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Seasonality in the early Holocene climate of Northwest Sudan: interpretation of *Etheria elliptica* shell isotopic data

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Abstract

The oxygen isotope ratios in the incremental growth layers in the shells of *Etheria elliptica* constitute a proxy record of rainfall patterns, and thus a record of seasonality. Analyses of shells of early Holocene age (6800 ^{14}C years BP or 5600 BC) collected from the lower reaches of Wadi Howar, near the confluence of that now-extinct river with the Nile, show an annual pattern of two rainy seasons in the present-day hyperarid southeastern Sahara, similar to that which prevails today in much of East Africa. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The study by Abell et al. (1996a) demonstrated that the freshwater oyster, *Etheria elliptica*, from the Winam Gulf of Lake Victoria accretes new layers of shell on the inner surfaces on a synodic or lunar monthly basis, with one discrete layer added to the inner surface each month. These layers were readily separated by heating under vacuum to destroy the protein matrix. Analyses of the individual layers and comparison with the penultimate layer of a series of shells collected at monthly intervals gave a series of isotope ratios which was clearly a function of shell growth, and correlated very well with rainfall patterns in the region, the more negative values of δ^{18}O corresponding to periods of heavier monsoonal rain. This technique could obviously be employed to elucidate seasonality in well-preserved "fossil" *E. elliptica* shells.

Application of this technique to some *Etheria elliptica* shells of early Holocene age from the lower reaches of Wadi Howar in northcentral Sudan (Fig. 1) would, therefore, be expected to provide information on past rainfall patterns of the area that was drained by that wadi which once was the largest tributary to the Nile (Pachur and Kröpelin, 1987; Kröpelin, 1993) and indicate whether the rainfall was monsoonal in character or more constant throughout the year. It has already been demonstrated that during the early Holocene, the northwestern Sudan was

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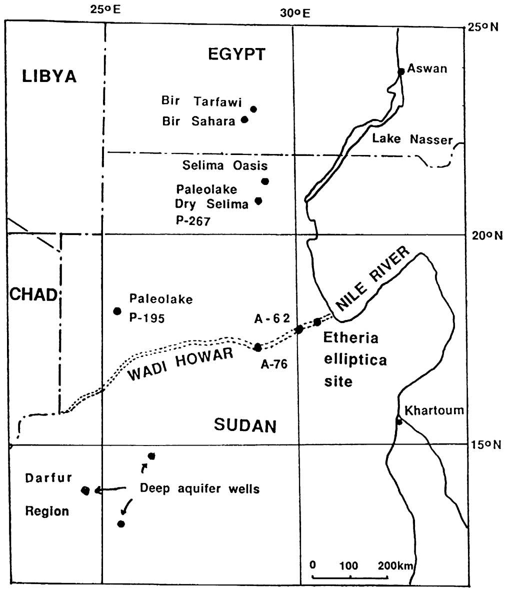

Fig. 1. Map of northwest Sudan and southwest Egypt showing the study area. Paleolakes have been identified at P-195 and P-267. The site from which *Etheria elliptica* shells were collected is about 50 km west of the former confluence of Wadi Howar with the Nile River.

substantially vegetated, with many shallow lakes, and inhabited by a wide variety of plants and animals and Neolithic man (Gabriel and Kröpelin, 1984; Haynes et al., 1989; Pachur and Hoelzmann, 1991; Kuper, 1994). The rainfall patterns or seasonality, i.e. monsoonal rains, would be expected to exert substantial control over the patterns of social behaviour of man and the biogeographical distribution of other life forms in the area, and have, therefore, been the focus of considerable interest (Abell et al., 1997).

For example, the northern side of Wadi Howar has numerous relict dunes, stabilised by a dense cover of Neolithic stone implements, pottery of Early Khartoum design (placing the first human occupation of the site somewhat older than 8000 years), and the remains of domesticated cattle (Gabriel et al., 1985). Indeed, Neolithic sites, fossil vertebrates and pollen data of similar age have been found over most areas of the Sahara, indicating that this early Holocene "greening" of the Sahara, possibly only as a consequence of substantial seasonal rains, was very widespread (Petit-Maire et al., 1995).

2. Geological context

2.1. Wadi Howar

At many localities along the lower Wadi Howar, there are gravel bars rising slightly above the surrounding, mostly sand-covered plain which otherwise shows no signs of any past fluvial activity. At a position 50 km west of the wadi's former confluence with the Nile, there is one such site (Site K 113; Fig. 1). This feature gives the impression of a unique depositional event. Backhoe sections show, however, that the pebble bars outcropping at the surface are merely the last event of a multiple fluvial cycle. The 270-cm-deep trench at this site produced a total of 11 gravel layers which serve as proof of fluvial processes under an elevated energy regime in the Lower Wadi Howar.

The early to mid-Holocene age assumed for these directly undatable sediments is based on their interlocking with adjacent Holocene lake and marsh sediments, in and on which there are numerous Neolithic sites, including burials with associated objects and large areas scattered with ancient pot sherds (Fig. 2a). Numerous bones of large mammals have been identified as elephant (*Loxodonta africana*), giraffe (*Giraffa camelopardalis*), roan antelope (*Hippotragus equus*) and other big bovines. Collagen dating of an elephant's jawbone yielded an age of 5430 ± 180 BP (Hv 15576; Kröpelin, 1993).

The geological and geomorphological evidence supporting a past fluvial environment in Lower Wadi Howar is also confirmed by biological indicators from other sites along the valley. These include large amphibian animals (*Hippopotamus amphibius*), reptiles (*Crocodylus niloticus*) and other wet biotope species such as the toad *Bufo regularis* (Kröpelin, 1993).

Various aquatic molluscs have been identified along the now extinct wadi. They include *Mutela nilotica*, the largest known bivalve of the Nile which lives on rocky ground and generally prefers greater water depths, *Corbicula fluminalis* which is by far the most frequent Nile bivalve and mainly occurs in backswamp areas and *Caelatura aegyptica* which can be found in brushwood along riverine banks.

The malacofauna of Lower Wadi Howar differs in very few respects only from the present-day Egyp-

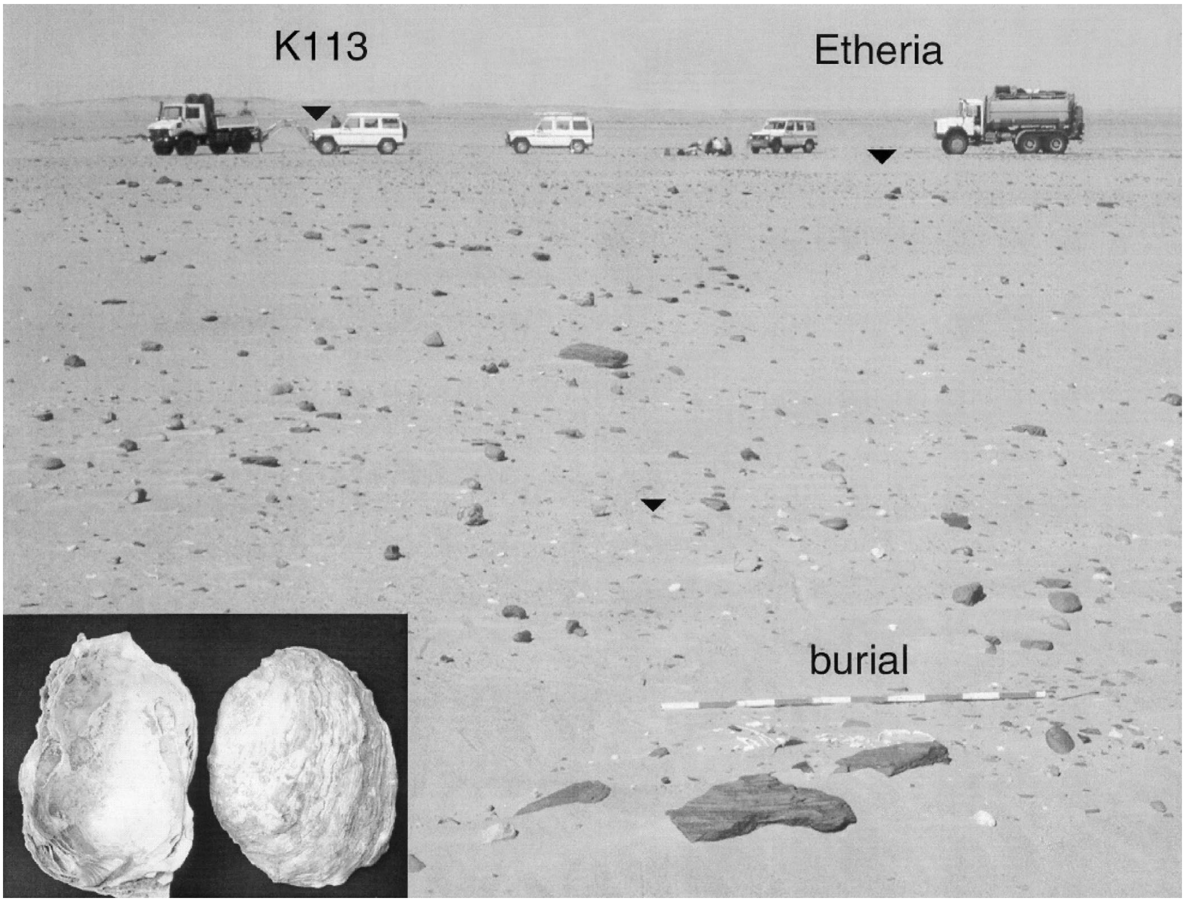

Fig. 2. Overview on site K 113 and shells of Nile oyster, *Etheria elliptica* (inset).

tian Nile fauna. The inferences drawn from the mollusc spectrum may be summed up as follows: "The [molluscan] fauna collected in Lower Wadi Howar is the typical fluviatile Nile fauna basically still inhabiting the middle and lower Nile today. It shows that this part of Wadi Howar has been a branch of the Nile" (Schütt in Kröpelin, 1993).

Apart from several Nile fish species like the pebbly fish *Alestes*, the perch *Tilapia zillii* and the shield-headed catfish *Synodontis* (Van Neer, 1988; Kröpelin and Soulié-Märsche 1991), river bivalves indicating running water such as *Aspatharia rubens* and *A. arcuta* are significant in this context.

Of particular interest for paleoclimatic inferences are the occurrences of the Nile oyster, *Etheria elliptica* (commonly referred to as the African freshwater oyster), at locality K 113 close to the gravel banks mentioned above. The 2–3-cm-thick shells of the specimens collected there are as much as 15 cm long and 10 cm wide (Fig. 2b). These river oysters need clear, well-oxygenated and hence flowing water, and mainly occur at the Nile cataracts. Like marine oysters, they are attached to rocks by one valve and can form sizable banks. Radiocarbon dates of 6835 $\pm$ 110 and 6635 $\pm$ 105 years BP (about 5600 BC) were obtained from these shells by Geochron Laboratories, Cambridge, MA (sample nos. GX-22370 and GX-22371).

3. Collection and treatment of shells

The *Etheria elliptica* shells analysed in this study consisted of a grouping of three shells that had grown together near their hinges. Only the half shells of these bivalves were in place in this specimen.

Unfortunately, the Wadi Howar shells provided complications in sampling as compared to the modern shells of Lake Victoria (Abell et al., 1996a). They contained numerous voids between the layers producing a shell structure in many places similar to corrugated cardboard or honeycomb, and only in a few sites on this group of shells was there satisfactory material in closely stacked contiguous layers suitable to provide a sequence of sufficient number of layers to span at least a full year of shell growth. However, a satisfactory site comprised of 15 layers, free of voids, was found near the hinge of one of the shells (Fig. 3). This site was sampled twice, a few millimetres apart, by cutting out small blocks of material with a diamond saw. These samples were baked at 400°C under vacuum to destroy any residual organic matrix and gave stacks of easily separable layers for carbon dioxide preparation and stable isotope measurement. The separation of the incremental growth layers, when the shell is heated, is presumably at the protein layer deposited at regular lunar monthly intervals when the organism cycles back to calcite deposition.

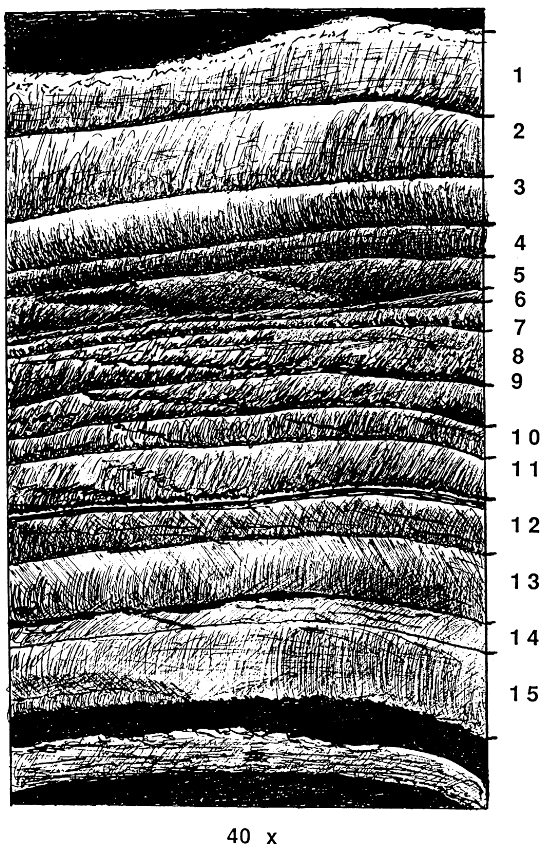

Fig. 3. Section of *Etheria elliptica* shell analyzed in this study. Magnification approximately 40×.

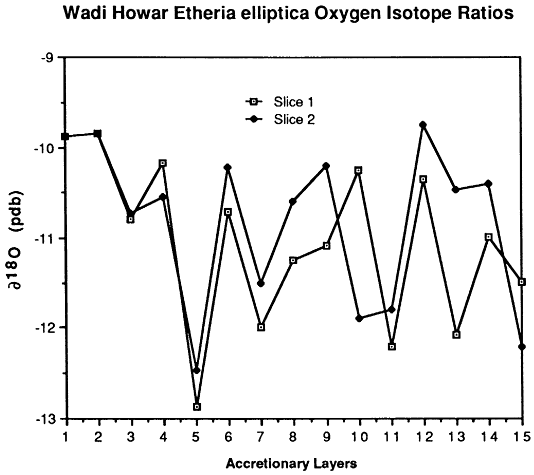

Fig. 4. Oxygen isotope ratios in *Etheria elliptica* shell plotted against accretionary layers identified in Fig. 3.

Carbon dioxide was prepared from these separated layers by treatment with 100% phosphoric acid on a vacuum line, followed by analyses using a V.G. Micromass 602-D mass spectrometer. Calibration of the instrument using an internal standard, which in turn was calibrated against the NBS-20 standard, enabled us to report the results, calculated in the usual way, against the PBS standard. These combined to give two sequences of isotope ratio measurements (Fig. 4), which, on the basis of the earlier work on the Lake Victoria *Etheria elliptica* specimens, we believe correlate with the prevailing rainfall pattern. The deposition of the aragonite in the nacreous layers of the shell produces a somewhat flaky texture which could sometimes be confused with the synodic layering, although for the most part the separation of the layers was obvious and clean.

4. Discussion and paleoclimatic conclusions

Etheria elliptica grows in the shallow waters of many of the streams and lakes of Africa, with only minor variations in shell morphology (Van Damme, 1984). This molluscan species is intolerant of salinity, alkalinity and desiccation. These habitat restraints provide us with some useful clues as to the climate along Wadi Howar during the early Holocene. Thus, we are assured that at the time these shells grew, Wadi Howar was providing them with a habitat of continuous freshwater in sufficient quantities to maintain the colony through any dry season that may have occurred. If monsoonal rains prevailed in the region, then storage of water in ponds and sediments upstream must have been sufficient to keep the wadi flowing to some degree throughout the year. The utilization of stable oxygen isotope ratios in the shells of freshwater molluscs of Africa to yield information on climatic conditions and/or seasonality at the time the mollusc was living is now a well-established technique (Abell, 1985; Abell et al., 1996a; Ayliffe et al., 1996).

Due to lack of information on the isotopic content or the temperature of the parent body of water, the interpretation can only be qualitative. Nevertheless, analysis of sequential populations or analysis of sequential accretionary layers in the shells of molluscs can provide valuable information. Analysis of the shells of molluscs in sequential populations can give indications of progressive changes in the climate in the area, while analysis of sequential. accretionary layers can yield valuable information on the seasonality. It must be assumed that the shell accretion is in isotopic equilibrium with the aqueous environment of the growing mollusc. However, relatively little is known concerning the process of shell building. Belcher et al. (1996) have demonstrated that crystal growth of aragonite in abalone shells (*Haliotis rufescens*) is under the control of specific polyanionic proteins. After initial deposition of a very thin calcite layer, the abalone shifts over to the production of aragonite under control of a different suite of polyanionic proteins, producing the polycrystalline plates which constitute the nacre of the shelf. Assuming that the deposition of incremental shell layers is substantially the same in *Etheria elliptica* as in *H. rufescens*, such plates of aragonite produce a flaky texture in the *Etheria elliptica* shells after destruction of the protein matrix.

The climatic conditions in the early to mid-Holocene provided habitats for many species of molluscs in the southeastern Sahara (Kröpelin, 1999). It has already been established that the rainfall during the early Holocene was sufficient to maintain several large lakes north of Wadi Howar (Abell et al., 1996b; Gabriel and Kröpelin, 1984). Hoelzmann et al. (2000) estimate that a lake centered near 18°N–25°E (Site P-195 in Fig. 1) may have occupied an area possibly as large as 7000 km^2 and certainly as large as 1100 km^2, and a smaller one at site P-267. This was at a time when mega Lake Chad may have occupied an area of 150,000 km^2 (Durand, 1982). There were doubtless many other lakes throughout the Sahara in the early Holocene (Petit-Maire and Riser, 1983; Gasse et al., 1987; Petit-Maire and Kröpelin, 1991). The water to feed the precipitation that maintained these lakes originated in the tropical Atlantic Ocean, and moved eastward in air masses across Africa in the same manner as observed today but with far greater intensity as the Inner Tropical Convergence Zone (ITCZ) moved northward in the early Holocene (Fig. 5; Gasse and van Campo, 1994; Van Zinderen Bakker, 1967) which also is now recognized in paleoclimate models (Braconnot et al., 2000). The oxygen isotopic content of the water in the air mass was continuously fractionated by convective evaporation and precipitation, so that by the

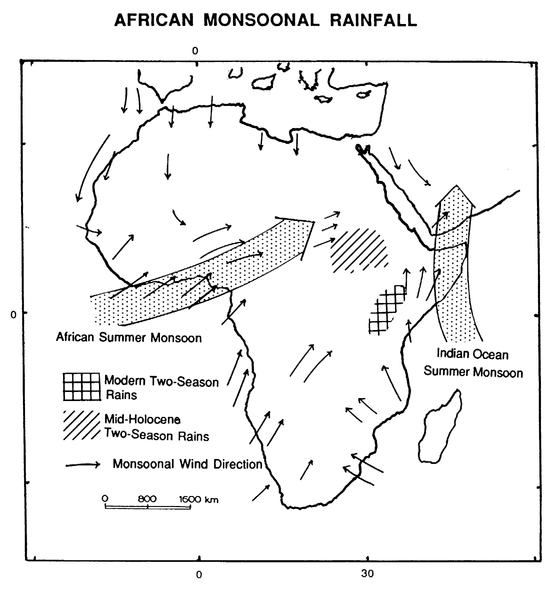

Fig. 5. Paleomonsoonal pattern in the mid-Holocene with apparent northward shift of the double rainy season at 6800 years BP.

time the air masses reached northwest Sudan, the rainfall would have had an isotopic composition of about −10‰ to −12‰ (SMOW). This is the range of isotopic values of the "fossil" water which is present in the massive aquifers of northern Sudan, southern Egypt and much of Libya (Thorweihe et al., 1990).

The advent of heavy monsoonal rains at the beginning of the rainy season would have provided surface water run-off, ground water buildup, the accumulation of water in the lakes, and the flow of water in the wadis, all highly depleted in ^{18}O. This depletion would have been manifested in the shells of the molluscan population, where oxygen isotope ratios of about −10‰ to −12‰ (PDB) are observed. Between the rainy seasons, there would have been periods of evaporative concentration of surface waters to yield ^{18}O-enriched water, which would have given the more isotopically enriched shell.

It is apparent that there were two episodes of such increased negative oxygen isotope ratios during the approximately 1 year of growth (14 identifiable layers of shell). There is a major rainy season, covering 4 or 5 months, the "long rains", followed by a second, less significant, rainy season of only a couple of months duration. These probably duplicate the timing of the two rainy seasons observed in East Africa today — in March–April–May and September–October–November — but there is no certainty that this is indeed the same pattern as 7000 years ago in northwest Sudan. The filling of the lakes and wadis of most, if not all, of the Sahara with isotopically depleted water demands a shift of the ITCZ far to the north of its present limits at around latitude 18°N, but we have less information on the changes in the Indian Ocean–Arabian monsoon that may have taken place at the same time (Sirocko, 1996).

The extremely negative magnitude of the oxygen isotope ratios of these shells is most striking. The "fossil" waters of the Darfur region of the Sudan certainly indicate that water of $\delta^{18}O$ (SMOW) of about −10‰ to −12‰ was falling in this region in the early Holocene (Thorweihe et al., 1990), but here we have runoff from that rain that was at best only slightly altered by evaporative concentration of the $H_2{}^{18}O$. This is in contrast to the oxygen isotope ratios of shells and bulk carbonates from the paleolake sites at P-195 and P-267 (Fig. 1) several hundreds kilometres west and north of the site at which these oysters grew, and which give evidence that the isotopic content of the water was substantially altered during or after precipitation with $\delta^{18}O$ values near ∼6‰ to −8‰ (Abell et al., 1996b).

Clearly, the *Etheria elliptica* shells preserve only a very brief moment in climatic history, and their sensitivity to increased aridity would have removed them from the scene very rapidly had highly evaporative conditions occurred. This supports the notion that the Wadi Howar was a major freshwater stream with continuous flow of water for some periods of time during the early to mid-Holocene, with water derived largely from two rainy seasons, but with only minor post-precipitational alteration of the isotope ratios. This is a somewhat different history than we see at the paleolake sites mentioned above, where there is clearly a very considerable alteration of the original isotope ratios of the rainfall during or after precipitation.

The carbon isotope ratios in these shells were also of interest in that they covered a wide range of values indicative of substantial changes in the organic material used as the food supply for these molluscs. There is a good parallel behaviour between the carbon isotope ratios and the oxygen isotope ratios but we can only speculate on the reasons for this correlation as there is insufficient information on the nature of the food supplies. Ranges of $\delta^{13}C$ that extend from −10‰ to −5‰ suggest very substantial seasonal changes in the source carbon in the food chain that leads up to these oysters. But little is known as to the sources and mechanism of incorporation of carbon into their shells. It is probable that seasonality in vegetation would accompany seasonality in rainfall patterns, so it is not surprising to find this variability.

5. Main points

This study provides the first application of the use of *Etheria elliptica* as a proxy for seasonality in paleoclimatology. We expect to apply this technique to other sites in Africa as samples of the oysters become available.

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