Quaternary International 300 (2013) 62–74

Contents lists available at SciVerse ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

An early MIS 3 pluvial phase in Southeast Arabia: Climatic and archaeological implications

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ARTICLE INFO

Article history:
Available online 22 February 2013

ABSTRACT

Climatic changes in Arabia are of critical importance to our understanding of both monsoon variability and the dispersal of anatomically modern humans (AMH) out of Africa. The timing of dispersal is associated with the occurrence of pluvial periods during Marine Isotope Stage (MIS) 5 (ca. 130–74 ka), after which arid conditions between ca. 74 and 10.5 ka are thought to have restricted further migration and range expansion within the Arabian interior. Whilst a number of records indicate that this phase of aridity was punctuated by an increase in monsoon strength during MIS 3, uncertainties regarding the precision of terrestrial records and suitability of marine archives as records of precipitation, mean that the occurrence of this pluvial remains debated. Here we present evidence from a series of relict lake deposits within southeastern Arabia, which formed at the onset of MIS 3 (ca. 61–58 ka). At this time, the incursion of monsoon rainfall into the Arabian interior activated a network of channels associated with an alluvial fan system along the western flanks of the Hajar Mountains, leading to lake formation. Multiproxy evidence indicates that precipitation increases intermittently recharged fluvial systems within the region, leading to lake expansion in distal fan zones. Conversely, decreased precipitation led to reduced channel flow, lake contraction and a shift to saline conditions. These findings are in contrast to the many other palaeoclimatic records from Arabia, which suggest that during MIS 3, the latitudinal position of the monsoon was substantially further south and did not penetrate the peninsula. Additionally, the occurrence of increased rainfall at this time challenges the notion that the climate of Arabia following MIS 5 was too harsh to permit the further range expansion of indigenous communities.

1. Introduction

The Arabian Peninsula is uniquely positioned with respect to both archaeological and palaeoclimate studies (see Groucutt and Petraglia, 2012 for review). While much of Arabia presently experiences arid/hyper-arid conditions, the palaeoenvironmental record confirms that during the Late Quaternary, many regions within the interior experienced periods of increased humidity. During such times, the arid Arabian environment was transformed into an ameliorated landscape with a sufficient supply of freshwater to support a wide variety of flora and fauna (Parker, 2009). Conversely, during periods of increased aridity, the deserts of Arabia likely presented a considerable obstacle to human expansion. Our understanding, therefore, of early demographic shifts is informed by palaeoclimatic records through which 'windows' of favourable climatic conditions can be identified. Unfortunately, there is a paucity of climatic data for key periods such as Marine Isotope Stage (MIS) 3 (ca. 60–24 ka). As such, the suitability of Arabia for the expansion and/or occupation of early communities at this time remains unresolved.

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1040-6182/$ – see front matter © 2013 Elsevier Ltd and INQUA.
http://dx.doi.org/10.1016/j.quaint.2013.02.016

Climatic changes within Southeast Arabia are critically tied to the periodic migrations of the Inter-Tropical Convergence Zone (ITCZ) and associated monsoon rainfall belt. These are driven by a land–sea thermal contrast and transequatorial pressure differences, directly coupled with insolation changes and glacial boundary conditions (e.g. Prell and Kutzbach, 1992; Clemens and Prell, 2003; Fleitmann et al., 2003; Leuschner and Sirocko, 2003). Periodic incursions of the Indian Ocean Monsoon (IOM) system during times of increased summer season insolation, are recorded in a variety of palaeoenvironmental archives, which reveal an increase in monsoon rainfall during MIS 5, specifically, at ca. 130–120 ka (MIS 5e), ca. 105–100 ka (MIS 5c) and ca. 82–78 ka (MIS 5a) (e.g. Burns et al., 1998; Fleitmann et al., 2003; Fleitmann and Matter, 2009; Fleitmann et al., 2011; Rosenberg et al., 2011, 2012). During these periods, the favourable climatic conditions within SE Arabia enabled the dispersal and range expansion of human populations into the peninsula (Armitage et al., 2011; Petraglia et al., 2011; Rose et al., 2011; Rosenberg et al., 2012). However, detailed evidence for climatic changes for the period between 74 and 10.5 ka, is scarce. Problems regarding geochronology and data availability mean that at the present, there are few terrestrial records that provide detailed palaeoclimatic data for these periods, which are generally considered to have been hyper-arid. For instance, climatic conditions during MIS 4 (ca. 74–60 ka), which were typified by a period of intense hyper-aridity, witnessed an increase in dune mobility resulting in only minor aeolian deposition and sediment preservation (e.g. Preusser et al., 2002; Radies et al., 2004; Stokes and Bray, 2005; Preusser, 2009).

2. MIS 3 in Southeast Arabia

Radiocarbon age estimates of lake deposits and fluvial terraces within the Arabian interior have been used to suggest the occurrence of late MIS 3 humid episodes between ca. 35 and 20 ka (e.g. McClure, 1976, 1984; Whitney, 1983; Sanlaville, 1992; Woods and Imes, 1995). These early records, however, suffer from a lack of well-defined chronologies and significant age-estimation problems. Recent redating of lacustrine sediments from Mundafan and Khujaymah (Rosenberg et al., 2011) utilising Optically Stimulated Luminescence (OSL) indicates that lake formation within the region occurred ca. 125 ka (MIS 5e), ca. 100 ka (MIS 5c), and ca. 80 ka (MIS 5a). These age estimates, therefore, are synchronous with evidence for increased monsoon rainfall derived from established speleothem records and indicate that humid episodes within Arabia have been largely confined to MIS 5. Whilst these findings do not directly challenge radiocarbon data from other regions (i.e. Clark and Fontes, 1990; Sanlaville, 1992), they provide a stark reminder of the fallibilities of early/mid-MIS 3-age radiocarbon age estimates, which lie at the upper end of the dating limit for the technique.

A number of marine records, however, indicate a notable increase in monsoon intensity during the early stages of MIS 3 (e.g. Schulz et al., 1998; Altabet et al., 2002; Higginson et al., 2004; Des Combes et al., 2005; Ivanochko, 2005; Govil and Naidu, 2010; Kessarkar et al., 2010). The onset of MIS 3 was also characterised by intense millennial-scale temperature oscillations that exceeded 6 °C; more than half of the glacial–interglacial temperature change itself (Sakai and Peltier, 1999). There is a paucity of terrestrial evidence for an early MIS 3 humid phase, however, with only a small number of records providing possible evidence of monsoon variability. Blechschmidt et al. (2009) report evidence from alluvial fans within the southwestern margin of the Oman Mountains, from which OSL age estimates indicate that minor channel regeneration occurred at 45 ± 5 ka. Additionally, McLaren et al. (2008) identify a series of interstratified sands and gravel deposits within central Saudi Arabia, which indicate that the aggradation of fluvial gravels occurred prior to 53.9 ± 4.2 ka. Both studies state, however, that fluvial aggradation at this time may have been the result of localised regional changes in precipitation, rather than increased continental humidity. Recent geological mapping of the UAE has also confirmed the presence of fluvio-lacustrine deposits near Remah, Abu Dhabi which have been dated to the early stages of MIS 3 (Farrant et al., 2012). OSL ages from the uppermost part of a fluvio-lacustrine sequence have yielded dates of 54.1 ± 3.1 and 53.4 ± 3.8 ka. Additional evidence of early MIS 3 monsoon variability, albeit outside the Arabian interior, comes from $\delta^{18}O$ values of speleothems from Socotra Island in the Indian Ocean (Burns, 2003). U/Th age determinations indicate that between ca. 55 and 42 ka, SE Arabia experienced an increase in monsoon precipitation, fluctuations of which were coeval with North Atlantic temperature variations over Dansgaard/Oeschger (D/O) Events 9–13. The emerging palaeoclimatic record suggests, therefore, that whilst increased humidity at this time was not as pronounced as the last interglacial, monsoon rainfall may have penetrated the Arabian Interior.

Similarly, the archaeological record of Arabia at this time is also sparse. However, there is now enough evidence to verify the presence of human populations across southern Arabia during MIS 3. Of particular importance is the stratified archaeological sequence at Jebel Faya rockshelter in the United Arab Emirates, which provides evidence for a lithic assemblage (A) dating to MIS 3 (Armitage et al., 2011). Analysis of Assemblage A has led to the conclusion that the technology may be derived from the underlying Assemblage B and has no analogies to any other lithic industry in or around Arabia. The findings suggest, therefore, that the MIS 3 population at Jebel Faya must derive from a local tradition confined to eastern Arabia (Armitage et al., 2011), perhaps associated with the posited Gulf Oasis refugium (Rose, 2010). In addition to the stratified site of Jebel Faya, two in situ assemblages – Shi'bat Dihya (SD) 1 and 2, were excavated from a sedimentary basin in Wadi Surdud, Yemen, with bracketing ages of ca. 63 and 42 ka (Delagnes et al., 2012). Similar technological traits within the SD1 and SD2 assemblages, indicating cultural continuity through the MIS 3 sequence. The assemblages from Wadi Surdud do not belong to any coeval technocomplex in Africa, the Levant, or Jebel Faya Assemblage A, indicating that, like Jebel Faya, the technology developed from a local Middle Palaeolithic industry.

There is some overlap between Wadi Surdud and the unidirectional-parallel/convergent core reduction strategies described from Wadi Dauan (Amirkhanov, 2006), as well as with numerous 'Nejd Leptolithic' surface scatters mapped throughout the Dhofar region in southwestern Oman (Hilbert et al., 2012). It has been suggested that many of these blade-based assemblages distributed across southern Arabia belong to an autochthonous Upper Palaeolithic (or Late Palaeolithic) tradition (Rose and Usik, 2009; Hilbert et al., 2012). Most recently, researchers working in the Dhofar region of southwestern Oman, report 78 surface sites belonging to an undated lithic industry, the Mudayyan, that appears to be derived from the preceding MIS 5c Nubian Complex occupation (Usik et al., 2013) and is estimated to fall somewhere between MIS 5a and MIS 3. Importantly, there is a resemblance between Mudayyan core reduction strategies and MIS 3 Middle–Upper Palaeolithic transitional assemblages in the southern Levant (e.g., Marks, 1983; Clark et al., 1997; Richter et al., 2001). As such, this industry is particularly relevant to the question of population movements within Arabia during MIS 3 and, therefore, the existence of an early MIS 3 humid phase.

From the current archaeological evidence, it seems that after MIS 5, the different lithic traditions within Arabia develop along separate trajectories, with no indication of additional input from Africa. Recent genetic evidence (Fernandes et al., 2012) also indicates that the relict distribution of minor haplogroups N1, N2 and X, reflects an ancient ancestry of these groups within the Arabian Peninsula which, the authors conclude, then spread from the Gulf region toward the Near East and Europe between 55 and 24 ka. The potential occurrence of increased humidity within the Arabian interior during MIS 3 would, therefore, have been instrumental in determining the success and trajectory of the autochthonous development of early human communities within the region at this time. Although Rosenberg et al. (2012) may be correct in their description of Arabia between ca. 75 and 10.5 ka as a natural barrier for human dispersal, it is possible that indigenous inhabitants may have persisted in environmental refugia around Arabia, such as the Gulf Oasis (e.g. Rose, 2010). The occurrence of a pluvial phase during the early stages of MIS 3, therefore, may have facilitated a range expansion of early humans previously contained within such refugia. To address these important issues, we present a multiproxy record of an early MIS 3 wet phase from a palaeolake sequence within the continental interior of SE Arabia.

3. Environmental setting

The study area is situated approximately 35 km south of Al Dhaid, an oasis town located within the Emirate of Sharjah, UAE (Fig. 1). The region is dominated by the Al Faya Anticline which extends approximately 30 km from Jebel Buhais in the south, through Jebel Faya, Jebel Emaylah and Jebel Al A’zab, to Sha’biyyat As Saman, reaching maximum height of 407 m on Jebel Emaylah (Farrant et al., 2006). The region is largely covered by Quaternary sediments, although Palaeogene limestones and Oman-UAE ophiolite, which constitutes most of the Hajar Mountains, are

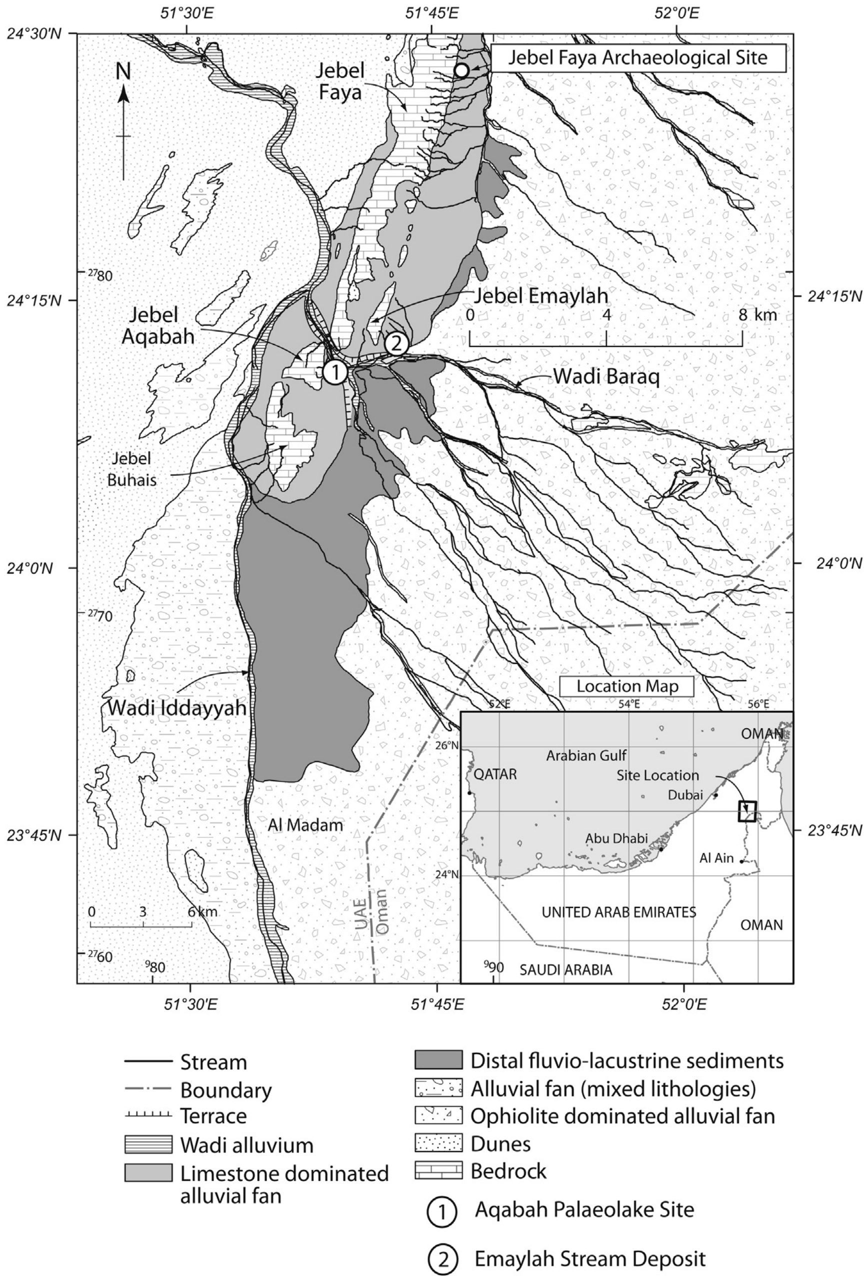


Fig. 1. Map of the study region within the UAE (inset). Location of the study sites at Jebel Aqabah (1) and Jebel Emaylah (2), geomorphological/drainage features and lithologies are shown.

well exposed in the Al Faya range. Outcrops of the fluvial conglomerate Barzaman Formation also occur locally along the mountain front and within interdunal areas (Macklin et al., 2012). The presence of the Al Faya anticline strongly determines the morphology of alluvial and aeolian features within the region, presenting a barrier to the eastward migration of dunes and a confluence point for W/NW-oriented channels that drain towards the Gulf.

Fluvial channels within the Faya region comprise the medial–distal component of alluvial fan drainage systems that emanate from the Hajar Mountains, approximately 16 km east of the site, trending W–NW towards the Gulf. These form part of a vast bajada of alluvial fans that flank the Oman Mountains from the northern Emirates down to the Wahiba Sands in Oman. Their extent is narrow within the northern Emirates (Styles et al., 2006), whereas directly west of the Wahiba they widen to around 200 km (Glennie and Singhvi, 2002). These sediments, termed the Hili Formation, are a lithologically variable unit of Late Quaternary fluvial deposits that extend as far west as Abu Dhabi, which comprise a fining-up sequence of interbedded alluvial fan silts, sands and gravels (Farrant et al., 2006). Within the study region, the alluvial fan extends west to Jebel Faya, where it is dominated by distal fan sand-skirts and braid plains (Fig. 1). The bedrock inliers of the Faya range serve to channelise flow into two distinct wadis. Wadi Iddayyah, the main drainage feature within the Al Faya complex, channels run off from as far south as Jebel Sumayni in Oman, passing to the west

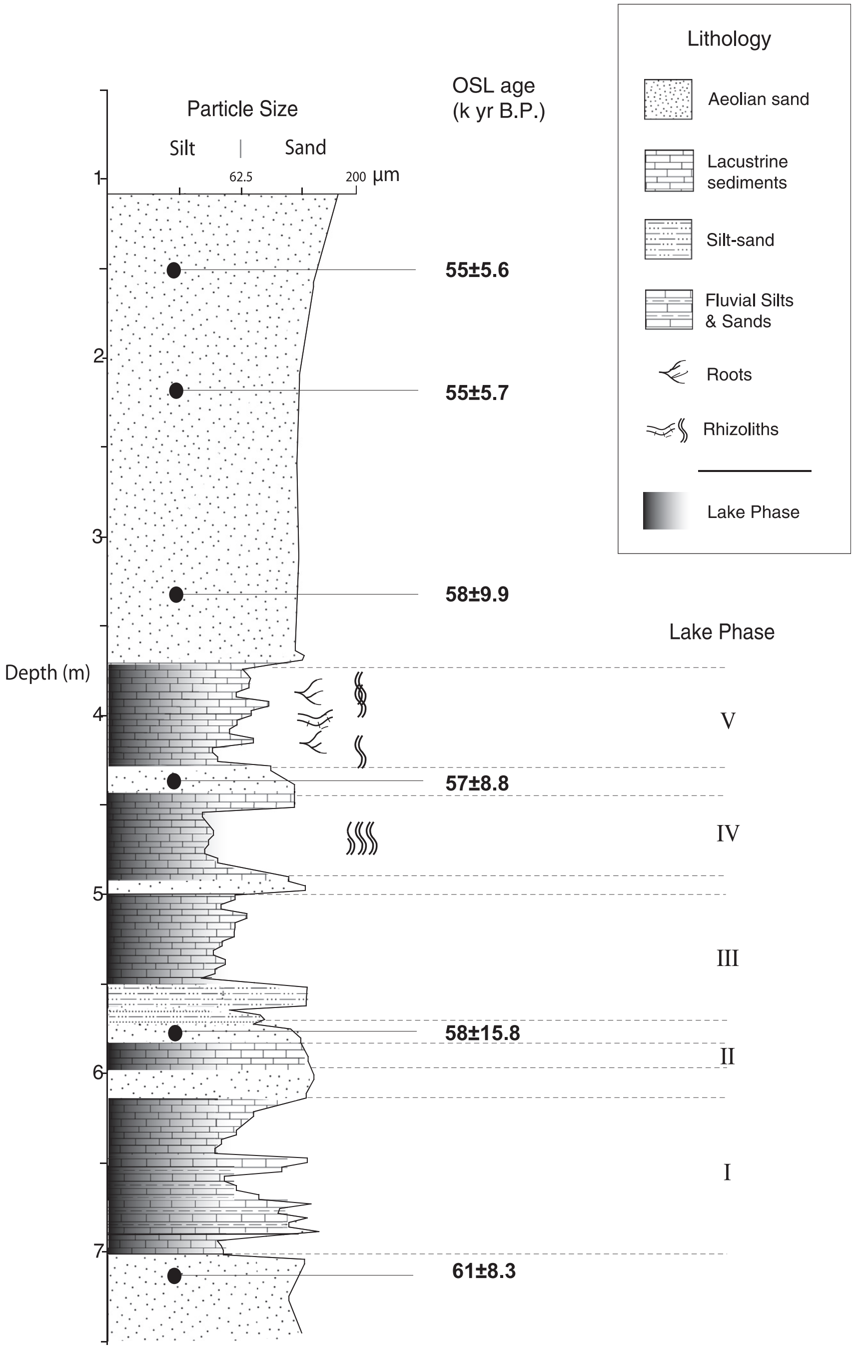


Fig. 2. Stratigraphic log of the sequence at Aqabah. Grain size (laser granulometry) values, location of OSL dates and interpreted lake phases (LP1–5) are shown.

of Jebel Aqabah. Periods of fluvial aggradation by this major wadi induced local ponding and subsequent lake formation at the lower end of the smaller wadi Baraq, which passes between Jebel Aqabah and the southern end of Jebel Faya. The competitive aggradation of these two streams led to the deposition of a thick (>10 m) sequence of fluvio-lacustrine and aeolian sediments within this tributary valley. Subsequent incision has left these sediments preserved as a series of terraces either side of the Jebel Aqabah — Jebel Buhais valley (Drechsler, 2008), up to 20 m above the present valley floor. Geomorphological evidence, therefore, suggests that fluvio-lacustrine deposits within this valley were formed during sustained humid episodes that enabled sufficient aggradation of the larger Wadi Iddayyah to block stream flow from Wadi Baraq.

Very little pre-Holocene palaeoclimatic research has been conducted within the immediate vicinity of the Al Faya complex, although there is some evidence for a pluvial phase within the region during the early stages of MIS 3. Two OSL dates from a wadi terrace near the base of Jebel Emaylah suggest that wadi activation occurred at some point occurred between 48 ± 5 and 63 ± 5 ka (Krbetschek, 2008). Whilst such dates provide an important confirmation of wadi activation during MIS 3, an absence of a refined chronology, or sedimentological and environmental evidence, means that it is difficult to determine a framework of climatic and landscape change for the region from these dates alone.

4. Methodology

4.1. Field measurements

Following a detailed geomorphological investigation of the Jebel Aqabah — Jebel Buhais valley, a partially exposed sequence of interstratified aeolian, fluvial and lacustrine sediments ca. 50 m from the base of the adjacent Jebel Aqabah (N25°02′16.8″ E055°48′22.1″) was excavated to a depth of 7.35 m (Fig. 2). The section (JA08) was cleared and logged in the field, whilst samples for optically stimulated luminescence (OSL) dating were removed in lightproof tubes from both Aqabah and an ephemeral stream deposit which channels run off from the adjacent Jebel Emaylah (approximately 2 km east of Jebel Aqabah). This was to provide a supporting date that would help to establish that fluvial channels within the wider relict terrace sequence were coeval with lake formation at Aqabah. Mass specific, low frequency magnetic susceptibility measurements (χ_{lf}) were obtained in the field using a Bartington MS2 meter with an MS2C sensor at 0.1 SI sensitivity (Dearing, 1999). Contiguous 1.5 cm samples were extracted from JA08 to a depth of 7.35 m for further analysis in the laboratory. Multiproxy analyses were limited to samples between 3.75 m and the base of the sequence owing to the homogeneity of the overlying dune sands.

Table 1
Summary of OSL data from Aqabah (OSL1-6) and Jebel Emaylah site (X3857).

Sample field code	Sample laboratory code	Radioisotopes[a]			Field water (%)	In situ external γ-dose rate[b] (Gy/ka)	Total dose rate (Gy/ka)	Palaeodose (Gy)	Age (ka)
		K (%)	Th (ppm)	U (ppm)					
OSL 1	X3586	0.89	1.0	0.8	3 ± 3	0.365 ± 0.018	1.27 ± 0.07	70.73 ± 6.20	55 ± 5.6
OSL 2	X3588	0.92	1.4	0.8	3 ± 3	(*0.365 ± 0.370)*	1.29 ± 0.07	71.20 ± 6.10	55 ± 5.7
OSL 3	X3590	1.00	1.4	0.9	3 ± 3	0.365 ± 0.018	1.33 ± 0.07	77.38 ± 12.53	58 ± 9.9
OSL 4	X3345	0.98	2.2	1.0	3 ± 3	0.417 ± 0.021	1.40 ± 0.07	80.31 ± 11.57	57 ± 8.8
OSL 5	X3346	0.96	1.2	0.6	3 ± 3	*0.373 ± 0.019*	1.08 ± 0.05	72.59 ± 19.34	58 ± 15.8
OSL 6	X3347	0.99	1.2	0.6	3 ± 3	0.379 ± 0.019	1.15 ± 0.06	77.33 ± 9.60	61 ± 8.3
Emaylah	X3875	0.83	1.6	0.9	3 ± 2	Not measured	1.25 ± 0.08	72.80 ± 3.48	58 ± 4.5

[a] Measurements were made on dried, homogenised and powdered material by fusion ICP–MS with an assigned systematic uncertainty of ±5%. Dry beta dose rates calculated from these activities were adjusted for the measured field water content expressed as a percentage of the dry mass of the sample.

[b] Based on in situ measurements made by Dr S. Armitage (Royal Holloway, University of London) using a portable γ-ray spectrometer equipped with a NaI (Tl) scintillator crystal and calibrated against the Oxford blocks (Rhodes and Schwenninger, 2007). No field spectroscopy measurement was available for sample X3588 but given the identical external dose rate calculated for the overlying and underlying samples we used the same value with an inflated error of 10%.

4.2. Laboratory analyses

Water content, loss on ignition organic content (LOI$_{org}$) and carbonate content (LOI$_{carb}$) were conducted following the standard procedures described in Dean (1974) and Heiri et al. (2001). To determine grain size, samples of air-dried sediment were gently disaggregated in de-ionised water and analysed using a Malvern Mastersizer 2000. Bulk geochemical analysis of elemental concentrations within the samples was determined by Inductively Coupled Plasma–Atomic Emission Spectrometry (ICP–AES) at Royal Holloway, University of London. Samples for bulk (<63 μm fraction) inorganic carbonate isotope analysis ($^{18}O_{carb}$ and $^{13}C_{carb}$) were prepared following the procedure described by Lamb et al. (2000) and all measurements made using a VG Optima mass spectrometer. Organic carbon isotope ($^{13}C_{org}$) values, %N and %C measurements derived from the bulk organic component of samples were made using a Carlo Erba 1500 online to a VG TripleTrap and Optima duel-inlet mass spectrometer, and prepared following the procedure described by Leng et al. (2005). All stable isotope analyses were conducted at the NERC Isotope Geosciences Laboratory, Keyworth, Nottingham.

4.3. OSL dating

Optically stimulated luminescence (OSL) dating was performed on sand-sized quartz grains extracted from six samples (see Table 1) collected from aeolian material intercalated with lacustrine deposits within the sequence at JA08. Laboratory procedures were designed to yield sand-sized (180–250 μm) mineral grains of quartz for optical dating according to standard preparation methods, including wet sieving, HCl acid digestion, density separation and etching in 68% HF acid to dissolve feldspar minerals and remove the outer 6–8 μm alpha-dosed layer. A prolonged 2 week acid digestion in saturated fluorosilicic acid was necessary in order to reduce concentrations of feldspar contaminants.

OSL measurements were conducted using an automated luminescence reader (Risø TL/OSL-DA-15 system) and are based on a single-aliquot regeneration (SAR) measurement protocol (Murray and Wintle, 2000). Equivalent dose estimates were obtained for 3–4 mm diameter aliquots and twelve repeat measurements were made for each sample. Optical stimulation for single aliquots was provided by blue light emitting diodes (42 Nichia 470Δ20 nm;

36 mW cm^{-2}). The natural and regenerative doses were preheated at 260 °C for 10 s, and the fixed test doses (which are used to correct for any sensitivity changes) were preheated at a reduced temperature of 240 °C for 10 s, before optical stimulation. This was based on a single dose recovery test done on three aliquots of sample X3345 and which provided a recovered dose within 4% of the known laboratory dose. The absence of infrared-sensitive minerals (e.g., feldspars) was checked and confirmed using an infrared bleach provided by a solid state laser diode (830Δ10 nm; 1 W cm^{2}) at 50 °C for 50 s before blue light stimulation. The ultraviolet OSL emission at ca. 370 nm was detected over a period of 100 s using an Electron Tubes Ltd 9235QA photomultiplier tube fitted with a blue–green sensitive bialkali photocathode and 7.5 mm of Hoya U-340 glass filter. Laboratory doses used for constructing dose response curves were given using a calibrated ^{90}Sr/^{90}Y beta source housed within the reader.

To calculate dose rates, we combined the results of in situ γ-ray spectroscopy measurements with elemental analysis by inductively coupled plasma mass spectroscopy (ICP–MS) using a lithium metaborate/tetraborate fusion carried out by Actlabs (Canada). The on-site measurements provided direct estimation of the external gamma dose rate applicable to individual samples whereas the beta dose rate was derived from the concentrations of potassium, thorium and uranium obtained by laboratory based elemental analyses of sub-samples of sediment. The cosmic-ray dose was calculated according to standard data reported by Prescott and Hutton (1994), taking into account sample depth and overburden density, along with the geomagnetic position of the site (latitude, longitude and altitude). Estimates of radionuclide concentrations were converted to dose rates according to conversion factors proposed by Adamiec and Aitken (1998), using corrections for grain size (Mejdahl, 1979) and water content (Zimmerman, 1971). The past water content of the sediments may, for short times, have deviated from the modern field values but the present moisture contents (ranging from 0.5 to 1.5%) may be considered to represent a good indication of the average water content of the samples throughout their burial history. To accommodate any significant attenuation effects caused by past changes in pore water on the total dose rate received by the quartz mineral grains, a mean water content of 3 ± 3% was applied to all the samples. Multi-grain palaeodose estimates were determined from the first 2 s of OSL, using the final 10 s as background noise. Dose–response curves were fitted using a saturating-exponential-plus-linear function and a systematic laboratory reproducibility uncertainty of two percent was added (in quadrature) to each OSL measurement error to account for uncertainties in the calibration of the beta source. Errors on the age estimates are reported at 1sig. The measured SAR palaeodose values and the calculated OSL age estimates are shown in Table 1 and De distributions for samples X3586 and X3588 are shown in Fig. 3.

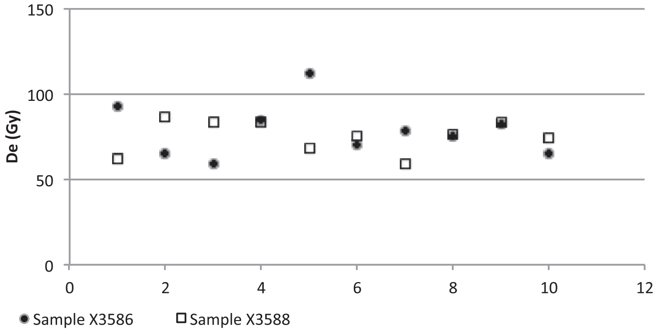


Fig. 3. Example of De distributions for samples X3586 and X3588.

5. Results

5.1. Sedimentology and grain size analysis

The sedimentary sequence at Aqabah (Fig. 2) comprises a stratified 7.35 m sequence of colluvium, aeolian sands and fluvio-lacustrine silts and sands. The whole sequence is overlain by a 1.15 m colluvial deposit comprised of moderately sorted, subangular–angular limestone clasts within a sand matrix. The colluvial deposit generally displays a fining-up sequence, with clasts having an a-axis length of 5 cm. Grain size analysis indicates that the main sedimentary sequence between 1.15 m and 7.35 m is comprised of two principal components that reflect lacustrine and aeolian depositional processes. The aeolian component comprises moderately well sorted fine sands with near symmetrical skewness (−0.02 for all samples), mesokurtic kurtosis (0.97–0.94φ) and a unimodal distribution reflecting a single sedimentary component. The skewness and kurtosis values of the aeolian components within the sequence are in accordance with the granulometric sand type typical of the active sand crests of migrating dunes within the region (Besler and Ritter, 2009). These sedimentary characteristics are representative of the larger sand unit (1.15–3.65 m) and of minor (<20 cm) sand layers intercalated with lacustrine facies (3.60–7.35 m), indicating that periods of increased regional aridity and dune mobilization occurred between each phase of lake formation.

Lacustrine facies are comprised of very fine sand and silt sediments and are designated as lake phases (LP1–5). OSL age estimates indicate that lake formation at Aqabah occurred during five phases between ca. 61 ka and 58 ka, however, the relatively narrow range of ages mean that it is not possible to determine the duration of each phase of lake formation. Structural, granulometric and multiproxy characteristics of these units indicate deposition under different hydrological regimes. LP1 is comprised of an initial silty marl layer (7.00–6.80 m), followed by interdigitated silts and sands between 6.80 m and 6.50 m, overlain by silty marl (6.50–6.20 m). LP2 represents a brief phase of sedimentation that may correspond to a brief overbank flood event and is comprised of calcareous silt-sands, whilst LP3–5 are finely laminated lacustrine silt and sand deposits. Both the fluvial sand and silt sediments are poorly- to very poorly-sorted with bimodal grain size distribution reflecting varying contributions of silt/sand to each sample, and reflecting more than one sedimentary or transportation process (e.g. An et al., 2012). Given the proximity of the Rub' al-Khali to the west of the site, it is likely that aeolian material would have made an important contribution to the suspended load of channels converging at the Aqabah site. Highly laminated sediments throughout LP4 and LP5 show profuse root and plant impressions and a high degree of manganese staining between laminae, indicative of sustained lake activity and seasonally fluctuating conditions. Additionally, vertically and horizontally-bedded rhizoliths (root structures preferentially cemented by gypsum) are also present and indicative of increasingly saline conditions.

5.2. Magnetic susceptibility

Other studies (e.g. Parker et al., 2006; Preston et al., 2011) have shown that closed basin lakes in SE Arabia record increases in magnetic susceptibility (MS) during arid phases, owing to an increased mobility of Fe-rich dune sands. The fluvial sedimentary record at Aqabah, however, is strongly influenced by the minerogenic influx of material eroded from the ophiolite-rich Hajar Mountains and as such, higher magnetic susceptibility (χ_{lf}) values occur during lake phases. There are substantial increases throughout LP1-5 (Fig. 4), with peak χ_{lf} values occurring at the

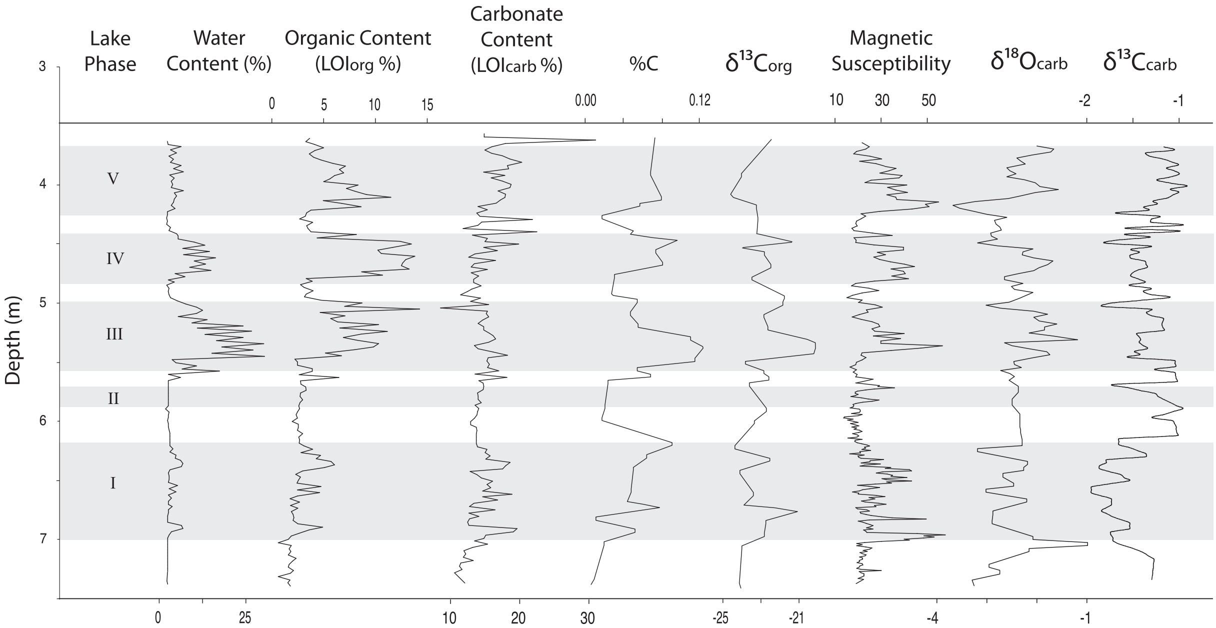


Fig. 4. Multiproxy record of the Aqabah sequence between 3.75 and 7.20 m including interpreted pluvial phases.

onset of LP1 (55.4), and further high values during LP3 (53.4) and LP5 (51.9). Abrupt increases in χ_{lf} values occur at the onset of fluvial deposition at the site (6.90 m) and during phases of lacustrine sedimentation (5.40 m, 4.70 m and 4.25 m), suggesting that post-depositional authigenesis may be an additional controlling factor of magnetic values.

5.3. Organic matter content

Nitrogen (N_{total}) content was below the detection range and is not discussed. Fluctuations in all organic proxies display a close relationship with facies changes throughout the sequence, with notable increases in water content, organic content (LOI_{org}), %C and $\delta^{13}C_{org}$ during phases of lake formation (LP1 and 3–5) and generally lower values during phases of aeolian deposition. Substantially higher LOI_{org} than %C values throughout the sequence are likely due to the loss of volatile salts, inorganic carbonates and structural water between 425 and 550 °C (Boyle, 2001), leading to over estimations of organic content. It is suggested that the influx of carbonate material, weathered from the surrounding catchment and deposited at the site during lake formation, has led to this overestimation. Estimated %C values show a good degree of correlation (Table 2) with LOI_{org} ($R = 0.47$), recording increases that are coincident with the deposition of lacustrine material. Peak %C values are achieved within LP3 (0.13%), whilst lower values correspond with the deposition of aeolian sand, achieving a minimum at the base of the sequence (0.02%). %C throughout LP5, LP4 and LP3 abruptly increases at the onset of lake formation, before declining towards the upper part of each unit. $\delta^{13}C_{org}$ values also display some positive increases during LP1, 3 and 4. The most substantial positive shift is achieved during LP3 (−20.2‰) at a depth of 5.4 m, coincident with peak %C and water content values. The most negative $\delta^{13}C_{org}$ values (−24.2‰) occur within LP5 at 4.22 m, corresponding with increases in LOI_{org}, %C and an abundance of fossil plant remains and rhizoliths within the sedimentological record.

Table 2
Correlation coefficients (*R*) for selected sedimentology, geochemical, organic and palaeohydrological proxy data from the Aqabah record.

	$^{18}O_{carb}$	$^{13}C_{carb}$	Mag. Sus.	%C	$^{13}C_{org}$	LOI_{org}	LOI_{carb}	Water content	Grain size	Mg/Ca	Al	Fe	Mg	Mn	K	P
$^{18}O_{carb}$																
$^{13}C_{carb}$	0.13															
Mag. sus.	0.40	−0.13														
%C	0.04	0.05	0.32													
$^{13}C_{org}$	0.17	−0.06	−0.13	0.32												
LOI_{org}	0.30	0.03	0.35	**0.47**	0.18											
LOI_{carb}	0.13	0.02	0.06	**0.41**	0.06	0.23										
Water content	0.34	−0.01	0.26	**0.58**	**0.52**	**0.62**	0.13									
Grain size	−0.25	−0.04	−0.22	**−0.46**	−0.39	**−0.52**	−0.13	−0.27								
Mg/Ca	0.20	0.14	**0.54**	**0.46**	0.03	**0.79**	0.11	**0.53**	−0.35							
Al	0.20	0.24	**0.42**	**0.44**	0.01	**0.55**	0.22	0.26	−0.30	**0.77**						
Fe	0.16	0.28	**0.50**	**0.44**	−0.05	**0.63**	0.23	0.29	−0.27	**0.89**	**0.92**					
Mg	0.14	0.18	**0.55**	**0.52**	−0.01	**0.74**	0.21	0.39	−0.35	**0.95**	**0.82**	**0.95**				
Mn	0.13	0.20	**0.55**	**0.49**	−0.03	**0.73**	0.18	0.42	−0.33	**0.94**	**0.82**	**0.96**	**0.97**			
K	0.12	0.31	0.31	0.23	−0.14	**0.52**	0.13	0.23	−0.19	**0.77**	**0.86**	**0.88**	**0.82**	**0.82**		
P	0.09	0.51	**0.51**	**0.48**	0.05	**0.76**	0.13	**0.44**	−0.35	**0.91**	**0.75**	**0.91**	**0.94**	**0.97**	**0.79**	
Ca	−0.09	−0.08	−0.16	0.05	−0.06	**−0.42**	−0.08	**−0.52**	0.05	**−0.59**	−0.21	−0.38	**−0.42**	**−0.45**	−0.39	**−0.49**

Bold values are significant at a 99% confidence interval.

5.4. *Inorganic matter content*

Carbonate content (LOI_{carb}) values are somewhat variable throughout the sequence (Fig. 4). However, notable peaks occur at 4.40–4.25 m, achieving a maximum value of 29.6% at 3.65 m, which likely indicates an increase in the mobility of deflated carbonate material following the termination of lacustrine conditions at the end of LP5. Variations in $\delta^{18}O_{carb}$ throughout the sequence show some degree of correlation with facies changes. In particular, $\delta^{18}O_{carb}$ values show a shift to more negative values at the onset of each lake phase, with values becoming most depleted ($-3.35‰$) at 4.20 m. The greatest shift between positive and negative values occurs at the onset of LP1 (7.10 m). Significantly, throughout the whole sequence $\delta^{18}O_{carb}$ values appear to correlate well with magnetic susceptibility values ($R = 0.40$) and to a lesser extent, LOI_{org} ($R = 0.30$). During lake phases, the $\delta^{18}O_{carb}$ signal is characterised by an initial depletion followed by fluctuations between positive and negative values. $\delta^{13}C_{carb}$ values display similar fluctuations throughout the profile including a shift to more negative values at the onset of lake formation. A distinct feature of the $\delta^{13}C_{carb}$ record, however, is its narrow range and weak correlation with other proxies. Additionally, throughout the $\delta^{13}C_{carb}$ signal there is a lack of distinction between aeolian and lake phases, with peak (positive) values ($-0.42‰$) occurring during LP1 (4.02 m).

5.5. *Bulk geochemistry*

There is an excellent correlation between organic elements P and Mn ($R = 0.97$), both of which appear highly sensitive to facies changes within the upper part of the sequence and show a strong correlation with LOI_{org} ($R = 0.76$ and $R = 0.73$ respectively). Similarly, there is an excellent correlation between inorganic elements Al, Fe and Mg, which also strongly correlate with variations in LOI_{org} and magnetic susceptibility. Ca concentrations are unsurprisingly high throughout the sequence (Fig. 5), although notably higher values occur between 6.90 and 5.70 m. Additionally, there is a significant negative correlation between Ca and LOI_{org} ($R = -0.42$), Mg/Ca ratios ($R = -0.59$), Mn ($R = -0.45$) and P ($R = -0.49$). Increases in the salinity of the lake are indicated through associated increases in the Mg/Ca ratio (i.e. Eugster and Kelts, 1983; Huntsman-Mapila et al., 2006). At Aqabah, whilst Mg/Ca ratios are invariant and generally low between the base of the sequence and 5.70 m, there is a good correlation between salinity and facies changes between 5.70 and 3.65 m (LP3–5). A strong correlation between Mg and Al ($R = 0.82$), Fe ($R = 0.95$) and magnetic susceptibility ($R = 0.55$) suggest that Mg concentrations may also be influenced by the input of Mg-rich waters, however, correlation between increases in salinity and a shift to more positive $\delta^{18}O_{carb}$ values, in particular, during LP3 ($R = 0.33$) and LP4 ($R = 0.43$), indicate that salinity changes track well with the isotope signal.

6. Discussion

6.1. *Palaeoclimatic interpretation*

The palaeoenvironmental record at Aqabah indicates that five episodes of overbank flooding/lake formation occurred during the early part of MIS 3 between ca. 61 and 58 ka, following an increase in regional humidity. During this time, a northward incursion of monsoon rainfall into SE Arabia would have led to the widespread activation of alluvial fan and widiyyan systems trending W–NW from the Hajar Mountains. Of these, two drainage systems associated with Wadi Iddayah and Wadi Baraq, coalesced at the southern extent of Jebel Faya. The aggradation of fluviatile sediments to the west of Jebel Aqabah (which translates from Arabic as '*barrier*') by the larger Iddayah system, caused ponding of the westward-trending Wadi Baraq, initiating overbank flood events and lake formation. The depositional record at Aqabah is consistent with that of lakes formed within distal alluvial fan and braid plain environments, however, sedimentary and multiproxy evidence indicates the progression of two distinct hydrological systems

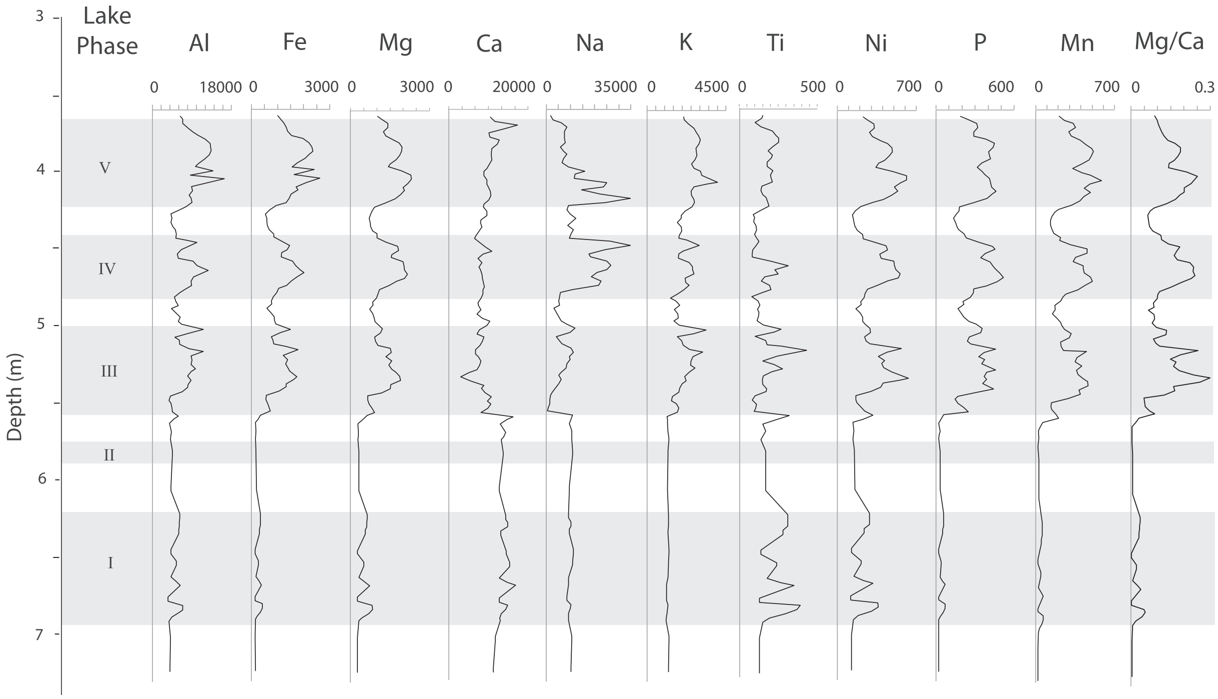


Fig. 5. Geochemical stratigraphy of the sequence at Aqabah, including interpreted pluvial phases (units in ppm).

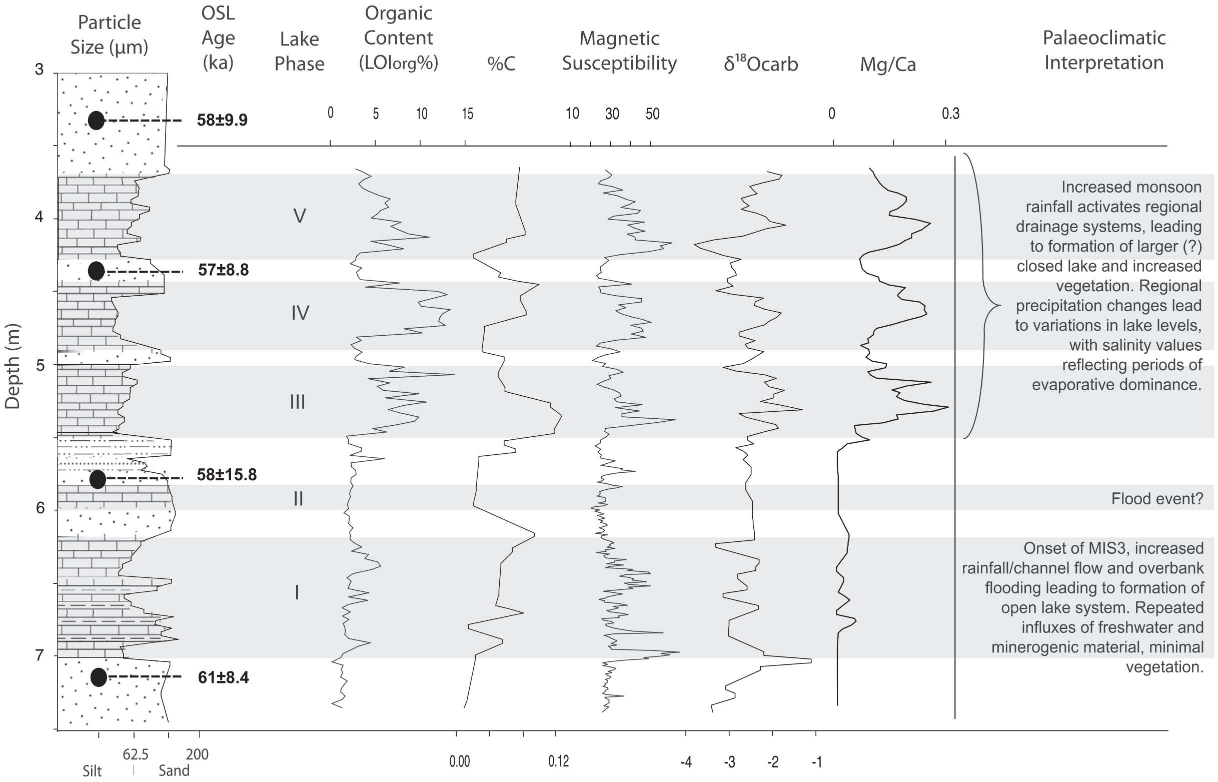
throughout the sequence. Fig. 6 provides a summary of the palaeoclimatic interpretations, including correlation of selected proxies.

Sedimentary and granulometric analysis of facies changes indicate that lake formation at the site began with an influx of fluvial silts and the accumulation of a marl layer. Prior arid conditions would have facilitated the fluvial weathering and transport of aeolian and bedrock material from within the catchment. The mobilisation and influx of minerogenic material is evidenced by abrupt increases in magnetic susceptibility values at the onset of LP1, whilst an abrupt negative shift (−1.01 to 2.55‰) in $\delta^{18}O_{carb}$ values indicates a rapid input of freshwater to the site. During LP1, interdigitated coarse fluvial sands and silts indicate the waxing and waning of overbank flood events. Silt-sized particles are easily transported in suspension outside the confines of the channels during flood events, rapidly prograding within proximal overbank areas.

Lake level variability is also reflected through abrupt changes in minerogenic influx (χ_{lf}) and small positive/negative shifts in $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ values. Given the interstratified nature of the sequence, correlation of $\delta^{18}O_{carb}$ and $^{13}C_{carb}$ values to establish whether the water body at Aqabah was hydrologically open or closed (e.g. Talbot, 1990; Sinha et al., 2006), is problematic. Therefore, to decouple the isotopic signals from facies changes, correlation coefficients were calculated within individual lacustrine facies (LP1–5). Facies-dependent correlations between $\delta^{18}O_{carb}$ and $^{13}C_{carb}$ values are particularly weak throughout LP1 ($R = 0.001$), indicating that hydrologically open conditions persisted within the lake during this time. This is supported by a narrow range of $\delta^{18}O_{carb}$ values (2.68–1.94‰) and low Mg/Ca ratios, which alongside the sedimentary record and a lack of accumulated inorganic elements, indicate a continual flushing of the hydrological system. Similar fluctuations between more positive/negative values are evident within the $\delta^{13}C_{org}$ record during LP1, with an abrupt shift from lower (−23.7‰) to higher (−20.9‰) values that correspond with a brief decrease in %C.

Following this initial lake phase, an influx of aeolian sand reflects the onset of regional aridity at the site. This is punctuated by a deposit of homogenous silt-sand material (LP2) for which all proxy values are invariant, and which likely represents a brief overbank flood event. A lack of proxy data for this phase, however, prevents further interpretation. Lake phases 3–5 occurred under a different hydrological regime, with consistently similar variations within proxy data for each phase. The onset of aggradation-induced overbank flooding and lake formation within each lake phase is marked by an abrupt influx of minerogenic material, reflected by increased magnetic susceptibility values and inorganic elemental concentrations. During open hydrological conditions (LP1) the bulk geochemical record remains invariant, however, increases in Al, Fe, and Mg, reflect an increased weathering of silicate and aluminosilicate minerals from the ophiolitic bedrock within the catchment area and fluvial reworking of alluvial fan surfaces to the east of the Al Faya anticline. This is consistent with the mineral magnetic record, which displays a strong positive correlation with Al ($R = 0.42$), Fe ($R = 0.49$) and Mg ($R = 0.55$). The abrupt increase in these inorganic elements indicates that lake phases from this point were also of greater intensity than previously experienced at the site.

Lake phases 3–5 are also marked by a depletion of $\delta^{18}O_{carb}$ and $^{13}C_{carb}$ values and an abrupt increase in organic production (LOI$_{org}$, %C, P and Mn). A strong correlation between $\delta^{18}O_{carb}$ and $^{13}C_{carb}$ values during LP3 ($R = 0.45$), LP4 ($R = 0.61$) and LP5 ($R = 0.54$), indicate that hydrologically closed conditions persisted during these lake phases. This is supported by a greater variability in values from ca. 5.50 m and a period of isotopic enrichment following depletion/overbanking, indicating a predominance of water loss through evaporation and a cessation of fluvial input. The instability of both $\delta^{18}O_{carb}$ and $^{13}C_{carb}$ records throughout LP3–5 also indicates



Increased monsoon rainfall activates regional drainage systems, leading to formation of larger (?) closed lake and increased vegetation. Regional precipitation changes lead to variations in lake levels, with salinity values reflecting periods of evaporative dominance.

Flood event?

Onset of MIS3, increased rainfall/channel flow and overbank flooding leading to formation of open lake system. Repeated influxes of freshwater and minerogenic material, minimal vegetation.

Fig. 6. Correlation of selected proxies from the Aqabah record (3–7.35 m). Lake phases and palaeoclimatic interpretation of the multiproxy record is given.

that the water body at Aqabah underwent rapid lake level changes and was not large enough to dampen the effects of short term climatic variation (Lamb et al., 2000). Similarly, more positive $\delta^{18}O_{carb}$ values throughout LP3 may reflect shorter water residence times during that period. Such shifts may be the result of seasonal variations in lake levels. This is supported by highly laminated lacustrine sediments throughout LP3–5 which, in the case of LP4 and 5, contain profuse root and plant impressions and a high degree of manganese staining between laminae, indicative of seasonally fluctuating lacustrine conditions.

Similarly, the presence of rhizoliths reflect an increase in lake salinity following and coincide with increased salinity proxy values (Mg/Ca). Abrupt increases in Mg/Ca ratios are indicative of increased evaporation and a lowering of lake levels, whilst peaks in salinity are also coincident with positive shifts within the $\delta^{18}O_{carb}$ signal. The general pattern of increase and decline within both sets of values during LP3–5, indicates a recharging of lake waters. Despite a whole-sequence correlation between $\delta^{18}O_{carb}$ values and magnetic susceptibility ($R = 4.0$), a lack of positive correlation during LP3 ($R = 0.11$), LP4 ($R = 0.09$) and LP5 ($R = -0.53$) indicates that detrital contamination is not the primary mechanism controlling the isotope signal during lake phases. Therefore, the lack of evidence for an increased influx of fluvio-mineragenic material, suggests that lake water increases were likely the result of increased localised precipitation or groundwater recharge.

An abrupt positive shift in $\delta^{13}C_{org}$ (−20.2‰) at the onset of LP3 is incongruous with correlative peaks in minerogenic influx and the depletion of $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ values. The absence of C/N data to constrain organic material sources makes an accurate interpretation of the $\delta^{13}C_{org}$ signal during LP3 problematic, however, a positive shift during LP3 may indicate that $\delta^{13}C_{org}$ values are primarily responding to aquatic productivity, leading to an enrichment of ^{13}C in the lakes total dissolved inorganic carbon (TDIC) reservoir (Meyers, 1994). This may be supported by $\delta^{13}C_{org}$ values, which throughout the sequence (mean = −22.7‰) are indicative of submerged aquatic macrophytes (−24.0 to −13.0‰) (Mischke et al., 2008). It is also likely, however, that during periods of increased fluvial influx (and watershed erosion), positive shifts in $\delta^{13}C_{org}$ reflect a contribution of terrestrially derived plant debris from watershed vegetation. This is particularly the case for deltaic and terminal lakes formed within distal alluvial fan settings and indicates that during this time, an expansion of regional vegetation occurred. A lack of correlation between Mg/Ca ratio changes and $\delta^{13}C_{org}$ values during LP3, indicate that the in situ variation of $\delta^{13}C_{org}$ due to salinity changes (resulting in a shift to HCO_3-based photosynthesis) (Holmes et al., 1997; Enzel et al., 1999; Leng et al., 2009), is not a factor.

6.2. *Palaeoclimatic implications*

The presence of a water body within SE Arabia during the early stages of MIS 3 has important implications for both our understanding of monsoon variability and the archaeological record of the region. Previously, incursions of the ITCZ and associated monsoon rainfall belt into Arabia have been viewed as predominantly characteristic of interglacial periods and substages MIS 5c and MIS 5a (i.e. Burns et al., 1998, 2001; Fleitmann et al., 2003, 2011; Fleitmann and Matter, 2009), with the period between MIS 4 and MIS 2 typified by arid to hyper-arid conditions. Additionally, previous evidence for increased humidity during MIS 3 (e.g. McClure, 1976, 1984; Garrard et al., 1981; Schulz and Whitney, 1986), has recently been called into question (Rosenberg et al., 2011, 2012) and as such, radiocarbon chronologies for this time period are viewed with caution.

Within this study, OSL age estimates indicate that monsoon incursion into SE Arabia during the early stages of MIS 3 (ca. 61–58 ka) activated drainage networks along the western flanks of the Hajar Mountains, leading to distal-zone lake formation at Aqabah. This is supported by a further date of 58.44 ± 4.57 ka obtained from the base of Jebel Emaylah, ca. 2 km east of Jebel Aqabah, which confirms that a network of ephemeral channels within the region were also active at this time. Additionally, dates from both sites help to constrain previous age estimates for other terrace formations within the region, which demonstrate that wadi activation occurred between 48 ± 5 and 63 ± 5 ka (Krbetschek, 2008). Under present day conditions, the episodic flooding of wadis in the region results in the activation of ephemeral channels with no sediment aggradation. Whilst the narrow range of age estimates from Aqabah prevent a determination of lake phase duration, geomorphological, sedimentological and palaeohydrological evidence indicates that pluvial conditions were sufficiently sustained to allow widespread terrace formation within the region, and the subsequent development of vegetative and lacustrine processes. Additionally, the estimated ages for increased humidity at Aqabah are in agreement with a growing number of records, which indicate a strengthening and latitudinal shift of the Indian Ocean Monsoon from ca. 58 ka.

In particular, the activation of fluvial systems within the region corresponds to an intensification of the monsoon recorded in a number of marine records (e.g. Schulz et al., 1998; Altabet et al., 2002; Higginson et al., 2004; Des Combes et al., 2005; Ivanochko, 2005; Govil and Naidu, 2010) and a stacked marine record of the Indian Summer Monsoon (ISM) (Clemens and Prell, 2003; Leuschner and Sirocko, 2003). Although doubts have been expressed as to whether such marine records provide a record of monsoon wind strength as opposed to precipitation (e.g. Burns et al., 2001; Fleitmann et al., 2011), the terrestrial record at Aqabah provides compelling evidence for an early MIS 3 incursion of monsoon rainfall into the Arabian interior. Furthermore, the correlation of lake phases at Aqabah with marine records from the Arabian Sea and Indian Ocean, indicate that the sensitivity of monsoon regions to Northern Hemispheric climate change during the early stages of MIS 3 (Altabet et al., 2002; Burns, 2003) may also be detectable within terrestrial sedimentary archives.

In terrestrial records, there is some degree of correlation between the Aqabah record and OSL dates from central Saudi Arabia (McLaren et al., 2008), which indicate increased rainfall at 53.9 ± 4.2 and 54.0 ± 5.4 ka. However, whilst the evidence from Saudi Arabia may be somewhat regionally defined, the record at Aqabah suggests that monsoon rainfall may have affected a significant expanse of the Arabian interior. The deposition of lacustrine sediments at Aqabah was triggered by the aggradation of alluvial fans whose catchments are situated between 16 and 30 km to the east, along the western flanks of the Hajar Mountains. This fan system is part of a vast bajada of fans and drainage systems that flank the Oman Mountains, from the Northern Emirates down to the Wahiba Sands in Oman. Once monsoon rainfall had breached the watershed divide of these mountains, drainage networks along their western flanks would have channeled a substantial volume of freshwater W–NW towards the Gulf. Indeed, the corresponding deposition of fluvio-lacustrine deposits near Remah, Abu Dhabi at 54.1 ± 3.1 and 53.4 ± 3.8 ka (Farrant et al., 2012) indicate that the activation of drainage networks was ubiquitous along the western flanks of the Hajar Mountains during the early stages of MIS 3. It is reasonable to assume, therefore, that lake formation within other distal fan environments may have been recurrent during this time.

Two explanations for the absence of other early MIS 3 fluvio-lacustrine deposits within SE Arabia are conceivable. Firstly, there is a conspicuous lack of detailed palaeoclimatic reconstruction based upon fluvial/alluvial fan archives along the western flanks of the Hajar/Oman Mountains. Secondly, any evidence of fluvial aggradation during MIS 3 would require specific sediment depositional conditions conducive to archive preservation. The generally arid to hyper-arid conditions of the later stages of MIS 3 and MIS 2 (Glennie and Singhvi, 2002; Fleitmann et al., 2003; Fleitmann and Matter, 2009; Preusser, 2009; Atkinson et al., 2011), means that sediments accumulated during an early MIS 3 humid phase, would have been subject to considerable deflation and reworking following sustained aridity. This notion is supported by a paucity of preserved MIS 4 sediments within Arabia (Stokes and Bray, 2005). In this respect, the natural barrier of Jebel Aqabah facilitated sediment aggradation during the early stages of MIS 3 and sediment preservation during the proceeding arid phases. A shortage of similar early MIS 3 fluvial deposits within SE Arabia is, therefore, indicative of the poor sediment preservation potential of Arabia during phases of increased aridity.

Climatic amelioration during MIS 3 also has important implications for the archaeological record of the region. In particular, the occupation of sites such as Jebel Faya, United Arab Emirates, during the early stages of MIS 3 (Armitage et al., 2011), would have been strongly influenced by the activation of drainage systems at this time. The close proximity of a lake at Aqabah to the Jebel Faya rockshelter site (approximately 9.5 km) would have provided an important source of freshwater for both human communities and faunal populations. Although a precise chronology for Assemblage B at Jebel Faya is at present absent, it is reasonable to assume that occupation of the site during MIS 3 would have been coincident with lake formation at Aqabah. Additionally, the presence of freshwater at this time may have facilitated the autochthonous development of early human communities. This is supported by a lack of technological affinities between Jebel Faya's assemblages A and B and any other known lithic industry. The activation of drainage systems and the development of lakes within the Arabian interior during MIS 3 would, therefore, have been instrumental in the development of local traditions confined to eastern Arabia. In this respect, the question arises as to whether a later wave of expansion from Africa into Arabia may have occurred. If such an expansion took place, a technological package reminiscent of the African late MSA/early LSA would be expected (Brandt et al., 2012), however, of the known MIS 3 archaeological sites in Arabia, none fit this description.

7. Conclusions

The formation of a water body at Aqabah occurred during the early stages of MIS 3 (ca. 61–58 ka), when the northward incursion of the ITCZ and associated monsoon rainfall activated a dense network of channels associated with an alluvial fan system along the western flanks of the Hajar Mountains. The competitive aggradation of fan sediments and the coalescing of channels, led to overbank flooding near the base of Jebel Aqabah and eventual lake development. This occurred during four distinct lacustrine phases and a brief overbank flood event, which were punctuated by increased aridity and temporary lake desiccation. Initially, the lake at Aqabah was a complex open hydrological system in which the dominant control over lake levels at the site was the episodic influx of freshwater by stream channel flow. During subsequent lake phases, sedimentological, palaeohydrological and magnetic susceptibility evidence indicates that an intensification of rainfall within the region occurred, leading to the formation of precipitation-fed, hydrologically closed water bodies. Although lacustrine sedimentation appears to have remained constant throughout each lake phase, the multiproxy record suggests that lake water levels and vegetative processes fluctuated. Additionally, the location of the site within the medial–distal zone of a vast relict bajada of alluvial fan deposits along the western Hajar, suggests that lake formation and stream channel flow may have been spatially extensive during brief periods of increased precipitation.

OSL age estimates for lake formation at Aqabah are in good accordance with both marine and terrestrial records from Arabia, which confirm the occurrence of an intensification of the monsoon following the onset of MIS 3 at ca. 58 ka. Whilst lake formation within the region may have been relatively short-lived, the sequence at Aqabah confirms that the activation of extensive drainage systems within the region may have facilitated the expansion of Arabia's indigenous inhabitants, following an initial dispersal during MIS 5.

Acknowledgements

We would like to acknowledge the help and support of: the Department of Culture and Information of the Emirate of Sharjah, the British Geological Survey, the Ministry of Energy, UAE, NERC for student funding during 2009, Simon Armitage for making the in situ radioactivity measurements, the Quaternary Research Association for sponsoring some of the OSL dating through the RLAHA-QRA OSL dating award and in no small part, Sophie, Freya and Elda. ARF publishes with the permission of the Executive Director, BGS

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