Quaternary Science Reviews 191 (2018) 348–362

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Pedo-sedimentary constituents as paleoenvironmental proxies in the Sudano-Sahelian belt during the Late Quaternary (southwestern Chad Basin)

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A R T I C L E I N F O

Article history:
Received 26 October 2017
Received in revised form
11 April 2018
Accepted 16 May 2018

Keywords:
Pedogenic carbonate nodules
Vertisol genesis
Soil water balance
Optical methods
Radiogenic isotopes
Quaternary
Monsoon
Western Africa

A B S T R A C T

Climate and environmental changes since the Last Glacial Maximum in the tropical zone of West Africa are usually inferred from marine and continental records. In this study, the potential of carbonate pedo-sedimentary geosystems, i.e. Vertisol relics, to record paleoenvironmental changes in the southwestern part of Chad Basin are investigated. A multi-dating approach was applied on different pedogenic organo-mineral constituents. Optically stimulated luminescence (OSL) dating was performed on the soil K-rich feldspars and was combined with radiocarbon dating on both the inorganic ($^{14}C_{inorg}$) and organic carbon ($^{14}C_{org}$) soil fractions. Three main pedo-sedimentary processes were assessed over the last 20 ka BP: 1) the soil parent material deposition, from 18 ka to 12 ka BP (OSL), 2) the soil organic matter integration, from 11 cal ka to 8 cal ka BP ($^{14}C_{org}$), and 3) the pedogenic carbonate nodule precipitation, from 7 cal ka to 5 cal ka BP ($^{14}C_{inorg}$). These processes correlate well with the Chad Basin stratigraphy and West African records and are shown to be related to significant changes in the soil water balance responding to the evolution of continental hydrology during the Late Quaternary. The last phase affecting the Vertisol relics is the increase of erosion, which is hypothesized to be due to a decrease of the vegetation cover triggered by (i) the onset of drier conditions, possibly strengthened by (ii) anthropogenic pressure. Archaeological data from Far North Cameroon and northern Nigeria, as well as sedimentation times in Lake Tilla (northeastern Nigeria), were used to test these relationships. The increase of erosion is suggested to possibly occur between c. 3 cal ka and 1 cal ka BP. Finally, satellite images revealed similar geosystems all along the Sudano-Sahelian belt, and initial $^{14}C_{inorg}$ ages of the samples collected in four sites gave similar ages to those reported in this study. Consequently, the carbonate pedo-sedimentary geosystems are valuable continental paleoenvironmental archives and soil water balance proxies of the semiarid tropics of West Africa.

1. Introduction

In the tropical zone of West Africa, major climatic changes are documented in marine (e.g. deMenocal et al., 2000; Lézine and Cazet, 2005; Weldeab et al., 2007) and lacustrine (Gasse, 2000; Shanahan et al., 2015) sedimentary sequences since the Last Glacial

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https://doi.org/10.1016/j.quascirev.2018.05.022
0277-3791/

Maximum (LGM, 26.5–19 ka BP). Following arid conditions recognized during the LGM period, climate became wetter since 14.8 cal ka BP, i.e. at the beginning of the African Humid Period (AHP), until c. 5 cal ka BP (ODP 658C; ~20°N; deMenocal et al., 2000). The timing of the end of the AHP was shown to vary with the latitude due to the southward migration of the maximal northern extension of the monsoon system (Shanahan et al., 2015), and it is thought to have occurred between 8 cal ka and 4.5 cal ka BP over northern Africa (Wright, 2017). Climate changes directly influenced the water budget at the surface of the continent, impacting the dynamic of landscape evolution in both aquatic (rivers and lakes) and terrestrial (vegetation and soils) environments. These environmental changes are tracked in sparse continental sedimentary sequences, or geosystems, such as lacustrine, alluvial, or palustrine environments (e.g. Gasse, 2000; Lézine et al., 2011; Sangen et al., 2011). The occurrence of soil layers in these sedimentary sequences is generally interpreted as boundaries and/or as a hiatus in the sedimentary record, while they can contain precious paleoenvironmental information (e.g. Retallack, 2001).

Soil dynamic relates directly to the environmental conditions at the time of their formation (Jenny, 1941). Paleosols, as terrestrial sediment archives, can thus be used to describe past environments and to assess the various basin-scale sedimentary and biogeochemical processes (Hyland and Sheldon, 2016). They are precious large-scale paleo-landscape archives and many pedogenic components, such as weathering products, secondary salts or organic compounds, are used as proxies for paleoprecipitation, paleotemperature, or paleovegetation reconstructions, respectively (see references in Hyland and Sheldon, 2016). Nevertheless, in order to capture lateral physico-chemical variations in soils, it is now clear that a multi-proxy approach is needed (Tabor and Myers, 2015). Therefore, this study aims at showing the potential of carbonate pedo-sedimentary geosystems to act as paleoenvironmental archives. Such geosystems were described and investigated in the southwestern part of the Chad Basin (Diaz et al., 2016a, Fig. 1A–B). They are (i) clay-rich/smectitic-rich, (ii) enriched in pedogenic carbonate nodules, and (iii) display mound morphologies, termed "mima-like" mounds, within present-day stream networks (Diaz et al., 2016a, Fig. 1C). They were interpreted as Vertisol relics, i.e. degraded Vertisols, which can be considered as soil-sediment functional continuums resulting from a four-step (S) succession of sedimentary and pedogenic processes: (S1) the soil parent material deposition, comprising a mixture between aeolian and saprolite compounds (Dietrich et al., 2017), (S2) the soil development and associated organic matter integration, (S3) the precipitation of secondary pedogenic carbonates, and (S4) the increase in erosion leading to the present-day "mima-like" mound landscape (Diaz et al., 2016a). This relative four-step chronological succession must reflect environmental changes responding to condition changes driven by external factors, i.e. climate and/or human activity. However, the numerical chronology of this succession, which would allow these environmental transitions to be compared to regional (or global) climate changes, still remains unresolved. In order to address this issue, three different constituents of the pedogenic carbonate nodules sampled in the Vertisol relics have been dated using different methods.

K-rich feldspar minerals trapped within the nodules constitute a residual fraction of the host soil (Diaz et al., 2016a). Optically Stimulated Luminescence (OSL) dating was applied to this mineral fraction to assess the deposition age of the soil parent material (S1). Radiocarbon dating was performed on the organic ($^{14}C_{org}$) and inorganic ($^{14}C_{inorg}$) carbon fractions of nodules, in order to date the soil organic matter integration (S2) and the carbonate nodule precipitation (S3), respectively. Finally, the increase in erosion (S4) was not directly dated but tentatively assessed using archaeological records from Far North Cameroon and Nigeria, in combination with lacustrine sedimentation rates in Lake Tilla (northeastern Nigeria). Comparing the resulting ages with the Chad Basin stratigraphy and West African records, our results allow to assess (i) how did the pedo-sedimentary geosystem respond to environmental changes, and (ii) how did it record them. Finally, preliminary studies show that similar carbonate geosystems seem to occur beyond our local study area, encompassing the whole Sudano-Sahelian belt. Such observations are promising for further paleoenvironmental studies, particularly in these areas, where low preservation of conventional paleoenvironmental records, e.g. lacustrine sediments, due to erosion and/or organic fraction mineralisation, usually results in a lack of paleoenvironmental data (Chase, 2009; Bristow and Armitage, 2016; Cordova et al., 2017).

2. Material and methods

2.1. General settings

The Far North Region of Cameroon belongs to the Sudano-Sahelian belt of West Africa (Fig. 1A). The study site is located in the Diamare piedmont near Maroua, in the southwestern part of the Lake Chad Basin (Fig. 1B). The piedmont lies between the Mandara Mountains, which are mainly granitic and gneissic (Brabant and Gavaud, 1985), and the Yayres floodplain belonging to the Logone River watershed. Precipitation varies gradually (Fig. 1B) from 1000 mm yr^{-1} in the Mandara Mountains (Mokolo) to 800 mm yr^{-1} in Maroua and 600 mm yr^{-1} in Waza. Mima-like mound areas are widespread in all the piedmont (Fig. 1B) and are associated with clay-rich sediments (Diaz et al., 2016a). From the Mandara Mountains to the Yayres floodplain, these clay-rich sediments are intercalated with some arenitic sands, evolving from colluvium to alluvium (Morin, 2000). The grain-size distribution of the mima-like mounds is characterized, on average, by 32 ± 12.8% (n = 186) clay (<2 μm), with a maximum of 67% (Diaz et al., 2016a). High proportions of smectite are also present, comprising an average of 34 ± 7% (n = 25) of the total clay fraction. The soil structure is prismatic to massive, with localized vertical cracks and secondary minerals, such as calcitic nodules and Fe-Mn-oxyhydroxyde micro-nodules, found in abundance at the surface but also at various depths. These characteristics point to Vertisol properties (Wieder and Yaalon, 1974; Wilding, 2004; Southard et al., 2011), however these mima-like mounds are rather truncated Vertisols. They are essentially mineralogenic, with organic content <1%. Moreover, as mentioned above, calcitic nodules and Fe-Mn-oxyhydroxyde micro-nodules are found in high proportions at the soil surface and are interpreted as a remnant part of a former deeper Bk (i.e. calcic) horizon (Diaz et al., 2016a). As these nodules outcrop at the mima-like mound surface, the mima-like mounds are interpreted as Vertisol relics, implying that these soils are no longer in equilibrium with present-day environmental conditions (Retallack, 2001).

2.2. Sampling

Thin section observations of carbonate nodules showed that they are composed of a residual soil fraction cemented by calcite (Diaz et al., 2016b). This trapped soil fraction is composed of primary minerals, clays, and little amount of organic matter. The dating of these constituents, i.e. K-rich feldspar primary minerals with OSL, organic matter and carbonate with ^{14}C, aims at understanding the chronology of S1, S2 and S3 pedo-sedimentary steps. Nine carbonate nodules were selected at different depths, from 0 to 130 cm, in a mima-like mound (M1) located at the main study site (Fig. 1B). Geomorphological settings and pedogenic characteristics