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Holocene freshwater carbonate structures in the hyper-arid Gebel Uweinat region of the Sahara Desert (Southwestern Egypt) ☆

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A B S T R A C T

The eastern part of the Sahara is at present the driest region of the desert. Yet the extensive animal rock art in the area, presumed to depict real activities in the lives of the painters, suggests that environmental conditions were significantly different when the rock art was produced. Here we report on exploration of the area, which led to the discovery of morphologically-distinct carbonate structures that line the walls of two valleys in Gebel Uweinat, and were likely formed in standing water. The carbonate structures comprise what appear to be shoreline carbonate formations, and date back to 8100 and 9400 years BP. The chemical and morphological similarity of these formations to carbonate structures from modern lakes suggests that these lakes contained fresh, standing water suitable for human and animal use. However, the significant quartz content suggests that windblown sand was pervasive, and thus the vegetation cover may have been sparse. This discovery supports the possibility of grasslands in the area, which may have been able to support human habitation, and adds to the evidence for a wetter climate in the area in the early Holocene.

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1. Introduction

The mountainous Gebel Uweinat region of the Sahara Desert, near the triple border of Egypt, Sudan, and Libya (N22°, E25°), receives negligible rain at the present time (Fig. 1; Haynes, 2001). Yet, extensive rock art in the area depicts scenes of abundant animals, and in 1933 the Hungarian explorer László Almásy discovered rock art depicting swimmers (Almásy, 1934). Studies of the rock art have assumed that the animals and scenes depicted on the walls represent real activities in the lives of the painters (Haynes, 1980). Thus the images indicate that there were very different environmental conditions in this region during the time the rock art was produced, though precipitation rates and the extent of vegetation cover are uncertain. Previous exploration of the Egyptian desert has found supporting evidence of a wetter climate 10,500–5000 years ago, concurrent with the expected timeframe for the creation of the rock art (Haynes, 2001; Hoelzmann et al., 1998, 2004; Kuper and Kröpelin, 2006; Navarro-González et al., 2007; Nicoll, 2001). Here we report on morphologically-distinct carbonate structures in two narrow valleys in the Gebel Uweinat area within this currently hyper-arid zone which have similar morphology and composition (Fig. 1) to carbonate shore deposits seen, *inter alia*, in Pavilion Lake, Canada (Laval et al., 2000) and Lake Alchichica, Mexico (Kaźmierczak et al., 2011).

While there is general agreement that during the early Holocene conditions in the Gebel Uweinat area were more clement than at present, the details of the climatic history are uncertain. Dateable artifacts of past humid periods there are limited to an ostrich egg-shell, with a radiocarbon age of 7280 ± 90 years BP (~9200 calibrated years BP; Wendorf and expedition, 1977). While some parts of southwest Egypt have been extensively explored – such as Gilf Kebir (200 km NE from the study sites) (Haynes, 2001; and references therein), the Selima Sand Sheet (300 km to the east, including Gebel Kamil) (Haynes, 1982), and other more distant sites (shown in Fig. 1) – these sites generally suggest intermittent rainfall that produced ephemeral watering holes and ponds and questions remain about the extent of vegetation cover (Kröpelin, 1987; Lindstädter and Kröpelin, 2004). Gebel Uweinat is of particular interest because its location in what is now the driest core of the Western Desert of Egypt provides an important constraint on the magnitude and geographic extent of wetter conditions during the early Holocene.

In this paper we report on the composition and morphology of the discovered carbonate structures and suggest their likely mode

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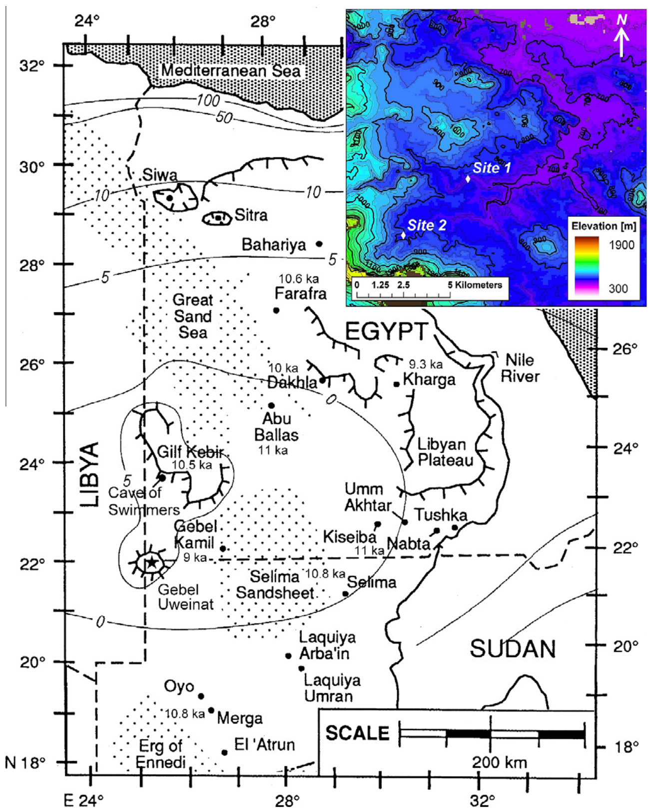

Fig. 1. Contextual map of the eastern part of the Sahara and the studied sites. Map is modified from Nicoll (2001). The study area, Gebel Uweinat, is indicated (star; N22°, E25°). The Cave of the Swimmers (north of the study sites) and the timing of onset of the most recent wet period for select sites in the eastern Sahara are labeled (Kuper and Kröpelin, 2006; Nicoll, 2001). Ages are reported in calibrated years BP. The modern annual precipitation amounts in millimeters (isohyet contours) are overlaid (Haynes, 2001). The inset shows the topography of the northeast part of Gebel Uweinat (Shuttle Radar Topography Mission), where the study sites are found: Site 1 (N21°58′, E25°06′) and Site 2 (N21°56′, E25°04′).

and timing of formation. These results provide constraints on the environmental conditions in the Eastern Sahara during the carbonates' formation period.

1.1. Site description

Gebel Uweinat is a mountainous range in the southwest of Egypt, with a maximum elevation of 1934 m. The basement rock is Precambrian granites, granite gneisses, and diorites, which are exposed at elevations above ~1000 m (Issawi, 1980). The last significant deformation and plutonism occurred during the Precambrian, Kröner et al. (1994) gives ages for the emplacement of the basement rock of 700–800 Myr. At lower elevations and at the study sites, the Precambrian basement is overlaid by a Cambro-Ordovician unit of quartzitic sandstone beds interbedded with highly consolidated conglomerate and syenite porphyry sheets (Burollet, 1963; Issawi, 1980).

During our preliminary exploration of the Gebel Uweinat region, two valleys were discovered that contain morphologically-distinct carbonate structures and at one of the sites form a bench along the valley wall. Both of these valleys are located in likely ancient valley network channels, as apparent from aerial photographs, and from the area's topography (Fig. 1b). At Site 1, the carbonate structures form a distinct bench along the sandstone valley wall; the bench is continuous for over 50 m and is about 1 m thick vertically (Site 1, N21°58′, E25°06′, elevation 715 m; Figs. 1 and 2a and b). The carbonate bench is "pasted" onto the valley wall and is not part of, or aligned with, the stratigraphic sequence. At this location the valley is about 20 m deep. No apparent shorelines were observed. Site 2 is located about 5 km away in a neighboring valley, and at a slightly higher elevation than the first site (Site 2, N21°56′, E25°04′, elevation 775 m; Figs. 1 and 2c). The height of the surrounding, broader valley is about 10 m. The carbonates structures had a similar, distinct morphology, but did not form a bench along the valley walls: they were distributed both along the valley walls and along the valley floor. Their macro-morphology and distribution may be the result of

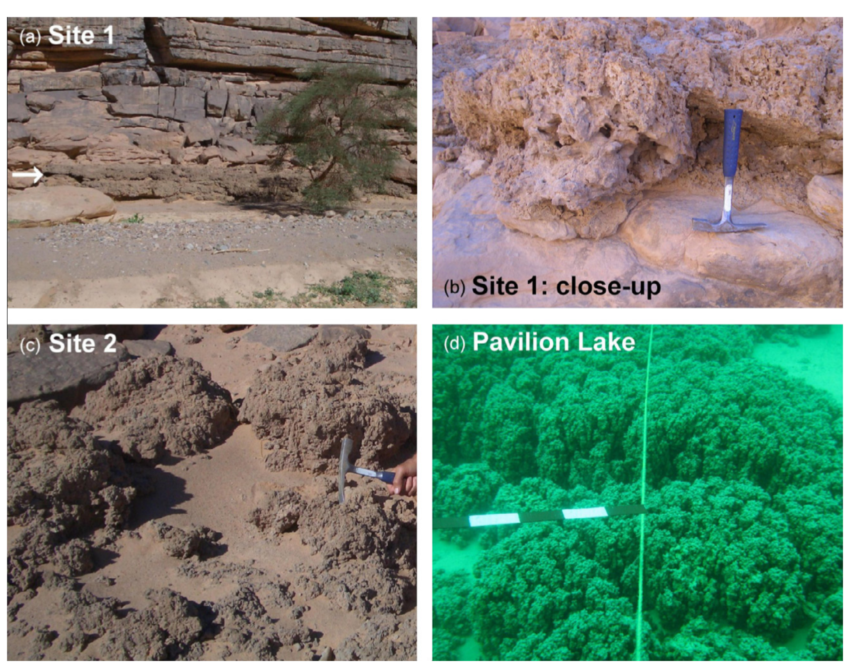

Fig. 2. Carbonate structures at the study sites: (a) carbonate bench (arrow) lining the side of the valley at Site 1, (b) close-up of carbonates at Site 1, and (c) the structures at Site 2. Calcite structures that are morphologically and chemically similar to those at Gebel Uweinat are found in Pavilion Lake, British Columbia, Canada (d) at a depth of 10–15 m (Laval et al., 2000; Lim et al., 2009); each segment on the scalebar is 10 cm.

erosion, as these structures had a much more weathered appearance compared to the carbonate structures at Site 1. The two sites have similar geological characteristics and combine downrange in a larger channel.

2. Methods

We collected a single large sample (~20 cm across) from each of the two sites in Gebel Uweinat, Site 1 and Site 2, during November 2005. The sides of the formations were sampled, and were selected because they were unambiguously morphologically distinct. Each sample was subsampled into three pieces from different parts of the rock. Information on the orientation of the collected samples was not preserved.

The samples were examined for mineral composition, microscale morphology, and the age of formation was determined using radiocarbon methods. Total carbonate content was determined by weighing the samples before and after acid digestion with acetic acid (0.5 M). The mineralogical composition was studied using X-ray powder diffraction (XRD) on a Phillips X-Pert Pro diffractometer with Cu Kα radiation. Measurements were taken in the range of $5^\circ \leqslant 2\theta \leqslant 75^\circ$ at 45 kV and 40 mA. Step size was 0.008°, with a scan step time of 100 ms. The mineralogical composition was determined using X'Pert High Score software. The internal morphology of the samples was analyzed with scanning electron microscopy, using the LEO 1550 VS FESEM system. X-ray energy dispersive spectrometer (EDS) analysis was conducted with the Oxford INCA Energy 300 system.

Radiocarbon ages and carbon isotopic composition ($\delta^{13}C$, vs. PDB-1) were determined by Beta Analytic, Inc., using accelerator mass spectrometry (AMS) and isotope ratio mass spectrometry (IR-MS), respectively; the lab accession numbers for the samples were Beta-260177, Beta-260178, and Beta-262282. For radiocarbon analysis, the samples were not pre-treated, and were only washed with de-ionized water before analysis. The modern reference standard was 95% the ^{14}C activity of the National Institute of Standards and Technology (NIST) oxalic acid (SRM 4990C); the Libby ^{14}C half-life (5568 yr) was used. The reported results are corrected for isotopic fractionation using the measured $\delta^{13}C$ (versus PDB-1). Calibrated ages are calculated using the INTCAL04 Radiocarbon Age Calibration (2004).

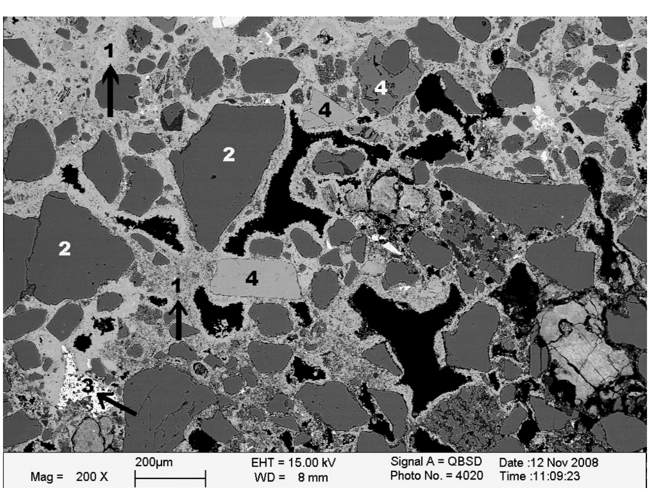

Fig. 3. Calcite matrix and composition. SEM image of a thin-section of the calcite structures at Site 1. The matrix is calcite (1), the most ubiquitous incorporated mineral is quartz (2); iron oxides/ilmenite (3, bottom left), pyroxenes (Na, Al pyroxenes in this image; 4), and orthoclase (5) are also present. The lack of significant rounding of the grains suggests short transport distances. The morphology and composition at Site 2 are similar.

3. Results

Bulk XRD mineralogical analysis of the samples showed carbonates and quartz as the main minerals, with other minor constituents (less than a few percent total weight fraction). The carbonate is in the form of calcite, with less than 5 M% magnesium. The average total carbonate weight fraction (as determined by acid digestion) is 46% for Site 1, with the three subsamples giving 42.5%, 49.0%, and 46.8% by weight. For Site 2, the average total calcite content was 28% by weight, with the three subsamples giving 29.2%, 28.2%, and 26.0% by weight. The quartz component was likely contributed by the ubiquitous sand sheets and dunes in the region. Energy dispersive spectrometer (EDS) analyses showed some of the minor mineralogical components to be calcium sulphate, magnetite, ilmenite, (Na, Al) pyroxenes, and orthoclase (Fig. 3). The composition at both sites is similar, consistent with their close proximity. The organic carbon content of the samples is below the detection limit of the measurement: less than 0.3 weight percent.

Microscopic examination of the samples from both sites shows a calcite matrix primarily embedded with quartz, with other mineral grains as a minor component (Fig. 3). The quartz grains are angular with little rounding, similar to the angular nature of the quartz grains in the surrounding sandstone rocks (Issawi, 1980). The persistent angular grains suggest short transport distances. No fossils or pollen grains were observed.

The calcite structures were dated using radiocarbon dating of the bulk sample. Two subsamples from Site 1 were dated, giving similar dates: 8190 calibrated years BP and 7970 cal. years BP. For Site 2, the carbonate age is 9440 cal. years BP (Table 1). The $\delta^{13}C_{PDB}$ values for samples from Sites 1 and 2 are −6.0‰ (both subsamples) and −6.1‰, respectively, and are consistent with a mostly atmospheric carbon source with contribution from soil respiration (Smith et al., 2004; Romanek et al., 1992; Pearson and Hanshaw, 1970).

4. Discussion

The distinct morphology of the calcite structures discovered at Gebel Uweinat, which is similar both on the exterior and the interior of the formations (Fig. 3), and the constant elevation, "bath-tub ring", and pasted-on appearance of the structures at site 1 (Fig. 2a), imply that the morphology is authigenic and not the result of weathering; weathering would be expected to modify the flat top surface of the bench and result in a difference between the morphology of the outer and inner fabric. Features of re-precipitation or texture change are not visible within the collected samples (Fig. 3). The constant elevation, bench-like structure is consistent with formation in the shallows of a lake, implying long-term standing water. Both sites are currently in enclosed topographic lows in their respective channel beds. Both basins are quite shallow and partially filled in with sand. Although they are evident when directly observed in the field, they are hard to distinguish in the DEMs shown in Fig. 1. The basin for Site 1, which has a more fully developed structure, is deeper and better defined.

The shapes of the deposits are unlike typically tower-like tufa deposits that form when springs enter low pH lake water. Well-known examples of such deposits are the Trona Pinnacles carbonate deposits in Southern California (e.g. Ford and Pedley, 1996) and also in Mono Lake CA, Pyramid Lake, CA or Salda Lake in Turkey. The level of the deposits reported here is uniform across the valley wall consistent with formation from lake water and in this respect compares well with similar structures in Pavilion Lake, as mentioned above, and Lake Alchichica in Mexico (Kaźmierczak et al., 2011). In addition the deposits are not aligned with features in

Table 1
Summary of chemical and isotopic analysis of the samples from both sites. The carbonate composition and ^{13}C compositions for both sites are very similar, while Site 1 has a higher carbonate content and is about a 1000 years younger.

Site	Bulk composition	Carbonate composition	^{14}C ages	$\delta^{13}C$ (‰)
Site 1	46 wt% carbonate (triplicate values: 42.5%, 49.0%, 46.8%) ~50% quartz few % other constituents (Ca sulphate, magnetite, ilmenite, pyroxenes, orthoclase)	Calcite, <5 mol% Mg	8190 cal. years BP (1σ = 8320–8170 cal. years BP); 7400 ± 60 BP radiocarbon age	−6.0
			7970 cal. years BP (1σ = 8010–7940 cal. years BP); 7150 ± 50 BP radiocarbon age	−6.0
Site 2	28 wt% carbonate (triplicate values: 29.2%, 28.2%, 26.0%) ~70% quartz few % other constituents	Calcite, <5 mol% Mg	9440 cal. years BP (1σ = 9470–9400 and 9350–9320 cal. years BP); 8380 ± 50 BP radiocarbon age	−6.1

the underlying sandstone as might be expected for springs. Tufa and travertine deposits associated with springs are reported in the Eastern Desert of Egypt (e.g. Hamdan, 2000). The Gebel Uweinat deposits may be similar to the "lake travertine" reported by Hamdan (2000), which he suggests formed in shallow lakes with evaporation playing an important role in its formation.

Samples from both sites have very similar chemical compositions, consistent with their proximity and the similarity of their geological settings. This includes their predominantly calcite and quartz composition. The low molar Mg/Ca ratio (<0.05) in the calcite suggests that the structures formed in fresh water (Eugster and Hardie, 1978; Gasse and Fontes, 1992; Pachur and Hoelzmann, 2000), since the Mg cation acts conservatively at low concentrations, and only becomes incorporated in precipitated minerals as the concentration increases (Yu et al., 2002). In addition, carbonates formed in saline environments commonly contain evaporates (Lisker et al., 2009), which were not found in the analyzed samples. The inferred fresh nature of the water is consistent with findings from South Saharan paleo-lakes further to the West, where low salinity has been inferred from diatom assemblages and carbonate $\delta^{18}O$ (Gasse, 2002). The low salinity suggests increased atmospheric humidity in the early Holocene, reducing evaporation compared to today (Gasse, 2002).

The presence of quartz in the samples is not unexpected due to the ubiquitous quartz sand dunes throughout the region. However, the quantity of the quartz and the relation of the quartz grains to the calcite provide information on the local conditions at the time of carbonate precipitation. Exposed sand dunes with some vegetation cover can persist through wetter climates, until precipitation is sufficient to support extensive vegetative cover. The high levels of quartz in the calcite matrix suggest that while standing water was present, as required for the formation of the carbonate structures, blowing sand was common and the vegetation cover was minimal. Note that previous work suggested that grassy vegetative cover stabilized aeolian sands in southwestern Egypt during the Early Holocene (Nicoll, 2004). However, the high quartz content in our samples suggests the vegetation cover in the driest core of the Sahara Desert was still low enough to allow sand movement.

Microbial carbonate structures are reported from a diversity of environments and in the fossil record. However, most modern occurrences are in extreme environments in which the disruptive presence of metazoan grazers is limited (Grotzinger and Knoll, 1999; DesMarais, 2003; Garcia-Pichel et al., 2004; Kaźmierczak and Kempe, 2006). There have recently been reports of carbonate microbialites in freshwater environments (Laval et al., 2000; Solari et al., 2010) and some of these have a similar morphology to the structures we sampled. In particular, the well-studied carbonate structures at Pavilion Lake (British Columbia, Canada) have a very similar morphology and carbonate composition to the structures from our Sahara sites (Fig. 2d; Laval et al., 2000; Lim et al., 2009). At Pavilion Lake, the carbonate structures seen at 10–15 m represent similar macro and micro morphologies, including overall size of the structures. Their composition is also calcite with up to 5% Mg. The only compositional difference between the structures at Pavilion Lake and Gebel Uweinat is the minimal presence of quartz in the carbonate structures in Pavilion Lake, due to the extensive vegetative cover at the site and therefore limited availability of windblown sediment.

Both carbonate structures were formed in the early Holocene. While the measured radiocarbon ages should be taken as maximum ages, there is no apparent mechanism for incorporating substantial amounts of old carbon. Carbonate-bearing rocks are not present upstream of the study sites, based on geological mapping surveys (Burollet, 1963; Issawi, 1980) as well as our own exploration. No active springs were found upstream, although one spring is known on the other side of the mountain and carbon input from groundwater cannot be fully ruled out. Thus, we expect the measured ages to be close to the absolute formation ages of the carbonate structures. The similarity in $\delta^{13}C$ between the two sites suggests that their carbon sources were also similar, and thus the small relative age difference between the sites is probably real. The range of measured ages between the two sites is likely due to an extended period of carbonate precipitation and the limited number of samples collected at each site. The timing of carbonate formation may also have been influenced by minor differences between the sites, such as erosion or dune movement. We also cannot rule out slight differences in water chemistry affecting the rate of calcite precipitation through time.

The calcite structures indicate a wetter climate in the area in the early Holocene (approx. 8100 and 9400 years BP). This finding provides a new and unique data point for the Gebel Uweinat area. The results are consistent with previous studies of Egypt's Western Desert and Northern Sudan, which show the last humid period in the area to have been 10,500–5000 years BP. These data are based on stratigraphy and radiocarbon dating of carbonates, charcoal and organic matter (Haynes, 2001; Hoelzmann et al., 1998; Kuper and Kröpelin, 2006; Nicoll, 2001), thermoluminescence dating (Navarro-González et al., 2007), reconstruction of lake levels through shoreline and geochemical analyses (Damnati, 2000), and pollen analyses (Ritchie et al., 1985). The ages also correlate with the time of the creation of the local rock art. Paleo-lake records from other parts of the Saharan desert further to the West similarly show a period of humid conditions in the early- to mid-Holocene from around 11,000–5000 years BP, with an interruption of around 1000 years centered around 8000 years BP (Gasse, 2002, and references therein). Even farther afield, a decrease in the deposition of terrigenous, aeolian sediment off the coast of Mauritania between 12,000 and 5500 years BP has been interpreted as more humid conditions and greatly expanded vegetation cover in the dust source region in the Saharan desert (Adkins et al., 2006; deMenocal et al., 2000). The ages of the Gebel Uweinat carbonates therefore fit well into the general picture of wetter early Holocene conditions throughout the Saharan desert, while adding a new constraint on the magnitude of the climatic change by being located in the driest part of the desert today.

At Pavilion Lake, the carbonate morphology that is similar to the Saharan sites is found to have a growth rate of 2.5–5 cm/1000 year (Brady et al., 2009; Laval et al., 2000). If the net precipitation rates at the Gebel Uweinat sites were similar, this would suggest long-term, of order thousands of years, standing water in the vicinity of the Cave of the Swimmers (located in the Gilf Kebir as shown in Fig. 1) and other numerous rock art sites. Our findings are therefore in contrast to previous suggestions that any lakes in the area were ephemeral (Kröpelin, 1987; Lindstädter and Kröpelin, 2004), though there is uncertainly in the lake duration required for forming mud layers and other observed playas. Further exploration of the region to map any additional carbonate formations as well as more extensive dating of the discovered structures may be important next steps in deciphering the climatic history of the eastern Sahara.

5. Conclusions

The discovered calcite benches in two narrow valleys in Gebel Uweinat in southwest Egypt indicate the presence of long-term standing water, but sparse vegetation cover, about 8100 and 9400 years BP. While the duration of the lake presence remains uncertain, the time required to form extensive carbonate structures suggests that the onset of increased rainfall, presence of standing water, and likely human habitation were earlier than the reported dates of the carbonate structures. Our results therefore agree well with previous findings of more humid conditions throughout the Saharan desert starting around 11,000–10,000 years BP (Damnati, 2000; Gasse, 2002; Haynes, 2001; Hoelzmann et al., 1998; Kuper and Kröpelin, 2006; Navarro-González et al., 2007; Nicoll, 2001; Ritchie et al., 1985). At the same time, the location of our study site in the driest core of the Saharan desert puts a new constraint on the magnitude of early Holocene humidity. The age of the structures suggests standing water at a time that is in agreement with the plausible ages for rock art in the area, as well as for the images in the Cave of the Swimmers (Almásy, 1934).

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