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Hydroclimatic conditions and fishing practices at Late Paleolithic Makhadma 4 (Egypt) inferred from stable isotope analysis of otoliths

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ABSTRACT

The late Paleolithic site of Makhadma 4, located along the Nile River in Upper Egypt, yielded an important ichthyofauna characterized by a very high proportion of tilapia (*Oreochromis niloticus*). We used isotopic analysis ($\delta^{18}O$) of well-preserved otoliths ("ear stones") of tilapia to reconstruct the former hydrological conditions, as well as the fishing strategies of the site's inhabitants. Otoliths from two modern fish captured in the Nile River near Esna were also examined to test how accurately tilapia otoliths reflect their ambient environment. All otoliths were sequentially micromilled to recover high resolution isotopic profiles along the main growth axis. Comparison of the modern otolith profiles with environmental data shows that tilapia $\delta^{18}O$ values record seasonal variations of the modern Nile hydroclimate but that their values are offset. The archaeological otoliths record very large intra-individual cyclical variations in $\delta^{18}O$ values, with relatively consistent amplitude, as well as very high seasonal maximum values (up to +8.3‰), compared with the modern otoliths. The hydrological regime of the water body in which the archaeological fish lived was characterized by a reduced Nile water inflow that could not negate the effect of local evaporation during spring. The reconstructed hydrological conditions are in accordance with a new model of Nilotic behavior that assumes the creation of lakes by damming of the Nile as a result of a high eolian activity during hyper-arid periods of the Late Pleistocene. Although large seasonal evaporation may have resulted in a severe seasonal reduction in the lake's volume and extent, the lake was, nevertheless, maintained for several years. Cyclic variations in otolith $\delta^{18}O$ values permit reconstruction of the period of the hydrological cycle during which the fish were captured. Fishing of young individuals occurred mostly after the maximum input of inflow water from the Nile, when evaporitic conditions were at their lowest, i.e. during fall.

1. Introduction

The discovery of numerous sites along the Egyptian Nile with abundant fish remains shows the importance of fishing in human subsistence from the Late Paleolithic onward (Van Neer, 2004). A recent revision of the archaeological and geomorphological data from the Late Pleistocene of the Egyptian Nile valley discusses the relations between human population densities, environmental conditions and behavior of the Nile River (Vermeersch et al., 2006; Vermeersch and Van Neer, 2015). Analysis of conventional and AMS ^{14}C dates demonstrates that in the Nile River Valley there were two main periods of occupation during the Paleolithic, namely, between about 23 and 20 ka calBP and, again, between about 16 and 14 ka calBP. The first period falls within Greenland Stadial 2.1c (GS-2.1c); the second period starts during Greenland Stadial 2.1a (GS-2.1a) and ends during Greenland Interstadial 1a (GI-1a) (Rasmussen et al., 2014; Vermeersch and Van Neer, 2015). The GS episodes coincided with sea surface cooling and extreme climatic conditions in many unglaciated regions, including the tropics (Stager et al., 2011; Castañeda et al., 2016; Drake and Breeze, 2016). They were among the most extreme and widespread megadroughts of the past 50,000 years in the Afro-Asian monsoon region, with

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potentially serious consequences for Paleolithic cultures (Stager et al., 2011). It is believed that during the Late Pleistocene, in particular during the Late Glacial Maximum, dunes from the Western Desert transitioned into the Nile Valley at several places in Upper Egypt, creating dams that resulted in the formation of lakes (Vermeersch and Van Neer, 2015). The flow of the Nile was reduced during these arid periods due to the absence of lake overflow in the headwaters of the White Nile (Williams, 2012) and the Blue Nile (Lamb et al., 2007). Because of this reduced discharge, the river could not erode all of the eolian sand. However, the lakes may not necessarily always have persisted for long periods; smaller lakes may have disappeared when the dunes were breached (Vermeersch and Van Neer, 2015).

The presence of lakes in the Nile Valley during GS-2.1c and GS-2.1a/GI-1 offered humans possibilities for food exploitation in otherwise very harsh climatic and environmental conditions. These water bodies attracted Late Paleolithic hunter-fisher-gatherers who relied heavily on fishing, as shown by the numerous fish remains found at some of the archaeological sites at high elevations, associated with eolian and Nilotic deposits. Examples of such sites with abundant fish remains – and that can be associated with lacustrine conditions – are the site of Makhadma 4 (Van Neer et al., 2000) and sites E–81-3, E–82-3 and E–81-4 at Wadi Kubbaniya (Gautier and Van Neer, 1989). Unlike the fish faunas from other Late Paleolithic sites, which are dominated by Nile catfish (family Clariidae), the fauna of the sites listed above show a high proportion of tilapia (tribus Haplotilapiini, previously called Tilapiini). Fish faunas dominated by tilapia are nowadays typical of both natural and artificial lakes (Petr, 1975; Agaypi, 1992). The occupation at Makhadma 4 is restricted to the second half of the Late Paleolithic with probably a repeated occupation over many years. The two main occupations occurred at the end of GS-2.1a and during the first part of GI-1e (start of the Bølling-Allerød chronozone). The ichthyofauna from Makhadma 4 is peculiar compared with that of other Late Paleolithic sites of the Nile Valley because it contains a large quantity of tilapia otoliths ("ear stones"). Previous reconstructions suggested that the site was contemporaneous with the "Wild Nile" stage, an irregular Nile regime, with floods reaching 6 m above the modern floodplain at Makhadma 4 (Van Neer et al., 1993). This "Wild Nile" was considered to have been a direct consequence of climatological changes from arid to (more) humid in the headwaters of the Nile, at the transition from isotopic stage 2 to isotopic stage 1. In this reconstruction, the annual flood would have created seasonal ponds in the floodplain, where fishing could have been practiced with a relatively limited output of labor at the time of minimum flooding (Van Neer et al., 1993). New interpretations of the archaeological, sedimentological and geomorphological data from the site, however, suggest a different behavior for the river, as well as the existence of a lake as a result of dunes blocking the Nile (Vermeersch and Van Neer, 2015).

Otoliths are accretionary calcium carbonate ($CaCO_3$) structures presenting growth marks (Campana and Neilson, 1985). The incremental growth and permanent nature of otoliths provides a continuous time series of a fish's environment over the organism's life span. Developments in micrometric sampling techniques associated with the measurement of oxygen isotope values ($\delta^{18}O$) have enabled the retrospective reconstruction of the complexity of life chronology (Wurster et al., 1999; Gerdeaux and Dufour, 2015). The presence of tilapia otoliths at Makhadma 4 offers an excellent opportunity to infer the hydrological conditions experienced by an organism living in the lake at the seasonal scale. This time scale is rarely reached by other past environmental indicators and otolith analysis will bring independent and complementary data to that brought by previous archaeological, sedimentological and geomorphological studies. Such reconstruction can also bring new insight into the fishing strategies of the site's inhabitants. Intra-otolith analysis of $\delta^{18}O$ values was performed on eight well preserved specimens that were first sequentially microsampled. Because this is the first time tilapia otolith isotope measurements have been used, the relationship between $\delta^{18}O$ values and environmental parameters, temperature and ambient water $\delta^{18}O$ values were first examined for two modern fish caught in the Nile River close to the site.

2. Nile River hydroclimate

The Nile River is about 6700 km long and flows South to North, emptying into the Mediterranean Sea (Dumont, 2009) (Fig. 1). North of about 18°N, from northern Sudan throughout Egypt, rainfall is negligible (below 50 mm a year), except along the northern Mediterranean coast (Alexandria 180 mm) (Camberlin, 2009). Egypt has a hot and dry desert climate characterized by a strong relationship between air and Nile water temperatures (Abdel-Satar, 2005). A sharp seasonal trend with a rise in water temperatures during summer up to 29 °C, followed by a gradual decline to a minimum of 16 °C in winter, has been observed at Minia (28°10′N) for the period 2007–2008 (Kobbia et al., 1991, Fig. 2a). The Minia record is similar to the temperature compilation obtained for multiple sites along the main Nile River in Egypt (Abdel-Satar, 2005).

Due to minimal precipitation, the waters of the Nile in most of Egypt originate from its tributaries, mainly the White Nile and the Blue Nile. They are sourced from meteoric waters that accumulate in Equatorial Africa for the White Nile (Lake Victoria) and the Ethiopian Plateau for the Blue Nile. The $\delta^{18}O$ values of water ($\delta^{18}O_w$), the relative contribution and the evaporation of these sources determine the ultimate $\delta^{18}O_w$ value of the Nile (Langman, 2015). The White Nile basin receives precipitation characterized by lower $\delta^{18}O_w$ values than the Blue Nile, but the White Nile streamflow is affected by strong evaporation in the Sudd region. Median $\delta^{18}O_w$ values of −4.8‰ and +2.43‰ were calculated upstream and downstream of the Sudd, respectively (Langman, 2015). The isotopic value of the White Nile streamflow is therefore higher than that of the Blue Nile, with mean values of +1.3‰ and −1.5‰, respectively (Malberg and Abd el Shafi, 1975). However, the overall contribution of the White Nile is small because of the dominance of the Blue Nile in the combined streamflow. The White Nile's influence is noticed only during the fall, when its contribution exceeds that of the Blue Nile (Langman, 2015). The wet period in the Ethiopian Highlands occurs from July through September. As a consequence, the flood of the Blue Nile peaks rapidly in late August to early September, with a rise of ~10 m above its low season flow at Khartoum, near the confluence of the Blue and White Nile rivers (Williams et al., 2000). It is the main driver of Nile River streamflow observed downstream (Fig. 2b). Due to evaporation over its long course, $\delta^{18}O_w$ values of the river undergo changes moving northwards. The local habitat $\delta^{18}O_w$ value will also depend on the volume of water received from the Nile and on local evaporation, especially in regions lacking input from local rainfall, such as the study region.

The construction of the Aswan High Dam resulted in a significant modification of the hydrodynamic regime of the Nile downstream from Aswan. The Nile's flow is now regulated, ensuring a regular, year-round freshwater supply for agricultural purposes. The annual flood that normally occurred in summer (Fig. 2b) has ceased. Due to the rarity or lack of precipitation in the region, the waters of the Egyptian Nile mainly reflect the High Dam Lake outflow. Air temperature fluctuations are therefore assumed to be the major factor controlling water seasonality of the modern Nile hydroclimate. $\delta^{18}O_w$ data available for the Nile $\delta^{18}O_w$ are scarce; they are summarized in Table 1. The effect of the High Dam on

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