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Egyptian mummies record increasing aridity in the Nile valley from 5500 to 1500 yr before present

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ABSTRACT

Oxygen isotope compositions were measured in teeth ($n=29$) and bones ($n=41$) from Egyptian mummies of humans ($n=48$) in order to track the $\delta^{18}O$ evolution of the Nile from 5500 to 1500 B.P. The combination of $\delta^{18}O$ values of apatite carbonate and phosphate was used to filter the database for *post mortem* alteration of bioapatites, while $^{87}Sr/^{86}Sr$ ratios were used to detect potential allochthonous people buried in the various archeological sites located along the Nile. This approach led to only five apatite samples out of seventy to be discarded from the database. The remaining oxygen isotope compositions of both tooth and bone phosphates from ancient Egyptians were converted into the composition of ingested water ultimately originating from the Nile. It was found that $\delta^{18}O$ of Nile waters increases progressively from −1.6 to +1.5 (‰ VSMOW) from the Predynastic (~5500 B.P.) through the Late Period (~2550 B.P.). This trend towards higher Nile $\delta^{18}O$ values acquired in more recent times is coherent with a general drying trend in Northeast Africa, which was not limited to a drying spell at the end of the Nabtian Pluvial (ca. 12,000 B.P. –ca. 6000 B.P.), but extended far into the following millennia nearly to the beginning of the Common Era (1950 B.P.).

1. Introduction

The Egyptian civilization has had a long, complex, and fascinating history, which has been carefully recorded since the earliest times. The ancient Egyptians themselves kept registers of past kings and their greatest achievements (Palermo stone, 5th dynasty, ~4400B.P.). In these early records they also kept track of the annual Nile levels (Bell, 1970), showing that not only did the climate parameters controlling the Nile have a profound and direct impact on the everyday lives of Egyptians, but also, on a much larger scale, on the history of Egypt itself. For example, since land irrigation was managed through natural flooding (Butzer, 1976; Hassan, 1997; Manning, 2002), a drastic reduction of the flood would jeopardize food supply, causing unrest in the country and destabilization of the sitting government (Butzer, 1984; Hassan, 2007). At several stages during ancient Egyptian history, climate has been called upon as one of the causes, among many, of the end of a political system (Butzer, 1984; Krom et al., 2002; Stanley et al., 2003). To better understand the impact of climate on the Egyptian civilization, knowledge is required about how the climate has varied over its history. Several climate reconstructions have already been proposed but suffer from discontinuous records through time. These models are based on a combination of analysis of texts (Bell, 1970, 1971, 1975), faunal assemblages, pollen spectra, and sedimentary deposits (Hassan, 1986; Butzer, 1976; Bonnefille and Hamilton, 1986; Said, 1993; Williams, 2009). The record of flood levels in particular is highly fragmented with too few data to infer a general trend over the time span of the Egyptian civilization. Bell (1970) proposed that the Nile floodplain was 6–7 m higher during 5100–5000 yr B.P. than during the 4th Dynasty (~4500 B.P.), after which flood discharge decreased enough to generate episodic floodplain dissection. All these studies do, however, point towards increasing aridity through time.

Climate changes can be tracked through the oxygen isotope fractionations that take place during the various stages of the surface water cycle, which involve water evaporation and condensation of humid air masses. The oxygen isotope composition of meteoric waters ($\delta^{18}O_w$) strongly depends on the trajectories of humid air masses, air temperature and humidity, and the amount

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of precipitation (Dansgaard, 1964; Craig and Gordon, 1965). Knowledge of changes in $\delta^{18}O_w$ values through time for a given locality allows for a qualitative estimate to be made of past variations of these climate parameters. Except at high latitudes, where water can be stored as ice for over hundreds of thousands of years, the oxygen isotope composition of rainfall cannot, in most cases, be measured directly. To get around this difficulty, we measured the $\delta^{18}O$ value of mineralized tissues, such as teeth and bones ($\delta^{18}O_p$), of ancient Egyptians who were consuming water from the Nile. Using the isotopic fractionation equation determined by Daux et al. (2008) for present-day humans, we were able to track the $\delta^{18}O_w$ evolution of the Nile from 5500 to 1500 B.P. We show that $\delta^{18}O_w$ increased progressively from the Predynastic Period (~5500 B.P.) to the Late Period (2550 B.P.), reflecting a decrease in the amount of precipitation at the sources of the Nile and/or an increase in temperature and evaporation.

2. Material and analytical techniques

2.1. The collection of studied Egyptian mummies

Samples of tissues from Egyptian mummies were provided by the Musée des Confluences and the Musée d'Anatomie, both in Lyon, France. Most of the samples come from the Theban region (the localities of Deir-el-Medineh, Gournah, Khozan, and Thebes), while a few samples coming from Lower Egypt (Roda and Antinopolis) or southward in the region of Elephantine (Fig. 1). The most ancient mummies studied are from the Predynastic Period (~6000 to ~5000 B.P., 'PR'). A second group of mummies belong to the Dynastic Period, which is composed of the Old Kingdom (3rd–6th Dynasties, 4636–4131 B.P., 'OK'), the Middle Kingdom (12th Dynasty, 3941–3736 B.P., 'MK'), the New Kingdom (18th–20th Dynasties, 3517–3035 B.P., 'NK'), and several Intermediate Periods. These mummies were assigned to distinct dynasties by E. Chantre. A third group consists of mummies belonging to the 26th Dynasty (2614–2475 B.P., 'LP'), while the more recent mummies belong to three sub-groups with overlapping temporal extensions. These are first the Ptolemaic mummies ('PT') with ages ranging from 2282 to 1980 B.P. Second, the Greco-Roman mummies ('GR'), which encompass both the Ptolemaic and Roman Periods of Egypt, with ages ranging from 2282 to 1955 B.P. And third, the Coptic mummies ('CO') belonging to the Roman Period and the Byzantine Period of Egypt, with ages comprised between 1980 and 1310 B.P.

Enamel and bone samples were obtained from 48 human and 5 animal mummies for isotopic analysis of oxygen and strontium. In some cases, two or more samples are from the same individual mummy and are hence labeled with the same individual reference ('Ind. Ref' in Supplementary Table 1). Bone samples were collected using a toothless saw blade fitted to a drill, then ground into powder with an agate mortar. Most teeth were extracted from the skull by gently pulling them out of their cavities. To avoid damage to occasionally well-preserved faces of some of the mummies, only teeth that were already loosely attached were collected, hence precluding selection of tooth type. The enamel was rinsed with ethanol prior to being drilled with a diamond-head from which the resulting powder was further ground with an agate mortar.

2.2. Oxygen isotope ratios of apatite phosphate

Bone and enamel powders were pretreated using 10% hydrogen peroxide to remove organic matter. This gentle chemical pretreatment, carried out at room temperature, was limited to a duration of maximum 1 h, and therefore should not have any impact on the isotopic ratios according to the observations made by Grimes and Pellegrini (2013). The powders were then rinsed three times with double-deionized water and dried in an oven at 50 °C. 2 mL of concentrated HF were added to the powders, leading to apatite dissolution and precipitation of CaF_2, which was separated from the sample solution by centrifugation. The phosphate in solution was then isolated using a strong anionic resin (Amberjet) before being precipitated as silver phosphate following to the method first described by Crowson et al. (1991) and slightly modified by Lécuyer et al. (1993). The oxygen isotope data were obtained using a high-temperature pyrolysis continuous flow technique developed by Fourel et al. (2011). For each sample, five aliquots of 400–500 μg of silver phosphate were mixed with 500 μg of nickelized carbon in silver foil capsules. Pyrolysis was performed at 1450 °C using an Elementar-varyoPYROcube™ elemental analyzer.

Oxygen isotope compositions were calibrated against silver phosphate samples precipitated from the NIST SRM 120c standard, for which the $\delta^{18}O$ value was fixed at 21.7‰ V-SMOW for correction of instrumental mass fractionation during CO isotopic analysis. The average value of 21.7‰ obtained for the standard SRM 120c was proposed by Lécuyer et al. (1993) who fluorinated silver phosphate crystals with bromine pentafluoride and calibrated the oxygen isotope ratios against the NBS28 quartz international standard. Recently, Halas et al. (2011) confirmed the absence of any sizeable isotopic fractionation effect during the conversion of silver phosphate into CO and suggested a mean $\delta^{18}O$ value of 21.8 ± 0.2‰ for SRM 120c on the basis of an interlaboratory calibration. Chenery et al., 2010 likewise proposed a value of 21.7 ± 0.7‰ after a 6-month period of repeated measurements of SRM 120c calibrated against NBS127 barium sulfate. SRM 120c standards that were converted into silver phosphate along with the samples from each chemistry batch have $\delta^{18}O_p$ values that range from 21.54‰ to 21.92‰ with a mean value of 21.71 ± 0.15‰ ($n=22$). To bracket the isotopic range of mummy samples documented in this study, internal standards of synthetic Ag_3PO_4 ($11 \leq \delta^{18}O \leq 25$‰ V-SMOW) for calibration of raw isotopic data were obtained by reacting dissolved potassium dihydrogen phosphate (KH_2PO_4) with waters of various oxygen isotope compositions according to the method developed by Lécuyer et al. (1999, 2007). In addition, we also analyzed the "Durango apatite", which gives a mean $\delta^{18}O$ value of +9.45‰ ($n=3$) by offline pyrolysis against a value of +9.6‰ obtained by fluorination using BrF_5 reagent (C. France-Lanord, personal communication).

2.3. Oxygen isotope ratios of apatite carbonate

Oxygen isotope ratios were determined by using a MultiPrep™ automated preparation system coupled to a dual-inlet Elementar Isoprime™ isotope ratio mass spectrometer. For each pretreated sample, an aliquot of about 2–3 mg of apatite was reacted with anhydrous supersaturated phosphoric acid at 90 °C for 20 min. An acid fractionation factor value of 1.0080 was used to calculate the oxygen isotope composition of the carbonate. This same factor was used for the reaction between calcite and anhydrous phosphoric acid at 90 °C by Swart et al. (1991), which is also the value recommended by Passey et al. (2007) for modern tooth enamel. Isotopic compositions are reported in the delta notation in ‰ relative to VSMOW. All sample measurements were adjusted to the international reference NIST NBS19 according to the method developed by Werner and Brand (2001). The reproducibility of the oxygen isotope measurements was ± 0.1‰ (1σ).

2.4. Strontium isotope compositions of teeth and bones

Bone samples with a high content of organic matter (87, 21, and 98 in Supplementary Table 2) were pretreated in order to remove any organic material, which could otherwise clog the resin during