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A record of Holocene climate change from lake geochemical analyses in southeastern Arabia

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Abstract

Lacustrine sediments from southeastern Arabia reveal variations in lake level corresponding to changes in the strength and duration of Indian Ocean Monsoon (IOM) summer rainfall and winter cyclonic rainfall. The late glacial/Holocene transition of the region was characterised by the development of mega-linear dunes. These dunes became stabilised and vegetated during the early Holocene and interdunal lakes formed in response to the incursion of the IOM at approximately 8500 cal yr BP with the development of C3 dominated savanna grasslands. The IOM weakened ca. 6000 cal yr BP with the onset of regional aridity, aeolian sedimentation and dune reactivation and accretion. Despite this reduction in precipitation, the lake was maintained by winter dominated rainfall. There was a shift to drier adapted C4 grasslands across the dune field. Lake sediment geochemical analyses record precipitation minima at 8200, 5000 and 4200 cal yr BP that coincide with Bond events in the North Atlantic. A number of these events correspond with changes in cultural periods, suggesting that climate was a key mechanism affecting human occupation and exploitation of this region.

Keywords: Arabia; Archaeology; Geochemistry; Holocene; Lake levels; Abrupt climate change

Introduction

It has long been recognised that the early Holocene period across Arabia was characterised by pluvial conditions with the widespread development of lacustrine sediments across the Arabian sub-continent including the Rub' al-Khali (Empty Quarter) (McClure, 1976; Gebel et al., 1989), Ramlat as-Sabatyn (Lézine et al., 1998) and Nafud (Schultz and Whitney, 1986) desert regions. The period between 9000 and 6000 ^{14}C yr BP (10 500 to 6500 cal yr BP) has been identified as a major phase of lacustrine development in Arabia (McClure, 1976; Lézine et al., 1998) corresponding with increased solar heating across the Northern Hemisphere causing intensified monsoon precipitation fluxes over Arabia, North Africa and Asia (deMenocal et al., 2000; Gasse and Van Campo, 1994). Only a few sites have been identified with records extending into the late Holocene period, and these areas appear to have been supplied by additional winter-fed rainfall derived from cyclones that originated in the Mediterranean region. These sites are found in the Nafud region of Saudi Arabia (Schultz and Whitney, 1986) and the north-eastern extremity of the Rub' al-Khali in the United Arab Emirates (UAE) where the orographic effects of the Musandam mountains accentuate the rainfall (Parker et al., 2004).

While the character of the early to mid-Holocene period is broadly known, few detailed palaeoenvironmental analyses have been undertaken as most lake sequences recorded are shallow in depth and do not form substantial lithostratigraphic sequences. Vegetation reconstruction from Arabia is scant, with few pollen studies existing (Lézine et al., 1998; Garcia Antón

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and Sainz Ollero, 1999; Parker et al., 2004). The eastern Arabian Gulf has been an important focus for humans during the Holocene as it lies at the interface between the sea, the desert, gravel plains and mountain environments. The area is situated on a major trade route between South and Southeast Asia, and Europe and the Near East. This trade route was of importance from the earliest times when it joined two "cradles of civilization" and has maintained this importance through time. This region has a rich archaeological record when compared with the desert interior and the chronological and material–cultural sequence is fairly well established for the last 8000 yr (Potts, 1990a,b). While environmental archaeological analyses have provided insight into the botanical (e.g. Ishida et al., 2003), zoological (e.g. Uerpmann, 2002) and geomorphological (e.g. Goudie et al., 2000a,b,c) contexts for a number of archaeological sites, only a few long Holocene environmental sequences (e.g. Gebel et al., 1989; Parker et al., 2004) have been identified from which a framework of climate and landscape change may be developed.

Recent work in the southeastern Arabia, in the Emirate of Ras al-Khaimah, has revealed a long Holocene lake record (8500–3000 cal yr BP) with a preserved pollen and phytolith record (Parker et al., 2004). The site reveals a number of important floristic changes in the Holocene related to changes in the duration and intensity of the Indian Ocean monsoon from the early to mid Holocene, and winter derived cyclonic rainfall during the mid to late Holocene. The early Holocene landscape was characterised by the development of Pooid C3 dominated Savannah grassland between 8500 and 6000 cal yr BP with a strong woody element of *Acacia* and *Prosopis*. Between 6000 and 4000 cal yr BP the grassland element was replaced by Panicoid C4 types as the climate became more arid. This changed to a sparse vegetation cover of Chloridoid C4 grasses and sedges since 4000 cal yr BP (Parker et al., 2004). The sediment record reveals a number of abrupt changes that are not always clearly evident in the vegetation analyses. On this basis, the geochemistry of the sediment record was investigated to look further into the nature of the stratigraphic changes.

Few lake geochemical analyses have been conducted in the Middle East and southwest Asia and those undertaken to date are based on isotopic geochemical measurements rather than elemental analyses (Lemcke and Sturm, 1997; Enzel et al., 1999, 2003). In Arabia, no lake sediment geochemical analyses have been conducted to date. Closed basin lakes are useful repositories for palaeoclimatic study as the geochemical signatures in these systems should record changes in phases of allogenic (aeolian) and authigenic (lacustrine) sedimentation, which along with changes in the hydrological regime and salinity, reflect variations in precipitation and evaporation as a direct response to prevailing climatic conditions (Eugster and Hardie, 1978; Sinha and Smykatz-Kloss, 2003).

The aim of this paper is to present a Holocene chronology of palaeomonsoon rainfall variability and fluctuations in westerly-induced winter rainfall from southern Arabia from a lacustrine sediment record. From this, a framework of Holocene climate variability is constructed against which the archaeology of the region may be set.

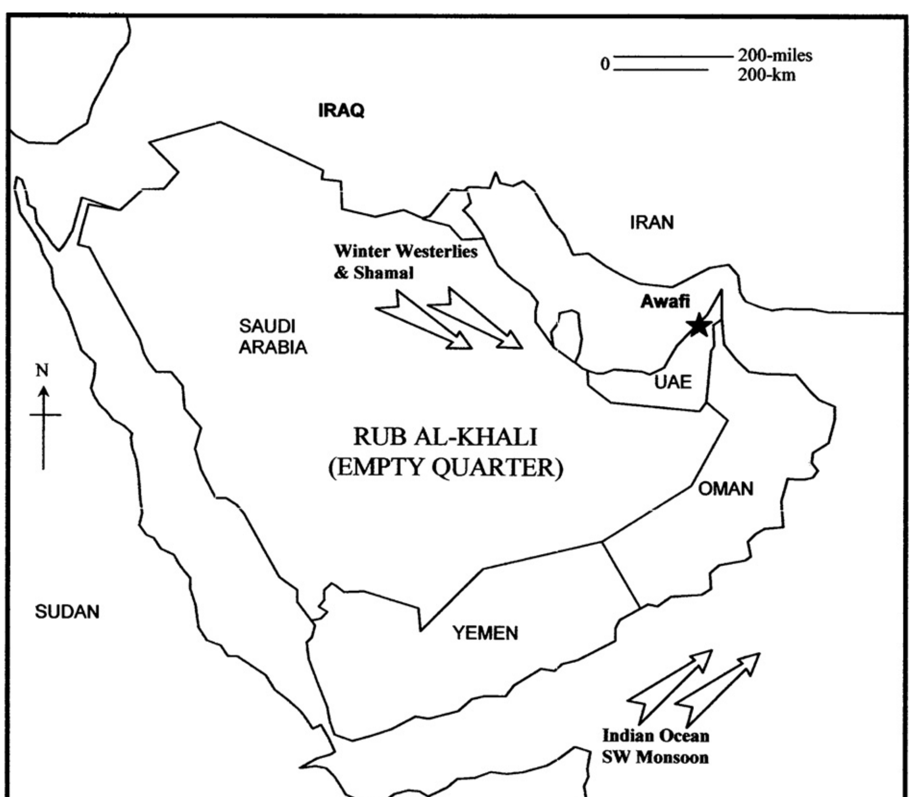

Figure 1. Map of Arabia showing the location of Awafi and the relative positions of the Indian Ocean Monsoon and westerlies (Shamal) based on Parker et al. (2004).

Environmental setting

The southeastern part of Arabia (Fig. 1) lies at the interface between the hot desert climate of the Rub' al-Khali desert and the mountains of the Ru'us al Jibal (max. elevation 2042 m asl) which dominate the Musandam/Oman peninsula (Parker et al., 2004). The region is characterised as arid to hyper-arid and is presently located outside the range of the Indian Ocean Monsoon (IOM). The orographic effects of the Musandam enhance winter rainfall. This rainfall is associated with middle-high latitude westerly depressions that originate as cyclonic depressions in the eastern Mediterranean. Rainfall is characteristically low (~120 mm), but higher than most other places in the UAE, and there is a strong precipitation gradient across the region between the Ru'us al Jibal (~140 mm) and Dubai (~80 mm). The wind regime is complex with 52% of sand moving winds blowing from the west and north west, driven by the Shamal, and 28% of sand moving winds blowing from the south east (Goudie et al., 2000a; White et al., 2001; Parker et al., 2004).

Within southeastern Arabia, a number of inter-dune dry lakes have been identified (White et al., 2001; Parker et al., 2004). Awafi, Ras al-Khaimah, UAE (25° 42.95 N, 057° 55.95 E) is a 2 km^2 dry, closed lake basin of Holocene Age bounded by 50 m high mega-linear dunes of Late Glacial Maximum (LGM) and Younger Dryas and earliest Holocene age (Parker et al., 2004; Dalongeville et al., 1991; Goudie et al., 2000c). The site is located 80 km south of the Straits of Hormuz. To the north and east, the site is surrounded by the fertile and relatively well-watered Shimal plain, an alluvial deposit densely planted with date palm groves and covered with small rural settlements (Kennet, 1997). Close by to the east rise the Oman mountains of the Musandam Peninsula, dominated by limestones, cherts and ophiolites. Large, low angle alluvial fans coalesce at the mountain front where wadi systems debouch from the Oman Mountains. The coastline is characterised by spits, bars, beaches and coastal sabkhas (Goudie et al., 2000b). This region of southeastern Arabia has been a focal point for human settlement since at least 8000 cal yr BP, and the location has always given access to agricultural and marine resources as well as trade routes, a combination which is unique on the western coast of the Oman Peninsula. The archaeological record is rich when compared to the rest of the Arabian Gulf region, with all of the key periods identified in the regional record present.

Archaeology of the eastern Arabian Gulf and Oman Peninsula

The chronological and material–cultural sequence is fairly well established for most periods but there is still uncertainty regarding economic, demographic and settlement trends that make it difficult to present a reliable overview of growth and decline that might be related to climatic fluctuations.

The Upper Pleistocene and earliest Holocene in Eastern Arabia are problematic as no securely dated material from this time has yet been reported (Petraglia and Alsharekh, 2003, Potts, 1990a,b). However, Rose (2004a,b) has pointed out that the wide variety of lithic reduction sequences present in Southeast Arabia must span a wider temporal range than the Neolithic. The leptolithic reduction tradition that these industries share might suggest an autochthonous development beginning during the late middle Pleistocene but deriving ultimately from East Africa (Rose, 2004a,b, 2006). The uncertainty surrounding this period makes it impossible to characterise settlement at this time.

The archaeological sequence for the region is presented in Table 1 and the key periods from 7000 to 2300 cal yr BP are briefly discussed below.

Neolithic

The earliest phase of occupation in the region is the 'Qatar B' period which is a blade-arrowhead industry found at a few sites throughout the Oman peninsula and Qatar (Potts, 1990a,b, 1993; Uerpmann, 1992). There are relatively few Qatar B sites known compared to the following Arabian Bifacial and 'Ubaid' (6500–5800 cal yr BP/4500–3800 BC) period (Potts, 1990a,b).

Table 1
Cultural Periods for Eastern Arabia and the Oman Peninsula 7000–2300 cal yr BP (5000–300 BC)

Date (BC)	Period	Characterisation	Alternative Names	References
5000–4500	Qatar B		Late Prehistoric A (Potts, 1993).	Potts, 1990a,b: 32–37; 1993: 170–173. Uerpmann, 1992.
4500–3800	Arabian Bifacial and 'Ubaid'	Growth	Late Prehistoric B (Potts, 1993). Suruq (Uerpmann, 1992).	Potts, 1990a,b: 37–61; 1993: 173–177. Uerpmann, 1992
3800–2800	Fourth Millennium	Decline?	Late Prehistoric C (Potts, 1993)	Potts, 1990a,b: 62–72. Potts, 1993: 178–180. Uerpmann, 1992
3400/3200–2500	Hafit	Growth	Protohistoric A and B (Potts, 1993).	Potts, 1990a,b: 72–92. Potts, 1993: 180–186.
2500–2000	Umm al-Nar	Growth	Protohistoric B and Early Historic A (Potts, 1993).	Potts, 1990a,b: 93–150. Potts, 1993: 184–191.
2000–1600	Wadi Suq	Decline?	Classic Wadi Suq (Carter, 1997). Early Historic B (Potts, 1993).	Carter, 1997. Potts, 1990a,b: 232–260; 1993: 191–196. Velde, 2003.
1600–1300/1250	Late Bronze	Decline	Late Wadi Suq (Carter, 1997). Early Historic C and D (Potts, 1993).	Carter, 1997. Potts, 1990a,b: 232–260; 1993: 196–199. Velde, 2003.
1300/1250–1100	Iron I	Growth?		Potts, 1990a,b: 354–400. Magee, 1996, 2003.
1100–600	Iron II	Growth	Rumeilah I (Boucharlet and Lombard, 1985).	Potts, 1990a,b: 354–400. Magee, 1996, 2003.
600–300/250	Iron III	Decline	Rumeilah II (Boucharlet and Lombard, 1985).	Potts, 1990a,b: 354–400. Magee, 1996, 2003.

A large number of sites have been found all over the Oman Peninsula, both on the coast and in the interior. Many sites on the Gulf coast have yielded 'Ubaid' pottery and obsidian indicating trade contacts with Mesopotamia. Interior sites show a herding economy based on cattle, sheep, goat and equids with a little hunting. Coastal sites show exploitation of shellfish, crabs and small fish (Potts, 1990a,b, 1993; Uerpmann, 1992).

In the Fourth Millennium (5800–4800 cal yr BP/3800–2800 BC) very few sites are known from Eastern Arabia (Potts, 1993). It has been suggested that this might be related to the onset of more arid conditions but a rise in sea level during the early third millennium may have inundated sites of this time (Potts, 1990a,b). On the east coast of Oman Peninsula a number of coastal sites with seasonal occupation have been identified (Potts, 1990a,b). This led Uerpmann (2002) to suggest that conditions on the east coast were somewhat better at this time.

Bronze Age

During the Hafit period (5400–4500 cal yr BP/3400/3200–2500 BC) very few settlements have been recorded, but the period is well known through the numerous and highly visible stone cairn burials that are situated on ridges across the Oman Peninsula. This suggests a good-sized population whose focus of settlement was quite different from later periods (Potts, 1990a,b, 1993).

In the Umm al-Nar period (4500–4000 cal yr BP/2500–2000 BC) an increasingly large number of occupation and funerary sites have been reported. At this time Oman (ancient Magan) is thought to have played an important part in the production of copper and its sale to Mesopotamia and possibly also the Indus Valley (Potts, 1990a,b; Weeks, 2004).

The Wadi Suq period (4000–3600 cal yr BP/2000–1600 BC) appears to represent a cultural development from Umm al-Nar period, though it shows a greater degree of regional differentiation (Cleuziou, 1981; Potts, 1990a,b; Velde, 2003). It has been argued that fewer settlements are known from this period than from the second half of the third millennium (Carter, 1997).

The Late Bronze Age period (3.6–3.25 ka cal BP/1600–1250 BC) was once thought of as a "dark age" during which time the population of the peninsula turned to "full time nomadism" (Cleuziou, 1981). However, this impression may, to some degree, have been given by inadequate fieldwork (Potts, 1993). Despite this, the low number of settlements that are known may be indicative of population and/or economic decline (Carter, 1997).

Iron Age

The Iron I (3300–3100 cal yr BP/1300/1250–1100 BC) is an enigmatic period. The material definition is relatively recent and it not yet accepted by all working in the field (Magee, 1996; Magee and Carter, 1999). Very few settlements are known, either inland or coastal. Based on the analysis of two major coastal sites (Tel Abraq and Kalba), Magee and Carter (1999) have interpreted this period as one of incipient growth, developing overseas trade contacts, increasing social hierarchy and settlement agglomeration as a precursor to the more marked growth in the succeeding period, and in contrast to the preceding Late Bronze Age.

Iron II (3100–2600 cal yr BP/1100–600 BC) is well defined in terms of its material culture. It is clearly distinct from the preceding period in terms of its material culture and is well defined chronologically (Magee, 1999, 2003). It is generally accepted as having been a period of significant intensification of settlement (Magee, 2003: Potts, 1990a,b). It is also thought to be the period during which *qanat* or *falaj* irrigation technology was first employed, though it is not clear whether this development may have led to or resulted from increased population (Magee, 1999; Potts, 1990a,b). Magee proposes the development of complex polities in piedmont and desert as well as increased trade contacts (Magee, 1999).

Iron III (2600–2250 cal BP/600–300/250 BC) is a rather obscure period about which relatively little is known (Magee, 1996, 2003). It probably represents the decline of the settlement system that developed during the Iron II period as very few settlements are known.

Methods

Sediments were collected in the field from a 100 m long open trench excavated into the lakebed at Awafi from which a total depth of 3.3 m of sediments was sampled. The total organic carbon was measured as a proxy of biological activity in the record using a Carlo Erba CHN elemental analyser (Parker, 1995). Mass specific, low frequency mineral magnetic susceptibility (χlf) was measured on individual samples using a Bartington MS2b sensor (Walden et al., 1992). Low mineral magnetic values correspond to low levels of magnetic materials in the lake sediment sequence implying periods of stability associated with wet conditions, the establishment of full lacustrine conditions and vegetation cover. High mineral magnetic values relate to the influx of aeolian materials derived from the surrounding dune field blown in during phases of aridity, vegetation loss and landscape instability (Thompson and Oldfield, 1986).

Samples for geochemical analyses were finely ground using a Fritsch Pulverisette 7 agate ball mill at 650 rpm for 2 ½ min. Approximately 0.5 g of each sample was weighed into acid-washed Teflon beakers. In addition three reference certified material samples, AGV-1, SCO-1 AND SDC-1, were prepared under the same conditions. All samples were acid-digested using HNO_3 to remove organic material followed by $HF/HClO_4$ digestion (Totland et al., 1992). Final aqueous samples were filtered using Whatman No.40 paper and then transferred into 60 ml plastic bottles. Samples were run on a JY70C ICP-AES, having been calibrated using single and multi-element standard solutions.

Accelerator Mass Spectrometry (AMS) radiocarbon dating was undertaken on selected molluscan remains of *Melanoides tuberculata* or the organic fraction of the sediment at the Radiocarbon Accelerator Unit, Poznan, Poland. The OSL

Table 2
Absolute ages from Awafi, Ras al-Khaimah, United Arab Emirates (OSL and ^{14}C)

Depth (cm)	Lab. Code.	Uncal. ^{14}C Age	OSL Age kyr	Age Cal. yr BP (2σ)
60	Awafi 1	–	4.10±0.24	4600–3600
100	Poz-3933	4670±40	–	5580–5310
150	Poz-3881	5190±50	–	6170–5750
170	Poz-3882	6800±50	–	7470–7570
190	Poz-3934	7040±40	–	7950–7750
230	Poz-3529	7170±50	–	8110–7880
240	Poz-3685	7240±40	–	8350–8060
270	Awafi 2	–	17.65±1.79	21450–13950

Calibration of ages is based on OxCal 3.9.

(SAR) dates were produced by the Luminescence Research Group, Oxford University. The Awafi lake core chronology was established by calibrating the AMS radiocarbon dates using OxCAL (Table 2) and applying a linear regression through these dates. Pollen, phytolith and carbon isotope analyses are reported elsewhere in Parker et al. (2004).

Results

Four main sedimentary units (Fig. 2) were identified in the field. A basal gravel deposit overlain by yellow/orange mottled sand (Unit 1) was dated to the Last Glacial Maximum (LGM). Unit 2 comprises early Holocene carbonate-rich marl with laminations, followed by mid-Holocene marls and sands (unit 3). The late Holocene upper Unit 4 is primarily aeolian red sands with fine carbonate laminae indicating a dry lake basin with periodic inundation.

Figure 3 shows the sediment time–depth curve for the Awafi sequence along with the sediment accumulation rates based upon linear interpolation. It should be noted that ^{14}C in arid regions is problematic owing to a range of factors which include low quantities of organic carbon in lake sediments along with the potential for hard water errors from carbonates and rootlet penetration. Whilst the potential for error is higher than in many other sedimentary environments the dates obtained from Awafi display stratigraphic conformity based on a combination of both OSL and ^{14}C ages. On the basis of assumed linear accumulation rates the record indicates high accumulation rates.

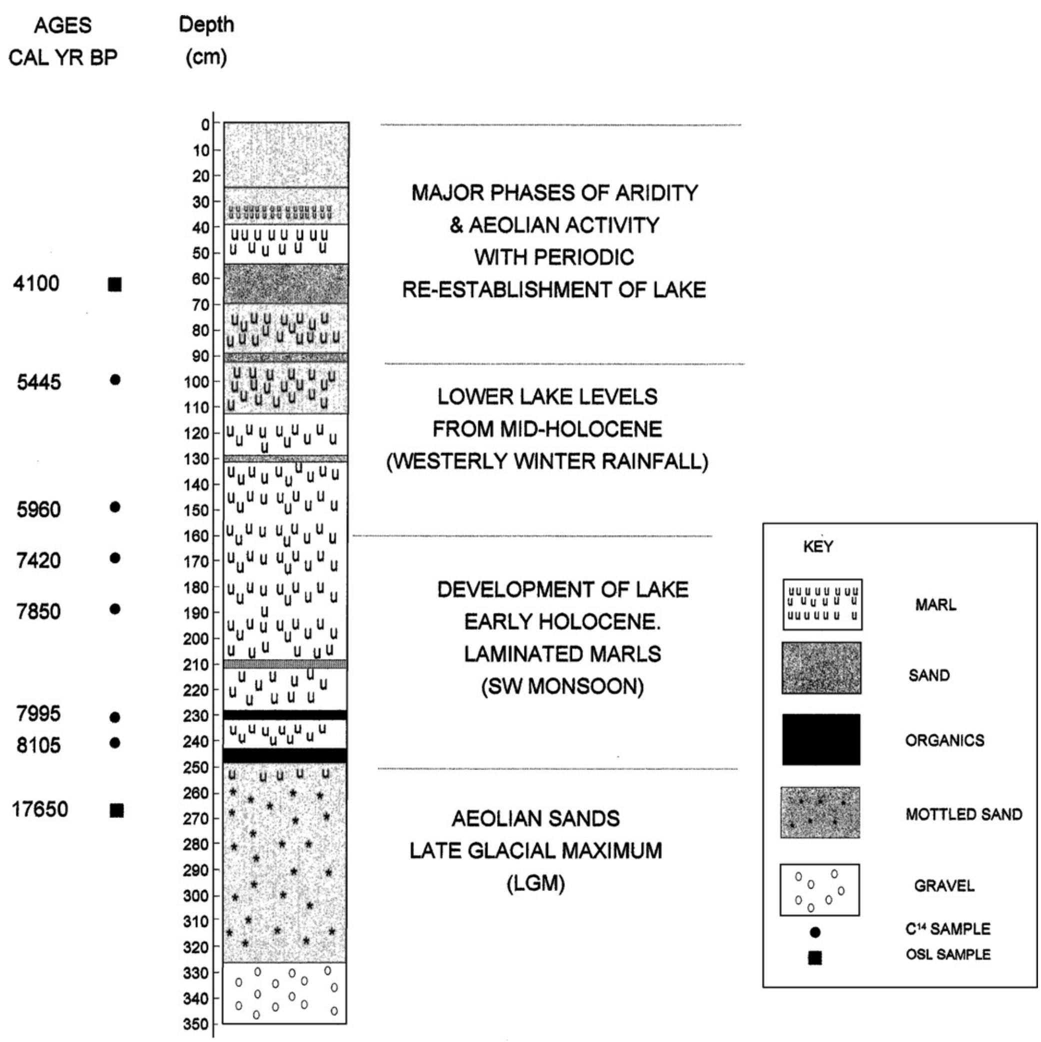

Figure 2. The Awafi sediment profile showing the main stratigraphic units and position of the samples dated.

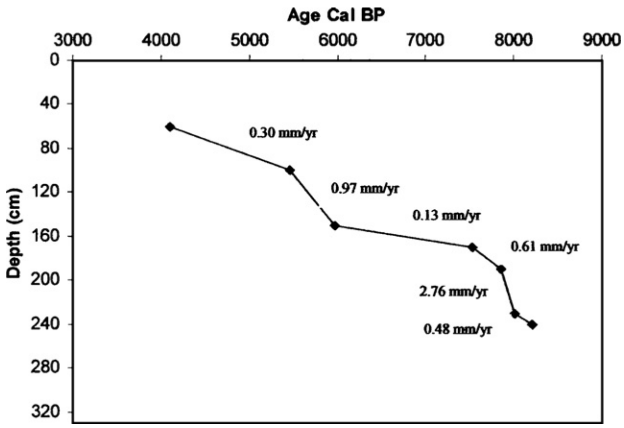

Figure 3. Time–depth curve and sediment accumulation rates for the Awafi sequence.

Selected physical sediment properties, elemental cations and ratios are presented in Figure 4. These can be grouped into those which reflect aeolian (allogenic) and lacustrine (authigenic) inputs into the lake sediments. The allogenic fraction is represented by the elements titanium, aluminium, iron and potassium which are derived from aeolian materials, whilst strontium, sodium and magnesium reflect the authigenic fraction. Calcium, which is often an important component of the authigenic fraction in dryland lake sediments, appears to have both authigenic and allogenic components.

In order to remove the effects of the detrital chemistry, in the absence of silica, titanium was taken to represent an element that is relatively immobile during weathering (Young and Nesbitt, 1998) and stays predominantly in the allogenic phase. In many freshwater lake systems Na:K ratios are used to infer variations in aridity, with low ratios reflecting humid phases and high ratios increased salinity and aridity leading to increased halite concentrations (Eugster and Hardie, 1978; Sinha and Smykatz-Kloss, 2003). However, in arid regions high Na may reflect phases of increased lacustrine authigenic development, with low ratios reflecting increasing Ti levels due to increased lake lowering, aridity and input of aeolian allogenic fractions rich in Ti. The preservation of halite in the sediment, thus supporting the above notion, was confirmed using XRD.

The geochemical results for the four main sedimentary units are outlined below:

Zone 1 (330–255 cm) Late Glacial Maximum

The basal sediments comprised a gravel lag deposit overlain by iron-stained sands (325 cm to 255 cm). An OSL date from this underlying sand unit at 2.7 m yielded an age of 17.65 ± 1.79 kyr. This sediment unit has a constant χlf signal ~0.75. TOC values from the base of the sequence to ~260 cm are low (less than 0.5%). The sediments in this zone are dominated by allogenic elements derived from the aeolian fraction as represented by the high Ti, Al, Fe and K values.

Zone 2 (255–150 cm) 8500–5900 cal yr BP

Lacustrine sedimentation began ~8500 Cal yr BP (interpolated age). A series of four AMS dates were obtained in this zone. The assumed sediment accumulation rates in this zone range between 0.28 to 0.13 mm/yr. The lowermost lacustrine unit (255 to 150 cm) consists of carbonate-rich marl, overlain by finely laminated lake sediments, which has a low χlf signal c. 0.30×10^{-6} m^3 kg^{-1}. In this unit there is a sharp increase in TOC to c.4%. There is a sharp reduction in the allogenic component (Ti, Al, Fe, K) indicating a decrease in the aeolian component of the sediment. The Na/Ti, Na/K and Sr/Ti ratios rise in this zone with some larger variations. Major peaks are noted at 210, 190 and 160 cm.

Zone 3 (150–60 cm) 5900 to 4200 cal yr BP

Between 150 and 60 cm the sediments comprise of marl with distinct bands of sand occurring. The assumed sediment accumulation rates range from 0.98 mm/yr between 150 cm to 100 cm to 0.30 mm/yr between 100 cm to 60 cm. There is a steady increase in the χlf signal from 0.50 at 150 cm to c.1.00×10^{-6} m^3 kg^{-1} at the top of the zone. TOC values rise to a peak of 4.2% at 140 cm. This is followed by a rapid decrease in value to 0.3% at the top of the zone. It should be noted that there is a small increase in TOC to 1.0% at 120 cm. Ti, Al, Fe and K values increase from 140 cm and peak at 90 cm and 70 cm. There is a steady decrease in Na/Ti, Na/K and Sr/Ti ratios in this zone.

Zone 4 (60 cm-top) 4200 cal yr BP to present

The lowest unit in this zone comprises a 15 cm thick sand unit between 70 cm and 55 cm. An OSL date at 60 cm yielded an age of 4.1 ± 0.24 kyr. Between 50 cm and 40 cm a distinctive marl layer was observed. A sandy unit with some carbonate-rich laminations overlay this. The magnetic susceptibility values rise to over 2.00×10^{-6} m^3 kg^{-1} with a dip at 40 cm where levels fall to c.0.50×10^{-6} m^3 kg^{-1}. TOC is low throughout the zone with values around 0.3%. The peak in Ti values at 60 cm (4200 cal BP) is followed by a dip in values between 50 and 40 cm to 70 ppm. Ti values rise again to c.120 ppm from 30 cm to the top of the sequence.

Discussion

The Late Glacial and earliest Holocene (18 000–8500 cal yr BP)

OSL dates from the mega linear dunes that impound the lake basin at Awafi recorded dune emplacement between 12.0 and 9.0 ka (Goudie et al., 2000c). This coincides with the Younger Dryas in Europe, which is dated between 12 800 and 11 500 cal yr BP, and is close to the period of maximum rate of sea level rise in the Arabian Gulf (Lambeck, 1996). This supports the idea that sea level rise released sediment by coastal erosion, forming transgressive dunes that carried carbonate sand inland, driven by the Shamal winds (Hadley et al., 1998; Goudie et al.,

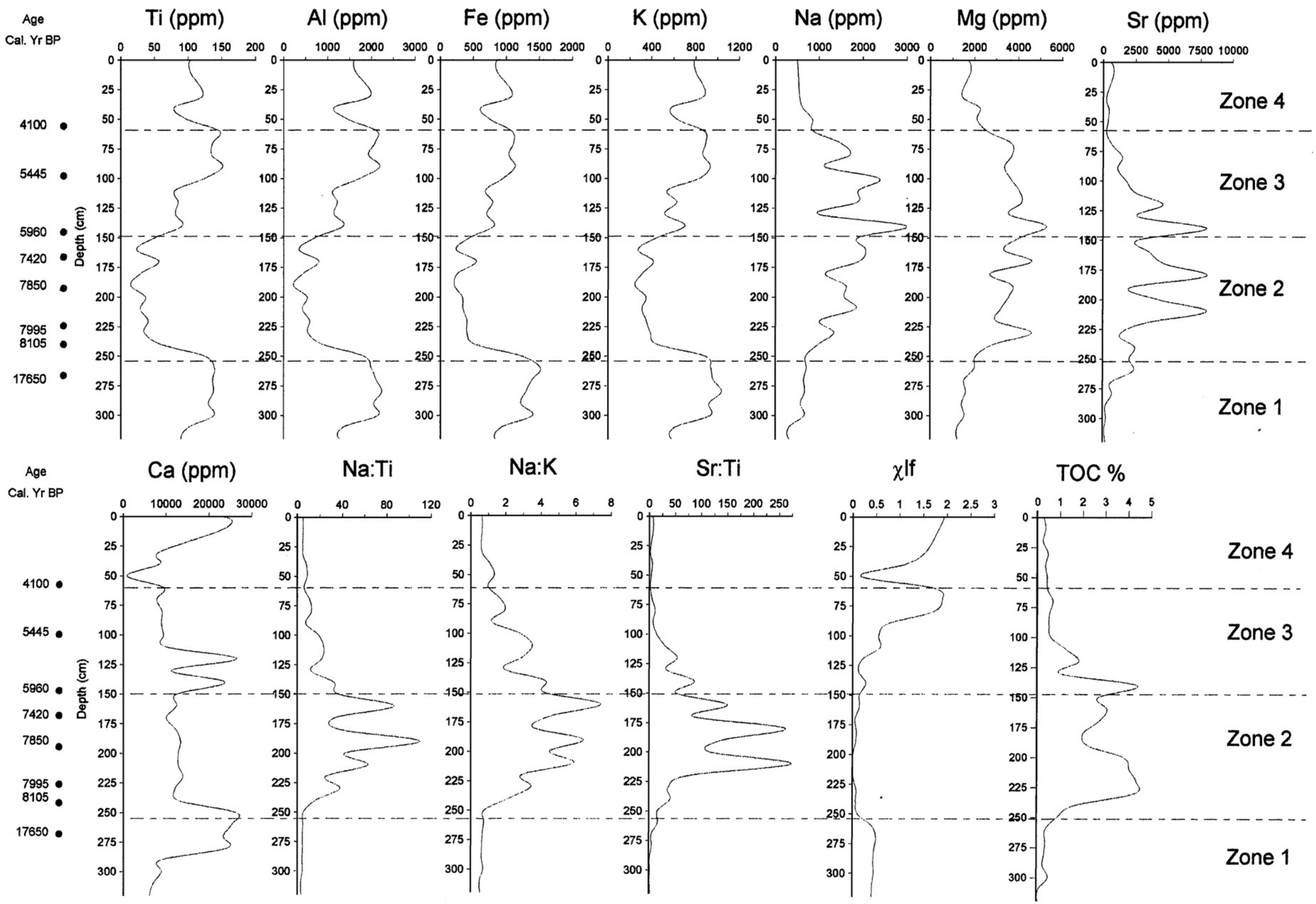

Figure 4. Sediment geochemistry record from Awafi (selected cations, ratios, magnetic susceptibility and organic carbon contents).

2000c). This notion is supported by the Ca values, which show an increase in dune carbonate content.

In contrast to this later phase of intense aeolian transportation and deposition in the Arabian Gulf region, southern Arabia was under the influence of the IOM at this time. Stalagmite records from Southern Oman (Fleitman et al., 2003) record the onset of IOM rainfall by 10.3 kyr and in northern Oman by 9.6 kyr (Neff et al., 2001). At Awafi the cessation of dune emplacement occurred at 9.0 kyr and the onset of lacustrine sedimentation did not take place until 8500 cal yr BP. There is a lag of approximately 1800 yr between Southern Arabia (15°N) and Northern Arabia (25°N). This poses important questions relating to the timing and causation of rainfall across eastern Arabia during the early Holocene.

The early Holocene lacustrine and climate record (8500–6000 cal yr BP)

The early Holocene sediments in the Awafi record comprise laminated marls suggesting the development of stratified sediments in deep water with the establishment of a permanent water body. Lake levels were initially low during the early phase of development and the surrounding dunes were partially mobile until they became stabilised by C3 dominated savanna grassland (Parker et al., 2004). Between 8500 and 6000 cal yr BP the archaeological record is represented by the Neolithic Qatar B and Arabian Bifacial/Ubaid periods (Table 1). The latter period is characterised by semi-nomadic herding of cattle, sheep and goats in the desert interior region (Potts, 1990a,b, 1993; Uerpmann, 1992). The archaeological evidence for herding is supported by the vegetation analyses reported earlier by Parker et al. (2004), which indicated the development of savanna grasslands across the region at this time corresponding with the optimum Holocene monsoon penetration and rainfall.

In addition, vast Ubaid period shell middens have been located along the coastal area between Abu Dhabi and Ras al-Khaimah (Boucharlet et al., 1991; Vogt, 1994; Uerpmann and Uerpmann, 1996). The finds of pottery, beads, net sinkers and flint tools represent the presence of a nomadic population living at the coast during the summer months. Some of the pottery shows is imported from Mesopotamia and indicates trade contacts as early as this time.

A series of short-lived, abrupt events occur in the early to mid-Holocene between 8500 to 7400 cal yr BP. Variations in the Na:Ti and Na:K ratios reflect changes in salinity and authigenic input into the lake system over this period, revealing reduced precipitation and increased aridity at 8200, 7900 and 7600 cal yr BP (Fig. 4). A similar pattern of three short-term events is recorded in the Oman speleothem record (Neff et al., 2001); where positive shifts in the δ^{18}O of calcite record precipitation minima. Although weakly expressed in the Awafi lake signature, the 8200 cal yr BP event corresponds with Bond Event 5 in the N. Atlantic record (Alley et al., 1997; Bond et al., 1997). This event is also expressed in N. Africa (Gasse and Van Campo, 1994; deMenocal et al., 2000), Near East (Bar-Matthews et al., 1997), the Arabian Sea (Gupta et al., 2003) and Oman stalactite records (Neff et al., 2001; Fleitman et al., 2003). The 7600 cal yr BP event is the most pronounced salinity event observed in the Awafi record between 8500 and 5100 cal yr BP, closely followed by the 7900 cal yr BP event.

The mid-Holocene lacustrine and climate record (6000–4200 cal yr BP)

Unlike most other lake records in Arabia (e.g. McClure, 1976; Lézine et al., 1998) the Awafi record extends beyond 6000 cal yr BP. For lacustrine conditions to persist at Awafi a precipitation source other that the IOM must have provided the additional rainfall. It is suggested that a switch to cyclonic winter rainfall originating from systems in the Mediterranean occurred. A similar pattern of winter rainfall was postulated in the Nafud in western Arabia but not for central or southern Arabia. The N. Oman speleothem record stops at 6000 cal yr BP (Burns et al., 1998) and marks a pronounced weakening across Arabia of the IOM.

Within the phase of continued lake development 6200 to 5400 cal yr BP a series of oscillations are observed in the lacustrine record. The record suggests a sharp decrease in lake level and a pronounced phase of aeolian activity is recorded at 5900 cal yr BP. This peak in aridity corresponds with Bond event 4, with cooler SSTs in the North Atlantic (Bond et al., 1997), which is also recorded in the Arabian Sea (Gupta et al., 2003). The vegetation record shows the development of C4 tall savanna grassland in the region at this time (Parker et al., 2004).

The geochemical (Ti, Al, Fe, K) and magnetic signatures indicate rapid dune activation and the influx of allogenic material into the lake basin from ca. 5400 cal yr BP. This marks the onset of major aridification, a strengthening/redevelopment of the Shamal winds and the major loss of vegetation cover. This large-scale increase in aeolian deposition continued with a peak in activity at 5200 cal yr BP.

The Awafi lake records show that the onset of major aridity was stepped in two phases with peaks in each step at 5900 and 5200 cal yr BP respectively. This pattern contrasts with the onset of aridity postulated for North Africa (deMenocal et al., 2000), which is abrupt, and from S Oman which is suggested as gradual (Fleitman et al., 2003). The archaeological record shows that Arabian Bifacial/Ubaid period came to an abrupt end in eastern Arabia and the Oman peninsula at 5800 cal BP, just after the phase of lake lowering and onset of dune reactivation. At this time, increased aridity led to an end in semi-desert nomadism, and there is no evidence of human presence in the area for approximately 1000 yr (Table 1). This period is described as the 'Dark Millennium' in the eastern Arabian Gulf region owing to the lack of known archaeological sites (Vogt, 1994; Uerpmann, 2002). Uerpmann (1992, 2002) has suggested that climatic deterioration caused dramatic changes in subsistence and settlement patterns around 6000 cal BP. In contrast to the sites on the Arabian Gulf, those on the Omani coast continued into the 4th Millennium.

There was a return to moist conditions with the development of a shallow lake between 5200 and 4200 cal yr BP. During this phase of wetter conditions, humans appear to have resettled the region with the presence of large numbers of burial cairns built in many locations including the high mountain plateau. These belong to the Hafit Period (5200–4500 cal yr BP).

The middle of the third millennium BC saw the rise of the Umm al-Nar Culture (4500–4000 cal yr BP), a very significant period in the development of social complexity in the UAE, with expansion of settlement, development of social complexity, overseas trade and social integration. Evidence suggests that trade in copper with Mesopotamia and the Indus valley made this area of the UAE wealthy during that period, and Mesopotamian sources mentioned it as the Land of Magan (Potts, 1990a,b; Weeks, 2004). There is some evidence, in the form of shallower wells, of a water table that was significantly higher in this period than in succeeding times (Cleuziou, 1989: plate 21a).

The late-Holocene lacustrine and climate record (4000 cal yr BP–present)

At 4200 cal yr BP total desiccation and the deposition of aeolian sand into the lake basin occurred. This phase of intense aridity is well documented in the North Atlantic marine records, Bond Event 3 (Bond et al., 1997), across North Africa (Gasse and Van Campo, 1994), the Middle East (Bar-Matthews et al., 1997), and the Arabian Sea (Cullen et al., 2000; Staubwasser et al., 2003). The intensity of this event is thought to have led to the collapse of the Akkadian Empire and termination of the urban-Harrapan civilisation along the Indus River, in Pakistan. However, Enzel et al. (1999) suggest that the event is only weakly expressed in the Lunkaransar lake sediments from the Thar Desert region of India rather than a rapid, abrupt event.

In the Arabian Gulf region, there is a sudden change in settlement pattern, style of pottery and tombs at this time. This event marks the end of the Umm al Nar period and the change to the Wadi Suq period. The Wadi Suq Period (4000–3600 cal yr BP) appears to represent a cultural development from the Umm al-Nar and it has been argued that fewer settlements are known from this period than from the second half of the third millennium (Carter, 1997). The Late Bronze Age period is indicative of population and/or economic decline. This period also marks the beginning of slow decline of Mesopotamia and the already advanced disintegration of urban structures in the Indus and in Iran.

After 4200 cal yr BP, a short lived wet phase occurred when the lake became re-established. This event is most likely to have occurred between 4000 and 3000 cal yr BP corresponding to similar events observed in N. and E. Africa (Gasse and Van Campo, 1994). Lückge et al. (2001) also suggest a wetter phase between 4000 and 3000 cal yr BP from a marine core in the northern Arabian Sea. Following this there was a return to intense arid conditions and OSL dates from the region show major dune emplacement from 3.0 kyr BP (Bray and Stokes, 2003). The northern Arabian Sea record that shows a switch from wetter conditions to arid conditions between 3000 to 2000 cal yr BP (Lückge et al., 2001) supports this view.

During this phase of increased aridity and dune reactivation there is a large increase in the number of settlements in this and adjacent regions during the Iron Age II period (3100–2400 cal yr BP) (Magee, 2003; Magee et al., 2002). This expansion included a number of settlements in desert areas as well as along the mountain fringes. The archaeological evidence to date suggests that some sites were large, internally complex, and spread over several hectares in size, indicating rapid settlement intensification. Magee (2004) has suggested that arid conditions during this period may have resulted in the use of innovative irrigation techniques, such as *qanat* or *falaj*. Magee also notes that the period of expansion was underpinned by increasing social and economic costs and political hierarchies associated with the control over irrigation technology.

The carbonate laminations in the top 30 cm of the record represent periodic inundation of the dry lake basin, which may indicate episodes of heavy rains over consecutive years rather than true lacustrine deposits. A phase of rapid dune accretion was recorded at Idhn, RAK, UAE (Goudie et al., 2000a) where 30 m of dune sand accumulated at c. 1.0 kyr. This intensification in aridity at c.1000 cal yr BP is also shown in the offshore marine records in the northern Arabian Sea (Lückge et al., 2001; Von Rad et al., 1999), indicating a regional shift in climate conditions and forcing.

Climatic implications of the Awafi record

The Awafi record raises a number of important climatic questions, which are not yet fully resolved. The first relates to the late onset of wet conditions and lacustrine development at 8500 cal yr BP when compared with elsewhere in Arabia. In the Rub al-Khali and Ramlat as-Sabatyn, lakes developed with a peak in wetness recorded around 9000 cal yr BP (McClure, 1976; Lézine et al., 1998). Speleothem records in Oman (Neff et al., 2001; Fleitman et al., 2003) and marine records from the Indian Ocean and Arabian Sea support this view (Gupta et al., 2003; Staubwasser et al., 2002), which indicates that the period of maximum monsoon strength occurred between 9500 and 8500 cal yr BP. The absence of lacustrine sediments coupled with the continued presence of dune emplacement until 9000 cal yr BP (Goudie et al., 2000c) show that the Awafi record is out of step with these other records. The development of dunes in the early Holocene suggests that Shamal winds driven by westerlies prevailed.

The second question relates to the nature of the Holocene moisture source at Awafi. Most palaeoclimate research to date has suggested that the Holocene pluvial was driven by precipitation derived from the northwards migration of the Indian Ocean monsoon (IOM) across the Arabian sub-continent (Lézine et al., 1998). Recent work has challenged this view for sites which lie northwards of 25°N. For example, in addition to precipitation from the IOM it has been suggested that winter rainfall derived from the Westerly winter rainfall was an important source in the northern Red Sea region (Arz et al., 2003) and northwestern Arabia (Schultz and Whitney, 1986) during the early to mid-Holocene. This is especially important for the development of mid–late Holocene lacustrine development and the persistence of lacustrine conditions after 6000 cal yr BP when most other records cease. The temporal and spatial patterns of human response to variations in the timing and magnitude of the IOM and Westerlies are emerging (Parker et al., 2004). This area of research warrants further investigation from new sites to test these ideas further.

The notion of how IOM rains migrated across Arabia during the early Holocene raises the third question. The existing literature suggests two opposing views. The first suggests that the IOM moved northwards owing to a shift in the ITCZ, bringing rainfall across the Arabian sub-continent (Gasse and Van Campo, 1994; Lézine et al., 1998). This work largely follows the model proposed for the early Holocene moist phases across North Africa. The second view is that monsoon rains did not migrate northwards by a shift in the ITCZ as this is not easily reconciled with Arabian Sea climatology and general atmospheric monsoon circulation. Instead it has been suggested that rainfall during the summer monsoon was derived from local convection, possibly augmented by local orographic effects (Staubwasser, in press). Again, this area requires more work to resolve these contrasting viewpoints.

The fourth question asks whether there is a teleconnective link between Bond's ice-rafted debris events in the North Atlantic (Bond et al., 1997) and the phases of intense aridity suggested in the Awafi record. The notion of a strong influence from the westerlies addressed above would imply a close relationship between the North Atlantic and Indian Ocean. Gupta et al. (2003) suggested a link between the IOM and the North Atlantic during the Holocene, whilst Leuschner and Sirocko (2003) suggested a link between Dansgaard/Oeschger events in the North Atlantic and Indian Ocean during the late Pleistocene. Furthermore, significant variability associated with North Atlantic Bond events and century-scale abrupt changes may be linked to albedo changes on the Himalayan/Tibetan plateau region (Leuschner and Sirocko, 2003).

Conclusions

The Awafi record reveals a long Holocene record, which records high amplitude variations in precipitation and aridity with respect to both the IOM and westerly airflows. The record suggests a strong correlation between cooler conditions in the N Atlantic and episodes of decreased monsoon activity and decreased winter rainfall in southeastern Arabia.

The lake geochemical analyses record precipitation minima at 8200, 5900, and 4200 cal yr BP, which coincide with Bond events in the North Atlantic region. In addition, low lake levels are also identified at 7900, 7600, and 5200 cal yr BP.

The Late Glacial/Holocene transition of the region was characterised by large scale sand dune emplacement with the development of mega-linear dunes. The active dune field became stabilised and vegetated with C3 grasslands during the early Holocene and interdunal lakes formed in response to the incursion of the Indian Ocean Monsoon (IOM) at approximately 8500 cal yr BP. The Ubaid (Neolithic) was characterised by the herding of animals as well as the widespread exploitation of marine resources. The IOM weakened ca. 6000 cal BP with the onset of regional aridity, aeolian flux and dune reactivation and accretion. Despite this reduction in precipitation, the lake was maintained by winter-dominated rainfall and there was a shift to drier adapted C4 grasslands across the dune field. The Ubaid period came to an abrupt end at 5900 cal yr BP and there is no further archaeological evidence present in the record for an entire millennium.

There was a reversion to moister conditions between 5200 and 4200 cal yr BP with an increase in lake level and the re-occupation of the landscape during the Hafit and Umm al-Nar periods. The latter witnessed the development of widespread trade with Mesopotamia, India and Iran with the exploitation and trading of copper resources. The change from the Umm al-Nar to the Wadi Suq period approximately coincides with a major arid event, with desiccation of the Awafi lake basin. It is suggested that the Iron Age period was characterised by aridification and witnessed the development of *qanat* and *falaj* irrigation systems.

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