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A multi-proxy analysis of the Holocene humid phase from the United Arab Emirates and its implications for southeast Arabia's Neolithic populations

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Abstract

An early- to mid-Holocene humid phase has been identified in various Arabian geo-archives, although significant regional heterogeneity has been reported in the onset, duration and stability of this period. A multi-proxy lake and dune record from Wahalah in the United Arab Emirates (UAE) documents significant variations in hydrology, biological productivity and landscape stability during the first half of the Holocene. These data reveal that post-Last Glacial Maximum dune emplacement continued into the earliest part of the Holocene, with the onset of permanent lacustrine sedimentation at the site commencing ~8.5 ka cal. BP. A long-term shift towards more arid conditions is inferred between ~7.8 – 5.9 ka cal. BP, with intermittent flooding of the basin and distinct phases of instability throughout the catchment area. This transition is linked to the southwards migration of the Intertropical Convergence Zone (ITCZ) and associated weakening of monsoon rains. A peak in landscape instability is recorded between ~5.9 – 5.3 ka cal. BP and is marked by a pronounced increase in regional dune emplacement. These variations are considered alongside the record of human settlement raising important questions about the interactions between population demographics, climate and environment in southeast Arabia during the Neolithic.

Keywords
Arabia, Holocene, Neolithic, Palaeolake, Dunes, Palaeoclimate

1. Introduction

Understanding climatic variability is crucial when examining archaeological records in the world's arid regions, where the landscape is highly sensitive to subtle shifts in precipitation and evaporation. This has led an increasing number of palaeoclimatic studies to link the rise and fall of early human societies to changing climatic conditions during the Holocene (e.g. Cullen et al., 2000; Brooks, 2006; Staubwasser and Weiss, 2006; Dixit et al. 2014a). However, it is important that causal relationships are not based solely on broad, continental-scale changes in climate, but instead assess their impact at a more local level in terms of landscape sensitivity and stability and the availability of environmental resources, such as freshwater and vegetation (Berger et al., 2012).

Geo-archives have revealed that areas of the presently hyper-arid Arabian sub-continent were transformed into an ameliorated landscape during the early- to mid-Holocene, with more favourable hydrological conditions leading to the expansion of lakes and vegetation throughout the desert interior (Parker et al., 2004; Lézine et al., 2010; Berger et al., 2012). This change is thought to have been driven by a northwards shift in the mean latitudinal position of the Intertropical Convergence Zone (ITCZ) and associated monsoon precipitation belt (Overpeck et al., 1996; Fleitmann et al., 2007). Speleothem δ^{18}O data from northern (Hoti Cave) and southern (Qunf Cave) Oman suggest that monsoon precipitation increased rapidly between ~10.6 and 10.1 ka BP and remained generally high until ~6.3 ka BP (Fleitmann et al., 2007; Fleitmann and Matter, 2009). These palaeohydrological reconstructions are in good agreement with marine records from the Northern Arabian Sea which show increased upwelling/productivity and reduced dust influx during the early- to mid-Holocene (Sirocko et al., 1993; Schultz et al., 1998; Gupta et al., 2003). Whilst these long-term, continuous sedimentary archives have proven invaluable in reconstructing broad climatic trends, they reveal little about the evolution of the terrestrial landscape at the local level. Indeed, a recent synthesis of a range of Arabian geo-archives demonstrated that there is significant regional heterogeneity (*sensu* Thomas et al., 2012) throughout the Peninsula during the Holocene (Berger et al., 2012). Fleitmann et al. (2007) linked these differences to the time-transgressive migration of the summer ITCZ, with the onset and termination of humid conditions, and whether these transitions were gradual or abrupt, dependent upon the geographical location of a particular site. The contribution of mid-latitude westerly (MLW) systems during this period, an important source of moisture throughout northern and central Arabia today, remains unclear. Speleothem δ^{18}O data from Hoti Cave indicate that these systems became increasingly important after ~6.3 kyr BP (Fleitmann et al., 2007). They may have contributed to continued lacustrine sedimentation at some sites north of 24°N during the mid-Holocene, when most palaeolake records from central and southern Arabia had ceased (Parker and Goudie, 2008). Understanding the significance of these differences is complicated further as most Arabian terrestrial geo-archives are prone to erosion, yield little dateable material and are rarely continuous (Berger et al., 2012). Furthermore, high-resolution palaeoclimate records reveal a series of millennial-scale, high amplitude, short-term periods of increased aridity superimposed on these long-term trends, further challenging the notion that the early- to mid-Holocene was stable and wholly humid (Fleitmann et al., 2007; Fleitmann and Matter, 2009). Indeed, it is now clear that the period was characterised by significant temporal and spatial climatic variability, in turn highlighting the importance of understanding the evolution of the terrestrial landscape at the local level when examining climate – human interactions. This variability is evident throughout the Peninsula today, largely as a consequence of changes in elevation, with higher precipitation in the mountainous terrain which runs along the eastern (al-Hajar Mountains, Oman), southern (Dhofar Mountains, Oman, and the Hadramawt Plateau, Yemen), and western (Yemeni Highlands) fringes of the Peninsula (Glennie and Singhvi, 2002). In addition, significant rainfall events, resulting in flash-flooding, have been recorded throughout parts of the UAE and Oman (Membury, 1997; Kwarteng et al., 2009).

Palaeoenvironmental evidence in southeast Arabia is derived from palaeolakes (Parker et al., 2004, 2006; Radies et al., 2005; Fuchs and Buerkert, 2008; Urban and Buerkert, 2009; Preston et al., 2012), fluvial deposits (Dalongeville, 1999), and aeolian sequences (Goudie et al., 2000a; Preusser et al., 2005; Stokes and Bray, 2005; Atkinson et al., 2011, 2012, 2013). These records have revealed that the environment underwent significant change during the early- to mid-Holocene in response to the continental-scale shifts in climate discussed above. Archaeological investigation has shown that the corresponding period marked a large-scale re-occupation of the landscape during the Neolithic, a time of significant cultural development (e.g. domestication of animals, changes in material culture, growth of maritime exchange relations) throughout Arabia (Potts, 2001). This paper presents a new, multi-proxy record of early- to mid-Holocene environmental change from Wahalah palaeolake, United Arab Emirates (UAE) (Fig. 1), which has potentially important implications for our understanding of the region's archaeological record. Previous work at the site by Atkinson et al. (2011) has provided important information on the age and development of the regional dune-fields that impinge on the basin. By comparing the multi-proxy lake record with the chronology from the surrounding dunes and with data from other geo-archives from southeast Arabia, this study seeks to develop a reliable framework of climate change and landscape evolution within which to examine the region's Neolithic archaeology.

2. Environmental and archaeological setting

Wahalah (N25° 38' 48", E55 47' 26"; 10 m asl), is a dry, inter-dunal lake basin of ~2.4 km^2 situated in the Emirate of Ras' al-Khaimah, approximately half-way between the cities of Ras' al-Khaimah and Umm al-Quwain in the UAE (Fig. 1). The site lies 4 km inland from Jazirat al-Hamra on the Arabian Gulf coast and approximately 30 km to the west of the al-Hajar Mountain range.

Provenance studies of the dune sands in the UAE have shown that both the Arabian Gulf basin and al-Hajar Mountains (Musandam and Ru'us al Jibal Groups) are major sources of carbonate in the region, with the latter also contributing ultramafic igneous material (Semail Ophiolite Suite). Fe-rich quartz grains, derived from the Arabian continental interior, are a third major component of the region's dune sands (El-Sayed, 1999; White et al., 2001; Garzanti et al., 2003; Farrant et al., 2012).

Wahalah is considered to have been a closed basin with an overall catchment area of less than 5 km^2 and is bordered by northeast – southwest trending linear mega-ridges which rise >50 m above the basin floor and mark the north-eastern limit of the Rub’ al-Khali sand sea (Fig. 2). Whilst the orientation of the main mega-ridge features is broadly northeast – southwest, reworking by the current *Shamal* wind regime has formed multiple transverse, northwest – southeast orientated, ridges on the more gently graded northwestern flanks. These features are typically up to 15 m high with frequent coalescence of multiple ridges at Y-junctions (Atkinson et al., 2011). The southeastern slip faces are considerably steeper, resulting in a distinct asymmetric profile. Many factors influence dune accretion, migration and stabilisation (Thomas and Burrough, 2012; Leighton et al., 2013), predominantly sediment supply, the transport capacity and direction of the wind, and vegetation cover and sediment availability (Preusser, 2009). Extensive industrial development at the site over the past decade exposed the internal architecture of the dune ridges bordering the basin, from which Atkinson et al. (2011) obtained 26 Optically Stimulated Luminescence (OSL) dates as part of a previous study on dune chronology in the region. Section UAE06-1 (25°38′28.44″N, 55°47′25.80″E) was a 16.4 m profile proximal to a northeast – southwest mega-ridge axis, located in the gently sloping northeastern flank, on the southern side of the lake basin (Fig. 2). Section UAE 06-2 (25°38′56.97″N, 55°47′46.35″E) was a 17.7 m profile located approximately 1 km northeast of UAE06-1 in a substantial secondary ridge that is orientated approximately west – east (Fig. 2). Both sections and most of the lake basin have now been lost due to further industrial development. Ages from these sections, along with those obtained from other dune deposits in the northern UAE, revealed discrete phases of activity within the periods 22 – 20 ka, 16 – 10 ka and 7 – 3 ka (Atkinson et al., 2011; Leighton et al., 2014). The latter two periods are broadly separated by a lacustrine phase during which a series of water bodies formed in many of the inter-dunal corridors (Parker et al., 2004, 2006). Palaeoclimatic investigation of one of these basins, located 18 km to the northeast of Wahalah, has demonstrated that lacustrine conditions persisted from ~8.5 – 4.2 ka cal. BP, during which a series of significant changes in lake hydrology, dune-field vegetation and landscape stability are recorded (Parker et al., 2004, 2006; Preston et al., 2011, 2012).

Today the region is characterised by arid to hyper-arid conditions and is currently located well to the north of the notional summer position of the ITCZ and thus monsoon sources of rainfall (Fig. 1). While highly variable, mean annual precipitation (~120 mm/yr.) is somewhat higher than at other coastal areas of the UAE (e.g. ~80 mm/yr. in Dubai), highlighting the significant orographic effect of the al-Hajar Mountains on precipitation gradients. Most rain falls during the winter months and is associated with MLW systems which originate as cyclonic depressions in the eastern Mediterranean and are enhanced by the warmth of the Arabian Gulf. Although rare, extreme rainfall events (>50 mm per day) do occur throughout the northern al-Hajar Mountains, resulting in flash flooding and extensive land degradation (Kwarteng et al., 2009). The current wind regime is broadly bimodal, with ~52% blowing from the west and northwest (*Shamal*) and ~28% from the southeast (Goudie et al., 2000b). The dune-fields of the north-eastern Rub’ al-Khali are vegetated by a mix of *Cornulaca monacantha, Hammada elegans, Calligonum comosum, Pennisetum divisum, Citrullus colocynthis, Tamarix,* and *Tribulus sp,* while *Cyperus conglomeratus, Crotalaria aegyptiaca,* and *Leptadenia pyrotechnica* are common in areas of dune exposure. *Prosopis cineraria* and *Calotropis procera* are found on the leeward sides of dunes and in the inter-dunes.

Archaeological investigations have revealed the presence of multiple shell middens along the coastal zone between Abu Dhabi and Ras' al-Khaimah, which span the Neolithic (~11.0 – 5.1 ka cal. BP), Bronze Age (~5.1 – 3.3 ka cal. BP), Iron Age (~3.3 – 2.3 ka cal. BP), Late Pre-Islamic (~2.3 – 1.4 ka cal. BP) and Islamic era (1.4 ka cal. BP to present). Evidence from the Neolithic has revealed a rich assemblage of marine resources which, along with finds of pottery, net sinkers and flint tools, represent the presence of a nomadic population (Boucharlat et al., 1991; Vogt, 1994; Uerpmann and Uerpmann, 1996; Philips, 2002). In addition, bone material reveals the herding of goats, sheep and cattle in the surrounding area. Evidence of trade between the southern Gulf region and Mesopotamia is characterised by the presence of Ubaid pottery originating from Mesopotamia (Potts, 2001).

Archaeological survey work in the vicinity of Wahalah was first undertaken in the early 1980s along the coast near Jazirat al-Hamra (Uerpmann, 1992), where Vogt (1994) mapped 60 shell midden sites, most of which were located on a Pleistocene, northeast – southwest orientated, mega-ridge. Much of this coastal dune has been destroyed by construction work, although remnant parts survive and run parallel to the coast for some 10 km with a maximum width of 300 m. Coastal *sabkha* (salt flats), reflecting former Holocene marine high stands, are recorded on either side of the mega-ridge. Further surveys were conducted in 2009, 2010 and 2013 by the French Archaeological Mission to the UAE (led by V. Charpentier and S. Méry), and included the dunes further inland around Wahalah, during which an additional 36 new shell midden sites were located (Fig. 2). Of the 60 sites originally mapped by Vogt (1994), less than a third survive due to recent urban development. Whilst the density of ecofacts and degree of fragmentation varies, the shell middens mainly comprise extended disarticulated shell concentrations, with some comprising stratified contexts. These shell concentrations attest to the exploitation of marine resources and in particular species associated with mangroves including the mangrove whelk, *Terebralia palustris* (a species now extinct in the Arabian Gulf). Artefacts found include lithic debitage (flint, chert, chalcedony, and carnelian), Ubaid pottery, net sinkers, stone crushers and Veneridae shell scrapers. Of note, a Fasad point attributed to the early Holocene was found on a shell midden located 2 km further inland from Wahalah in Wadi Misekhin. Several other Fasad points have been documented in the area (e.g. Millet, 1988).

A series of Neolithic posthole structures were also identified at three sites (JH1, JH9 and JH45 according to Vogt's (1994) site classification)) and represent the most important known occupation sites from the northern coast of the UAE. Neolithic architectural remains are also recorded at UAQ2 (Méry et al., unpublished), Akab Island, both Umm al-Quwain (Charpentier and Méry, 2008) and Dalma Island, Abu Dhabi (Beech et al., 2000) (Fig 1).

3. Methodology

Contiguous 1 cm sediment samples for palaeoenvironmental analyses were retrieved from an open cut trench (2 m x 2 m x 2.14 m) excavated in the centre of the dry lake basin to a depth of 2.14 m (Fig. 2).

This study presents new radiocarbon ages from dune sections UAE06-1 and UAE06-2 and thereby builds on the previous dune chronological work at the site by Atkinson et al. (2011). At UAE06-1 a sample for radiocarbon dating was collected from a 20 cm-thick shell midden layer, dominated by disarticulated mangrove and littoral marine shell species including *Terebralia palustris*, *Murex kuesterianus*, *Ostrea cuculata* and *Marcia cf. hiantina*. The shell layer is recorded at a depth of 0.52 m beneath the modern dune surface and is therefore stratigraphically above the uppermost OSL sample (UAE06-1-14) collected by Atkinson et al (2011) at the section.

Section UAE06-2 includes a significant unconformity at 6.5 m with a 20 cm-thick shell layer and a weakly developed palaeosol from which a charcoal sample was collected for radiocarbon dating. OSL samples were previously taken above and below the midden layer (UAE06-2-8 and UAE06-2-9, see Atkinson et al., 2011). At 6.15 m, between OSL samples UAE06-2-8 and UAE06-2-7 (Atkinson et al., 2011), a distinct charcoal-rich horizon running over 20 m in length was visible across the section. A total of three samples were collected from this horizon for radiocarbon dating.

3.1 Laboratory analyses

Mass specific, low frequency mineral magnetic susceptibility measurements (χlf) were made following the procedure outlined in Dearing (1999), using a Bartington MS2 meter with a MS2B sensor at 0.1 SI sensitivity. Dry bulk density (P_b) measurements were made using calibrated brass pots as described in Parker (1995). Loss on ignition organic content (LOI_{org}), carbonate content (LOI_{carb}) and minerogenic content (LOI_{min}) followed the standard preparation procedure outlined in Heiri et al. (2001). For particle size analysis, samples were taken at 5 cm intervals and soaked overnight in a solution of 5% sodium hexametaphosphate dissolved in de-ionised water. Grain size distributions between 0.02 and 2000 µm were determined by laser diffraction spectrometry using a Malvern Mastersizer 2000.

Geochemical analyses were performed at 2 cm intervals using Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES) at the NERC ICP-AES Facility, Royal Holloway, University of London. Sample preparation followed the procedure outlined in Engstrom and Wright (1984). Organic carbon isotope ($\delta^{13}C_{org}$) values and total organic carbon (%C) measurements were performed at 5 cm intervals using a Carlo Erba 1500 on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer, and prepared following the procedure outlined in Leng et al. (2005). Nitrogen levels (%N) were below the detection range and thus C/N data is not available. $\delta^{13}C_{org}$ values were calculated to the Vienna Peedee belemnite (VPDB) scale using a within run laboratory standard. Precision for $\delta^{13}C_{org}$, analyses based on duplicate analyses was ± 0.1‰ (1 std. dev.). All isotope analyses were performed at the NERC Isotope Geoscience Facilities, Keyworth, Nottingham. Microfossils (e.g. ostracods) were hand-picked from 2 g of sediment after it had been wet sieved at 63 µm and were identified under a binocular microscope.

3.2 Dating

The Wahalah lake chronology is based on four accelerator mass spectrometry (AMS) ^{14}C dates performed on *Melanoides tuberculata* shells (Poz-14898 and Poz-14897) and detrital organic samples (Beta-382525 and Beta-246361). Dating was undertaken at the Radiocarbon Accelerator Unit, Poznan, Poland and the Beta Analytic Ltd Radiocarbon Laboratory, Miami, USA. Four charcoal samples from the dune midden horizons at UAE06-2 were also dated (OxA-16911, OxA-16892, OxA-16913, and OxA-16912), along with a shell horizon at UAE06-1 (OxA-16855). These were dated at the Oxford Radiocarbon Accelerator laboratory and calibrated using Calib 7.0.2 software and the IntCal09 data set (Reimer et al., 2009). The marine shell date from UAE06-1 was corrected for the Arabian Gulf Marine reservoir effect using the ΔR value of 180±53 (Southon et al., 2002). Sediment depths were converted to ages by assuming linear sedimentation between the mean of the four depth-age points (Fig. 3). The ages of the basal sediments were estimated by extrapolating the sedimentation rate between 1.55 and 1.93 m to the base of the sequence. All ages are presented in Table 1.

4. Results and interpretation

4.1 Lake chronology

The ^{14}C dates performed on *M. tuberculata* shells yielded ages of 8.41 – 8.20 ka cal. BP (Poz-14898) and 7.93 – 7.70 ka cal. BP (Poz-14897), whilst those from the detrital organic samples returned ages of 6.49 – 6.32 ka cal. BP (Beta-382525) and 3.69 – 3.48 ka cal. BP (Beta-246361) (Table 1).

The four charcoal samples from the dune midden horizons at UAE06-2 were dated to 5.98 – 5.71 ka cal. BP (OxA-16911), 5.89 – 5.66 ka cal. BP (OxA-16892), 5.90 – 5.66 ka cal. BP (OxA-16913), and 5.89 – 5.61 ka cal. BP (OxA-16912). The marine shell horizon at UAE06-1 yielded an age of 5.19 – 4.80 ka cal. BP (OxA-16855).

4.2 Sediment analyses

Based on changes in lithology and variations in the multi-proxy data, the Wahalah lake sequence (2.14 – 0.0 m) is divided into six main sedimentary units (Fig. 4). The results from the multi-proxy analyses are shown in Fig. 5 and Fig. 6.

4.2.1 Unit I (~8.6 – 8.5 ka cal. BP, 2.14 – 2.06 m)

The lowermost Unit is homogeneous, fine to very fine sand (mean particle size range; 130 – 100 µm). It is unlikely that the base of this unit was reached in the field; compaction of the sediment prevented sampling beyond a depth of 2.14 m. Average P_b and LOI_{min} values are elevated compared to the following units, reflecting the high minerogenic/low organic content of the sediment. Based on the above properties Unit I is interpreted as an aeolian sediment which was deposited when the inter-dunal basin was dry.

4.2.2 Unit II (~8.5 – 7.7 ka cal. BP, 2.06 – 1.51 m)

At 2.06 m the aeolian sands grade into a shell-bearing unit composed of marls, with intermittent fine to very fine sand deposits (mean particle size range; 220 – 100 µm). The change in stratigraphy is consistent with the shift to lower P_b and LOI_{min} values. Extrapolation of the sedimentation rate between 1.93 and 1.55 m places this transition at ~8.5 ka cal. BP. LOI_{carb} values are highest during Unit II and together with the elevated Ca and Sr values reflect the deposition and preservation of stratified carbonate material. In arid settings the formation of calcareous sediment is typically linked to the following processes; (a) authigenic precipitation during periods of evaporative enrichment and/or CO_2 removal by photosynthetic activities, (b) the deposition of calcareous shells, (c) influx of detrital carbonate from the surrounding dune-fields, and (d) post-deposition diagenetic precipitation (Kelts and Hsü, 1978). Although (c) and (d) are not discounted, (a) and (b) were more likely during Unit II given the higher productivity levels and overall dune-field stability (see below). Elevated within-basin productivity is consistent with the abrupt increase in ostracod valves (*Cyprideis torosa*) and the presence of gastropod shells (*M. tuberculata*) in Unit II. While *C. torosa* is able to withstand strongly fluctuating ecological conditions, it requires a permanent water-body to reproduce (Anadon et al., 1986; Gasse et al., 1987), indicating the development of permanent lacustrine conditions in the Wahalah basin at this time. This is supported by the occurrence of *M. tuberculata*, a rapid coloniser that cannot survive desiccation events (Radies *et al*., 2005) and is typically found in fresh-to-brackish water at a depth of ~2.0 m (Engel et al., 2012; Dixit et al., 2014b).

Above average %C values suggest that organic productivity was raised at this time. %C is primarily controlled by organic input from both the lake and its catchment, together with preservation within the sediment column (Meyers, 2003). Higher values may therefore reflect greater biomass productivity and/or organic matter preservation, both of which can be linked to higher precipitation in arid regions (An et al., 1993; Chen et al., 2003). The absence of C/N data makes it difficult to determine the source of organic carbon in the Wahalah record. The range of $\delta^{13}C_{org}$ values during this unit (–18.9 to –17.8‰) are similar to those of submerged aquatic macrophytes (–24.0 to –13.0‰) (Mischke et al., 2008), suggesting that enhanced within-basin productivity may contribute to the raised %C values. This interpretation is supported by the peak in ostracod shells, while CO_2 removal during periods of enhanced aquatic photosynthesis would have contributed to carbonate formation within the water body (Kelts and Hsü, 1978). Input from a mixed $C_3 – C_4$ terrestrial vegetation cover may have also led to the range of $\delta^{13}C_{org}$ values observed in Unit II.

Low χlf values imply that the landscape remained generally stable between ~8.5 – 7.7 ka cal. BP. In this study χlf is used as a proxy for stability in the surrounding dune-fields, with values primarily controlled by the accretion of Fe-rich quartz during periods of dune remobilisation (Parker et al., 2006; Preston et al., 2012), and may in turn be linked to variations in vegetation cover, precipitation, sediment supply and/or wind strength (Tsoar, 2005; Yizhaq et al., 2009). Reduced detrital input is also inferred by below average Al, Fe, and Ti values, which correspond to the abundance of quartz, feldspars and sheet silicates, all of which are common components of the dune sands in the northern Emirates (El-Sayed, 1999; Garzanti et al., 2003; Farrant et al., 2013, 2015). It is proposed that these minerals are largely inert with respect to the lake system and thus can also be used to monitor stability in the surrounding dune-fields. Together these interpretations are consistent with an expansion of vegetation throughout the region and higher effective precipitation. Despite the overall dune-field stability, several of the proxy records show a clear change between 1.79 and 1.66 m, dated by linear interpolation to ~8.15 – 7.95 ka cal. BP. The event is marked by increases in bulk density (P_b), Al, Fe, Ti, and by small peaks in the sand content (%) of the sediment. A short-term phase of increased detrital influx and possibly aridity is inferred. A corresponding decline in ostracod numbers may be linked to ecological stress within the water body.

4.2.3 Unit III (~7.7 – 5.9 ka cal. BP, 1.51 – 1.08 m)

The stratigraphy becomes much more varied at ~7.7 ka cal. BP (1.51 m), with the deposition of alternating layers of fine to very fine sands (mean particle size range; 160 – 90 µm) and calcareous sediments. The higher minerogenic content is reflected by the steady increase in LOI_{min} values and higher sediment P_b. Similarly the particle size data shows a progressive increase in sand content and corresponding declines in silt and clay from ~7.4 ka cal. BP. Increased detrital influx, and thus dune-field instability, is inferred by the small increases in the χlf signal, coupled with the higher and much more variable Al, Fe, and Ti values throughout Unit III. Notable peaks in these data are recorded at ~6.9 – 6.7 ka cal. BP (1.31 – 1.27 m), ~6.4 ka cal. BP (1.19 m), and at ~6.1 ka cal. BP (1.12 m) corresponding with the deposition of aeolian sands in the Wahalah basin. The combined evidence suggests greater dune-field instability at this time, possibly as a consequence of a reduction in vegetation cover and effective precipitation. This is consistent with the generally lower %C and LOI_{org} values.

Aquatic shells are almost completely absent from Unit III, with the decline in *C. torosa* and *M. tuberculata* likely to reflect a shift from permanent to intermittent conditions at the site. A reduction in aquatic productivity would also account for the overall decline in organic matter within the sediment. In comparison to Unit II, $\delta^{13}C_{org}$ values display greater variability throughout Unit III, highlighted by the abrupt increase from –18.8 to –9.8‰ at the transition between the two units (~7.7 ka cal. BP). Such positive shifts in $\delta^{13}C_{org}$ may reflect: (a) a greater contribution from C_4 terrestrial plants; (b) aquatic vegetation growing in waters enriched in ^{13}C as a consequence of lower water levels (Talbot and Johannessen, 1992); and/or (c) an environmentally forced switch from CO_2 to HCO_3^- based photosynthesis as a result of CO_2 depletion during periods of enhanced aquatic productivity (Holmes et al., 1997). The corresponding peak in %C supports the latter case. Each cause implies a shift to more arid conditions, which resulted in an evaporation-driven change in the isotopic composition of the surface waters. The absence of a corresponding peak in detrital influx may imply that the water body was more sensitive to the increase in aridity at this time, with vegetation coverage throughout the dune-field possibly sufficient to initially buffer the impact of this change.

4.2.4 Unit IV (~5.9 – 5.3 ka cal. BP, 1.08 – 0.96 m)

A distinct change in stratigraphy is recorded at ~5.9 ka cal. BP (1.08 m), with the deposition of medium to very fine sands (mean particle size range; 280 – 120 µm). The transition is marked by clear increases in χlf, bulk density (P_b), Al, Fe, and Ti, and high LOI_{min} values. An abrupt and sustained influx of minerogenic material from the surrounding dune-fields is inferred. This is consistent with the particle size data, which shows a peak in the sand content during Unit IV, with corresponding lows in silt and clay. Together the data imply that the surrounding dune-fields were much more unstable between ~5.9 – 5.3 ka cal. BP, resulting in the deposition of aeolian sands in the basin. Increased climatic aridity and the subsequent loss of vegetation throughout the dune-fields are inferred. A reduction is regional vegetation is supported by the corresponding lows in %C and LOI_{org}.

It is uncertain whether the Wahalah basin contained water during this phase of aridity. Minor increases are observed in LOI_{carb} and Sr possibly reflecting authigenic precipitation although influx of detrital carbonates is also probable at this time. Microscopic analysis of the sediment revealed the presence of authigenic gypsum, a mineral commonly precipitated under highly evaporative conditions (Eugster and Kelts, 1983). It is possible, therefore, that the basin contained extremely saline waters intermittently between ~5.9 – 5.3 ka cal. BP. The absence of aquatic shells indicates that within-basin productivity remained low throughout this period and is compatible with the reduced organic matter content of the sediment. The shift to more depleted $\delta^{13}C_{org}$ values may reflect the reduction in aquatic productivity and increased rate of organic decomposition as the basin floor was sub-aerially exposed.

4.2.5 Unit V (~5.3 – 3.5 ka cal. BP, 0.96 – 0.64 m)

The deposition of fine to very fine calcareous sands at ~5.3 ka cal. BP (0.96 m) (mean particle size range; 240 – 100 µm) coincides with declining χlf, P_b, LOI_{min}, Al, Fe, and Ti values. A reduction in the minerogenic content of the sediment is inferred, possibly indicating a shift to more stable conditions in the surrounding dune-fields following the period between 5.9 – 5.3 ka cal. BP. Despite this abrupt peaks are recorded in χlf, bulk density (P_b), Al, Fe, and Ti at ~4.0 – 3.9 ka cal. BP (0.72 – 0.71 m), indicating increased aeolian activity and possibly aridity at this time. The increases in %C and LOI_{550} may reflect the expansion of vegetation onto the basin floor and surrounding dunes as the water-table rose at the site although the continued absence of aquatic shells indicates that such conditions are likely to have been intermittent. Similar to Unit III, $\delta^{13}C_{org}$ values are variable throughout (–19.51 to –15.06‰) and are more positive than Unit IV.

4.2.6 Unit VI (~3.5 ka cal. BP to present, 0.64 – 0 m)

The upper 0.64 m of the section is composed of medium to very fine calcareous sands (mean particle size range; 360 – 80 µm). Peaks in the clay and silt content of the sediment and a minor increase in Sr coincide with deposition of a well cemented carbonate deposit (0.64 – 0.56 m). A short-lived humid phase is inferred. Above this the proxy data are highly variable, with overall higher values in χlf, bulk density (P_b), Al, Fe, and Ti reflecting greater aeolian input into the basin, particularly towards the top of the section. The influence of modern plants may explain the rise in %C towards the top of the record (from 0.16 m), with the corresponding shift to more positive $\delta^{13}C_{org}$ values possibly reflecting input from C_4 vegetation.

5 Discussion

5.1 Dune dynamics and chronology

Ages obtained by Atkinson et al. (2011) from UAE06-1 show a record of continuous dune accumulation between 15.91±0.68 ka BP at 16.4 m depth (UAE06-1-1) and 10.29±0.5 ka at 2.5 m depth (UAE06-1-14), with a particularly rapid phase of accumulation at approximately ~13.5 ka. Above this, at 0.52 m a 2σ radiocarbon age of 5.19 – 4.80 ka cal. BP (OxA-16855) (Table 1) was determined as part of this study from the *in situ* shell midden within a weakly developed palaeosol horizon, suggesting a stabilized land surface at this time.

From the basal sample in UAE06-2 at 17.7 m (UAE06-2-20) to 13 m (UAE06-2-15), the age of the profile increases steadily from 13.05±0.62 ka to 11.13±0.43 ka, with 4.7 m of sedimentation (Atkinson et al., 2011). At 12 m, sample UAE06-2-14 generates an age of 10.38±0.44 ka and at 8 m sample UAE06-2-10 an age of 10.65±0.53 ka, indicating the rapid deposition of 4 m of sediment (Atkinson et al., 2011). At 6.5 m depth a distinctive low-angle unconformity is observed, with a weakly developed palaeosol horizon and anthropogenic shell midden, radiocarbon dated to

5.98 – 5.75 ka cal. BP (OxA-16911) (Table 1). This denotes a stabilized land surface, separating the underlying darker red aeolian unit from an overlying buff-pale red aeolian unit. Radiocarbon ages from the overlying charcoal-rich horizon at 6.15 m range from 5.90 – 5.66 ka cal. BP (OxA-16913), 5.89 – 5.66 ka cal. BP (OxA-16892), and 5.89 – 5.61 ka cal. BP (OxA-16912) (Table 1). OSL sample ages from the buff-pale red aeolian unit overlying the palaeosol/midden layers yielded ages of 5.85±0.31 ka (UAE06-2-7) at 6 m and 5.18±0.24 ka (UAE06-2-3) at 2 m, suggesting a rapid phase of dune accumulation (Atkinson et al., 2011).

At site UAE06-1, the lower 8.1 m of sediment accumulated and was preserved in less than 1 ka. At site UAE06-2, two phases of geologically rapid sediment accumulation occurred at approximately 5.5 ka and 10.5 ka respectively.

5.2 Climatic synthesis and implications

There is a substantial body of palaeoclimatic data from southern (Lézine et al., 1998, 2007, 2010; Wilkinson, 2005; Davies, 2006; Fleitmann et al., 2007), central (McClure, 1976; Preusser et al., 2005; Radies et al., 2005; Fuchs and Buerkert, 2008; Urban and Buerkert, 2009) and northern (Schultz and Whitney, 1986; Engel et al., 2012; Crassard et al., 2013) Arabia which indicates that after an arid post-Last Glacial Maximum phase, precipitation increased significantly throughout the Peninsula during the early- to mid-Holocene. At Wahalah, dune deposition, with a net accumulation rate of 3-4 m.ka^{-1} (Leighton et al., 2014), occurred between 15.9 – 10.3 ka. An increase in rainfall created a lake with permanent lacustrine conditions at the site between ~8.5 – 7.7 ka cal. BP during which the surrounding dune-fields were stabilised by vegetation. This is supported by palaeobotanical evidence from Awafi palaeolake (Fig. 1), which shows the development of a mixed C_3 – C_4 vegetation cover, with a peak in scrub woodland taxa (primarily *Acacia* and *Prosopis*) between ~8.3 – 7.6 ka cal. BP (Parker et al., 2004). These findings are consistent with models of groundwater recharge in the Liwa region, UAE, which estimate an annual precipitation of 200±50 mm/yr for the period 9.0 – 6.2 ka (Wood and Imes, 2003), approximately 4-5 times the present day value, which would infer an annual precipitation of approximately 400-500 mm/yr for the Wahalah region.

Despite reaffirming the broad regional trends, the Wahalah record does raise a number of important palaeoclimatic questions. Similar to Awafi, the onset of lacustrine sedimentation at the site (~8.5 ka cal. BP) appears to have been later than most other Arabian palaeolake records (Fig. 7) although it is acknowledged that Wahalah chronology is based on linear interpolation through a relatively small number (four) of radiocarbon ages. Despite this, lacustrine deposits from al-Hawa, Yemen are dated to ~11.0 ka cal. BP (Lézine et al., 2007) and ~9.7 ka cal. BP from Mundafan in the southwest Rub' al-Khali (Rosenberg et al., 2011), whilst Engel et al. (2012) report an age of ~10.2 ka cal. BP from Tayma in the An Nafud. In contrast, in the study region, the corresponding period was characterised by continued dune emplacement into the earliest Holocene as recorded from several dated sequences that ceased forming ~9.5 ka (Goudie et al., 2000a; Atkinson et al., 2011, 2012) (Fig. 8). Farrant et al. (2015) suggest that the aeolian record in the Gulf region is preservation limited, recording dune stabilisation and cementation at the onset of humid episodes. Determining why the lower Gulf region appears to have been out-of-phase with other areas of Arabia is complicated by the continuing uncertainty surrounding the different climatic systems influencing the Peninsula during the early-to mid-Holocene (Berger et al., 2012). Most palaeoclimate studies from central and southern Arabia link the arid-humid transition to the steady northwards migration of the ITCZ and associated monsoon rains, a notion well supported by the $\delta^{18}O$ data from the Omani speleothem records (Fleitmann et al., 2007; Fleitmann and Matter, 2009). Whether this source of moisture was as important at sites further than 23 – 24°N, including the study region, remains unclear. Indeed, it has been suggested that MLW systems originating from the eastern Mediterranean were more important throughout northern Arabia (Schultz and Whitney, 1986; Arz et al., 2003), although at present their influence across the Peninsula remains poorly defined (Berger et al., 2012). As a consequence of the region's geographical location, geo-archives from southeast Arabia are ideally positioned to study the interplay between these two climatic systems, however, the multi-proxy record from Wahalah is not sufficient to determine the dominant source of moisture at the site during the early- to mid-Holocene. The absence of lacustrine conditions at Wahalah (this study) and Awafi (Preston et al., 2012) prior to ~8.5 ka cal. BP does not necessarily imply a continuation of aridity in the region. Indeed, radiocarbon ages obtained from other lacustrine (Gebel et al., 1989) and fluvial deposits (Dalongeville, 1999) in the UAE, significantly pre-date those from the study site (Fig. 7) and suggest a much earlier onset of wetter conditions in the region. This may suggest that lacustrine formation at the site was driven by a subtle increase in the precipitation/evaporation ratio at ~8.5 ka cal. BP which in turn triggered a threshold response in the lake system (Fleitmann et al., 2007). Alternatively, it is possible that the site's 'Holocene' lake record extends beneath the maximum sampling depth of the present investigation (2.14 m). Whilst this latter hypothesis is valid, it is noted that the stratigraphic position and sedimentological characteristics of Unit I at Wahalah are similar to the basal sands (zone 1) reported at Awafi palaeolake, OSL dated to 17.65±1.79 ka (Parker et al., 2004, 2006). The rapid dune accumulation during the late Pleistocene – early Holocene (Fig. 8) is likely to reflect dune stabilisation brought on by reduced wind speed, the transition to more humid conditions, and the dune 'reconstitution' time. These morphological changes to the basin may have in turn affected the development of the early Holocene lake at the site.

The Wahalah record reveals a long-term shift to drier conditions from ~7.7 ka cal. BP, with increased inorganic input into the lake basin. This change coincides with a decline in woody vegetation cover and a small increase in xeric taxa in the Awafi record, which together imply a reduction in moisture availability (Parker et al., 2004). The above changes broadly coincide with the onset of a long-term shift to more positive $\delta^{18}O$ values in the Qunf Cave speleothem data (Fig. 7), a trend which has been interpreted as reflecting a gradual decline in monsoon rainfall owing to a reduction in solar insolation forcing (Fleitmann et al., 2007). The associated southern migration of the ITCZ has been linked to the termination of most Arabian palaeolake records by the mid Holocene (Fig. 7). Despite this, monsoon rains are suggested to have remained the main source of moisture at Hoti Cave until ~6.3 ka cal. BP. It is possible that the transition in both Wahalah and Awafi records reflects this long-term weakening, implying that monsoon precipitation is likely to have reached the region prior to this. A change in winter precipitation associated with MLW systems cannot be ruled out as a potential cause although, as outlined above, the contribution of these systems during this period is less well understood.

The deposition of aeolian-derived sediments in the Wahalah lake record occurred between ~5.9 – 5.3 ka cal. BP and corresponds to a rapid accumulation rate of over 7m/ka in the surrounding dunes (Leighton et al., 2014). This is suggested to mark a phase of major landscape instability and dune reactivation and deposition. A corresponding transition to a largely open landscape is reported from the Awafi, with woodland taxa (*Acacia*, *Prosopis* and *Tamarix*) replaced by open-ground, herbaceous and grassland taxa, dominated by (in order of total percentage): Poaceae, Cyperaceae, Chenopodiaceae, Asteraceae and Caryophyllaceae (Parker et al., 2004). A shift to C_4 grassland elements (C_4 Panicoid Sudanian tall grasses) more suited to warmer, drier conditions is also recorded at this time (Parker et al., 2004). Wood and Imes (2003) record a significant reduction in groundwater recharge at Liwa, between 6.2 – 5.5 ka BP, whilst a distinct positive shift of 1 to 3‰ in the Hoti Cave $\delta^{18}O$ record is recorded at ~6.3 ka BP (Fig. 7) (Fleitmann et al., 2007). This latter transition has been linked to a change from a southern (monsoon) to a northern (MLW systems) moisture source at the site between ~6.3 ka to 5.2 ka BP when speleothem deposition ceased (Fleitmann and Matter, 2009). The combined evidence from the lake sediments and dune record suggests that a long-term increase in regional aridity began at ~7.7 ka cal. BP and culminated in a rapid, abrupt end to the Holocene humid phase in southeast Arabia at ~5.9 – 5.8 ka BP.

In addition to the long-term patterns discussed above, the Wahalah record also identifies a number of short-term, abrupt changes centred on ~8.15 – 7.95, ~6.9 – 6.7, ~6.4 and ~6.1 ka cal. BP. Each is marked by distinct increases in minerogenic input, instability across the dune field and the loss/reduction in regional vegetation cover. A series of broadly synchronous changes have tentatively been inferred from the Awafi record at ~8.0 – 7.8, ~7.5 – 7.2 and ~6.5 – 6.2 ka cal. BP (Preston et al., 2012). It is acknowledged that the exact timing of these events is uncertain at this stage, owing to the error ranges associated with radiocarbon dates, coupled with the use of a linear interpolation age model at both sites. Nonetheless, the Hoti Cave $\delta^{18}O$ record also reveals a series of positive shifts, implying reduced precipitation, between ~8.2 – 8.0, ~7.5 – 7.2 and from ~6.3 ka BP (Fig. 9). The first of these corresponds with a global cooling event (Bond Event 5) at ~8.2 ka BP and is associated with a short-term weakening of the monsoon system (Gupta et al., 2003). The event has been reported from various records throughout the Middle East (Bar-Matthews et al., 1997), other Arabian palaeolake records (Lézine et al., 2010), the northern Arabian Sea (Staubwasser et al., 2003), and the Indus region (Dixit et al., 2014b).

5.3 Climate – human implications during the Neolithic

The changes in climate and environment inferred from the Wahalah lake and dune records have important implications for our understanding of climate – human interactions during the Neolithic. Examining this relationship was, for a long time, complicated by a lack of highly resolved, securely dated and continuous archives from both palaeoclimatic and archaeological contexts. Although the situation has improved in recent years, the precise timing and spatial extent of the abrupt changes in climate remain poorly defined, whilst few attempts have been made to establish a long-term chronology from the archaeological data. In light of this probability density function (PDF) plots are used to estimate more realistically the record of measured archaeological activity during the Neolithic (Fig. 9). The technique employs summations of the probability distributions of individual radiocarbon dates after calibration to construct a cumulative probability curve and has been used for both palaeoclimatic (e.g. Drake et al., 2013) and archaeological data (e.g. Kuper and Kröpelin, 2006). Despite this, we emphasise that these records are only as good as the data currently available, and may be affected by sampling bias towards particular archaeological periods or areas of the landscape, as well as material preservation (Michczyńska and Pazdur, 2004).

Evidence indicating the presence of human populations in southeast Arabia during the first two to three millennia of the Holocene is limited to a handful of sites containing securely dated archaeological contexts with *in situ* lithics attributed to the Fasad tradition. Examples are reported from inland sites at Nad al-Thamam and Jebel Faya FAY-NE01, Sharjah Emirate (Uerpmann et al., 2009), as well as undated finds from the coastal region around Jazirat al-Hamra and Umm al-Quwain. Whilst similar in appearance, these latter sites have Fasad points produced on flakes and are similar to those known from the interior, especially around Hili (cf. Kallweit, 2005), suggesting a possible distinct form from the “Faya” group. These finds suggest one or a combination of the following: (a) the region was sparsely populated during the earliest Holocene; (b) the population was largely mobile with scant evidence preserved in the record; and/or (c) a significant number of sites remain undiscovered. The former (a) cannot be discounted, with some noting that the period remains underrepresented when compared to the growing number of archaeological sites from the region (Drechsler, 2009). Despite this, it is suggested that the lack of archaeology is likely to reflect a reduction in the preservation of material during this period owing to the continuation of dune emplacement and thus site burial, coupled with the marine transgression of the Arabian Gulf basin, which has led to the submergence and loss of sites. The paucity of archaeological material means opinions are currently divided regarding the subsistence base of these early populations. Whilst some authors link the archaeological finds from this period to mobile herder-gatherers (Drechsler, 2009), others suggest they were left by hunter-gatherer populations (Charpentier, 2008; Rose, 2010) whose footprint on the landscape is likely to be less visible today. Furthermore, it is suggested that hunter-gather groups are more likely to have concentrated in areas of the landscape with greater ecological diversity and resource availability, which during the earliest Holocene is more likely to have been within the now submerged Arabian Gulf basin or within the al-Hajar Mountains and the alluvial piedmont bahadas.

A link between the development of humid conditions during the early- to mid-Holocene and the expansion of Neolithic populations throughout southeast Arabia has been suggested by several authors (Parker et al., 2006; Parker and Goudie, 2008; Drechsler, 2009; Uerpmann et al., 2009). However, the palaeoclimate data presented in this paper adds to the growing body of evidence suggesting that the period was punctuated by a series of abrupt, short-term phases of aridity, some of which have been suggested to have led to significant changes in the archaeological record. For example, although the archaeological chronologies during the earliest Holocene remain poorly defined, Drechsler (2009) links the climatic downturn between ~8.5 – 8.0 ka BP, to the transition between the earliest Holocene Qatar B/Fasad lithics and the proceeding Neolithic Arabian Bifacial Tradition (ABT) assemblages. Drechsler (2009) suggests that the interaction of various population groups in refuge areas of the landscape resulted in the development of a uniform material culture during the ABT. Evidence for occupation during the Neolithic comes from the extensive shell middens along the coast (Vogt, 1994; Uerpmann and Uerpmann, 1996; Philips, 2002; Charpentier and Méry, 2008) and inland across the dune-fields surrounding Wahalah. In addition, several important Neolithic sites have been examined from the interior including Jebel al-Buhais (Uerpmann et al., 2008) and Kharimat Khor Manahil (Kallweit et al., 2005). A broad correspondence between phases of reduced precipitation inferred from the Hoti Cave $\delta^{18}O$ record at ~7.5 – 7.2 and ~6.5 – 6.3 ka BP, and possible reductions in human activity (Fig. 9) has been noted in several recent publications (Parker and Preston, 2008; Preston et al., 2012; Preston and Parker, 2013). It is, however, acknowledged that such finer grained trends should not be overstated at this stage and remain speculative.

Fig. 9 reveals an abrupt decline in archaeological sites and dated occupation from across the Gulf region at ~5.9 ka cal. BP. This paucity of data and apparent decline in human population has been referred as marking the *Dark Millennium* (Uerpmann, 2003). This change has been widely linked to increased climatic aridity during the mid-Holocene (Uerpmann, 2003; Parker et al., 2006; Preston et al., 2012), a notion consistent with the palaeoclimatic data presented in this paper. Radiocarbon ages from the shell midden and charcoal horizons at UAE06-2 date to the terminal end of the Neolithic period in the lower Gulf region, and are overlain by approximately 5 m of sediment which accumulated rapidly from ~5.8 ka to 5.2 ka. Despite this, it is suggested that the pattern of human settlement during this period is more complex than has been suggested. Fig. 9 indicates that whilst evidence from the interior declines, occupation along the southern Arabian Gulf coast increased between ~6.3 – 5.7 ka cal. BP. This may suggest a concentration of settlements along the coast, maybe owing to greater availability of marine resources at this time as the interior became increasingly arid. Alternatively, it is noted that the increase approximately corresponds with maximum sea level rise in the Arabian Gulf (Lambeck, 1996), possibly suggesting the trend reflects the greater preservation of material at this time compared to earlier periods when rising sea levels are likely to have submerged many coastal sites. The subsequent decline in occupation from ~5.8 ka cal. BP corresponds with an intensification of activity along the Gulf of Oman coast (Biagi, 1994), supporting the notion that populations migrated to the latter region owing to its greater ecological diversity and availability of freshwater (Uerpmann, 2003).

Re-occupation of the region occurred during the early Bronze Age with several shell midden sites dated between ~5.2 – 4.4 ka BP at Al-Daith (Parker and Goudie, 2007), Jazirat al-Hamra, and Ras' al-Khaimah south (Atkinson et al., 2012). The radiocarbon age from the shell midden horizon recorded in the UAE06-01 section falls within this period. Increased landscape stability is inferred during this period, with a return to shallow water lakes at Awafi and Wahalah along with human demographic expansion.

6 Conclusions

Variations in multi-proxy lake and dune data are used to reconstruct the evolution of climate and associated landscape response during the early- to mid-Holocene, a period characterised by significant regional heterogeneity throughout Arabia. These data show that the earliest Holocene was characterised by continued dune emplacement until ~9.5 ka, with the onset of permanent lacustrine conditions at the site (~8.5 ka cal. BP) much later than most other Arabian palaeolake records, particularly those at more southerly latitudes. This supports the earlier work at Awafi palaeolake and highlights the importance of understanding the impact of broad, continental-scale changes in climate at a more local level. A long-term shift to drier conditions and increased landscape instability is recorded between ~7.7 – 5.9 ka cal. BP, possibly marking the gradual southern migration of the summer ITCZ and associated weakening of monsoon rains in the region. An abrupt decrease in moisture, regional vegetation cover and rapid dune reactivation and deposition is recorded between ~5.9 – 5.3 ka cal. BP. The shifts in climate identified in this study have important implications for our understanding of the region’s Neolithic archaeology in terms of both site preservation as well as their potential impact on human activity. The development of further high-resolution, securely dated archives from both palaeoclimate and archaeological contexts is essential if climate – human interactions during this period are to be better understood.

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9 Figure captions

Figure 1: (a) Map of the study region showing the location of key geo-archives and archaeological sites discussed in the text: Akab Island (Charpentier and Méry, 2008), Al Ain (Gebel et al., 1989; Atkinson et al., 2011), al-Daith 1 – 3 (Parker and Goudie, 2007, Atkinson et al., 2012, Parker unpubl.), Awafi (Goudie et al., 2000a; Parker et al., 2004, 2006; Preston et al., 2012), Emirates Highway (Atkinson et al., 2011), Hili (Kallweit, 2005), Idhn (Goudie et al., 2000a), Jazirat al-Hamra (Atkinson et al., 2012),

Jebel al-Buhais (Uerpmann et al., 2008), Jebel Faya (Uerpmann et al., 2009), Nad al-Thamam (Uerpmann et al., 2009), Ramlat ash-Shuruq (Atkinson et al., 2012), Ras' al-Khaimah south (Atkinson et al., 2012), Shu'ayb (Atkinson et al., 2011), Tawi Asmar (Atkinson et al., 2012), Umm al-Quwain 2 & Airstrip (Atkinson et al. 2012; Parker unpubl.), Wadi Dhaid region (Dalongeville, 1999), Wahalah (this study; Atkinson et al., 2011). (b) Map of the Arabian Peninsula showing the dominant atmospheric circulation patterns today and the location of key geo-archives and archaeological sites discussed in the text: al-Adhla (Wilkinson, 2005), al-Hawa (Lézine et al., 2007), An Nafud (Schultz and Whitney, 1986), Core 723A (Gupta et al., 2003), Dalma Island (Charpentier and Méry, 2008), Dhamar Highlands (Davies, 2006), Hoti Cave (Fleitmann et al., 2007), Liwa (Bray and Stokes, 2003; Wood and Imes, 2003; Stokes and Bray, 2005), Maqta (Urban and Buerkert, 2009), Mundafan and Rub' al-Khali (McClure, 1976; Rosenberg et al., 2011), Qunf Cave (Fleitmann et al., 2007), Tayma (Engel et al., 2012), Wahiba (Radies et al., 2005). Consultation of the original studies for the precise location of each site is recommended.

Figure 2: (a) Satellite image of Wahalah palaeolake in 2013. The locations of the sampling trench from this investigation, the dune sections sampled by Atkinson et al. (2011), and the axes of the main dune ridges are shown, as are the locations of the archaeological material found by the French Archaeological Mission to the UAE (led by V. Charpentier and S. Méry). (b) A photograph of Wahalah palaeolake looking north-east towards the centre of the basin (taken in 2005). (c) A cross-section of the palaeolake sediment sequence. (For interpretation of the references to colour in the figure legend, the reader is referred to the web version of this article).

Source of the satellite image: Google Earth.

Figure 3: Depth versus age plot for the Wahalah sequence. AMS ages (black circles) were calibrated using Calib 7.0.2 and the IntCal09 data set (Reimer et al., 2009). Calibrated ages are given with their 2σ error range. Sediment depths were converted to ages by assuming linear sedimentation between the mean of the four depth-age points from 1.93 to 1.55 m, 1.55 to 1.19 m, and 1.19 – 0.65 m (solid line). The age of the base of the sequence is calculated by extrapolation of the regression line (dashed line). The depths of stratigraphic Unit I – VI are shown.

Figure 4: The Wahalah sediment stratigraphy, with the main stratigraphic units and AMS dates.

Figure 5: Multi-proxy record of the Wahalah palaeolake sequence. The graphs are divided into the stratigraphic units (I – VI) discussed in the text.

Figure 6: Multi-proxy record of the Wahalah palaeolake sequence. The graphs are divided into the stratigraphic units (I – VI) discussed in the text.

Figure 7: Compilation of palaeoclimate records showing the key palaeoclimatic trends: (a) radiocarbon ages from selected Arabian lake and fluvial records (see Fig. 1 for the location and original reference of each site). All ages from lake and fluvial deposits have been re-calibrated using Calib 7.0.2 and the IntCal09 data set (Reimer et al., 2009), (b) Hoti Cave $\delta^{18}O$ record (Fleitmann et al., 2007), (c) Core 723A *G.*

bulloides upwelling record (Gupta et al., 2003), (d) Qunf Cave $\delta^{18}O$ record (Fleitmann et al., 2007), (e) June insolation at 30°N (Berger and Loutre, 1991).

Figure 8: Optically Stimulated Luminescence (OSL) ages from selected sites in southeast Arabia for the past 20 ka (See Fig. 1 for the location and original reference of each site). The ages obtained from UAE06-1 and UAE06-2 by Atkinson et al. (2011) are highlighted.

Figure 9: Comparison of the archaeological and palaeoclimate data, showing phases of aridity identified in the Hoti Cave record (black stars): (a) Awafi Fe data (Preston et al., 2012), (b) Wahalah Fe data (this study), (c) Hoti Cave $\delta^{18}O$ record (Fleitmann et al., 2007), (d) and (e) probability density function (PDF) plots of calibrated radiocarbon dates from archaeological contexts, (d) is based on 31 radiocarbon ages from interior sites and (e) is based on 50 radiocarbon ages from archaeological sites along the Arabian Gulf coast. Non-marine ages have been re-calibrated using Calib 7.0.2 and the IntCal09 data set (Reimer et al., 2009). Ages based on marine shells were corrected for the Arabian Gulf marine reservoir effect using the ΔR value of 180±53 (Southon et al., 2002), and calibrated using the Marine04 data set (Reimer et al., 2009). Each radiocarbon date is represented by a peak in the PDF curve, with the relative width of each determined by the error of the age estimate. The height of the curve is determined by the number of overlapping age estimates, with higher values reflecting a greater number of similar radiocarbon ages.

Table 1: Details of the Wahalah lake and dune radiocarbon data from the present investigation. Calibration was carried out using Calib 7.0.2 and the IntCal09 data set (Reimer et al., 2009).

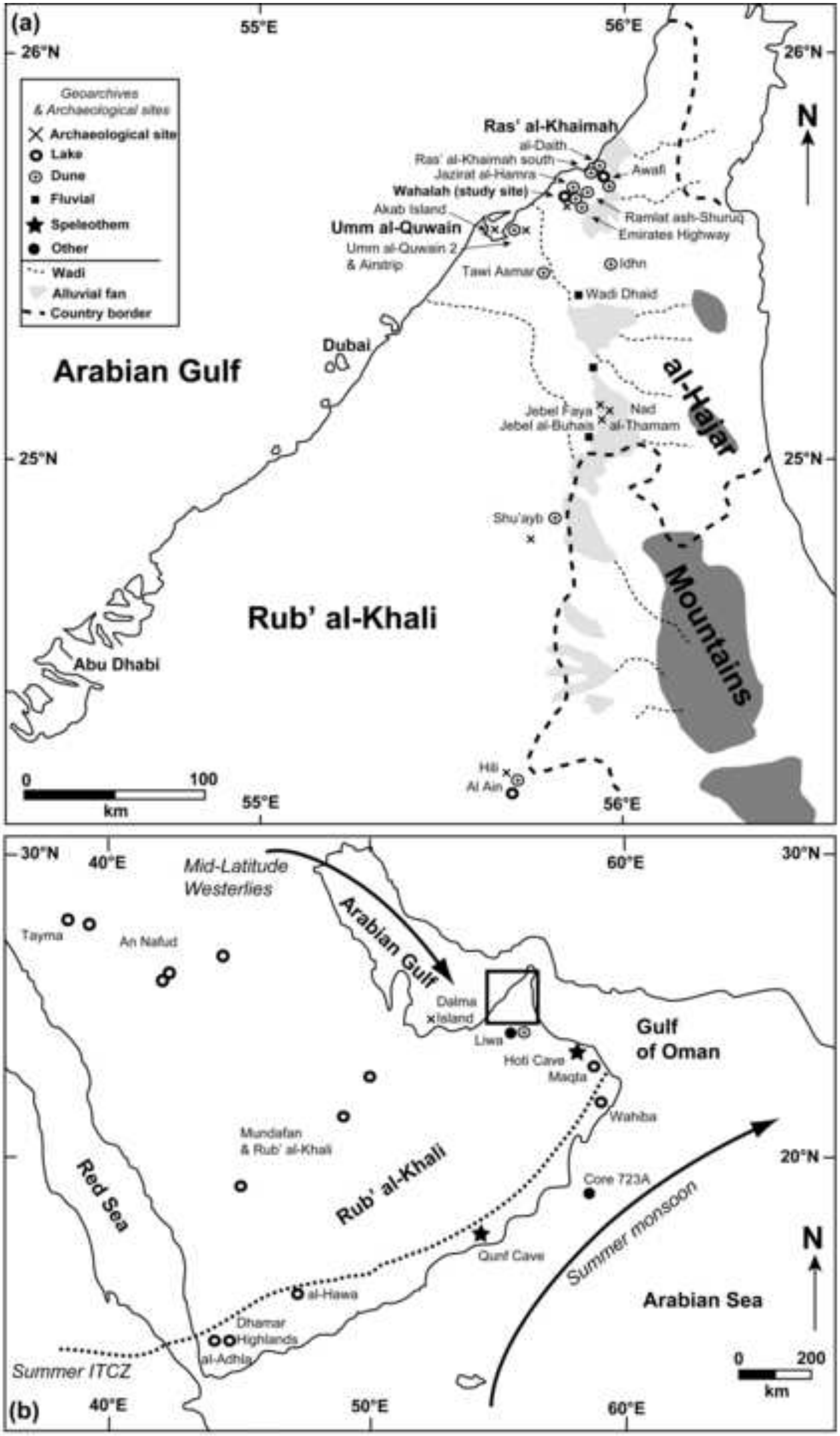
(a)
26°N
55°E
56°E
26°N
Geoarchives
& Archaeological sites
× Archaeological site
○ Lake
⊙ Dune
■ Fluvial
★ Speleothem
● Other
Wadi
Alluvial fan
Country border
N
Ras' al-Khaimah
al-Daith
Ras' al-Khaimah south
Jazirat al-Hamra
Wahalah (study site)
Awafi
Akab Island
Umm al-Quwain
Umm al-Quwain 2
& Airstrip
Ramlat ash-Shuruq
Emirates Highway
Tawi Aamar
Idhn
Wadi Dhaid
Dubai
Arabian Gulf
al-Hajar
Jebel Faya
Nad
Jebel al-Buhais
al-Thamam
25°N
25°N
Shu'ayb
Mountains
Rub' al-Khali
Abu Dhabi
Hili
Al Ain
0
100
km
55°E
56°E
30°N
40°E
Mid-Latitude
Westerlies
60°E
30°N
Tayma
An Nafud
Arabian Gulf
Dalma
Island
Liwa
Gulf
of Oman
Hoti Cave
Maqta
Wahiba
Mundafan
& Rub' al-Khali
Rub' al-Khali
20°N
Red Sea
Core 723A
Summer monsoon
Qunf Cave
N
al-Hawa
Arabian Sea
Dhamar
Highlands
al-Adhla
0
200
km
Summer ITCZ
(b)
40°E
50°E
60°E

Figure 2

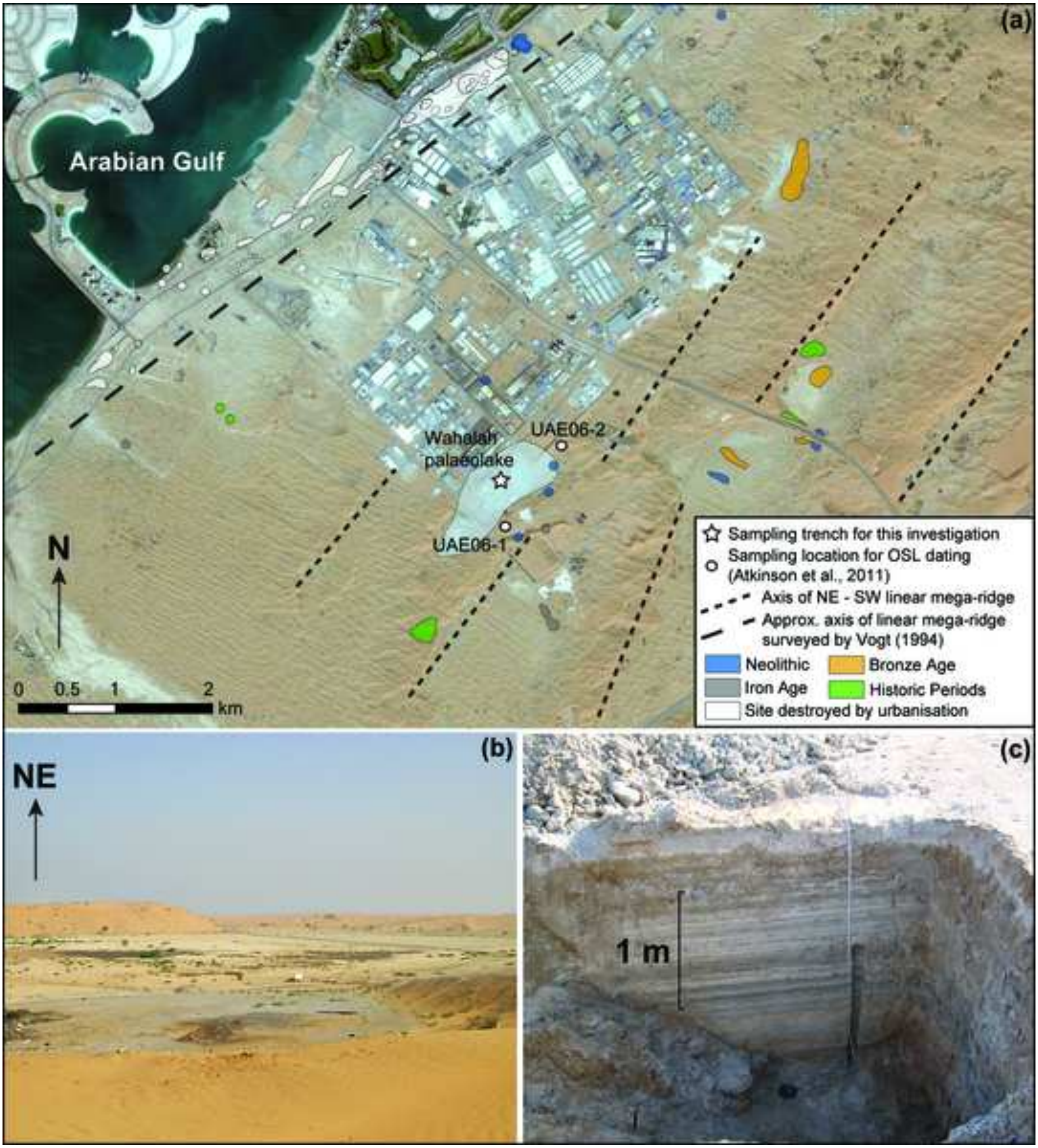
(a)
Arabian Gulf
Wahalah palaeolake
UAE06-2
UAE06-1
N
0 0.5 1 2
km
Sampling trench for this investigation
Sampling location for OSL dating (Atkinson et al., 2011)
Axis of NE - SW linear mega-ridge
Approx. axis of linear mega-ridge surveyed by Vogt (1994)
Neolithic
Bronze Age
Iron Age
Historic Periods
Site destroyed by urbanisation
(b)
NE
(c)
1 m

Figure 3

Click here to download high resolution image

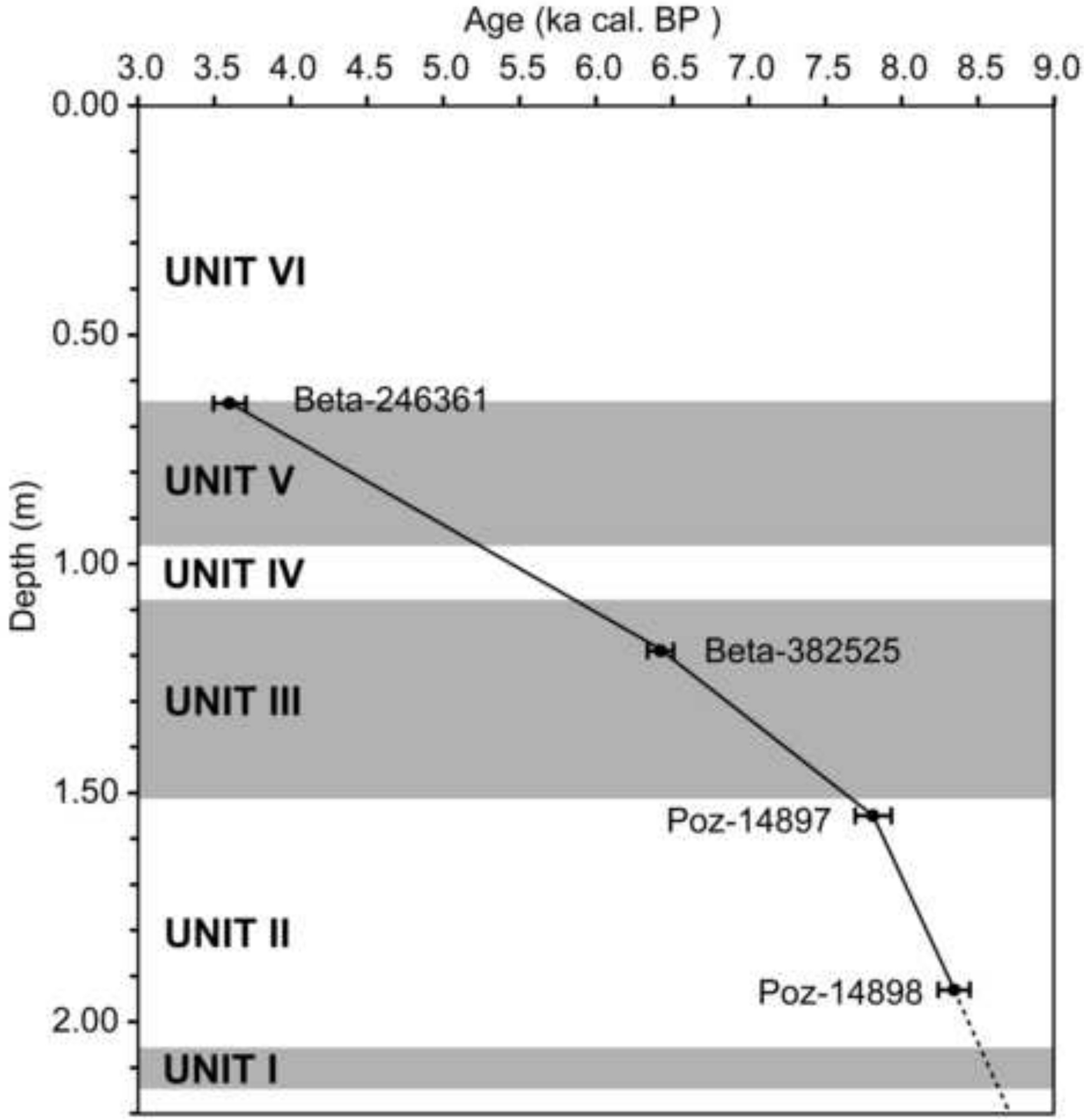

Figure 4

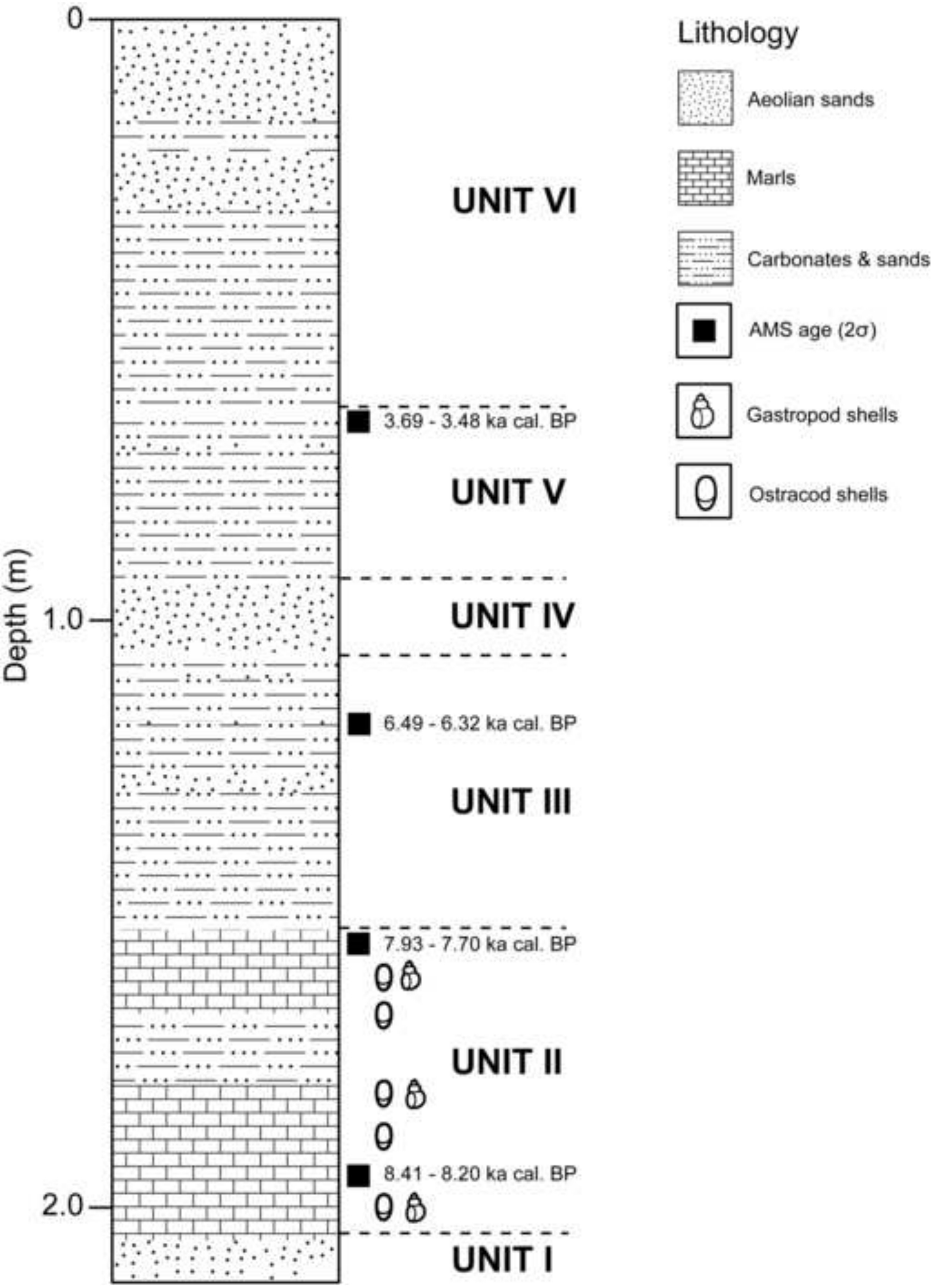
0
1.0
2.0
Depth (m)
UNIT VI
3.69 - 3.48 ka cal. BP
UNIT V
UNIT IV
6.49 - 6.32 ka cal. BP
UNIT III
7.93 - 7.70 ka cal. BP
UNIT II
8.41 - 8.20 ka cal. BP
UNIT I
Lithology
Aeolian sands
Marls
Carbonates & sands
AMS age (2σ)
Gastropod shells
Ostracod shells

Figure 5

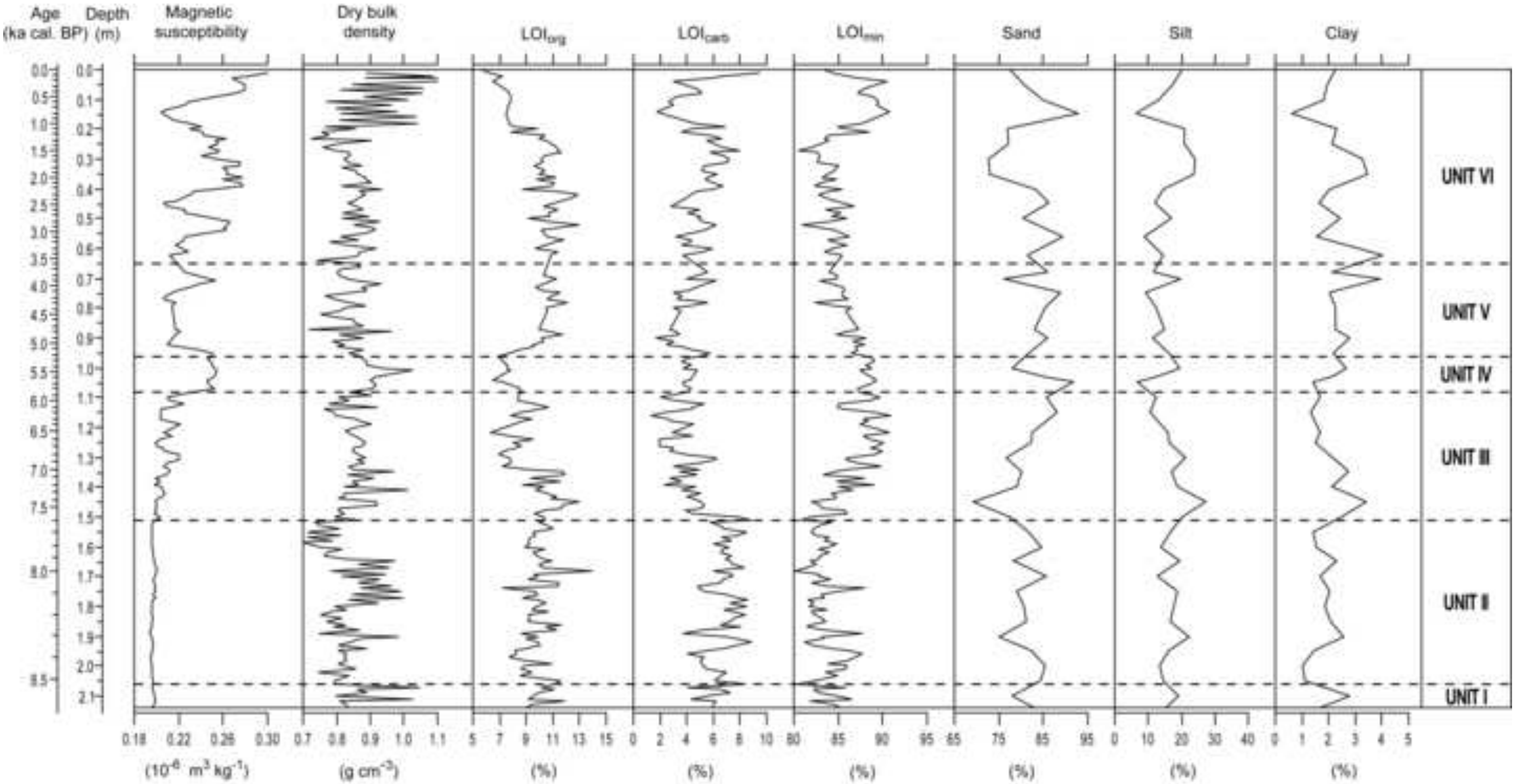
Age (ka cal. BP)
Depth (m)
Magnetic susceptibility
Dry bulk density
LOI$_{org}$
LOI$_{carb}$
LOI$_{min}$
Sand
Silt
Clay
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
UNIT VI
UNIT V
UNIT IV
UNIT III
UNIT II
UNIT I
0.18 0.22 0.26 0.30
$(10^{-6}\ m^3\ kg^{-1})$
0.7 0.8 0.9 1.0 1.1
$(g\ cm^{-3})$
5 7 9 11 13 15
(%)
0 2 4 6 8 10
(%)
80 85 90 95
(%)
65 75 85 95
(%)
0 10 20 30 40
(%)
0 1 2 3 4 5
(%)

Figure 6
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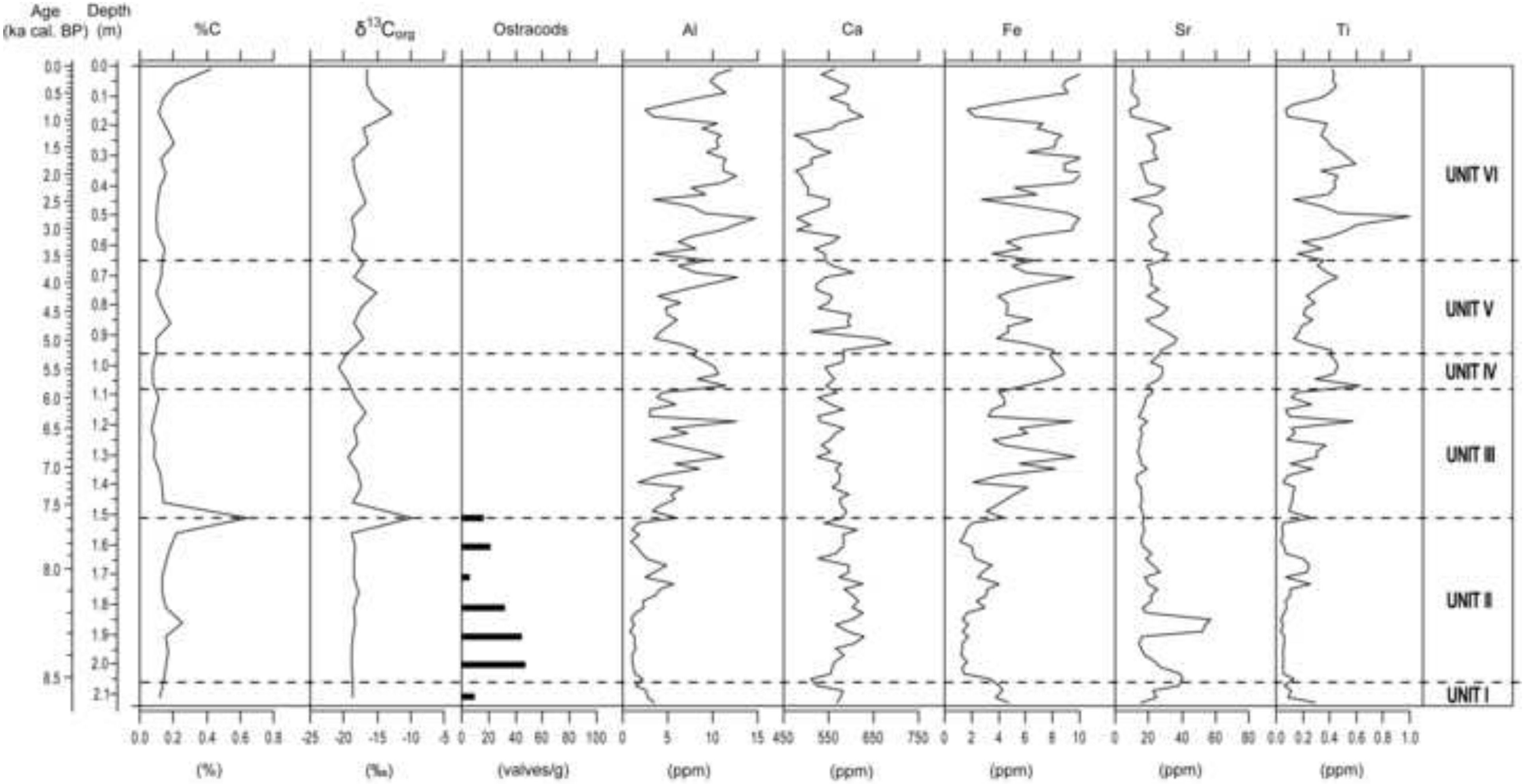

Figure 7

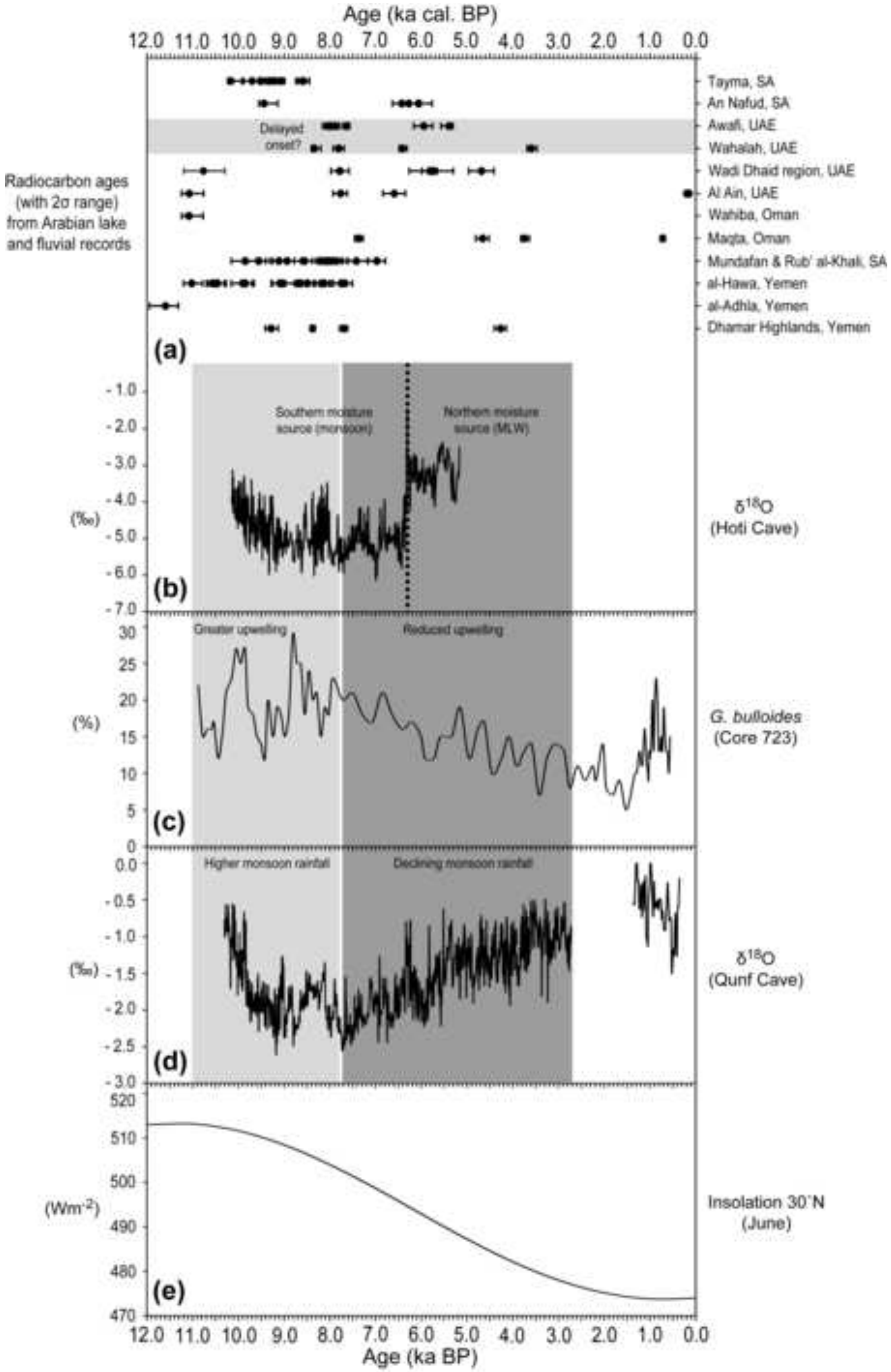
Age (ka cal. BP)
12.0 11.0 10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0
Radiocarbon ages (with 2σ range) from Arabian lake and fluvial records
Tayma, SA
An Nafud, SA
Awafi, UAE
Wahalah, UAE
Delayed onset?
Wadi Dhaid region, UAE
Al Ain, UAE
Wahiba, Oman
Maqta, Oman
Mundafan & Rub' al-Khali, SA
al-Hawa, Yemen
al-Adhla, Yemen
Dhamar Highlands, Yemen
(a)
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
(‰)
Southern moisture source (monsoon)
Northern moisture source (MLW)
δ18O (Hoti Cave)
(b)
30
25
20
15
10
5
0
(%)
Greater upwelling
Reduced upwelling
G. bulloides (Core 723)
(c)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
(‰)
Higher monsoon rainfall
Declining monsoon rainfall
δ18O (Qunf Cave)
(d)
520
510
500
490
480
470
(Wm-2)
Insolation 30°N (June)
(e)
12.0 11.0 10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0
Age (ka BP)

Figure 8

Click here to download high resolution image

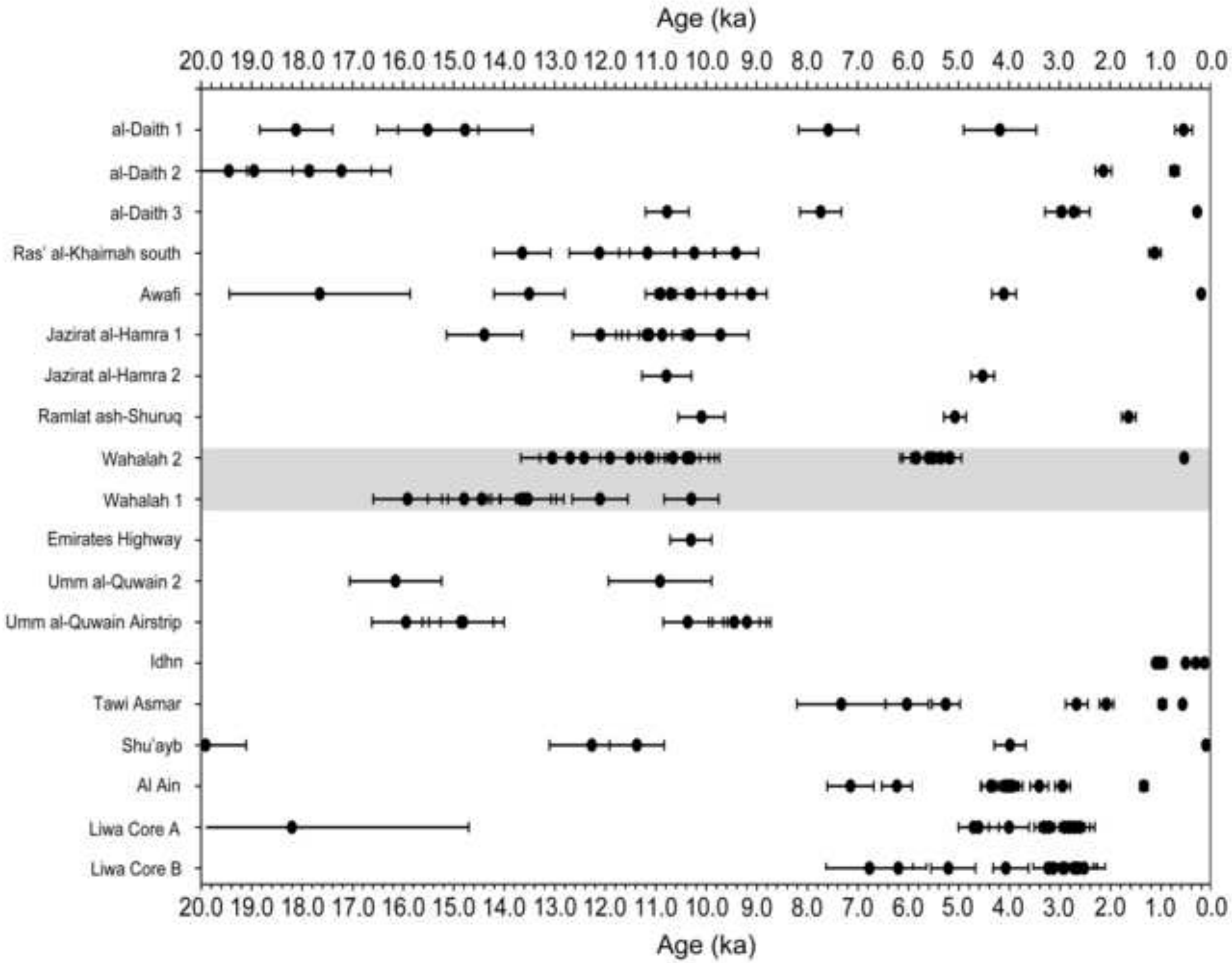

Figure 9

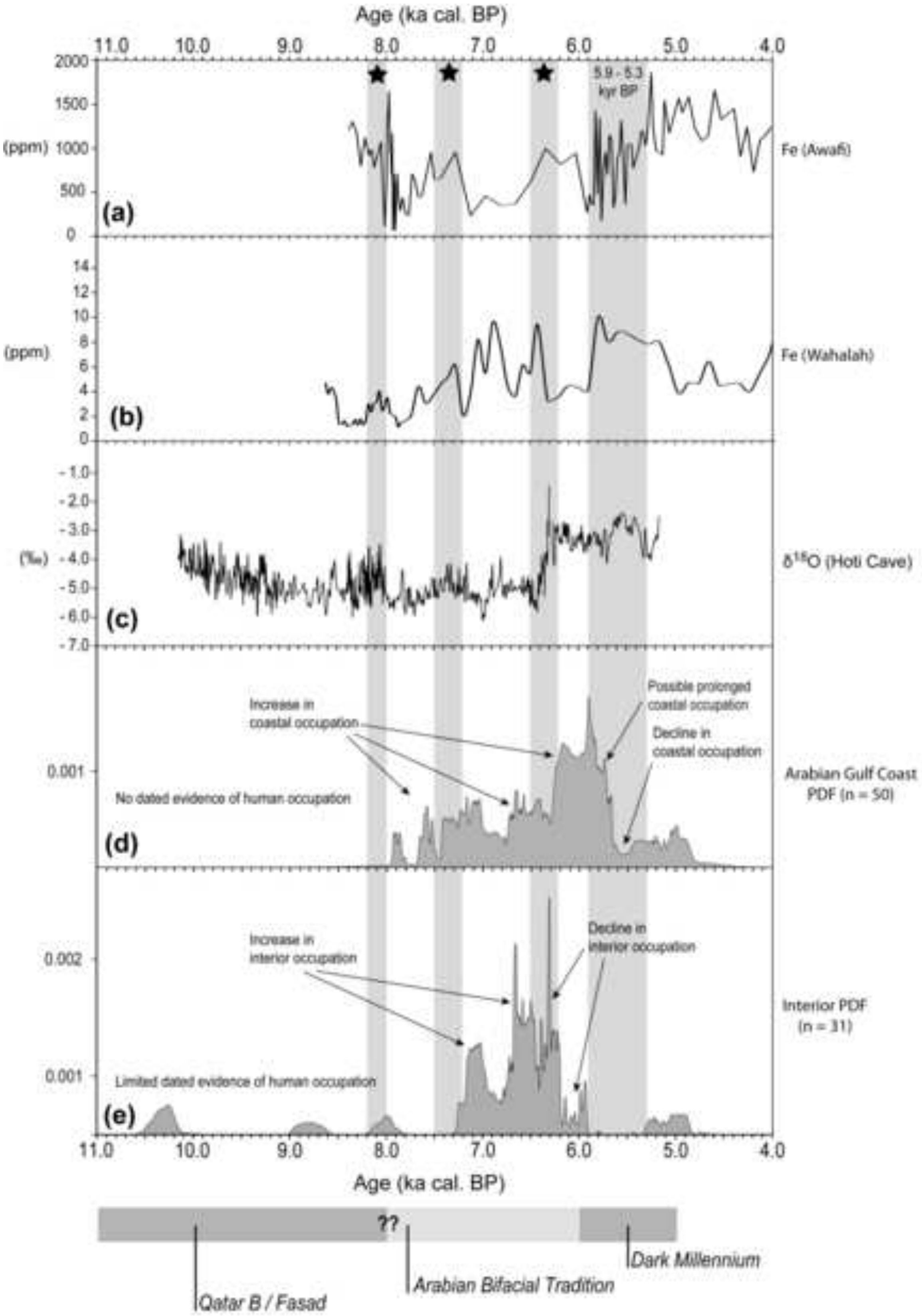
Age (ka cal. BP)
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
2000
1500
(ppm) 1000
500
0
(a)
5.9 - 5.3 kyr BP
Fe (Awafi)
14
12
10
8
(ppm)
6
4
2
0
(b)
Fe (Wahalah)
- 1.0
- 2.0
- 3.0
(‰) - 4.0
- 5.0
- 6.0
- 7.0
(c)
δ18O (Hoti Cave)
0.001
No dated evidence of human occupation
Increase in coastal occupation
Possible prolonged coastal occupation
Decline in coastal occupation
(d)
Arabian Gulf Coast PDF (n = 50)
0.002
0.001
Increase in interior occupation
Decline in interior occupation
Limited dated evidence of human occupation
(e)
Interior PDF (n = 31)
Age (ka cal. BP)
??
Qatar B / Fasad
Arabian Bifacial Tradition
Dark Millennium

Table 1

Sample ID	Depth (m)	Material	Radiocarbon age ^{14}C (yr BP)	Calibrated age (ka cal. BP)	Calibrated range (ka cal. BP) (2σ)
Wahalah Palaeolake					
Beta-246361	0.63 – 0.67	Organics	3360 ± 40	3.602	3.481 – 3.694
Beta-382525	1.17 – 1.21	Organics	5640 ± 30	6.423	6.321 – 6.490
Poz-14897	1.55	*M. tuberculata*	6980 ± 50	7.814	7.695 – 7.931
Poz-14898	1.93	*M. tuberculata*	7520 ± 50	8.344	8.202 – 8.409
UAE06-1 (dunes)					
OxA-16855	0.52	*Terebralia*	4880 ± 33	4.937	4.802 – 5.186
UAE06-2 (dunes)					
OxA-16912	6.15	Charcoal	4992 ± 35	5.717	5.614 – 5.887
OxA-16913	6.15	Charcoal	5039 ± 38	5.811	5.663 – 5.901
OxA-16892	6.15	Charcoal	5017 ± 35	5.758	5.657 – 5.892
OxA-16911	6.50	Charcoal	5131 ± 34	5.892	5.751 – 5.983

Amendments made to manuscript QUATINT-D-14-00701 and responses to reviewers' comments:

We thank the anonymous reviewers for their insightful comments on the revised manuscript. Please see our responses below. All of the amendments to the text have been highlighted in green.

3. Methodology:
Revision:
A sentence has been added describing the main marine shell species found in the midden layer at UAE06-1.

3.2. Dating:
Revision:
This section has been amended to remove reference to the radiocarbon results. Instead the section now briefly describes how many dates were obtained, the material the dating analyses were performed on, and which laboratories performed them.

4.1. Lake chronology:
Revision:
A new section has been added in which the radiocarbon results obtained from the lake and dune records are described. Subsequent subsections in this section have been renumbered accordingly.

4.2.2. Unit II:
Revision:
Reference to Farrant et al. (2015).

5.2. Climatic synthesis and implications:
Revision:
Reference to Farrant et al. (2015).

7. Acknowledgments:
Revision:
Construction changed to constructive.

8. References:
Revision:
Farrant et al. (2015) added to reference list.