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Paleoenvironmental reconstruction of the Asbole fauna (Busidima Formation, Afar, Ethiopia) using stable isotopes ☆

Reconstruction paléoenvironnementale de la faune d'Asbole (Formation de Busidima, Afar, Éthiopie) utilisant les isotopes stables

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Abstract

The Middle Pleistocene environmental and climatic conditions at Asbole, lower Awash Valley, Ethiopia were reconstructed using stable carbon and oxygen isotopic composition (^{13}C, ^{18}O) of fossil tooth enamel coupled with faunal abundance data. We analyzed the isotopic composition of a total of 80 herbivorous tooth enamel samples from 15 mammalian taxa, which archive the dietary preferences and drinking behavior from the ''Asbole faunal zone''. The carbon isotopic data signify a wide range of foraging strategies, across the entire spectrum of pure C4 to C4-dominated diet, mixed C3/C4 diet and C3-dominated diet. The oxygen isotopic enrichment between evaporation sensitive and insensitive taxa ($\varepsilon_{ES\text{-}EI}$) is 3.7‰ which provides an estimate of the mean annual water deficit of the Middle Pleistocene at Asbole of 1470 mm, a value characteristic of modern arid landscapes in this part of the Awash Valley. The isotopic data coupled with faunal abundance data indicate an arid C4-dominated open-vegetated region, with an abundance of forest-dwelling primates that identify the presence of gallery forests flanking tributary streams to the paleo-Awash River. Thus, with these combined methodologies, it is possible to explicate a more detailed character of the ''mosaic'' of environments characteristic of Neogene savanna ecosystems. These findings, clearly indicate the importance of avoiding oversimplification of Pleistocene environmental reconstructions, based on single proxies at isolated localities.

Keywords: Asbole; Ethiopia; Carbon and oxygen isotope; Tooth enamel; Paleoenvironment

Résumé

Les conditions environnementales et climatiques du Pléistocène moyen à Asbole, dans la basse vallée de l'Awash (Éthiopie), ont été reconstituées en utilisant les compositions isotopiques du carbone (^{13}C) et de l'oxygène (^{18}O) de l'émail dentaire fossile, combinées avec des données de proportions fauniques. Nous avons analysé l'abondance isotopique des 80 prélèvements d'émail dentaire provenant de 15 taxons des mammifères, qui archivent les préférences alimentaires et les comportements de boisson de la « zone faunique d'Asbole ». Les données isotopiques du carbone indiquent des stratégies d'approvisionnement variées, à travers tous les régimes entre C4 pur et C3-dominé. L'enrichissement isotopique en ^{18}O entre les taxons « sensibles à l'évaporation » et les taxons « insensibles à l'évaporation » ($\varepsilon_{ES\text{-}EI}$) est de 3,7‰, fournissant une évaluation du déficit annuel de l'eau durant le Pléistocène moyen à Asbole de 1470 mm, une valeur caractéristique des paysages arides modernes dans cette partie de la vallée de l'Awash. Les données isotopiques combinées avec celles d'abondance faunique témoignent d'une région ouverte et aride, dominée par une végétation en C4, avec une abondance de colobes qui montrent la présence des forêts galeries flanquant des fleuves tributaires du paleo-Awash. Ainsi, avec ces approches combinées, il a été possible de préciser les caractéristiques de la « mosaïque »

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d'environnements et d'écosystèmes néogènes de la savane à Asbole. Nos résultats indiquent clairement d'éviter, lors de reconstructions d'environnements pléistocènes, les simplifications excessives basées sur l'utilisation de proxys uniques et de localités isolées.

Mots clés : Asbole ; Éthiopie ; Isotope du carbone et de l'oxygène ; Émail dentaire ; Paléoenvironnement

1. Introduction

Measurements of natural variations in stable isotope ratios have become vital tools in fields as diverse as geochemistry, hydrology, ecology, and anthropology. The application of stable isotopes to paleoceanography and marine paleoclimatology has been spectacularly successful, revealing both long-term trends in marine climate and the response of the oceans to short-term orbital forcing and sudden events (Imbrie et al., 1984; Zachos et al., 1993). Isotopic reconstruction of conditions on land is more difficult, however, because terrestrial ecosystems and climates exhibit greater spatial and temporal heterogeneity and the isotope systems applied in these settings are more complex. Even so, over the past decade, there has been a surge in studies of continental paleoclimates and paleoenvironments, spurred by the increased need to understand the response of the more variable land ecosystems to past climate change (e.g., Swart et al., 1993).

Analyses of stable isotopes of carbon and oxygen extracted from fossils have contributed substantially to our understanding and ability to reconstruct paleoenvironmental and paleoclimatic parameters in the Neogene of tropical Africa, which is characterized by mixed C3 and C4 vegetation (Lee-Thorp et al., 1989; Morgan et al., 1994; Bocherens et al., 1996; Kohn et al., 1996; Cerling et al., 1997a, 1997b; Kingston, 1999a, 1999b; Sponheimer and Lee-Thorp, 1999a, 1999b, 1999c; Sponheimer et al., 1999; Zazzo et al., 2000). These approaches have been critical in documenting ecological shifts, elucidating hominin dietary adaptations, constraining vegetation types in past ecosystems, characterizing habitat heterogeneity in space and time, revealing dietary niche partitioning in fossil terrestrial communities, and correlating climatic perturbations and oscillations in terrestrial ecosystems (Kingston and Harrison, 2007). The present study uses stable isotopes of mammalian tooth enamel to assess the paleoclimate conditions and understand the distribution of different types of vegetation between 0.8–0.64 Ma at Asbole in the Awash Valley of Ethiopia, a site which has a direct relevance to the understanding of the paleoenvironmental contexts of Pleistocene hominins in the Horn of Africa (Geraads et al., 2004; Wynn et al., 2008).

2. Controls on the isotopic composition of tooth enamel

Stable carbon and oxygen isotopic analysis of tooth enamel has been established as a valuable tool for reconstructing terrestrial paleoenvironments (Bocherens et al., 1996; Koch, 1998; Franz-Odendaal et al., 2002; Kohn and Cerling, 2002; Cerling et al., 2003c; Sponheimer and Lee-Thorp, 2003; Schoeninger et al., 2003; Boisserie et al., 2005; Kingston and Harrison, 2007). Tooth enamel is an ideal substrate for preserving stable isotopic signatures because it is almost entirely inorganic and has very low porosity (>96% inorganic component by weight and <1% organic material; Wang and Cerling, 1994). The inorganic mineral phase of tooth enamel is hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), a relatively stable mineral in surface-weathering environments. As such, tooth enamel is less susceptible to diagenesis than bone or dentine because of its lower organic content, higher density, and larger crystalline size (Ayliffe et al., 1994; Bryant et al., 1994). Enamel forms by accretion without remodeling and mineralization is complete prior to tooth eruption. Like enamel, dentin grows by accretion with little remodeling (Lowenstam and Weiner, 1989). However, because of its resistance to diagenetic alteration, enamel is the most suitable fossilized material of vertebrates for paleoenvironmental study using stable isotopes (Wang and Cerling, 1994).

2.1. Carbon isotopes

The interpretation of carbon isotopic composition of tooth enamel is based on differences in isotope fractionation between plants that use the two major photosynthetic pathways (C3 and C4), and the consumption of C3 and C4 vegetation by mammalian fauna (Smith and Epstein, 1971). The C3 pathway is most common, occurring in the vast majority of trees and shrubs, as well as those herbs and grasses with a cool and relatively moist (i.e., non-evaporative) growing seasons. C3 plants have $\delta^{13}C$ values (mean ≈−27‰, range: −22 to −35‰) that are much lower than those of atmospheric CO_2 (≈−7.7‰; O'Leary, 1988). C4 photosynthesis is less common and occurs in grasses and some sedges and herbs, but only those that grow under sufficiently dry and/or warm (i.e., evaporative) growing season climates in which this energy-intensive pathway is able to gain a competitive advantage over the C3 pathway. C4 plants have $\delta^{13}C$ values (mean ≈−13‰, range: −19 to −9‰) that are more similar to those of the atmosphere (O'Leary, 1988).The crassulacean acid metabolism (CAM) pathway is least common, occurring in succulent plants adapted to arid climates. CAM plants fix CO_2 by both pathways, separating their use of each pathway during high and low light conditions, and thus exhibit a range of $\delta^{13}C$ values intermediate between those of C3 and C4 plants (Ehleringer and Monson, 1993).

Dietary differences are recorded in developing tissues of animal such as teeth with a relatively constant fractionation factor (Cerling and Harris, 1999). Because most C4 plants are tropical grasses, Koch (1998) suggest stable carbon isotope values can readily distinguish grazing from browsing mammals.