 ka cal BP), which may be the expression of a temporary depletion of discharge corresponding to a prolonged hydrological deficit indicated by the fall in the level of many African lakes around 7.2 to 6.5 ka cal BP (Gasse, 2000; Gasse, 2005; Shanahan et al., 2006). More generally, the abundance of charcoal of all sizes, including many identifiable as riverain (Eichhorn and Neumann, 2007), raises the question of a human origin of the fires. Unfortunately, the rarity of archaeological material attributable to this period makes it impossible to verify such a hypothesis.

6. Hydrosedimentary changes and desiccation from 4 to 2.4 ka cal BP (Late Holocene 2)

The sediments of the second part of the Late Holocene are deposited in discordance with earlier formations and evidence a prior erosion phase without a prolonged sedimentary hiatus (Lézine, 1998). The sedimentary facies change clearly. The sedimentation corresponds to bedded formations organized in six successive sequences characterized by the alternation of silty sand beds (1–2 cm) rich

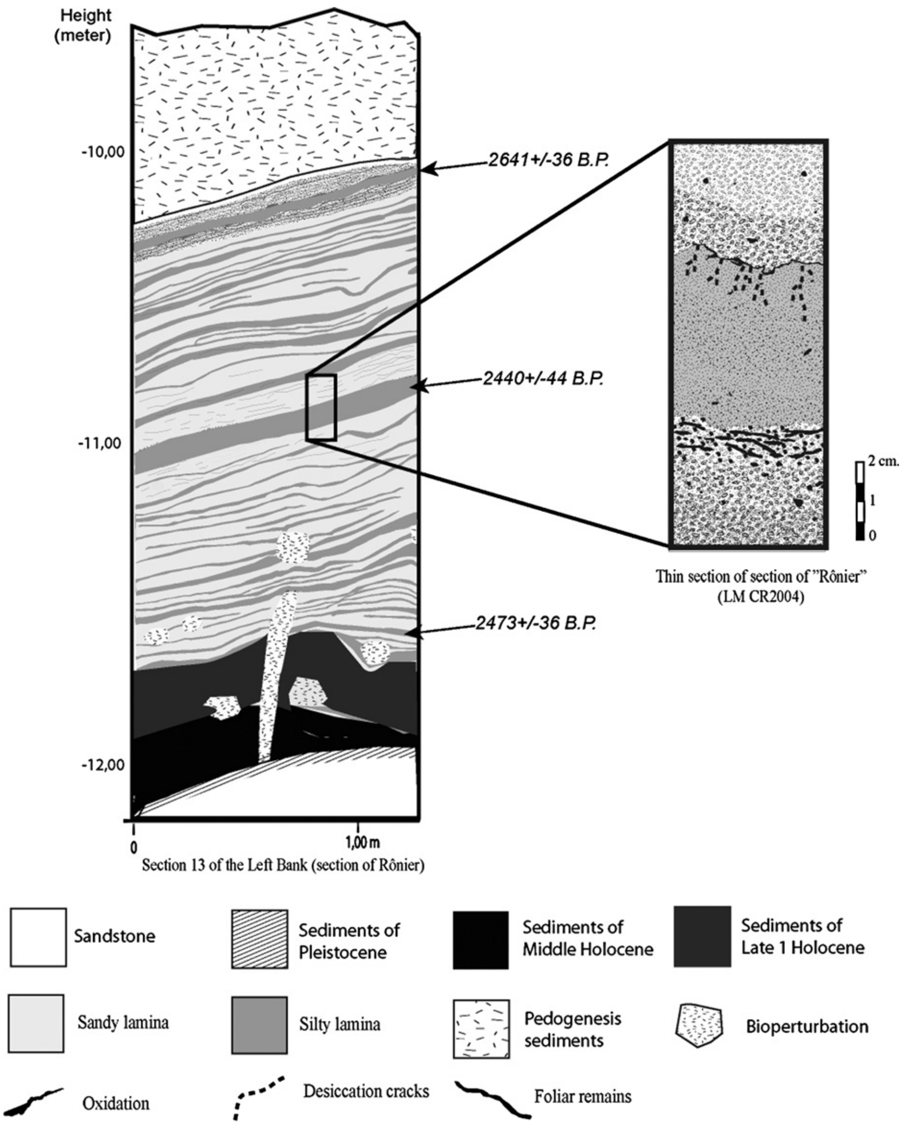

Fig. 4. Section at Rônier and thin-section of the sediments in the HR2 period.

Fig. 4. Coupe chronostratigraphique à Ronier et lame mince des sédiments de la période HR2.

in charcoal and macro-vegetal material (leaves, seeds) and silty beds with fine sands (0.5–1 cm) containing many charcoal particles. This alternation of coarse and fine sediments forms sequence that include 100 to 200 pairs of laminae in sequences lasting between 100 and 300 years based on radiocarbon dates (Fig. 5). The silty sand laminae contain rare coarse rounded charcoal particles. They are overlain by organic layers with abundant leaf material, seeds and elongated charcoal particles in sub-horizontal position. The sandy silt laminae are characterized by vertical positive graded bedding and are rich in fine elongated charcoal particles in sub-horizontal and/or vertical position (Fig. 3c). At their summit, an oxidation horizon and desiccation cracks (Fig. 4) are present and are increasingly clear between 4 to 2.4 ka cal BP (Lézine, 1998).

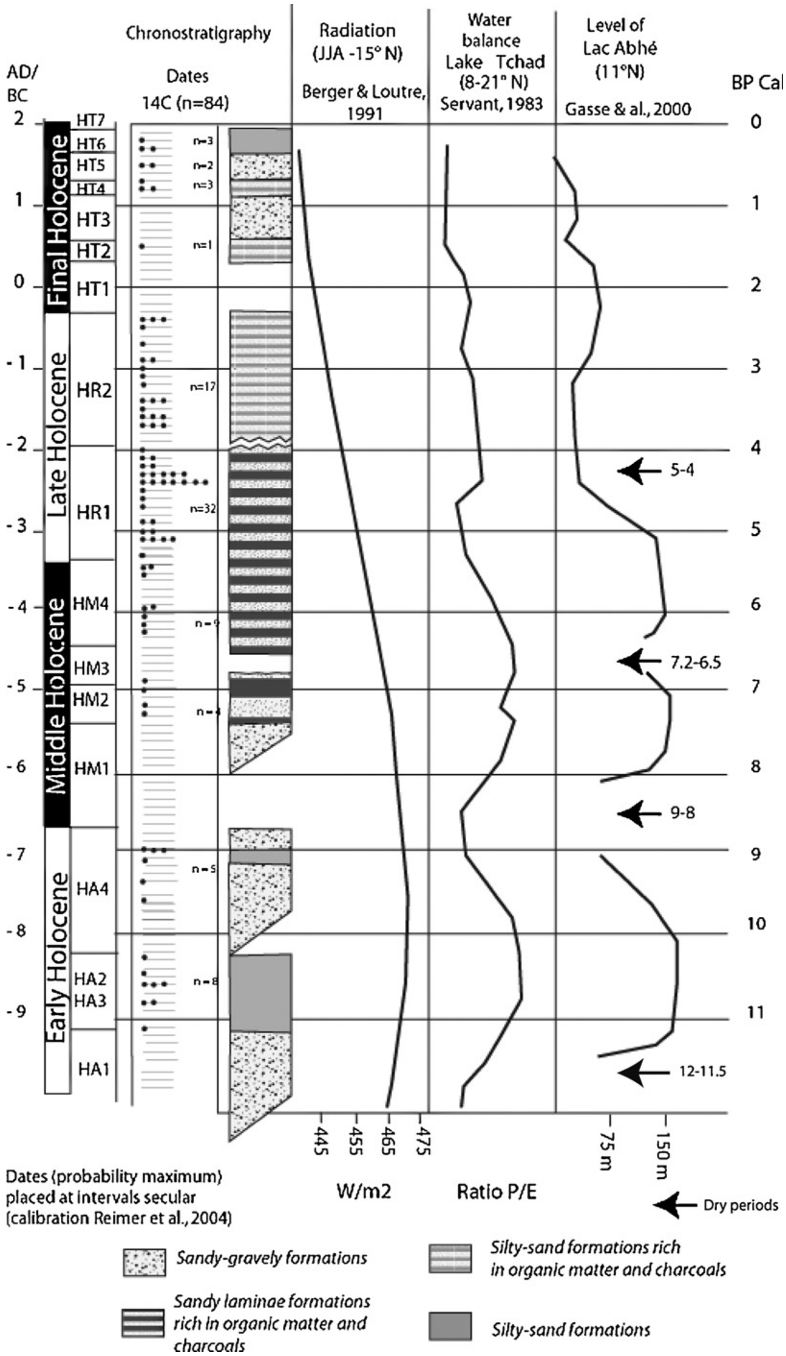

Fig. 5. Synthetic chronostratigraphy of the alluvial filling at Ounjougou and comparison with palaeoclimatic data from northern tropical Africa.

Fig. 5. Chronostratigraphique synthétique du remplissage alluvial du site d'Ounjougou et comparaison avec les données paléoclimatiques de l'Afrique nord-tropicale.

These sediments evidence a new metamorphosis of the Yamé Valley. The granulometry of high energy sedimentation in the channels clearly decreases while affirmation of deposition of material in suspension in environments of low energy indicate the predominance of slow and slight morphogenetic discharge in an alluvial plain characterized by a paludal environment and residual pools. This change is the cause of conservation of a sedimentation, which is clearly regulated by the seasons. The silty sand laminae were deposited at the beginning of the rainy season, with a contribution of coarse and fine sands by runoff. Sandy silt laminae, typical of seasonally functioning residual pools, indicate the presence of a stretch of calm water whose depth decreased with the advancing of the dry season. Complete drying at the end of the dry season caused superficial oxidation and desiccation cracks observed in thin sections. This sedimentation attests to an increase in the duration and/or the intensity of the dry season. This is in agreement with data in Sahelian and Sudanian Africa indicating an increase in aridity between 5 and 3 ka cal BP (DeMenocal et al., 2000; Gasse, 2000; Lézine, 1998; Makaske, 1998), often connected with a dry period dated to around 4 ka cal BP (Gasse, 2000; Marchant and Hooghiemstra, 2004).

At the same time, the abundance of charcoal, their presence in each thin or coarse lamina and the absence of inversion of ^{14}C dates for the period concerned confirm the regularity of the fire signal and the influx of charcoal in the valley. This indicates savanna landscapes with Sudano-Sahelian affinities, annually crossed by fire, with a gallery forest that persists (Le Drézen, 2008; Le Drézen and Ballouche, in press). The regularity and importance of fires in the valley slopes to the banks of the Yamé suggest an anthropic origin and their inclusion in an emergent agrosystem (Eichhorn and Neumann, 2007; Le Drézen, 2008), which is also supported by archaeological evidence (Ozainne et al., 2009). During the same period, other sites in West Africa show the development of agriculture (Huysecom et al., 2004).

7. From 2.4 to 0.1 ka cal BP, an increasing human impact (Final Holocene)

The final period of the Holocene begins with a phase without significant sedimentation (2.4–1.7 ka cal BP) (Le Drézen, 2008; Le Drézen et al., 2006). This sedimentary hiatus, again recorded for nearly a thousand years (2.4–1.7 ka cal BP), is similar to that recorded at the beginning of the Holocene and the same interpretation can be proposed. This is very likely in connection with the period of greatest drought recorded in the Inner Niger Delta (Makaske, 1998), but also in most of the African lakes around 2 ka cal BP (Gasse, 2000; Gasse, 2005; Russel and Johnson, 2005).

Next, bedded and detritic alluvial formations formed of beds of medium to coarse sands containing centimetric gravels and with oblique, sometimes intersecting, sedimentation, alternate with sub-horizontal beds of fine sands and gray sandy silts containing some organic material. Micromorphological analysis of these Final Holocene deposits shows regulated sediments (Fig. 3d) in which silty laminae (a few millimeters thick) and fairly coarse sands (a few millimeters thick) alternate. The finest laminae are very rich in small charcoal particles and organic material (leaves, seeds, algae). It is possible to identify some traces of desiccation and oxidation bands, but they are less developed in comparison with the preceding period (Le Drézen, 2008; Lespez et al., 2008). Near the top, the fine sequences demonstrate the progressive disappearance of alternating silty and sandy laminae, replaced by very dense silts rich in algae, shells and abundant elongated charcoal particles (Fig. 3e). Instability of sedimentation is the rule. The formations observed indicate the succession of periods characterized by active discharge in fairly large channels and periods in which the channels are narrower in the middle of an alluvial plain containing many residual pools. This instability recorded in the Inner Niger Delta is also present in many African regions (Maley, 1981) and may be due to climatic instability (Nicholson, 2000), but also due to an increasing human influence on the valley slopes (Le Drézen and Ballouche, in press; Le Drézen and Ballouche, 2009; Mayor et al., 2005) that makes it difficult to decode the rates of alluvial sedimentation over the last two thousand years.

8. Conclusion

The hydrosedimentary system of the Yamé is an excellent record of Holocene palaeoclimatic and palaeoenvironmental fluctuations in Sudano-Sahelian West Africa. It confirms the expression of palaeoclimatic fluctuations recorded in African lakes and thus offers a new continental milestone for understanding of the environmental effects of Holocene monsoon oscillations evidenced in the east in the central Sudano-Sahelian lakes and in East Africa. The potential achieved by these initial chronostratigraphic analyses demonstrate the relevance of river systems as a palaeoenvironmental record. Future investigations will be focused on higher resolution analysis of the sedimentary dynamics for each of the periods defined. In addition, multiparametric analyses, in particular those for bio-indicators (fire signal, palynology, phytolith analysis), will be developed in order to examine in more detail the role of human and palaeoclimatic factors in the Holocene dynamics of Sudano-Sahelian hydrosystems.

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