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Hydrologic and climatic implications of stable isotope and minor element analyses of authigenic calcite silts and gastropod shells from a mid-Pleistocene pluvial lake, Western Desert, Egypt

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Abstract

Authigenic calcite silts at Wadi Midauwara in Kharga Oasis, Egypt, indicate the prolonged presence of surface water during the Marine Isotope Stage 5e pluvial phase recognized across North Africa. Exposed over an area of ~4.25 km^2, these silts record the ponding of water derived from springs along the Libyan Plateau escarpment and from surface drainage. The $\delta^{18}O$ values of these lacustrine carbonates (−11.3‰ to −8.0‰ PDB), are too high to reflect equilibrium precipitation with Nubian aquifer water or water of an exclusively Atlantic origin. Mg/Ca and Sr/Ca of the silts have a modest negative covariance with silt $\delta^{18}O$ values, suggesting that the water may have experienced the shortest residence time in local aquifers when the water $\delta^{18}O$ values were highest. Furthermore, intra-shell $\delta^{18}O$, Sr/Ca, and Ba/Ca analyses of the freshwater gastropod *Melanoides tuberculata* are consistent with a perennially fresh water source, suggesting that strong evaporative effects expected in a monsoonal climate did not occur, or that dry season spring flow was of sufficient magnitude to mute the effects of evaporation. The input of a second, isotopically heavier water source to aquifers, possibly Indian Ocean monsoonal rain, could explain the observed trends in $\delta^{18}O$ and minor element ratios.

Keywords: Pleistocene; Egypt; Pluvial; Lacustrine environment; Stable isotopes; Minor elements; Paleoclimate; Gastropods; *Melanoides tuberculata*; Authigenic calcite

Introduction

The Marine Isotope Stage (MIS) 6/5e pluvial event, recorded in the Western Desert of Egypt by fossil-spring deposits and lacustrine sediments (McKenzie, 1993; Crombie et al., 1997; Smith et al., 2004a), marks a time of significantly enhanced precipitation in North Africa relative to the present. Sediment cores off the west coast of Morocco indicate MIS 5e (~125 ka) was particularly humid in North Africa, as Saharan dust input was at a relative minimum (Moreno et al., 2001). $\delta^{18}O$ records from speleothems in Oman and Israel also indicate enhanced rainfall at ~125 ka, suggesting that increased precipitation extended beyond the Sahara to regions currently receiving Mediterranean or Indian Ocean monsoonal rainfall (Bar-Matthews et al., 2000; Burns et al., 2001). Sapropel records from the Eastern Mediterranean suggest significant centennial- to millennial-scale climatic variability within this humid event, possibly representing fluctuations in fresh water discharge from the African continent associated with shifting monsoonal and high-latitude circulation (Rohling et al., 2002). However, little is known directly about short-term climate change in the Eastern Sahara because continuous terrestrial archives of Pleistocene humid phases are rare. One such record, from lacustrine sediments at Bir Tarfawi in Southern Egypt suggests there were several discrete stages within the MIS 5e pluvial phase, attributable to northward intensification of the Atlantic monsoon and the changing influence of groundwater and local rainfall to the water budget of the lake (McKenzie, 1993).

Current understanding of annual climate variation (seasonality) during the ~125 ka pluvial event in the Eastern Sahara is

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largely derived from the predictions of global circulation models (GCMs). GCMs suggest that during the ~125 ka and Holocene pluvial events, the Intertropical Convergence Zone was displaced northward of its current range, as a result of increased insolation at tropical latitudes (Prell and Kutzbach, 1987; de Noblet et al., 1996; Kutzbach and Liu, 1997). Thus, the Sahara would have received Atlantic-sourced precipitation during the summer, while other seasons remained relatively dry. GCM results for the Holocene pluvial event are supported by δ^{18}O profiles of mollusk shells from paleolakes in northern Sudan, which suggest a highly seasonal climate (Abell and Hoelzmann, 2000; Rodrigues et al., 2000). Stable isotope analyses of monthly growth laminae in the bivalve *Etheria elliptica* indicate that during the Holocene pluvial event, northern Sudan experienced both a long rainy season characterized by isotopically light Atlantic monsoon rainfall as well as a shorter season of isotopically heavier Indian Ocean rainfall (Rodrigues et al., 2000). While GCMs predict an intensification of the Indian Ocean monsoon during North African pluvial phases, consistent with regional proxy records, the extent of its effect on the Eastern Sahara is poorly understood (de Noblet et al., 1996; Sirocko, 1996; Burns et al., 2001; Liu et al., 2003). Constraining seasonal and millennial-scale climate variability in North Africa would inform our understanding of potential climate feedbacks associated with varying albedo and vegetation cover and would help assess the feasibility of hominids inhabiting or migrating through North Africa throughout the Pleistocene (e.g. Caton-Thompson, 1952; Petit-Maire et al., 1991; Kleindienst, 2000).

Quaternary deposits at Wadi Midauwara

Gastropod-bearing lacustrine silts from Wadi Midauwara, near Kharga Oasis, Egypt (Fig. 1), provide an outstanding opportunity for characterizing seasonal and millennial climatic trends during MIS 5e. Located along the edge of the Libyan Plateau, Wadi Midauwara has extensive accumulations of fossil tufa, indicative of increased groundwater discharge in the past (Smith et al., 2004a, Smith et al., 2004b). At least three chronologically distinct tufa stratigraphic units occur at Wadi Midauwara, which represent fluvial and paludal environments. In addition, low-Mg calcite silts are exposed over ~4.25 km^2 (a considerably larger area than that mapped by Smith et al., 2004b), indicating a substantial body of standing water at Wadi Midauwara (Figs. 2 and 3). The silts are >90% low Mg calcite, based upon 25 measurements of percent carbonate by dissolution in 10% HCl and X-ray diffraction analysis. Likely formed by the damming or filling of a deflation basin (Smith et al., 2004b), the lake in which these silts were deposited could have persisted for ~7–30 kyr (sedimentation rates of 1.1 mm/yr and 0.26 mm/yr for authigenic calcite-rich sedimentation in lakes in semi-arid climates; McKenzie, 1993; Abell and Hoelzmann, 2000). The silts are beige-colored and friable, with fine (<1 mm), faint lamination, and reach a thickness of 7.8 m near the western margin of the paleolake. The silts overlie Wadi Tufa 1 (U/Th date >350 ka) and are capped in areas by clastic tufa deposits, and then (almost ubiquitously) by a reed-cast rich facies of Wadi Tufa 2 (U/Th date 126±4 ka; Fig. 3; Smith et al., 2004b). The lacustrine silts are presumably associated with the

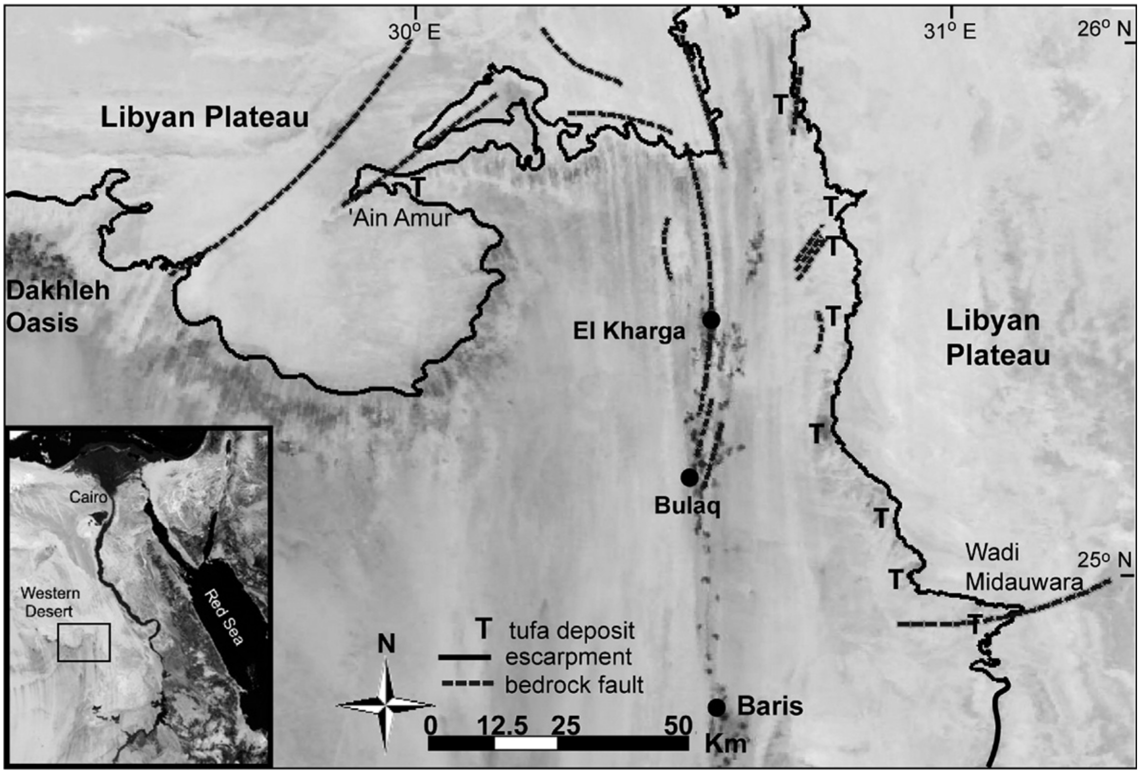

Figure 1. Kharga Oasis region, with bedrock faults (after Hermina, 1990), and tufa deposits (after Caton-Thompson, 1952). Image credit: J. Descloitres, NASA Visible Earth.

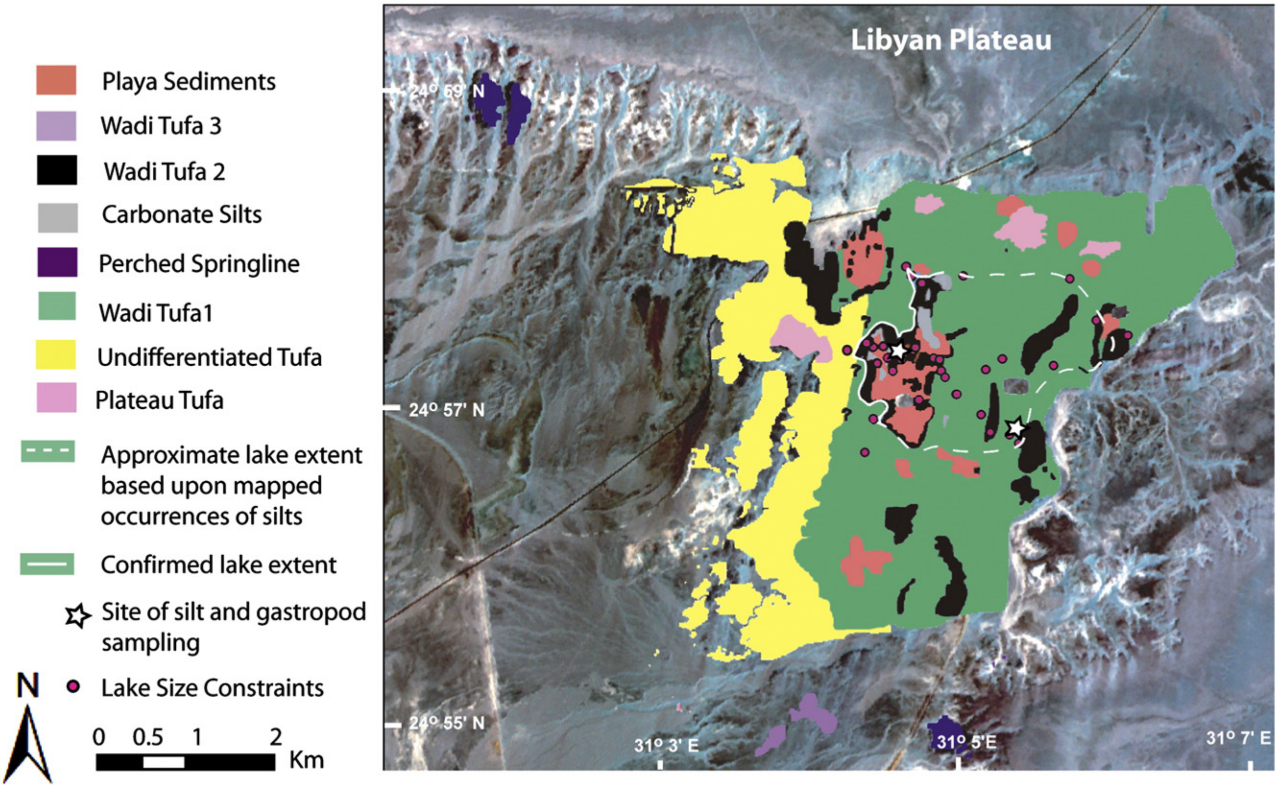

Figure 2. Quaternary geologic units (after Smith et al., 2004a) and approximate outline of paleolake boundaries at Wadi Midauwara mapped on ASTER image (Bands 1, 2, 3N). Confirmed lake boundary mapped where lacustrine silts were observed to pinch out completely, whereas approximate lake boundary based upon isolated occurrences of silts. Lake size constraint points correspond to differential GPS points that either represent contacts between lake sediments and overlying/underlying tufa deposits (within lake) or contacts between these same tufa units where no lacustrine silts are present (outside lake).

same humid event as the tufa which overlies them, as it is unlikely that the unconsolidated sediments could survive the intense aeolian erosion associated with a prolonged arid phase. Although the elevation of the contact between the lacustrine silts and overlying tufa deposits varies by about 2 m, some erosion would be expected during the transition from a lacustrine to a primarily fluvial sedimentary regime, as documented by laminated clastic tufa deposits overlying the silts. Further-

Figure 3. Upper 3 m of the measured section of silts. Silts are capped by ~1 m of clastic tufa and reed casts, indicating the transition to a fluvial/paludal regime. Backpack on right for scale (~40 cm high).

more, considerably more than 2 m of deflation would be expected in the absence of the tufa cap in the case of a prolonged arid phase for such friable sediments (e.g. in Dakhleh Oasis; Churcher et al., 1999). An irregular initial basin surface similar to the yardang-covered landscape present today may also contribute to the topography in this contact (Smith et al., 2004b). The silts thin towards the northern margin of the basin, whereas the southernmost extent of the silts is marked by a 200-m wide set of carbonate-cemented deltaic foresets. Due to its lateral extent, this feature most likely represents a primary entry point for overland flow into the basin (Smith et al., 2004b).

Regional and hydrologic setting

The Quaternary deposits at Wadi Midauwara overlie the late Cretaceous to early Eocene sediments of the Libyan Plateau. The local sandstone units of the Nubian aquifer in the Kharga depression are the Upper Cretaceous Maghrabi and Taref Formations (Hermina, 1990). These units primarily comprise interbedded siltstones and sandstones of moderate permeability (Hermina, 1990; Thorweihe, 1990). They are overlain by the Quseir, Duwi, and Dakhla Formations, primarily mudstone and shale with interbedded sandstone, which form the base of the Kharga depression (Hermina, 1990). Near Wadi Midauwara, the escarpment is formed by the Paleocene Tarawan Formation limestone, late Paleocene–early Eocene Esna Formation, a marly shale, and the Eocene El Rufuf Formation limestone (Hermina, 1990). Dissolution features on the plateau surface, as well as evidence for groundwater sapping at the base of the El Rufuf limestones, suggest the El Rufuf Formation acted as a perched aquifer during humid phases, supplying the carbonate-rich water from which tufas were deposited along the edge of the Libyan Plateau (Luo et al., 1997).

The spatial distribution of tufa deposits appears to be in part controlled by the location of bedrock faults, suggesting that faulted zones serve as regions of preferential water storage and/or bedrock dissolution (Fig. 1b; Hinnawi et al., 1978). These faults could have also acted as conduits for the movement of deep Nubian aquifer groundwater towards the surface. Recharged at the Uweinat uplift in northern Sudan during pluvial phases, this deep water is thought to have a residence time of ~490 kyr at Kharga Oasis (Sturchio et al., 2004; Patterson et al., 2005). Thus, if the Nubian aquifer contributed to spring discharge at Wadi Midauwara, then the tufas and associated deposits would not just record local climatic events, but also enhanced rainfall within the Nubian recharge area. Using geochemical data from Swanberg et al. (1984), PHREEQC calculations of calcite saturation indexes (Parkhurst and Appelo, 1999) for Nubian aquifer water sampled from pumped wells at Baris and Bulaq (west of Wadi Midauwara) indicate that Ca^{2+} and HCO_3^- concentrations are generally insufficient for calcite nucleation to occur at modern pH conditions and a temperature range between 20 °C and the modern (28.8–33.9 °C, likely warmer than paleoconditions as this water is pumped from depth; saturation indexes range between −0.51 and 0.09 for wells Baris 9A, Baris 9B and Bulaq 5 and Balad Bulaq). If Nubian aquifer water was the primary source for the Wadi Midauwara deposits, the necessary saturation state for calcite precipitation must have been reached through residence in the El Rufuf and/or Tarawan limestones with subsequent degassing of CO_2 away from springs along the escarpment. Due to its approximately neutral pH, considerable limestone dissolution by Nubian aquifer water is unlikely. However, infiltration of local, high pCO_2 waters derived from the soil zone above the plateau might facilitate the limestone dissolution necessary to produce the carbonates at Wadi Midauwara (e.g. Banner et al., 1996).

Lacustrine carbonates and gastropods as paleoenvironmental indicators

A small, shallow lake in a semi-arid environment sourced by $CaCO_3$-rich waters, such as that at Wadi Midauwara, would have reflected changes in water balance (seasonal or multi-annual) in the $\delta^{18}O$ values and the dissolved minor element cation (Mg, Sr, Ba)/Ca ratios of its water (Chivas et al., 1993; Curtis and Hodell, 1993; Valero-Garces et al., 1997; Wansard and Mezquita, 2001). The $\delta^{18}O$ value of lake water is primarily a function of the $\delta^{18}O$ of the input water (precipitation, stream flow, and groundwater if present), relative humidity, evaporation, and the residence time of the water in the lake (McKenzie and Hollander, 1993; Gat, 1995; Leng and Marshall, 2004). The $\delta^{18}O$ value of carbonates (authigenic or biogenic) precipitated in isotopic equilibrium with the water is related to the temperature of the water due to the temperature dependence of the $^{18}O/^{16}O$ fractionation factor (Epstein et al., 1951; Kim and O'Neil, 1997). Because calcite preferentially incorporates Ca as opposed to other compatible elements, such as Mg, Sr or Ba (Mucci and Morse, 1983; Tesoriero and Pankow, 1996; Huang and Fairchild, 2001), the element/Ca (El/Ca) ratio in the water would be expected to increase during intervals of $CaCO_3$ precipitation (Eugster and Hardie, 1978; Engstrom and Nelson, 1991; Xia et al., 1997), possibly corresponding to intervals of increased evaporation or productivity (Chivas et al., 1993; Teranes et al., 1999). Because evaporation can affect both the $\delta^{18}O$ and El/Ca ratios of the water, it may be possible to correlate changes that occur in the two records, thus decoupling the effect of temperature and evaporation upon $\delta^{18}O$ (Fig. 4). Because the distribution coefficient of Mg into calcite is temperature dependent, whereas that for Sr is independent of temperature (Huang and Fairchild, 2001), a comparison of the calcite $\delta^{18}O$, Mg/Ca and Sr/Ca trends can indicate the relative influences of temperature and evaporation upon the $\delta^{18}O$ of calcite precipitated at equilibrium conditions (Fig. 4).

The relationships discussed above have also been observed for tufa-depositing environments (e.g. Ihlenfeld et al., 2003; Andrews and Brasier, 2005) and karstic environments (e.g. Ayalon et al., 1999; Musgrove and Banner, 2004; McMillan et al., 2005) where the El/Ca ratio in the tufa/speleothem may reflect factors such as groundwater residence time and vadose zone processes within the aquifer, and along flow evaporation and carbonate precipitation after the water discharges from the spring. Thus, as the water that fed the lake at Wadi Midauwara

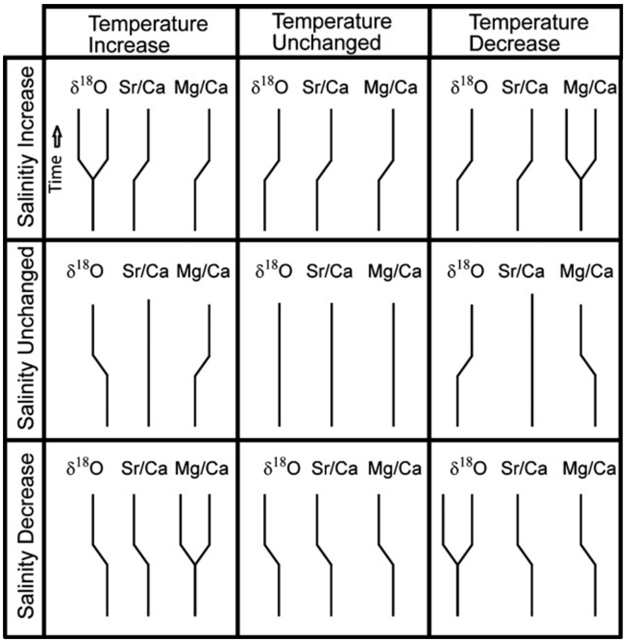

Figure 4. Effect of changes in temperature and water salinity (evaporation or aquifer residence time) upon the δ^{18}O, Sr/Ca, and Mg/Ca of authigenic calcite precipitated at equilibrium with the ambient water, after Curtis and Hodell (1993).

was likely derived from the same (or similar) source to that which formed the extensive tufa deposits in the area (Fig. 2), factors such as residence time of the water within the Refuf or Tarawan limestone also likely affected the hydrochemistry of the water that discharged from springs along the Libyan Plateau escarpment.

The gastropod, *Melanoides tuberculata*, abundant in the Wadi Midauwara silts, is a useful paleoclimate proxy as its shell reflects the chemistry of ambient lake water (Abell, 1985; Abell and Williams, 1989; Ayliffe et al., 1996). As the shell of *Melanoides* is excreted from the extrapallial fluid in approximate oxygen isotopic equilibrium with the surrounding water, the δ^{18}O values of shell aragonite reflect seasonal changes in water temperature and δ^{18}O (Abell, 1985; Leng et al., 1999). A recent study on *Melanoides* in isotopically and thermally invariant environments has found, however, that vital effects can cause ~0.5‰ variation in shell δ^{18}O, suggesting that minor along-shell isotopic variability cannot be interpreted climatically (Shanahan et al., 2005). The Sr/Ca and Ba/Ca ratios of *Melanoides* shell aragonite reflect the Sr/Ca and Ba/Ca ratios of the water in which the gastropod lived via distribution coefficients that do not appear to be temperature-dependent (Rosenthal and Katz, 1989). Thus, when sampled at regular intervals along the growth whorl, *Melanoides* shells can provide a geochemical record of the gastropods' habitat over their 1 to 2-yr lifespan (Abell, 1985; Leng et al., 1999).

Methods

Sampling and sample preparation

A 5.3-m-thick section of low-Mg calcite silts, selected for its accessibility, thickness and lack of cover by tufa debris, was sampled at 10-cm resolution (Figs. 2 and 3). *Melanoides* shells were obtained where present throughout the stratigraphy. A dense lens of shells about 50 cm from the top of the lake sediments along the east margin of the mapped paleolake was also sampled (Fig. 2). Gastropod shells were ultrasonically cleaned in deionized water, and samples extracted by drilling at 180° or 90° (for large gastropods "D" and "E") intervals from the aperture to the apex, using a 1-mm drill bit at low speeds to prevent aragonite destabilization (Gill et al., 1995). A minimum sample mass of 10 mg was necessary as the samples were split for stable isotope and minor element analyses. The remaining shell was analyzed by X-ray diffraction to verify that recrystallization to calcite had not occurred. A semi-quantitative determination of percentage aragonite was made according to the peak area method (Milliman et al., 1974).

Stable isotope analyses

Stable isotope analyses were performed on an automated Gas Bench II system, with a PAL autosampler. The samples were reacted with 100% orthophosphoric acid, and the evolved gas was analyzed on a Finnegan MAT 252 Mass Spectrometer. Samples were calibrated against NBS 19 and 20 to Vienna Pee Dee Belemnite (PDB). Both oxygen and carbon ä-values are reported as PDB. The analytical precision is 0.2‰ for δ^{18}O and is 0.1‰ for δ^{13}C. Calculations involving calcite–water equilibrium were conducted using the relationship of Kim and O'Neil (1997), and those involving aragonite–water equilibrium utilized the relationship of Grossman and Ku (1986).

Minor element analyses

Minor element analyses of the silts and gastropods were conducted via inductively coupled plasma mass spectrometry (ICP-MS). Samples weighing 1–10 mg were digested with 1 mL of 10% trace metal grade HNO_3 and were brought up to a volume of 10 mL with 1% trace metal grade HNO_3. They were then spiked with 1 mL of internal standard solution containing 100 ppb of Sc, Y, and In. A Finnegan MAT Element sector field ICP-MS was used to measure Ca, Mg, Sr, Ba, Sc, Y, and In concentrations in the digests. Sc was used as the internal standard for Ca and Mg, whereas Sr was standardized to Y, and Ba to In. Internal standards were chosen based upon similarity in ionization in plasma to the element of interest, lack of interference with the element of interest, absence in the sample, and coverage of the mass spectrum analyzed (Lea and Martin, 1996; Le Cornec and Correge, 1997). Calibration standards run as unknowns throughout the runs were typically within 1% of their expected values, and external standards analyzed repeatedly throughout each run exhibited precision of 2.7% for Ca, 2.9% for Mg, 3.7% for Sr, and 1.3% for Ba (Online appendix). Clean lab blanks (1% HNO_3) and procedural blanks were also run routinely, and had ~0.1 ppm in Ca, 1 ppb for Mg, and were undetectable for Ba and Sr.

Results

Stable isotope and minor element profiles of the silts

Results of stable isotope analyses of lacustrine silts are presented in Figure 5. $\delta^{18}O$ and $\delta^{13}C$ values do not covary substantially over the profile as a whole. The lower 200 cm of the $\delta^{18}O$ profile is significantly less variable ($1\sigma = 0.2‰$) than the upper portion of the section ($1\sigma = 0.6‰$; $F = 0.12$; $p < 0.001$).

Analyses of Mg, Sr, and Ba were normalized to Ca in order to account for any errors in sample mass measurement. Silt Mg/Ca and Sr/Ca are positively covariant, with values remaining relatively constant until 200 cm from the base of the section, where the values decrease for 150 cm, after which they become relatively steady (Fig. 5, Table 1). Both Mg/Ca and Sr/Ca are inversely related to silt $\delta^{18}O$ and Ba/Ca (Table 1), which gradually increases up-section (Fig. 5). A maximum positive covariance ($r^2 = 0.66$, $p < 0.001$) for $\delta^{13}C$ with Sr/Ca and Mg/Ca occurs between 240 and 430 cm.

Gastropod shell stable isotope and minor element analyses

XRD of the analyzed gastropod shells indicated that all were >95‰ aragonite. Figure 6 presents the $\delta^{18}O$ and Sr/Ca and Ba/Ca profiles for the *Melanoides* shells from the lacustrine silts. The gastropods from the lacustrine silts have a mean $\delta^{18}O$ of −10.7‰ and a mean along-shell variation of 0.6‰. The gastropods from the shell bed have an average $\delta^{18}O$ of −10.6‰, with a mean 1.05‰ variation along the two shells. The mean $\delta^{13}C$ value for the gastropods from the silts is −3.4‰, with a mean along-shell variability of 0.7‰. The mean $\delta^{13}C$ of the snails from the shell bed is −4.9 with a mean 1.45‰ variability in $\delta^{13}C$ along-shell. The Ba/Ca and Sr/Ca profiles do not consistently covary with the $\delta^{18}O$ or $\delta^{13}C$ of the gastropod shells in a statistically significant manner.

Table 1
R^2 values for the covariance between the stable isotope values and minor element ratios for the calcite silts ($n = 52$)

	$\delta^{18}O$	$\delta^{13}C$	Sr/Ca	Mg/Ca	Ba/Ca
$\delta^{18}O$		(0.13[#])	(0.58)	(0.65)	0.53
$\delta^{13}C$	(0.13[#])		0.29	0.29	(0.24)
Sr/Ca	(0.58)	0.29		0.9	(0.64)
Mg/Ca	(0.65)	0.29	0.9		(0.75)
Ba/Ca	0.53	(0.24)	(0.64)	(0.75)	

Numbers inside parentheses indicate negative covariance. Statistical significance is $p < 0.001$ unless denoted by [#] for $p < 0.01$.

Discussion

The following discussion of the stable isotope and minor element analyses of the lacustrine silts relies upon the effects of lake water temperature, evaporation, groundwater residence time, and the isotopic composition and amount of local rainfall upon $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, Sr/Ca, and Ba/Ca of calcite precipitated at isotopic and chemical equilibrium with the ambient water (Table 3).

Interpretation of lacustrine silt stable isotope and minor element analyses

Lake temperature

If lacustrine calcite precipitated in isotopic equilibrium with lake water (as is commonly the case; Teranes et al. (1999)), the

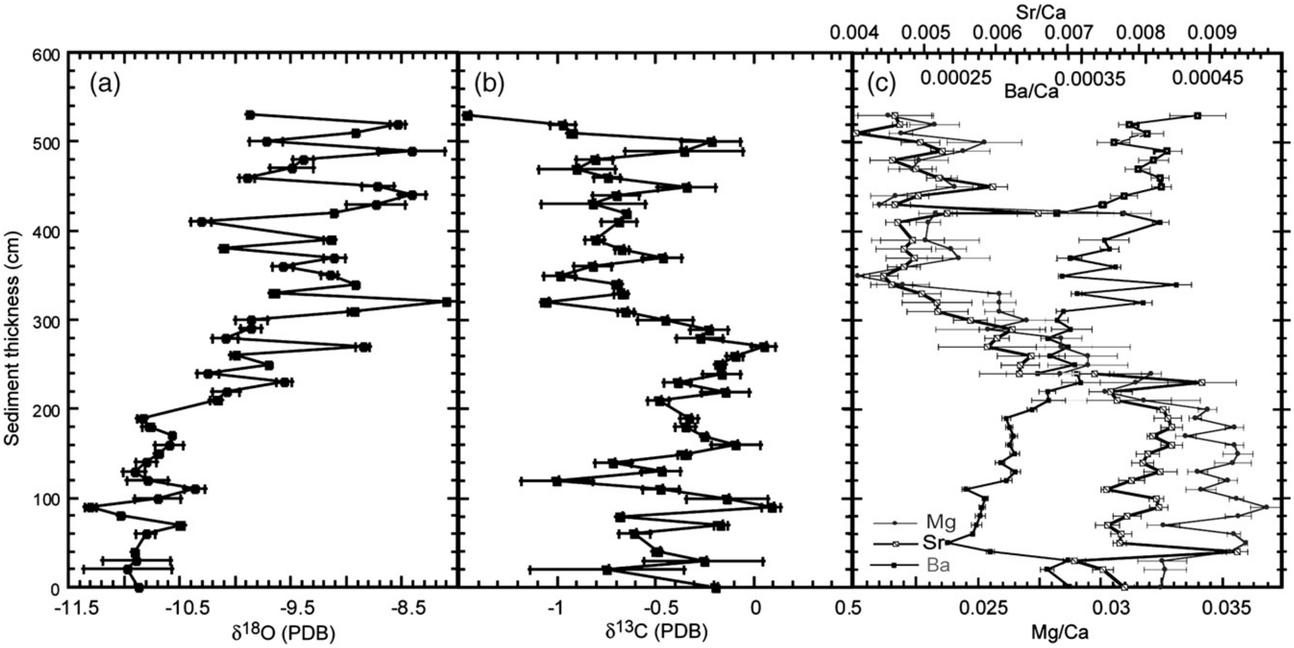

Figure 5. Stable isotope and minor element profiles for the silts from Wadi Midauwara, reported as PDB. Panels (a) and (b) show the $\delta^{18}O$ and $\delta^{13}C$ profiles where error bars correspond to the 1σ standard deviation for replicate analyses. Panel c shows the Mg/Ca, Sr/Ca, and Ba/Ca profiles for the silts. Error bars for the El/Ca data represent the replicate standard deviation for five runs and three passes on the ICP-MS.

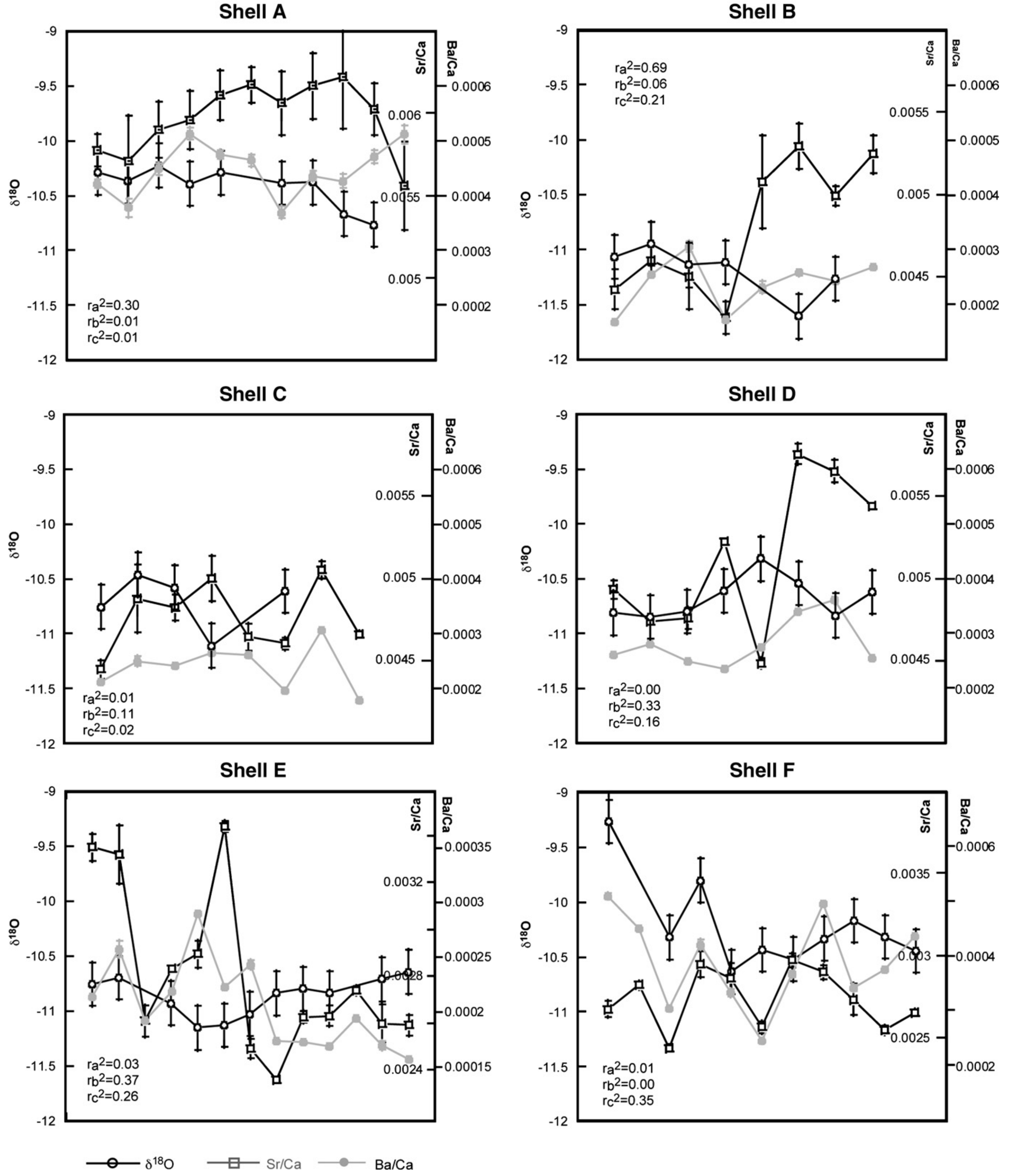

Figure 6. δ^{18}O and minor element profiles for the gastropods from Wadi Midauwara, reported as PDB. Shells A–C, and F are from the stratigraphic section sampled for isotopic and El/Ca analyses, and shells D and E are from shell lenses on the eastern margin of the lake. r^2_a r^2_b, and r^2_c are for correlations between δ^{18}O and Sr/Ca, δ^{18}O and Ba/Ca, and Sr/Ca and Ba/Ca, respectively.

isotopic stratigraphy of the lake silts records the changing isotopic composition and/or temperature of the water at Wadi Midauwara. To explain the 3.3‰ variability in δ^{18}O solely by temperature variability, 14.6 °C change would be required (Kim and O'Neil, 1997). This reduces to 2.3‰ when a three point running average is applied to the data, corresponding to 10.4 °C temperature change. Because GCMs (e.g. Prell and Kutzbach, 1987; de Noblet et al., 1996; Montoya et al., 2000) suggest that the summer land surface temperatures in North Africa during the last interglacial period were ~3–7 °C warmer than modern, a long-term temperature change explanation for the isotopic variability is unlikely unless lacustrine deposition began during MIS 6. Though some Kharga Oasis tufas do date to late MIS 6 (Smith et al., 2004b), a trend of increasing temperature is not reflected in the $\delta^{18}O$ profile for the silts. While the temperature at which calcite precipitation occurred may have some dependency upon water depth (Leng and Marshall, 2004), depth-controlled fluctuations in calcite $\delta^{18}O$ are expected to be muted, due to the typical link between shallow depths, warmer temperatures (lighter carbonates), and evaporation (heavier water/carbonates). Furthermore, the high correlation between Mg/Ca and Sr/Ca ratios for the silts (Table 1) suggests that the observed changes in $\delta^{18}O$ were not exclusively due to changes in water temperature as that would be expected to strongly affect calcite Mg/Ca but not Sr/Ca (Huang and Fairchild, 2001).

Lake evaporation/groundwater residence time and temperature

As temperature can be discounted as the dominant forcing mechanism for the changes in the Wadi Midauwara silt $\delta^{18}O$ values, the remaining factors include changes in the $\delta^{18}O$ of the input water and evaporation. Calculations of Rayleigh distillation (relationships from Criss, 1999) of a lake starting at $-9.1‰_{SMOW}$ (water in equilibrium with the lightest silt calcite at 24 °C, modern mean annual temperature) via evaporation (humidity = 0.3–0.6, semi-arid conditions) indicate ~25% of the lake water would need to evaporate to produce the observed 3.3‰ range in $\delta^{18}O$[2]. If evaporation were the principal control upon the oxygen isotope and minor element composition of the lake water, a positively covariant trend of $\delta^{18}O$ with El/Ca should result (Fig. 4) due to increasing minor element concentrations in lake water during times of enhanced evaporation and calcite precipitation, as Ca is preferentially incorporated into the calcite lattice (Chivas et al., 1993).

In karst-derived waters, Mg/Ca and Sr/Ca also increase with aquifer residence time due to progressive leaching of less compatible elements within the calcite lattice and reprecipitation of calcite within the aquifer itself (Fairchild et al., 2000; Verheyden et al., 2000; Musgrove and Banner, 2004). Thus, if dry times are associated both with the drawdown of long residence-time water from an aquifer, and enhanced evaporation, positive covariance between Mg/Ca, Sr/Ca, and $\delta^{18}O$ would be expected (Fairchild et al., 2000; Verheyden et al., 2000). However, in the Wadi Midauwara silts, a modest negative covariance between these variables occurs (Fig. 5, Table 1). Thus, evaporation was not likely the primary control upon the trends in $\delta^{18}O$, Mg/Ca, and Sr/Ca in Midauwara lake water. However, modest, statistically significant covariance of Mg/Ca and Sr/Ca with silt $\delta^{13}C$ suggests that aquifer residence time may have influenced the minor element composition of lake water, as limestone dissolution and reprecipitation of calcite within the aquifer can increase $\delta^{13}C$ and El/Ca (Garnett et al., 2004).

The observed increase in $\delta^{18}O$ correlated with decreases in Mg/Ca and Sr/Ca could be explained by a decrease in temperature, coupled to a decrease in salinity/groundwater residence time (Fig. 4). Given the estimated effect of temperature upon the Mg/Ca ratio (0.0012/°C between 15 °C and 25 °C; Huang and Fairchild, 2001), a decrease of 9.4 °C could explain the three-point running average decrease of 0.0113 in Mg/Ca upwards in the stratigraphy. Although this fits well with the 10.4 °C temperature change required to explain the increase in $\delta^{18}O$, the high correlation between the Mg/Ca and Sr/Ca ratios ($r^2 = 0.9$, $p < 0.001$) suggests that a considerable decrease in salinity would need to have occurred contemporaneously to account for the correlative decrease in Sr/Ca. The reduction in evaporation or groundwater residence time required to produce this decrease in salinity, presumably driven by an increase in rainfall, would also be expected to cause significant, non-temperature-related changes in both $\delta^{18}O$ and Mg/Ca. If a smaller temperature change were invoked, coupled to a decrease in evaporation/groundwater residence time, this would require further explanation for the remaining source of variation in $\delta^{18}O$ and Sr/Ca.

If water alkalinity decreased, such that more water would need to evaporate from the lake in order to reach calcite saturation, the observed relationship between Mg/Ca, Sr/Ca, and $\delta^{18}O$ might result. Such a change could be associated with increasing aridity causing a decrease in recharge area soil thickness or productivity, leading to lower soil pCO_2, less aquifer limestone dissolution (lower El/Ca ratios), and spring discharge less saturated with respect to $CaCO_3$. However, under such a scenario, longer aquifer residence times for water would also be expected, in which calcite reprecipitation within the aquifer itself would raise the El/Ca ratio of the groundwater. Increases in El/Ca ratios corresponding to arid periods have been documented in numerous speleothem and drip water records from semi-arid environments (e.g. Ayalon et al., 1999; Musgrove and Banner, 2004; McMillan et al., 2005).

Hypotheses regarding Ba/Ca variation

While variability in aquifer residence time can explain the positive covariance between Mg/Ca and Sr/Ca, it does not provide a satisfactory explanation for the negative covariance between Sr/Ca or Mg/Ca and Ba/Ca. In karstic environments, Sr/Ca and Ba/Ca generally positively covary (e.g. Ayalon et al., 1999; Hellstrom and McCulloch, 2000; Ihlenfeld et al., 2003; Andrews and Brasier, 2005). This has been attributed to soil-zone processes (Hellstrom and McCulloch, 2000), calcite precipitation within the vadose zone and along-flow away from springs (Ihlenfeld et al., 2003), and local bedrock dissolution and input of sea spray (Ayalon et al., 1999). Because the distribution coefficients for Ba/Ca and Sr/Ca are both less than one, in all dissolution/precipitation driven scenarios, positive covariance should be expected. Potentially, the negative covariance observed in the silts could be explained by the mixing of distinct low-Ba, high-Sr and Mg and high-Ba, low-Sr and Mg waters. Barite-containing sandstones have been reported in the upper

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[2] For details regarding this calculation, please refer to online supplementary information.

portions of the Nubian aquifer (El Wahab, 1999). However, Nubian aquifer water samples from Kharga and Dakhleh Oases have Ba/Ca values comparable with the inferred values for lake water, indicating that either the Ba concentration in artesian Nubian aquifer water during pluvial phases was higher, or that another source contributed relatively high Ba to the Midauwara lake water (Table 2). The additional input of Nubian aquifer water would have also resulted in a decrease in lake water $\delta^{18}O$, Mg/Ca and Sr/Ca, as it has considerably lower Mg/Ca, Sr/Ca, and $\delta^{18}O$ values than the reconstructed lake water (Table 2 and 3).

Detrital sediment could also provide a source for Ba, which is commonly adsorbed to clays. Although the silts are >90% (and mostly >95%) $CaCO_3$, the non-carbonate fraction predominantly comprises clay minerals. In the case that Ba content of lacustrine silts could be considered a proxy for detrital clay input (e.g. Li and Chan, 1979; Carroll et al., 1993; Sinclair and McCulloch, 2004), a positive covariance with Sr and Mg, also commonly adsorbed to clays, might also be expected. However, given the low silt Ba/Ca values, and the fact that the more abundant Sr and Mg were likely primarily derived from limestone dissolution, such a correlation would not necessarily occur. The lack of constraints on the potential sources for Ba input to the Wadi Midauwara lake at this time significantly restricts our understanding and interpretation of this unusual relationship between Ba and Sr in the lacustrine silts.

Implications of $\delta^{13}C$ analyses for lake hydrology

The relatively high $\delta^{13}C$ values of the silts are consistent with values from lakes in which waters are equilibrated with atmospheric CO_2 due to long residence times (e.g. McKenzie, 1985, Lamb et al., 2000). Indeed, the probable high surface area/volume ratio of the lake might have also facilitated prolonged equilibrium with atmospheric CO_2. However, the $\delta^{13}C$ values for the silts are also similar to the $\delta^{13}C$ values of tufas along the Libyan Plateau escarpment in Kharga Oasis, which range from −6.1‰ to 1.3‰ (Smith et al., 2004a). As the tufas were likely precipitated from the same water which fed as the lake, the high $\delta^{13}C$ values for the lacustrine silts do not necessarily reflect gradual equilibration of the DIC reservoir of the lake with atmospheric CO_2. Rather, they could reflect a pervasive regional trend in $\delta^{13}C$ values. If groundwater $\delta^{13}C$ was initially relatively heavy, perhaps due to the presence of C_4 vegetation (Smith et al., 2004a) and carbon derived from local limestone bedrock dissolution, then CO_2 degassing along flow from springs to the lake (e.g. Chafetz and Lawrence, 1994), as well as atmospheric equilibration within the lake itself, could result in lacustrine silts with $\delta^{13}C$ range of −1.5 to 0.1‰.

Table 2
Minor element data for Nubian aquifer water samples from Dakhleh and Kharga Oases (Bulaq), and average calculated minor element composition of Midauwara lake water (from distribution coefficients from Tesoriero and Pankow, 1996; Huang and Fairchild, 2001)

	Temperature	Alkalinity	Mg/Ca	Sr/Ca	Ba/Ca
Bashendi	32.5	79.90	0.88	0.02	0.02
Mut	30	64.87	0.51	0.01	0.01
Sheikh Wali	36.4	54.06	0.79	0.02	0.03
Qasr	>34	78.45	0.54	0.01	0.02
Bulaq	n.m.[a]	n.m.[a]	0.55	0.01	0.00
Lake water			0.90	0.10	0.03

Alkalinity (mEq/L) and temperature measurements (°C) were taken in the field (Rounds and Wilde, 2001). Water samples were acidified and filtered in the laboratory about one week after collection, and Mg, Ca, Sr, Ba concentrations were measured via ICP-MS[b].

[a] Not measured.

[b] Error for Mg/Ca, Sr/Ca and Ba/Ca water analyses is 0.01, 0.0009, and 0.0009, respectively.

Table 3
Inferred influence of climatic and hydrologic parameters upon the stable isotopic and minor element geochemistry of calcite formed at isotopic and chemical equilibrium with the ambient water

	$\delta^{18}O$	$\delta^{13}C$	Mg/Ca	Sr/Ca	Ba/Ca
Lake temperature					
Increase	−	/	+	/	/
Decrease	+	/	−	/	/
Lake evaporation[a]					
Increase	+	/[b]	+	+	+
Decrease	−	/[b]	−	−	−
Groundwater residence time					
Increase	/[c]	+	+	+	+
Decrease	/[c]	−	−	−	−
Nubian aquifer water input					
Increase	−	/	−	−	?/
Decrease[d]	/	/	/	/	/
Input water Atlantic sourced precipitation[e]					
Increase	−	−	−	−	−
Decrease	+	+	+	+	+
Indian Ocean/Mediterranean sourced precipitation[e]					
Increase	+	−	−	−	−
Decrease[d]	/	/	/	/	/

+: increase; −: decrease; /: no substantial direct effect.

[a] Presumes that inferred increase in lake salinity thereby increases calcite saturation.

[b] Evaporation may affect lake productivity/equilibrium with atmosphere CO_2, which in turn would affect the $\delta^{13}C$ of the dissolved inorganic carbon in the water.

[c] Increase in groundwater residence time would probably be associated with drier conditions, which might in turn be borne out in the $\delta^{18}O$ of the water.

[d] Baseline situation assumes that this water was not an important part of lake balance.

[e] Changes in $\delta^{13}C$ inferred as result of changes in aquifer residence time due to variation in the amount of precipitation.

The low covariance ($r^2 = 0.13$, $p = 0.001$) between $\delta^{18}O$ and $\delta^{13}C$ for the lacustrine silts may either indicate that the lake at Wadi Midauwara was hydrologically open, or that changes in water balance occurred very gradually (Talbot, 1990, Li and Ku, 1997). A comparison of the inferred Mg/Ca and Sr/Ca values for the lake water (distribution coefficients from Huang and Fairchild, 2001) between the lake at Wadi Midauwara and Bir Sahara, a coeval lake in southern Egypt that exhibits significant isotopic covariance ($r^2 = 0.91$), suggests that the Wadi Midauwara lake water was considerably less saline (McKenzie, 1993; De Deckker and Williams, 1993). If contained by a tufa barrage dam similar to those found in the Grand Canyon or Plitvice Lakes (Croatia) (Emeis et al., 1987; Ford and Pedley, 1997; Smith et al., 2004b), the lake could easily have been hydrologically open. To sustain the lake, spring flow from the escarpment must have been perennial, with sufficient rainfall and/or aquifer storage to support these springs year-round.

Climatic implications of silt chemistry

To account for source water variations in $\delta^{18}O$ and El/Ca, an explanation for the observed trends in the silts is required, which explains the apparent negative covariance of $\delta^{18}O$ with Sr/Ca and Mg/Ca in the silts. Precipitation in North Africa during the MIS 5e pluvial phase has been postulated by many authors (McKenzie, 1993; Crombie et al., 1997; Sultan et al., 1997) as being primarily Atlantic sourced, thus accounting for the light isotopic values of Nubian aquifer waters. However, calculations using a Nubian aquifer-type water source ($\delta^{18}O = -11‰_{SMOW}$) show that the typical water temperature necessary to precipitate calcite at equilibrium with a $\delta^{18}O_{PDB}$ of −9.9‰ (mean for the Midauwara silts) is approximately 9°C (Kim and O'Neil, 1997). While GCMs indicate increased seasonality during MIS 5e, it is extremely unlikely that the average temperature dipped three degrees below that predicted for glacial climates (e.g. de Noblet et al., 1996). Calcite precipitated in equilibrium with Nubian aquifer water at the modern mean annual temperature (24 °C; Vose et al., 1992) should have a $\delta^{18}O$ of −13.2‰. Therefore, either the waters that precipitated these carbonates experienced intense evaporation along-flow from the springs (e.g. Crombie et al., 1997), or the waters themselves were initially considerably heavier than those of the Nubian aquifer. However, intense along-flow evaporation of spring waters should have affected lake El/Ca and $\delta^{18}O$ (see above, Table 3; Ihlenfeld et al., 2003).

The input of isotopically heavier rainfall to the lake at Wadi Midauwara, corresponding to an increase in precipitation, and coupled to changes in groundwater residence times could account for the trends which are observed in the stable isotopes and the Mg/Ca and Sr/Ca ratios (Fig. 5). Indian Ocean monsoonal rainfall reached as far as northern Sudan during the Holocene pluvial phase (Rodrigues et al., 2000), a humid phase likely of lesser magnitude than the MIS 5e event (de Noblet et al., 1996; Rossignol-Strick and Paterne, 1999; Bar-Matthews et al., 2000). Prell and Kutzbach (1987) indicate that the Indian Ocean monsoon was intensified during MIS 5e as well. Their GCM suggests that moisture derived from the Indian Ocean would have traveled towards the Western Desert of Egypt during the MIS 5e pluvial phase. As discussed by Smith et al. (2004a), Indian Ocean-sourced precipitation in Kharga Oasis would be noticeably heavier ($\sim -3 \pm 2‰_{SMOW}$) than that produced by the Atlantic monsoon ($-11‰_{SMOW}$). It is conceivable that the Bir Sahara and Bir Tarfawi paleolakes, with an average carbonate $\delta^{18}O$ of −5.5‰ (McKenzie, 1993), may have received a component of Indian Ocean-sourced moisture. To produce the observed range of $\delta^{18}O$ values of the Wadi Midauwara silts by mixing an Atlantic-derived water with an Indian Ocean-derived water, at 24 °C, assuming equilibrium conditions and no evaporation, would require between 23% and 64% of the lake water to be derived ultimately from the Indian Ocean. When the effects of modest evaporation are taken into account, 64% is probably an overestimate, as the influence of the Indian Ocean monsoon was probably considerably less than the Atlantic (by analogy from the Holocene; Rodrigues et al., 2000). Nonetheless, input of this isotopically heavier precipitation could account for the isotopic enrichment observed in the carbonate silts that appears to be independent of intense evaporation (Table 3).

While the Indian Ocean is one potential source of isotopically heavier rainfall, the Mediterranean is also a possibility, as it is the main source for the minimal rainfall that the region currently receives. Arz et al. (2003) suggest that input of Mediterranean-sourced precipitation to the northern portion of the Red Sea occurred during the early portions of the Holocene pluvial phase, associated with a strengthened North Atlantic/Arctic Oscillation (NAO/AO). Rohling et al. (2002) implicate shifts between African monsoonal and high-latitude circulation as an explanation for the climatic variability observed in Mediterranean sapropels. $\delta^{18}O$ and Sr/Ca records of ~122 ka corals in the Gulf of Aqaba provide further evidence for the influence of the NAO upon Mediterranean climates during that time, with resulting increased seasonality in surface temperatures and a winter rainfall pattern (Felis et al., 2004). However, the GCM of Montoya et al. (2000) does not predict substantial winter precipitation in North Africa during the MIS 5e event, thus leaving the influence of Mediterranean-derived moisture as far south as the Kharga Oasis an open question. Whether additional precipitation was derived from the Mediterranean or, more likely, the Indian Ocean, a second rainy season with relatively high rainfall $\delta^{18}O$ would have both increased lake $\delta^{18}O$ values and resulted in a climate with less rainfall seasonality relative to one dominated by only Atlantic monsoon precipitation.

The effect of climate upon the local hydrology may be manifested in the El/Ca trends in the silts. A scenario in which an increased proportion of Indian Ocean (and/or Mediterranean)-sourced precipitation led to greater total precipitation and decreased aquifer residence times could explain the trend towards increased $\delta^{18}O$ and decreased Mg/Ca and Sr/Ca in the stratigraphic section (Table 3). Because Kharga Oasis is located near the maximum possible extent of Indian Ocean sourced wind vectors (Prell and Kutzbach, 1987), lower monsoon intensity would correspond with a decrease in the proportion of Indian Ocean rainfall, lighter lake water $\delta^{18}O$ values (as all rainfall would be Atlantic sourced), decreased annual precipitation, and higher groundwater residence time.

The most dramatic trend within the $\delta^{18}O$ and El/Ca profiles for the silts occurs between 200 cm and 350 cm (Fig. 5), corresponding to a decrease in $\delta^{13}C$, and increase in $\delta^{18}O$. Additionally, a maximum covariance between $\delta^{13}C$ and El/Ca occurs from 240 to 430 cm. Assuming that the El/Ca values of the silts do, indeed, reflect groundwater residence time, the interval of 200–350 cm could reflect a gradual increase in local precipitation and perhaps an interval of monsoon intensification. However, considerable structure occurs in the $\delta^{18}O$ profile that can not be fully explained by the suggested relationships between monsoon intensity, water sources, and aquifer residence time. In these intervals lake water evaporation may control $\delta^{18}O$, suggested by the peaks at 490 and 520 cm, which do correspond to peaks in Mg/Ca and Sr/Ca, though this is not always the case for the $\delta^{18}O$ peaks in the upper portion of the profile. Thus, for this interval of the lake at Wadi Midauwara, the lake probably experienced changes in the $\delta^{18}O$ values of its water, perhaps tied to changes in its water budget and local hydrology.

However, it is also prudent to consider whether there are any possible scenarios in which unusual hydrologic conditions rather than climatic change might result in the observed trends in lacustrine silt $\delta^{18}O$ and minor elements. A change in the hydrology of the Wadi Midauwara lake, such as its area/volume ratio, degree of hydrological closure, and lake water residence time could have resulted in the observed relationships between $\delta^{18}O$, Sr/Ca, and Mg/Ca. An increase in residence time of water in the lake, resulting in higher $\delta^{18}O$ values would be expected to also result in higher $\delta^{13}C$ values due to increased atmospheric equilibration (McKenzie, 1985), which is not observed. However, this assumes that no other climatically or hydrologically driven changes in $\delta^{13}C$ occurred, which may not be the case, given the correlation between $\delta^{13}C$ and El/Ca between 240 cm and 430 cm. Although a hydrologically open lake presents unique challenges in terms of decoupling the stable isotope and minor element trends (e.g. Smith et al., 2002), a satisfactory explanation for the observed relationships relying only upon changes in temperature, evaporation, and/or residence time has not yet been identified. Thus, the only explanation herein examined, which successfully explains the $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, Sr/Ca, and possibly Ba/Ca trends for the paleolake at Wadi Midauwara, is the input of an isotopically heavier water during overall wetter conditions.

Implications of gastropod $\delta^{18}O$ and minor elements

The mean $\delta^{18}O$ value for the gastropods from the silts of −10.7‰ is consistent with the $\delta^{18}O$ of the silts and similarly implies shell growth in oxygen isotopic equilibrium with water with $\delta^{18}O$ of −9.9‰ at 24 °C. The along-shell variations (mean = 0.6‰) measured at Wadi Midauwara are comparable to those present in modern and Quaternary samples of *Melanoides* from other relatively stable African lakes, which have between 0.3‰ and 2‰ change in $\delta^{18}O$ along-shell (Table 4), and furthermore are within the range of variation which may be caused by vital effects (Shanahan et al., 2005), suggesting negligible seasonal variation in lake water $\delta^{18}O$. The absence of strong seasonal variation in Midauwara gastropod shell $\delta^{18}O$ (Table 4) comparable to that observed in closed basin lakes in semi-arid climates (~6–17‰; Abell and Williams, 1989; Abell and Hoelzmann, 2000; Hailemichael et al., 2002), may result from a relatively brief residence time for Midauwara lake water due to significant outflow from the lake. The $\delta^{13}C$ values for the shells from the silts towards the center of the lake are generally between −2‰ and −3‰, whereas the authigenic carbonate silts vary between −1.5‰ and 0.1‰, suggesting the input of light dietary carbon into the gastropod shells (Leng et al., 1999). The $\delta^{13}C$ values for the gastropods from the shell bed near the eastern margin are 1–2‰ lighter than those from the lacustrine silts, varying between −4‰ and −5‰, suggesting either a more isotopically depleted DIC reservoir or a higher input of dietary carbon into the gastropod shells.

Minor element analyses along the whorls of the gastropod shells do not reveal any consistently statistically significant correlations with stable isotope analyses (Fig. 6). Though bulk shell analyses of *Melanoides* shell aragonite do not seem to indicate significant vital effects (Rosenthal and Katz, 1989), the existence of small-scale vital effects (c.f. Shanahan et al., 2005) in a controlled environment has not been thoroughly explored. In most shells, both positive and negative correlations between $\delta^{18}O$ and El/Ca appear to be present in different portions of the shell. For example, in shell "B" from the silts, for the first four data points, $\delta^{18}O$ loosely follows Sr/Ca and Ba/Ca, whereas for

Table 4
Maximum along-shell variability in $\delta^{18}O$ and mean $\delta^{13}C$ for modern and Quaternary African gastropod shells

Location	Age	Environment	$\Delta\delta^{18}O$	Mean $\delta^{13}C$	Species
[1]Lake Malawi	Modern	Lake	1.2	−0.8	*Melanoides tuberculata*
[2]Dry Selima, Sudan	5.57–8.82 ka*	Shallow lake	5.3	−8.2	*Biomphalaria pfeifferi*
[2]Dry Selima, Sudan	5.57–8.82 ka*	Shallow lake	1	−6	*M. tuberculata*
[2]W. Nubian Palaeolake	9.4–7.4 ka*	Shallow lake	4	−2.3	*M. tuberculata*
[2]Wadi Howar, Sudan	9.4–5.5 ka*	Pools in wadi	9.4	0.9	*M. tuberculata*
[2]Wadi Howar, Sudan	9.4–5.5 ka*	Pools in wadi	7.7	−6.8	*M. tuberculata*
[3]Chalbi Basin, Kenya	11 ka*	Lake	1	−6	*M. tuberculata*
[3]Buffalo Springs, Kenya	Modern	Springs	0.75		*M. tuberculata*
[4]Lake Besaka, Ethiopia	15–20 ka#	Lake	1	−3.3	*Cleopatra bulimoides*
[4]Lake Besaka, Ethiopia	11–9 ka#	Lake	1.5	−3.3	*M. tuberculata*
[4]Lake Besaka, Ethiopia	11.2 ka*	Lake	3.1	−4.7	*M. tuberculata*
[4]Aladi Springs, Ethiopia	11.07 ka*	Spring	1	−4.5	*M. tuberculata*
[4]Erer Springs, Ethiopia	6.67 ka*	Spring	1	−4.3	*M. tuberculata*
[4]Lake Lyadu, Ethiopia	Modern	Lake	3.7	−3.6	*Bulinus sp.*
[4]Lake Lyadu, Ethiopia	Modern	Lake	4	1.9	*Cleopatra bulimnoides*
[4]Lake Lyadu, Ethiopia	Modern	Lake	6.1	−2.3	*M. tuberculata*
[5]Lake Awasa	Modern	River fed lake	0.3	−4.8	*M. tuberculata*
[5]Lake Tilo	Modern	Crater lake	1.9	−6.5	*M. tuberculata*
[6]Kharga Oasis, Egypt	~125 ka	Lake	0.6		*M. tuberculata*
[7]Khaga Oasis, Egypt	~125 ka	Lake	0.6	−3.91	*M. tuberculata*

[1]Abell (1985); [2]Abell and Hoelzmann (2000); [3]Abell and Nyamweru (1988); [4]Abell and Williams (1989); [5]Leng et al. (1999); [6]Smith et al. (2004a); [7]This study; *^{14}C date, reported as yr BP; #estimated based upon archaeological assemblages.

the latter three points, an antithetic relationship exists. This may be explained by the changing influence of temperature and evaporation upon the δ^{18}O and El/Ca ratios. Given that the main rainy season was probably during the summer months, the warmest months were also likely the wettest. In the absence of a rainfall regime in which the driest months correspond to the coolest temperatures, a positive correlation between the minor elements and stable isotopes over the entire lifetime of the gastropods should not be expected. In a summer monsoonal climate, warmer temperatures (and therefore lighter carbonate values) would occur during times of maximum rainfall (and presumably lowest El/Ca), producing positive covariance. Negative covariance between δ^{18}O and El/Ca for the gastropod shells might correspond to increased carbonate precipitation (increase El/Ca) water during warmer conditions, possibly corresponding to drier months immediately preceding or following the monsoon season.

Conclusions

The authigenic calcite silts at Wadi Midauwara provide evidence for the prolonged presence of surface water in the Western Desert of Egypt at ~125 ka. Probably derived in large part from locally recharged groundwater, the lacustrine system at Midauwara was only subject to minor seasonal changes in water chemistry most likely associated with modest evaporation and seasonal temperature changes. If the lake was hydrologically open throughout the year, springs along the Libyan Plateau escarpment must have flowed perennially, maintaining the lake. This necessitates that enough local precipitation occurred for local aquifers to remain charged throughout the year.

The δ^{18}O values for the silts are inconsistent with precipitation at equilibrium with a Nubian aquifer (or predominantly Atlantic-sourced) water. While the relatively high δ^{13}C values for the silts suggest an approximate equilibrium of the ambient water with atmospheric CO_2, the negative rather than positive covariance between δ^{18}O and the Mg/Ca and Sr/Ca profiles for the silts suggests that evaporation was not the primary control upon their δ^{18}O values. This implies that for significant portions of the profile, the addition of isotopically heavier water is necessitated. This could have been provided by precipitation from the Indian Ocean monsoon, which has been shown to have been enhanced during the MIS 5e pluvial phase (Burns et al., 2001). However, as the observed trends could also be produced by unusual hydrologic conditions, further regional study of similar proxy records from the Western Desert of Egypt is required in order to assess whether the proposed input of isotopically heavier precipitation is a viable scenario.

The presence of perennial fresh water in the lake at Wadi Midauwara without the effects of significant evaporation has implications for the past occupation of the Western Desert of Egypt. Early Stone Age and Middle Stone Age tools are found within tufa units along the Libyan Plateau escarpment, attesting to the occupation of the area by early human groups (Caton-Thompson, 1952). Reliable fresh water resources would have facilitated human migration out of Africa into the Mediterranean, the Levant, and beyond.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.yqres.2007.07.010.

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