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# Timing and characteristics of Late Pleistocene and Holocene wetter periods in the Eastern Desert and Sinai of Egypt, based on $^{14}C$ dating and stable isotope analysis of spring tufa deposits

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There is very little dated evidence on wet periods in the Eastern Desert and Sinai Peninsula of Egypt during the Late Pleistocene and Holocene. To obtain such information, we have studied the petrography, isotope geochemistry and AMS radiocarbon ages of mostly relict tufas deposited by springs draining perched ground water bodies in metamorphic and volcanic rocks. The tufas unconformably overly Precambrian basic igneous rocks (basalt, diabase and gabbro). As the ages of tufa carbonate are frequently older than the true ages of the deposits because of the incorporation of old, $^{14}C$-dead carbon, we have dated both the carbonate matrix and insoluble organic material of the tufas. These ages show that the tufas were largely formed during two broad time periods, the most recent from 12,058 to 6678 cal yr BP (African Humid Period), and the other from ~31,200–22,500 cal yr BP, with preferential growth during the coldest times of this period namely during Heinrich Events 2 and 3 (H2 and H3) and the Last Glacial Maximum (LGM). The time span between 19,000–9000 cal yr BP, including the YD and H1, appears to have been relatively more arid than the earlier LGM or H2 periods or the later Holocene. The Late Pleistocene tufas are depleted in $^{18}O$ relative to the Holocene tufas and were deposited at a lower temperature (~14.0°–20.8 °C vs. 18.4°–23.4 °C). We believe that the Holocene tufas in the Sinai were formed by rainfall from the Mediterranean and those in the southern part of the Eastern Desert by African monsoon rainfall derived from the Red Sea-Gulf of Aden and Indian Ocean. In contrast, the moisture that fed the Late Pleistocene tufas, which are depleted in $^{18}O$ relative to Holocene deposits, and progressively depleted from north to south, was probably brought by the Westerlies from the Atlantic-Mediterranean Sea when the Westerly circulation was pushed southwards during the coldest periods of the Late Pleistocene. Periods of tufa deposition correlate with major documented paleoclimatic events in North Africa during the late Pleistocene and Holocene; such as the Nile floods, high sea level and the formation of sapropels in the Mediterranean.



## 1. Introduction

Global climate records for the last 25,000 years show a long-term trend from the cold, glacial conditions of the Late Pleistocene to the warm, interglacial conditions of the Holocene (Robinson et al., 2006). This long-term trend is punctuated by several shorter climatic events (e.g. Heinrich events, the Younger Dryas) that seem to have had a significant effect on climatic conditions over much of the Northern Hemisphere (Alley, 2000). Previous research has shown that hyperarid conditions prevailed in the Western Desert of Egypt during the Late Pleistocene (e.g. Wendorf and Schild, 1980). However, radiocarbon dating of Late Pleistocene lacustrine carbonates and organic fractions from the Eastern Sahara have suggested pluvial conditions in some areas between about 50 and 25 ka (Szabo et al., 1995).

Tufas are terrestrial carbonate deposits that form under open-air conditions in streams, rivers and lakes (Ford and Pedley, 1996). They precipitate at ambient temperature from waters containing calcium bicarbonate derived from dissolution of carbonate bedrock or secondary pedogenic or lacustrine calcrete. Tufa may be deposited at springs when dissolved $CO_2$ in groundwater, in

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equilibrium with soil $CO_2$ partial pressure, outgasses when it is exposed to lower $CO_2$ partial pressure in the atmosphere. If outgassing does not induce supersaturation at the spring, in many cases it is attained downstream at rapids or waterfalls because turbulence increases the surface area between water and air resulting in a sharp increase in the rate of outgassing of $CO_2$.

Activities of microbial (bacterial and cyanobacterial) and algal communities that occupy tufas, play an important role in tufa deposition. In addition, tufa growth frequently encrusts higher plants that live on the margins of streams, waterfalls and wetlands (Andrews, 2006).

Spring, stream and waterfall tufas are common in many arid and semiarid areas and frequently record much wetter conditions in the past (e.g. Butzer et al., 1978; Brandt and Brook, 1984; Brook et al., 1996, 1999; Andrews, 2006). In fact, spring and waterfall tufa deposits are not uncommon in the Western and Eastern deserts of Egypt, including the Kharga Oasis (Hamdan et al., 1998; Nicoll et al., 1999; Brook et al., 2002, 2003; Smith et al., 2004a, b; Kieniewicz and Smith, 2007), Kurkur (Crombie et al., 1997), Esh El Malaha (Hamdan, 2000), and Wadi Attala (Hamdan et al., 2001).

A number of tufas in Egypt have been dated by U/Th, most from the Western Desert (Sultan et al., 1997; Crombie et al., 1997; Hamdan et al., 1998, 2001; Brook et al., 2002, 2003; Smith et al., 2004a, b). A few U/Th ages have also been obtained for tufa deposits in the Eastern Desert (e.g. Wadi Attala – Hamdan et al., 2001) and North Eastern Desert (e.g. Esh Malaha – Hamdan, 2000). These ages fall into the five pluvial periods of Szabo et al. (1995): 320–250 ka, 240–190 ka, 155–120 ka, 90–65 ka and 10–5 ka, which correspond with interglacial Oxygen Isotope Stage (OIS) 9, 7, 5e, 5c, 5a and 1 (Hamdan, 2003).

Knowing the timing of wetter periods in the Eastern Desert of Egypt and Sinai Peninsula will enhance our understanding of late Pleistocene and Holocene human dispersal out of Africa and the characteristics of human behavior (Smith et al., 2007). Unlike the Sahara west of the Nile, the Late Pleistocene paleoclimates and paleoenvironments of desert areas east of the Nile are poorly known because of limited research and because of the scarcity of deposits with proxy records (such as lake deposits). However, there are numerous Upper Paleolithic and Neolithic Sites (Vermeersch et al., 1996, 2002) and huge galleries of prehistoric rock art that depict an environment that was clearly more humid than today, including several animal species no longer found in the area (Fuchs, 1989). Unfortunately, most of these sites lack reliable chronological data with tentative ages assigned on the basis of archaeological proxies, i.e. study of lithics, pottery and rock art; which hinders comparison of climatic and environmental variations between localities and regions (Smith et al., 2007). The study of tufa deposits should enable us to develop a late Pleistocene climatic chronology, as tufas are particularly amenable to chronometric dating by radiocarbon techniques. A robust, regionally-applicable chronology can be obtained by dating several tufas and the distribution of ages should reveal periods of increased wetness through the late Pleistocene and Holocene. Oxygen and carbon isotope analysis of tufa carbonates, which are proxies for climate, should allow changes in climate over time to be investigated. The identification of humid periods in the Egyptian desert during the Quaternary helps us to better understand changes in the discharge of the River Nile, and thus to better understand the climate conditions that led to the formation of sapropels in the Mediterranean Sea.

The aim of this research paper is to synthesize the existing data and present new work to provide a record of changing wetness/aridity in the Eastern Desert of Egypt and Sinai Peninsula, based on the study of 11 spring tufa deposits of Late-Pleistocene to mid-Holocene age. Tufa $\delta^{18}O$ values are utilized to constrain the nature and source of the carbonate-producing water and estimate temperatures of deposition.

## 2. The Eastern Desert and Sinai Peninsula

In contrast to the flat sandy Western Desert, the Sinai and Eastern Desert of Egypt are located within the Red Sea Mountain ranges, and are underlain by igneous and metamorphic rocks (Said, 1990, 1993). These are rugged areas with deep valleys and ravines, and intensely dissected plateaus. The Eastern Desert owes its ruggedness and morphological character to the uparching of the Arabian-Nubian Massif and the rifting that led to the formation of the Red Sea and Gulf of Suez. The rifting was initiated during the Late Oligocene and the uplift of the shoulder of the rift was completed by the Middle Miocene. Erosion of the sedimentary mantle overlying the older basement complex was accentuated by the Neogene structural relief. During the Miocene and most of the Pliocene, when the climate was tropical or subtropical, weathering and erosion led to a progressive denudation of the nascent Red Sea Mountains, beginning with the removal of the topmost Eocene limestone and the eventual removal of the Mesozoic–Paleozoic clastics of the Nubian Sandstone. Ultimately, the basement rocks were exposed and subjected to erosion (Said, 1993; Embabi, 2004).

The Eastern Desert and Sinai are located in the arid province of Egypt. Maximum and minimum recorded temperatures are 41 °C and 21 °C, respectively and increase from north to south, while relative humidity (RH) ranges between 56% and 30%, averaging about 43% in summer and 48% in winter (Abdel Moneim, 2005). Generally, the average annual rainfall ranges between 2.75 mm and >50 mm in the extreme southeast. Occasional heavy showers during winter (Aggour and Sadek, 2001) may cause flash floods.

Several researchers have studied the hydrogeology of the Eastern Desert (e.g. El Ghazawi and Abdel Baki, 1991; Sultan et al., 2000). The Red Sea Mountains in the Eastern Desert form a major water divide with wadis to the east draining to the Red Sea (e.g. Wadi Gemal, Gasus and Abu Had) and those to the west draining into the Nile Valley (e.g. Wadi Assuyti and El Markha). Structural elements, particularly faults and joints, are pathways for recharge and movement of ground water (Sultan et al., 2000). The depth, width and extent of fractures control the amount of groundwater in an area as well as the direction of flow. Fractures vary from several millimeters to several meters in width and NW–SE and NE–SW intersecting fracture systems cut the basement rocks of both the Eastern Desert and Sinai.

Fissured basement rock aquifers are the dominant type in the Eastern Desert and Sinai. Recharge to these aquifers depends more on the intensity of rainfall when it occurs than the mean annual precipitation. This is because the evaporation rate may exceed the infiltration capacity after low-intensity rainfalls severely limiting recharge amounts (Awad et al., 1996). Ground water is discharged naturally at springs or artificially through wells. Locally, dikes of variable rock type cut the granitic rocks. These dikes may prevent the free movement of ground-water and can sometimes cause localised ground water ponding.

## 3. Methods

Fifty six tufa samples were collected from eleven sites in the Eastern Desert and Sinai of Egypt (Fig. 1). The geological and geomorphologic setting of each tufa was recorded in the field and samples were taken for laboratory study. Sub-samples for isotopic and chemical analysis were cut or drilled from the hand samples, avoiding coarse-grained, secondary material. Tufa carbonate mineralogy was determined by XRD at Cairo University, Egypt. Oxygen and carbon isotope analyses were performed on CO gas