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Lakes or wetlands? A comment on 'The middle Holocene climatic records from Arabia: Reassessing lacustrine environments, shift of ITCZ in Arabian Sea, and impacts of the southwest Indian and African monsoons' by Enzel et al.

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Abstract

Enzel et al. (2015) reassess sedimentary records of Early to Mid-Holocene lake sites in Arabia based on a reinterpretation of published multiproxy data and a qualitative analysis of satellite imagery. The authors conclude that these sites represent palaeo-wetland environments rather than palaeolakes and that the majority of the Arabian Peninsula experienced no or, if at all, only a very minor increase of rainfall at that time mainly due to eastward expansion of the East African Summer Monsoon. We disagree with their reassessment and identify several cases where unequivocal evidence for early Late Pleistocene and Early to Mid-Holocene perennial lake environments in Arabia, lasting for centuries to millennia, was neglected by Enzel et al. (2015). Here we summarize findings which indicate the presence of lakes from the sites of Jubbah, Tayma, Mundafan (all Saudi Arabia), Wahalah, Awafi (both UAE), and the Wahiba Sands (Oman), supported by evidence including occurrence of barnacle colonies in living position, remnant bioclastic shoreline deposits, undisturbed varve formation, shallowing-up lacustrine sequences, various aquatic freshwater, brackish and saline micro- and macrofossils, such as ichnofaunal remains, which are the result of prolonged field-based research. While the precise depth, hydrology and ecology of these water bodies is still not entirely resolved, their perennial nature is indicative of a markedly increased precipitation regime, which, in combination with more abundant groundwater and increased spring outflow in terminal basins fed by charged aquifers, was sufficient to overcome evaporative losses. The palaeolakes' influence on sustaining prehistoric populations is corroborated by the presence of rich archaeological evidence.

Keywords: Arabian Peninsula, Late Quaternary palaeoclimate, Early Holocene Humid Period, Lake deposits, Palaeoenvironmental change

1. Introduction

The magnitude of climatic and environmental changes throughout the Saharo-Arabian belt during the Late Quaternary and their implications for human evolution, dispersal and behavioural change have been a matter of vivid debate and are not yet fully understood (e.g. Holm, 1960; Büdel, 1963; Kuper and Kröpelin, 2006; Parker, 2010). Therefore, the stimulation of the discussion on whether Holocene lacustrine deposits on the Arabian Peninsula (Fig. 1) indicate the presence of perennial lakes or palustrine wetlands by Enzel et al. (2015) is appreciated. For several sites where such deposits were interpreted as lake relicts, Enzel and colleagues conclude a wetland origin based on a reconsideration of sedimentary and fossil evidence and qualitative interpretation of satellite imagery. In synthesising a large body of published information, the authors contribute in clarifying the existence and spatio-temporal pattern of the Early to Middle Holocene Humid Period (EHHP) on the Arabian Peninsula. Furthermore, their article stimulates a much-needed discussion on the atmospheric sources of a possible precipitation surplus in the EHHP for different regions. Enzel et al. (2015) correctly recognize the relevance of the East African Summer Monsoon for creating surface runoff and charging aquifers in Arabia and, thereby, support recent evidence from numerical precipitation modelling (Herold and Lohmann, 2009; Jennings et al., 2015; Guagnin et al., 2016) (Fig. 2). However, we feel obliged to comment on specific aspects of their article, particularly on the existence of palaeolakes across the Arabian Peninsula during MIS 5 and in the EHHP.

2. Wetlands and lakes – a need for definitions

Clear definitions of terms are essential in the discussion of Arabia's aquatic palaeoenvironments. Ramsar (2016, inside cover) provides an extremely broad definition of wetlands including 'marshes, peatlands, floodplains, rivers and lakes, and coastal areas such as saltmarshes, mangroves, intertidal mudflats and seagrass beds, and also coral reefs and other marine areas no deeper than six metres at low tide […]'. According to this definition, lakes are a subtype of wetlands. Enzel et al. (2015, p. 70), however, contrast wetlands ('marshy or shallow water environments') and lakes ('open water bodies') and provide a table summarising typical geomorphic environments, depositional and erosional shoreline features, basin sediments and biological remains of both types in arid regions. These criteria apply to arid landscapes dominated by structural forms, rather than interdunal water bodies in soft sand areas some of which will be discussed here. Unfortunately, the reader does not learn about hydrologic and hydrographic criteria such as water depth, spatial extent, trophic ecology, the seasonal or interannual response of these parameters or any information about persistence which help to differentiate between 'shallow water environments' and lakes. Throughout Enzel et al. (2015) it remains unclear where the former ends and the latter begins.

In fact, the dichotomy of wetlands and lakes *sensu* Enzel et al. (2015) is not straightforward given the overlap between both landscape features (Meybeck, 1995). Modified definitions, which take the perception of Enzel et al. (2015) into account, are used here to limit confusion. Lakes are usually defined as permanent still-water bodies (lentic), mostly associated with a lower size limit between 0.01–0.1 km^2, and distinguished from intermittent and ephemeral water bodies which are not continuously covered by water throughout the course of one year or a longer time period (Meybeck, 1995; Kuusisto and Hyvärinen, 2000; Lehner and Döll, 2004). They persist for at least decades to centuries and conform with lacustrine environments described in Cowardin et al. (1979). On the other hand, wetlands are characterized by often only periodical (e.g. seasonal) presence of standing water 'either at the surface or within the root zone', representing a transitional environment between aquatic and terrestrial ecosystems (Lehner and Döll, 2004, p. 5). They may also include small (<0.1 km^2), shallow (<2 m deep at low water) ephemeral or permanent ponds, similar to the palustrine environments defined by Cowardin et al. (1979).

3. Holocene lakes in Arabia – multiple lines of evidence from multiple places

Given these definitions, we disagree with Enzel et al.'s (2015) characterization of the published evidence for Late Pleistocene and Holocene lakes on the Arabian Peninsula. Enzel et al. (2015) reinterpret and partly disregard evidence for palaeolakes in order to promote the idea that only wetlands were present during the EHHP. In order to demonstrate the existence of palaeolakes, we compile a site-by-site summary of the main lines of argument for the existence of standing water bodies. Accordingly, localities at Jubbah, Tayma, Awafi, Wahalah, Mundafan and those within the Wahiba Sands (Fig. 1) are presented here, areas which have been the subject of many years of field work for in-depth palaeoenvironmental studies by the authors.

3.1. Palaeoenvironmental evidence from the Jubbah Basin, southern Nafud

Late Pleistocene and Holocene lacustrine and lake-like deposits are reported from in and around the Jubbah basin in the southern Nafud Desert of northern Saudi Arabia (Fig. 1). Although not reassessed by Enzel et al. (2015), the Holocene lake records from Jubbah provide an important line of evidence through which to examine the nature of Early Holocene climate change in Arabia. The Jubbah basin comprises a c. 20 km x 5 km topographic depression impounded to the north and south by compound mega-barchanoid dunes up to c. 60 m in height, and to the east and west by outcrops of Saq sandstone. Of these, Jabal Sanman, which extends to a height of c. 400 m above the basin floor at the western end of the depression, has served to protect the basin from the eastward transport and deposition of aeolian material. Groundwater within the basin is derived from the Saq aquifer, and is generally very shallow throughout the Jubbah region, lying at or near the surface until the advent of modern agriculture.

At the eastern end of the basin, Crassard et al. (2013) describe a sedimentary sequence comprising aeolian sands, calcareous silts, lacustrine material, plant and mollusc remains dated to the Early Holocene. Radiocarbon ages from the sequence indicate that a water body formed within the basin before c. 8.7 ka BP and persisted until after 8.0 ka BP. This indicates a period of increased rainfall with reduced evaporation during the Early Holocene period, which was sufficient to sustain water bodies within the interior. At the western-end of the Jubbah basin at the site of Al Rabyah, Hilbert et al. (2014) also describe an interstratified sequence of sands, silts and marls featuring plant and mollusc remains dated to the Early Holocene. Basal marls were dated by optically stimulated luminescence (OSL) to 12.2 ± 1.0 ka, suggesting that lake formation at Jubbah may have occurred earlier than elsewhere in Arabia. The upper part of the sequence contained well-preserved assemblages of aquatic molluscan fauna, ostracods and charophytes, and was dated to 6.5 ± 0.5 ka. Molluscs comprised Lymnaeidae and a freshwater *Gyraulus* species identified as *G. convexiusculus*. In addition, two species of land snail were also identified at the site: *Vertigo antivertigo*, which is characteristic of wetland habitats with a Palaearctic distribution, and snails of the family Succineidae, which live in permanently wet environments such as marshlands and lake margins. The presence of a freshwater environment during the Early Holocene is also indicated by the presence of non-marine ostracod assemblages throughout the upper layers of the sequence. *Eucypris virens* is typical of fresh, grassy pools, while *Pseudocandona rostrata* is found in both permanent and temporary water bodies; both having maximum salinity tolerances of just 5‰. Taken together, these fossil assemblages indicate that permanent freshwater conditions existed in the southern Nafud during the Early Holocene (Hilbert et al., 2014).

The Jubbah depression is an endorheic basin with no inflowing drainage channels, which suggests that these water bodies were formed due to increased precipitation, with possible groundwater contributions. Given the morphological setting of the basin, the infiltration of rainwater through the surrounding extensive dune fields would also have been an important factor controlling lake water recharge. Within the region, annual rainfall of c. 80 mm per year will produce approximately 20 mm of water recharge through the dunes (e.g. Dincer et al., 1974), which will then seep into adjacent topographic depressions. As such, estimates of elevated annual rainfall levels in excess of 250 mm, and possibly as high as 420 mm during the Early Holocene (Guagnin et al., 2016) (Fig. 2) would have led to considerable infiltration into the basin. The presence of spring mounds near the base of Jabal Qattar (Crassard et al., 2013) also suggest that shallow groundwater associated with the Saq aquifer played a role in amplifying lake water recharge, as groundwater became unconfined at the margin of sandstone outcrops. Together, these water sources would have contributed to the perennial presence of a water body at Jubbah, and also to the apparent early age of lake formation, with the basin more sensitive to increased humidity than surrounding regions. A recent COSMOS climate simulation for northwest Arabia during the Early Holocene at 8 ka (Guagnin et al., 2016), suggests that a northward advance of the African summer monsoon was the likely source of rainfall at this time, with a maximum of 420 mm per model year (Fig. 2). This simulation agrees well with multiple climate simulations for the last interglacial (Jennings et al., 2015).

3.2. The Holocene palaeolake of Tayma, northwestern Arabia

Similar to the example of Jubbah, the presence of a variety of Early to Mid-Holocene lacustrine deposits at the oasis of Tayma, northwestern Arabia (approximately 800 m above modern sea level [asl]) (Fig. 1), found within a vertical range of 17 m was interpreted as remnants of a perennial water body in Wellbrock et al. (2011), Engel et al. (2012), Ginau et al. (2012), and Dinies et al. (2015). Enzel et al. (2015) consider the evidence for more abundant fresh to brackish water at Tayma in the Early Holocene as unequivocal by stating that faunal content and laminated deposits in the sabkha basin 'point to permanent standing water at least thinly covering the salt pan, although the depth is unclear'. However, they express doubts regarding 'the presence of a perennial (deeper than a few metres […]) lake encompassing all these deposits. The fauna identified are in fact found in shallow to deep lakes today, but they are also known to exist in smaller permanent water bodies (e.g., the freshwater gastropod *Melanoides tuberculatus*), such as springs, shallow wetlands, and small ponds' (Enzel et al., 2015, p. 75). Rather vague expressions are used here, but 'smaller permanent water bodies' – lakes per definition – is the key term. In fact, *M. tuberculatus* does not occur in temporary waters (van Damme, 1984; Pointier et al., 1992).

The only ostracod species *Cyprideis torosa* is found throughout the sequence of lacustrine deposits from all areas of the basin (Engel et al., 2012; Ginau et al., 2012; Pint et al., 2016. The species has a slow life cycle, is highly competitive in strongly fluctuating aquatic environments with salinities of up to 9%, and a strong indicator of permanent water cover, since their eggs cannot survive desiccation (Anadón et al., 1986; Gasse et al., 1987; Mesquita-Joanes et al., 2012), which is why it has been used to support inferences of stable lake conditions (Mischke et al., in press). Elements of the foraminiferal assemblage identified in the highest shoreline deposits of Early Holocene age (*Ammonia tepida* [dominating], *Quinqueloculina seminula* [common], *Flintinoides labiosa* [rare], *Trichohyalus aguayoi* [rare]; Pint et al., 2016, if found inland, are exclusively associated with permanent athalassic water bodies (e.g. Almogi-Labin et al., 1995; Abu Zied et al., 2007). Ecological conditions of permanent Lake Qarun of the Faiyum Depression, middle Egypt (3–10 m deep, 250 km^2 surface area), where *A. tepida* and *Q. seminula* dominate in recent sediments, in particular in the deepest part (Abu-Zied et al., 2007), may represent a quite accurate modern analogue to the ones at Tayma during the EHHP.

Enzel et al. (2015) do not consider findings of *in-situ* sessile colonies of *Amphibalanus amphitrite* associated with the Holocene lakeshore deposits (e.g. at site Tay 11/177 in Engel et al., 2012), a barnacle species which usually inhabits marginal marine, intertidal environments, is rare in permanent inland lakes, and has not been reported from wetlands (as per definition given above). Inland, in absence of usual marine competitors, balanids occur entirely submerged in tideless, saline lakes. As a sessile filter feeder, longer phases of subaerial exposure can be excluded (Foster, 1987).

A distinct pattern of Holocene laminated, primary open-water evaporites (mostly porous, stellar aragonite) and clastic (quartz and various clay minerals) graded sequences (1–10 mm per laminae) was found in many sediment cores from the inner and outer transitional zone as well as the central sabkha basin (Ginau et al., 2012; Neugebauer et al., 2016). Based on a recently established age model (Dinies et al., 2015), the lamination may represent seasonal hydrological changes, where thin, normally graded beds are related to the wet season of wadi activation and clastic sediment input into the lake, followed by settling out of suspension. Laminae comprising of aragonite, diatoms and organic matter (Neugebauer et al., 2016) represent the season when evaporation losses exceeded inflow, solutes concentrate and crystallize near the water surface, and settle as pelagic rain (e.g., Heim et al., 1997). All of these processes require a sufficiently large and permanent body of water. Furthermore, the presence of aragonitic ooids or pisoids, respectively, at the sabkha margins (Ginau et al., 2012) indicates wind-induced wave activity in the strandzone of a permanent lake rather than a wetland.

Based on satellite imagery, Enzel et al. (2015, p. 82) identify an 'asymmetric pattern of the fine-grained deposits in the Tayma basin' and consider it 'typical of ground-water, not lacustrine deposition'. They identify 'the light-colored fine-grained deposits at Tayma' to be located 'in an area just below the modern artesian springs, including the modern palm grove (Engel et al., 2012) that probably testifies of near surface ground water.' This is brought up as evidence for 'a paleodischarge across a confined seep-face, down slope of the springs. The presence of these deposits on the western, but not the eastern parts of the Tayma basin points to recharge from the west.' It is not easy to follow this chain of arguments, since the fine grained lake deposits – some organic-rich, some laminated as described above – can be found in all parts of the sabkha basin, east and west, in similar thicknesses (Engel et al., 2011, 2012; Ginau et al., 2012).

Enzel et al. (2015, p. 81) consider the lack of distinct shoreline ridges at Tayma as evidence to favour localized ground-water discharge over a permanent lake. Even though coarse bioclastic lake-shore deposits, preserved in pockets cut into the lowermost escarpment at elevations of 11 m above the present sabkha basin at site Tay 11/177 (Engel et al., 2012) (and elsewhere in positions between 4 and 13 m; Engel et al., 2011, 2012) are cited by the authors, they conclude that 'the basin conspicuously lacks evidence of shorelines at the 811.5 m or for that matter at any elevation. [...] Own inspections of satellite images' suggest to them 'that Tayma was probably not occupied by the deep lake envisioned by Engel et al. (2012)'. Enzel et al. (2015, p. 81) apparently mistook the description of the shoreline deposits' spatial distribution as 'disjunct' in Engel et al. (2012, p. 136) and associate the adjective with 'permanent water above the saltpan'. In a recent mapping campaign, a variety of in-situ and relocated shoreline indicators associated with the Holocene lake, including sessile *A. amphitrite* colonies, where found between 808 and 813 m asl all around the sabkha basin (Engel et al., 2016) (Fig. 3). However, the patchy distribution of coarse shoreline deposits can be explained by (i) masking through active dune deposits along the sabkha margin, (ii) erosion by episodic, strong surface discharge and corrosion, and (iii) the presence of lake-shore vegetation, such as reed (Dinies et al., 2015), hampering the formation of berms.

To sum up, the finely laminated occurrence of chemical precipitates and reduced sediments over the entire sabkha basin, a lack of bioturbation, the presence of shoreline facies rimming a closed basin, and the generally low diversity of fossils clearly characterise the sabkha of Tayma as a palaeolake according to the distinguishing characteristics of lake and wetland deposits in Pigati et al. (2014). Enzel et al. (2015) correctly point to the unusual high age (9–10 cal. ka BP) of the shoreline deposits in Engel et al. (2012). Meanwhile, parallel ^{14}C data of pollen indicate that those derived from gastropod shells, ostracods, and aquatic plant seeds presented in Engel et al. (2012) are biased by the hard water effect and appear >1000 years too high (Dinies et al., 2015).

3.3. Holocene lakes in the Rub' al-Khali of the United Arab Emirates: Awafi and Wahalah

In the southeastern Arabian Peninsula at Awafi and Wahalah, UAE (Fig. 1), the presence of over two metres of stratified marls, silts and sands in the inter-dune areas, were interpreted as the remnants of lacustrine deposits in Parker et al. (2004, 2006a, b), Parker and Goudie (2008) and Preston et al. (2012, 2015). However, Enzel et al. (2015) argue that: (1) both sites lack shoreline features, (2) both were ephemeral, very shallow water-bodies, and (3) the flooding of both sites was primarily linked to post-glacial sea level rise in the Arabian Gulf.

Enzel et al. (2015, p. 78) emphasise the absence of distinct shoreline ridges in 'satellite images' of the Awafi and Wahalah basins although unfortunately do not elaborate further on the source of the imagery they use. As has already been highlighted for the case of Tayma, the formation of berms may be hindered in small water-bodies fringed by reeds (e.g. *Typha*) and sedges rather than beaches. The pollen record from Awafi shows the presence of *Typha* during the Early Holocene high-stand (Zone II in Parker et al., 2004). This and the relatively small size of both basins (c. 2 km^2) may have prevented the development of typical shoreline features. Alternatively, it is conceivable that any shoreline features that existed have either been destroyed by human impacts on the landscape and/or buried by dune re-activation during the later Holocene. What appear to be former shoreline features are visible at both sites in the recently declassified CORONA images (KH-4A, 1025-1) dating to 1965, as well as the Maps Geosystems 1980 and 1996 1:40 000 and 1994 1:30 000 air photo imagery for the region (Fig. 4). Modern Google Earth images show the high level of industrial and commercial development at both sites, highlighting the possibility that the features visible in the older imagery have been destroyed or modified beyond identification. Indeed, no distinct shoreline features were observed during a 2005 field visit (Fig. 5), by which time human activity (buildings, vehicle tracks, quarrying) and modern vegetation coverage hindered detailed observations of these features at both basins. An additional consideration is the highly active aeolian conditions in the north-eastern Rub al' Khali during the Middle to Late Holocene (Atkinson et al., 2011, 2012, 2013). At Wahalah, Atkinson et al. (2011) OSL-dated a secondary west-east dune ridge on the periphery of the inter-dune to between 5.8 ± 0.3 and 5.2 ± 0.2 ka, suggesting a rapid phase of accumulation during which 4 m of material was deposited. Increased landscape instability is also recorded at Awafi from c. 6.0 cal. ka BP, with total desiccation and the deposition of aeolian sand in the basin OSL dated to 4.1 ± 0.24 ka (Parker et al., 2006a). This view is supported by evidence from Al Daith, 4.5 km north-west of Awafi, where an Early Bronze Age shell midden site dated to 5.24–4.86 cal. ka BP (2σ), was exposed in a sand quarry 2.8 m below the ground surface (Parker and Goudie, 2007). Thus it is conceivable that any shoreline features formed during the proposed Early Holocene high-stand have been buried by later dune encroachment.

Similar to the lacustrine-like deposits from the northwestern margin of the Nafud (Engel et al., 2012) and the Wahiba Sands (Radies et al., 2005), the palaeofaunal evidence from Awafi and Wahalah contradicts the re-interpretation of Enzel et al. (2015) that both sites represent ephemeral water-bodies. The presence of the freshwater gastropod, *Melanoides tuberculatus*, throughout the Early Holocene sediments at Awafi (Zone II in Parker et al., 2004) and Wahalah (Unit II in Preston et al., 2015) support that notion of perennial, probably brackish, conditions in the basin (Radies et al., 2005). This is supported by the complete demographic distribution of *Cyprideis torosa* populations throughout the same sections at both sites (Preston, unpubl. data), indicating autochthonous development (Whatley, 1988) in permanent waters characterised by strongly fluctuating salinities (Anadón et al., 1986; Gasse et al., 1987). The species was also reported from inland lacustrine deposits at Al Ain, UAE, dating to the Early Holocene (Gebel et al., 1989). The palaeofaunal evidence is currently being re-analysed at higher resolution and we are optimistic that a detailed record of the prevailing ecological conditions at both sites during the EHHP will be available in the near future.

The Awafi and Wahalah deposits were formed in inter-dune depressions bounded by mega-linear ridges OSL dated between 13.5 ± 0.7 ka and 9.1 ± 0.3 ka (Goudie et al., 2000), and 15.9 ± 0.7 ka and 10.3 ± 0.5 ka (Atkinson et al., 2011) respectively. Based on new age-depth modelling, lacustrine sedimentation is suggested to have commenced at c. 8.3 cal. ka BP and c. 9.0 cal. ka at Awafi and Wahalah respectively (Parker et al., 2016). Together the deposition of water-lain sediments (e.g. marls) and the palaeofaunal evidence described above imply that the groundwater table intersected the ground surface long enough for the permanent ponding of water in both basins. In contrast to Parker et al., (2004, 2006a) and Preston et al. (2015), Enzel et al. (2015) suggest that the rise in groundwater table was the result of postglacial sea level rise in the Arabian Gulf. Intriguingly they support their argument using altitude data derived from Google Earth and appear to ignore the information presented in Parker et al. (2004, p. 667) and Preston et al. (2015, p. 279). It should be noted that Google Earth uses digital elevation model (DEM) data derived from Shuttle Radar Topography Mission (SRTM) data, which has an absolute vertical accuracy of 16 m and a relative vertical accuracy of 10 m (Falorni et al., 2005). Likewise hand-held GPS receivers provide elevation data with poor accuracy and are not used here to for altitudinal data. Altitude data from both sites are derived from the 1991 1:50 000 Terra Survey geodetic survey (sheet E-04-14 Al Jazirat al Hamrah) UAE Military topographic map, using UAE National Grid Survey data based on surveyed spot height data. The modern inter-dune surfaces at Awafi and Wahalah are at altitudes of 10 m asl, respectively, rather than <3–5 m and 3–4 m asl as suggested in Enzel et al. (2015). Based on the original topographic surveyed data, the lowermost ‘lake’ deposits at Awafi (2.55 m below ground level) and

Wahalah (2.14 m below ground level) are c. 7.5 m and c. 7.9 m asl, respectively. Furthermore, it should be noted that global sea levels were much lower during the Early Holocene (e.g. Bruthans et al., 2006, Fig. 4), with levels not peaking in the Arabian Gulf until c. 6.3 cal. ka BP (Lambeck, 1996), therefore post-dating the onset of lacustrine sedimentation in both basins by over two millennia. Thus, in contrast to Enzel et al. (2015), we continue to propose that the development of water bodies was primarily a consequence of increased precipitation although the source of moisture remains open to debate (Preston et al., 2015). In addition to evidence from lacustrine and speleothem deposits from the Peninsula, groundwater recharge rates from the Liwa aquifer, UAE also suggest greatly increased rainfall levels compared to present (c. 200 ± 50 mm a^{-1}) during the EHHP (Stokes et al., 2003). Furthermore, the isotopic composition of the groundwater is indicative of being derived from southerly precipitation sources (Stokes et al., 2003; Wood, 2011).

Enzel et al. (2015, pp. 76–80) propose that variations in the $\delta^{13}C_{org}$ data from both Awafi and Wahalah reflect the presence of algal mats rather than changes in the relative proportion of C_3 and C_4 vegetation. The range of C/N and $\delta^{13}C_{org}$ values at Awafi, do indeed indicate that algae forms part of organic plant matter in the sediment (Preston, 2011). Despite this, peak C/N values of 16.3 mean that a mixture of aquatic and terrestrial sources cannot completely be dismissed, particularly during the deposition of sediments during the EHHP (Zone II in Parker et al., 2004). Indeed, clear variations between C_3 and C_4 vegetation are shown in the Awafi phytolith data at this time (Parker et al., 2004). The interpretation of the $\delta^{13}C_{org}$ record from Wahalah is less clear due to the absence of C/N data. This is compounded by the similar isotopic composition of aquatic and terrestrial C_3 plants utilising dissolved CO_2 in equilibrium with atmospheric CO_2, as well as the highly positive $\delta^{13}C_{org}$ values derived from algae when HCO_3 is the primary source of carbon (Meyers, 2003). $\delta^{13}C_{org}$ values at Wahalah range from -20.8 to -9.8‰, with an average of c. 17.7‰, and therefore broadly fall between generalised $\delta^{13}C_{org}$ values for marine algae and C_4 land plants (Meyers, 1994). Variations may thus reflect one or a combination of factors, including shifting C_3–C_4 vegetation dynamics and changing within-basin productivity, as suggested by Preston et al. (2015).

Enzel et al. (2015, p. 83) state: 'The Awafi pollen record, on the other hand, seems to be the only location showing a drastic environmental change. Its record shows an expansion of savannah grassland with woodland elements, which indicate a contribution of the Indian monsoon summer rains in an area currently dominated by winter rains (Parker et al., 2004; Parker and Goudie, 2008)'. Given that only a few pollen records currently exist from the entire Peninsula and the likelihood for regional heterogeneity, this is, in our opinion, a generalised and premature statement, particular in light of the recent findings from northern Arabia. At Tayma, in north-western Saudi Arabia, Dinies et al. (2015) noted distinct changes in vegetation during the EHHP. From 9.2 to 8.6 cal. ka BP high percentages of Chenopodiaceae/Amaranthaceae, low frequencies of Poacae and a near absence of arboreal pollen taxa were recorded suggesting arid, desert conditions. Between 8.7 and 8.6 cal. ka BP grassland expansion and the development of *Ephedra* steppe is indicated. Dinies et al. (2015) show that the maximum period of grassland expansion occurred between 8.6 and 8.0 cal. ka BP with Poaceae values reaching 34% of the total pollen sum. It should be noted that arboreal pollen types were also recorded during this period including *Acacia*, *Quercus*, *Dodonea* and *Pistacia* at low levels. They suggest that this phase of grassland expansion corresponded with increased moisture availability and a period of lake expansion. At 8.0 cal. ka BP an abrupt change in vegetation is recorded, with a sharp decrease in Poaceae and increasing *Artemisia* and *Haloxylon* indicating a change to more arid conditions. In sum, the Tayma record clearly demonstrates major changes in flora during the EHHP. To address this question fully more floral studies are required to ascertain the nature of vegetation changes from the diverse Arabian landscape.

We acknowledge that the Awafi pollen record differs from the few other Arabian records published to date. In this respect it is worth noting that both the Awafi and Wahalah sediment sequences persist longer into the Holocene than most other records from Arabia and are perhaps more similar in nature to sites in the Thar Desert region of India and Pakistan. The Awafi pollen diagram records the development of grassland with low levels of *Acacia* (up to 3%) and *Prosopis* (up to 2%) arboreal pollen mainly during the period of maximum lake extension (Zone II in Parker et al., 2004). The flora of this region of south-east Arabia has a strong Omano-Makranian element which forms part of the wider Nubo-Sindian centre of endemism (Mandaville, 1985; Ghazanfar and Fisher, 1998). Thus the floral distribution shows spatial differences when compared to other regions of Arabia which lack these floral elements. Indeed the pollen record from Awafi shows closer floral affinities to records from the Thar Desert region (e.g. Singh et al., 1990). In the Didwana record, Singh et al. (1990) noted the development of grassland with low levels c. 2% of *Prosopis*. Rainfall was attributed to increased monsoon precipitation with the addition of winter rainfall from proposed westerly sources. At Lake Lunkransar, also in the Thar Desert region, Enzel et al. (1999) recorded a high stand between c. 7.2 cal. ka BP and 5.5 cal. ka BP for which they proposed that an additional source of water beyond summer monsoon precipitation was required to maintain a perennial lake. This view is not dissimilar to that proposed from the Awafi and Wahalah records (Parker et al., 2004, 2006a; Preston et al., 2012, 2015). Lézine et al. (2010) claim that the proposed seasonality changes to summer rainfall at Awafi is unsupported by the pollen data and raised the need to reconsider the advocated moderate change in rainfall amounts. Based on the sedimentology and paleoecology evidence from both Awafi and Wahalah we continue to propose that a number of changes shown are rapid in nature and do correspond to changes in moisture. Sediment flux rate changes at both sites support the notion for increased pulses of detrital input between c. 8.2 cal. ka BP and 7.9 cal. ka BP and from c. 6.0 cal. ka BP which are related to positive biophysical nonlinear feedbacks driven by changes in precipitation, vegetation cover and sediment availability (Parker et al., 2016). OSL dating from multiple dune records from south-east Arabia support this view with increased rates of dune reactivation from the mid-Holocene (Atkinson et al. 2011, 2012, 2013; Farrant et al., 2015).

3.4. Holocene lakes in the Wahiba Sand Sea, E Oman

In the Wahiba Sands of SE Oman (Fig. 1), Radies et al. (2004, 2005) describe interdune deposits that are assigned to ponding during the Early to Mid-Holocene according to infrared stimulated luminescence (IRSL) and radiocarbon dating. In the northern part, the interdune deposits are IRSL-dated between 10.6 ± 1.5 and 8.4 ± 0.8 ka. The freshwater snails *Melanoides tuberculatus*, *Gyraulus* sp. and *Hydrobia* sp. as well as fish or reptile teeth have been found in the deposits (Radies et al., 2005). While *M. tuberculatus* is presently found in active wadi courses and oases (Neubert, 1998), *Gyraulus* sp. is indicative of a permanent lake with a vegetated shore zone (Radies et al., 2005). Even though both *M. tuberculatus* and *Hydrobia* sp. are tolerant to a wide range of salinities (e.g. brackish conditions), the former species in particular is indicative of perennial lake conditions – similar to Tayma in NW Arabia – as it is uncommon in periodically dry habitats (Pointier et al., 1992; Vogler et al., 2012). The deposits also show local bioturbation and a variety of trace fossils, in particular insect burrows, including the larval cells of soil-mining bees, pupal cells of dung beetles and structures attributed to termite nests. The occurence of dung beetles requires the presence of large herbivores in the area at that time. Termite nests indicate that plant material must have been available and pollen-, spore-, or nectar-producing plants must have been present near the position of the subterranean bee nests (Radies et al., 2005).

Near the coast, the interdune deposits are found as residual hills with a height of up to 5 m, and have been dated by IRSL to have formed between 7.6 ± 0.8 ka and 5.8 ± 0.8 ka ago. The sequence consists of silty fine-grained sand reaching an individual thickness of up to 10 cm, intercalated by layers of poorly sorted coarse-grained sand, indicating episodic flooding of the interdune depression due to heavy rainfall. The terrestrial snail *Pupoides coenopictus* is common in the deposits. These moderately bioturbated interdune sediments are characterised by a different suite of trace fossils compared to the lake deposits, in particular rhizotubules, but also termite nests (Radies et al., 2005).

In summary, the lacustrine-like deposits of the Wahiba Sands and their fossil content represent permanent water bodies surrounded by lake-shore vegetation, presumably in a savannah-like environment. In particular the ichnofauna and invertebrate remains conflict with reinterpretations of Enzel et al. (2015) that the interdune deposits derive from marsh and wetland environments. Radies et al. (2005) roughly estimate a minimum precipitation of 250 mm a^{-1} necessary to sustain perennial lake conditions over the time period of many centuries, compared to less than 100 mm a^{-1} observed today. This is in keeping with simulated annual precipitation for 8.0 ka ago (Guagnin et al., 2016) (Fig. 2).

3.5. Late Pleistocene palaeolakes in the Rub' al-Khali of Saudi Arabia

Although Enzel et al. (2015, p. 75) focus on a reassessment of Early and Middle Holocene lakes, they also include 'pre-Holocene lacustrine-like environments' in their analysis, and also implicitly question the open-lake nature of the Pleistocene lake beds of Mundafan (Fig. 1) and the Nafud desert. As for the Holocene counterparts, they emphasize the absence in reports of shoreline features (berms, beach scarps), being the most characteristic attributes of palaeolakes, which 'should be well preserved in the Arabian Peninsula, given its extreme aridity and generally modest relief' (Enzel et al., 2015, p. 80). This assumption does not apply to the highly active environments of the Rub' al-Khali and Nafud sand seas, where deflation during the long time span since deposition of the lake deposits during the early Late Pleistocene has resulted in only sporadic relicts of the original lake basin fills (e.g. Matter et al., 2015). In addition, as also applying to the examples of Tayma, Awafi and Wahalah, migrating dunes may cover entire palaeolakes, or parts of them, further hampering the mapping of any type of lake facies. Furthermore, the Pleistocene palaeolakes in the interior of the Rub' al-Khali and of the Nafud are located in depressions on the lee side of dunes. This, combined with their generally small size, hinders the build-up of waves, and thus the formation of berms. A close modern analogue exists with the Umm al-Heesh lakes in the eastern Rub' al-Khali, where groundwater from a leaking well flooded the depressions between star dunes (Matter et al., 2015) (Fig. 6). Neither shoreline ridges nor cliffs have developed in the several decades of their existence. Even if low-energy waves were occasionally present, they would anyway have no effect on the large parts of the shoreline that are protected by reed belts.

Enzel et al. (2015, p. 81) question (1) published lake level reconstructions used to determine water depths of the Mundafan palaeolakes, (2) argue that 'most of the deposits reported from Mundafan [...] present the characteristics of wetland discharge deposits' and (3) miss a topographic change from these deposits to those at the margins. The southeastern part of the Mundafan palaeolake where most of the recent work was carried out represents an asymmetric basin with a steep slope along the base of the Tuwayq escarpment and a low gradient southern basin floor. This geomorphological difference had a marked effect on lake-margin facies development. Sands with *Unio tigridis* reported by Rosenberg et al. (2011, Suppl. Fig. DR4, site 22.4) at 868 m asl at the base of the Tuwayq escarpment dated to c. 100 ka represent sediments deposited in a likely narrow exposed shore zone of an unequivocally permanent freshwater lake. In contrast, the coeval sequence at the same topographic elevation on the southern lake margin consists of a shallowing-upwards sequence with lacustrine marls at the base followed by palustrine sediments of a marginal marsh, rather than a beach and a palaeosol at the top (Groucutt et al., 2015). Towards the centre of this basin, c. 1.3 km from site 22.4 at a height of 859 m asl, two metres of fossiliferous marls, including *Unio tigridis* and *Darwinula stevensoni*, confirm the presence of an open freshwater lake, with a similar age of c. 100 ka (Fig. 2C in Rosenberg et al. 2011). The mussel *Unio* is an unequivocal indicator of permanent freshwater, and an indirect indicator of freshwater fish that require an intermediate host for its larvae (Matter et al., 2015). Resettlement experiments of *Unio* in Europe revealed that it takes approximately 30 years to establish a first generation. Therefore, the occurrence of mussels of differing sizes in individual beds of Pleistocene and Holocene age at Mundafan and the distal Wadi ad Dawasir basin, respectively, reveals multi-generation populations, i.e. a stable lake habitat lasting for one to several hundred years (Matter et al. 2016). We argue that the correlation of age-equivalent sequences combined with their topographic level and depositional environment, clearly support a permanent freshwater lake in a basin with a topographic relief and water depths ranging from c. 10 m in the southwestern part, to <30 m in the deepest area of the basin (Rosenberg et al., 2011).

Enzel et al. (2015, p. 79; 82) claim that the photographs in the Appendix of Rosenberg et al. (2011) reveal that the Holocene lake Mundafan was 'not a true lake' but 'discharge marshy deposits' that are ' similar to wetland/marsh deposits '. However, they do not elaborate on the diagnostic features in the photographs that support this conclusion. There is, however, conclusive evidence from the multi-proxy data presented by Rosenberg et al. (2011), Gennari et al. (2011) and Behrendt (2011) for a low-energy shallow perennial freshwater lake punctuated by brackish intervals. Moreover, the low ratio of adult vs. juvenile ostracod valves is a further indication of a quiet water environment (Fig. 9 in Behrendt, 2011). We therefore conclude that the Holocene shoreline was rimmed by reeds and sedges, rather than beaches that accounts for the abundance of *Typha* and *Phragmites* in the Holocene successions. There is no clear sedimentological evidence for intermittent ephemeral conditions, and the faunal elements rather indicate permanent water during deposition, unequivocally supporting the aforementioned lake definition.

4. Discussion and conclusions

We show that perennial lakes have occurred at several sites in the Arabian Peninsula during the Late Pleistocene as well as during the Early to Mid-Holocene, where a wide range of micro- and macrofossils provide the strongest, in most places unequivocal evidence. The apparent lack of shoreline deposits and landforms cited by Enzel et al. (2015) as sign of prevailing wetlands, is either the result of low preservation potential due to erosion by strong episodic surface discharge, deflation, corrasion, human activity, and covering by dunes, the establishment of reed belts hampering their formation, or, as in Tayma, due to the fact that such deposits are still currently under investigation (Engel et al., 2016). There is no doubt that more lakes existed and are still to be explored (Breeze et al., 2015).

The moisture surplus to sustain the Arabian lakes most likely derives from a combination of both increased precipitation and more abundant water in shallow aquifers, which indeed has been neglected in some earlier works (e.g. Wellbrock and Grottker, 2011; Engel et al.,2012). Enzel et al. (2015) refer to a lack of contributing watersheds at several of the lakes, indicating that, if there was no additional groundwater source, the amount of rainfall must have at least equalled evaporation rates of 2200–4000 mm a^{-1}. This statement is unfounded, as the palaeolake catchments are rather large and, thus, collected rainfall over wide areas, reflected by pluvial indices (palaeolake surface divided by drainage basin area) as low as 3% (Tayma), 0.5–0.6% (Mundafan) and even 0.1–0.2% (Awafi, Wahalah) (Enzel et al., 2015). In the case of Jubbah, the lowest depression in the south of the northern Nafud branch, the high infiltration rates over a vast area of the erg provided significant recharge to sustain the palaeolake. This view is furthermore corroborated by the substantially increased annual rainfall amounts during the early Late Pleistocene and the Early Holocene shown in palaeoclimate model simulations, predominantly derived through enhanced East African summer monsoonal activity (Herold and Lohmann, 2009; Jennings et al., 2015; Guagnin et al., 2016). An increase of winter rains due to stronger influx of Mediterranean depressions (Arz et al., 2003) during the EHHP was recently challenged (Guagnin et al., 2016). Therefore, the conclusion 'that during the middle Holocene, the southwest and southeast Arabian Peninsula were somewhat wetter than today but the core of the peninsula remained dry, as in the previous 300,000 years' (Enzel et al., 2015, p. 84) is unsustainable as it neglects a continually growing body of interdisciplinary evidence for increased rainfall and the formation of perennial lakes.

Furthermore, the archaeological record of Arabia provides compelling support for the degree of humidity change during the EHHP. The year-round presence of potable drinking water has clearly played a significant role in attracting human populations into the region, since most palaeolake sites, in particular those at Jubbah, are closely associated with the presence of archaeological assemblages as exemplified by some of the sites discussed here (Crassard et al., 2013; Hilbert et al., 2014) and elsewhere (e.g. Basell, 2008; Drake et al., 2011). At Jubbah, some lithic assemblages display close affinities with material from the Levant, suggesting that climatic conditions were favourable enough throughout what is now a hyperarid environment, to facilitate demographic connectivity between these regions during both the Holocene (Crassard et al., 2013) and Late Pleistocene (Breeze et al., 2016). Indeed, it is also logical to expect that such connectivity would only have been possible if (1) the distance between water sources was not substantial, and (2) those water sources were both potable and long-lived. In this sense, it could be argued that focus on whether the water bodies comprised 'lakes' or extensive, perennial wetlands is somewhat misplaced. While the precise depths, hydrology and ecology of these water bodies remains unresolved, their perennial, in most cases freshwater nature is indicative of a markedly increased precipitation regime, which was sufficient to overcome evaporative losses and sustain prehistoric populations, leaving behind a suite of relict deposits that have no contemporary analog (i.e. these landforms do not form under exclusively arid conditions). The sedimentary archives discussed here have greatly assisted researchers in developing a framework of landscape evolution against which to study the interactions between early human populations and the natural environment, a viewpoint shared by Enzel et al. (2015, p. 87). Indeed, while this palaeoclimatic debate is welcomed, it should not overshadow the importance of all types of water bodies, whether lake, wetland, or other, as recorders of environmental change at a scale that is relevant to early human populations.

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References

Abu-Zied, R.H., Keatings, K.W., Flower, R.J., 2007. Environmental controls on foraminifera in Lake Qarun, Egypt. J. Foramin. Res. 37, 136–149.

Almogi-Labin, A., Siman-Tov, R., Rosenfeld, A., Debard, E., 1995. Occurrence and distribution of the foraminifer *Ammonia beccarii tepida* (Cushman) in water bodies, Recent and Quaternary, of the Dead Sea Rift, Israel. Mar. Micropaleontol. 26, 153–159.

Anadón, P., de Deckker, P., Julia, R., 1986. The Pleistocene lake deposits of the NE Baza Basin (Spain): salinity variations and ostracod succession. Hydrobiologia 143, 199–208.

Arz, H., Lamy, F., Pätzold, J., Müller, P.J., Prins, M., 2003. Mediterranean moisture source for an early-Holocene humid period in the northern Red Sea. Science 300, 118–121.

Atkinson, O.A.C., Goudie, A.S., Thomas, D.S.G., Bailey, R.M., 2011. Late Quaternary chronology of major dune ridge development in the northeast Rub' al-Khali, United Arab Emirates. Quaternary Res. 76, 93–105.

Atkinson, O.A.C., Thomas, D.S.G., Goudie, A.S., Parker, A.G., 2012. Holocene development of multiple dune generations in the northeast Rub' al-Khali, United Arab Emirates. Holocene 22, 179–189.

Atkinson, O.A.C., Thomas, D.S.G., Parker, A.G., Goudie, A.S., 2013. Late Quaternary humidity and aridity dynamics in the northeast Rub' al-Khali, United Arab Emirates: Implications for early human dispersal and occupation of eastern Arabia. Quatern. Int. 300, 292–301.

Basell, L.S., 2008. Middle Stone Age (MSA) site distributions in eastern Africa and their relationship to Quaternary environmental change, refugia and the evolution of Homo sapiens. Quaternary Sci. Rev. 27, 2484–2498.

Behrendt, I., 2011. Charakterisierung von spätpleistozänen und frühholozänen Feuchtphasen in Saudi-Arabien mit Hilfe von Ostrakoden. BSc thesis, Technische Universität Braunschweig, 75 pp.

Berger, J.-F., Bravard, J.-P., Purdue, L., Benoist, A., Mouton, M., Braemer, F., 2012. Rivers of the Hadramawt watershed (Yemen) during the Holocene: Clues of late functioning. Quatern. Int. 266, 142–161.

Breeze, P.S., Drake, N.A., Groucutt, H.S., Parton, A., Jennings, R.P., White, T.S., Clark-Balzan, L., Shipton, C., Scerri, E.M.L., Stimpson, C.M., Crassard, R., Hilbert, Y., Alsharekh, A., Al-Omari, A., Petraglia, M.D., 2015. Remote sensing and GIS techniques for reconstructing Arabian palaeohydrology and identifying archaeological sites. Quatern. Int. 382, 98–119.

Breeze, P. Groucutt, H.S., Drake, N.A., White, T.S., Jennings, R.P., Petraglia, M.D., 2016. Palaeohydrological corridors for hominin dispersals in the Middle East c. 250–70,000 years ago. Quaternary Sci. Rev. 144, 155–185.

Bruthans, J., Filippi, M., Gersl, M., Zare, M., Melkova, J., Pazdur, A., Bosak, P. 2006. Holocene marine terraces on two salt diapirs in the Persian Gulf, Iran: age, depositional history and uplift rates. J. Quaternary Sci. 21, 843–857.

Büdel, J., 1963. Die pliozänen und quartären Pluvialzeiten der Sahara. Eiszeit. Gegenwart 14, 161–187.

Cowardin, L.M., Carter, V., Golet, F.C., LaRoe, E.T., 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Dept. of the Interior, Fish and Wildlife Service, Washington D.C., 131 pp.

Crassard, R., Petraglia, M.D., Parker, A.G., Parton, A., Roberts, R.G., Jacobs, Z., Alsharekh, A., Al-Omari, A., Breeze, P., Drake, N.A., Groucutt, H.S., Jennings, R., Régagnon, E., Shipton, C., 2013. Beyond the Levant: First Evidence of a Pre-Pottery Neolithic Incursion into the Nefud Desert, Saudi Arabia. PLoS ONE 8, e68061.

Dincer, T., Al-Mugrin, A., Zimmermann, U., 1974. Study of the infiltration and recharge through the sand dunes in arid zones with special reference to the stable isotopes and thermonuclear tritium. J. Hydrol. 23, 79–109.

Dinies, M., Plessen, B., Neef, R., Kürschner, H., 2015. When the desert was green: Grassland expansion during the early Holocene in northwestern Arabia. Quatern. Int. 382, 293–302.

Drake, N.A., Blench, R.M., Armitage, S.J., Bristow, C.S., White, K.H., 2011. Ancient watercourses and biogeography of the Sahara explain the peopling of the desert. Proc. Natl. Acad. Sci. 108, 458–462.

Engel, M., Brückner, H., Bosch, J., 2011. Geoarchaeological research at Tayma. In: Eichmann, R., Hausleiter, A., al-Najem, M.H., al-Said, S.F. (Eds.), Tayma - Autumn 2005 and 2006 (spring and autumn) - 3rd Report on the Joint Saudi Arabian-German archaeological project. ATLAL – J. Saudi Arab. Archaeol. 21, 61–77.

Engel, M, Brückner, H., Pint, A., Wellbrock, K., Ginau, A., Voss, P., Grottker, M., Klasen, N., Frenzel, P., 2012. The early Holocene humid period in NW Saudi Arabia – sediments, microfossils and palaeohydrological modelling. Quatern. Int. 266, 131–141.

Engel, M., Frenzel, P., Pint, A., Dinies, M., Gleixner G., Hoelzmann, P., Neugebauer, I., Plessen, B., Brückner, H., 2016. Barnacles Tell no Lies – Bioclastic deposits and *in-situ* balanid colonies delineate shorelines of the Holocene palaeolake at Tayma (NW Saudi Arabia). Geophys. Res. Abstr. 18, EGU2016-3974.

Enzel, Y., Ely, L.L., Mishra, S., Ramesh, R., Amit, R., Lazar, B., Rajaguru, S.N., Baker, V.R., Sandler, A., 1999. High-resolution Holocene environmental changes in the Thar Desert, northwestern India. Science 284, 125–128.

Enzel, Y., Kushnir, Y., Quade, J., 2015. The middle Holocene climatic records from Arabia: Reassessing lacustrine environments, shift of ITCZ in Arabian Sea, and impacts of the southwest Indian and African monsoons. Global Planet. Change 129, 69–91.

Falorni, G., Teles, V., Vivoni, E.R., Bras, R.L., Amaratunga, K.S., 2005. Analysis and characterization of the vertical accuracy of digital elevation models from the Shuttle Radar Topography Mission, J. Geophys. Res. 110, F02005.

Farrant, A.R., Duller, G.A., Parker, A.G., Roberts, H.M., Parton, A., Knox, R.W., Bide, T., 2015. Developing a framework of Quaternary dune accumulation in the northern Rub'al-Khali, Arabia. Quatern. Int. 382, 132–144.

Foster, B.A., 1987. Barnacle ecology and adaption. In: Southward, A.J. (Ed.), Barnacle Biology. Crust. Iss. 5, 113–134.

Gasse, F., Fontes, J.-C., Plaziat, J.-C., Carbonel, P., Kaczmarska, I., de Deckker, P., Soulié-Märsche, I., Callot, Y., Dupeuble, P.A., 1987. Biological remains, geochemistry and stable isotopes for the reconstruction of environmental and hydrological changes in the Holocene lakes from north Sahara. Palaeogeogr. Palaeoclim. Palaeoecol. 60, 1–46.

Gebel, H.G., Hanss, C., Liebau, A., Raehle, W. 1989. The Late Quaternary environments of Ain al-Faidha/Al-Ain, Abu Dhabi Emirate. Archaeology in the United Arab. Emirates 5, 9–48.

Gennari, G., Rosenberg, T., Spezzaferri, S., Berger, J.-P., Fleitmann, D., Preusser, F., Al-Shanti, M., Matter, A., 2011. Faunal evidence of a Holocene pluvial phase in southern Arabia with remarks on the morphological variability of *Helenina anderseni*. J. Foramin. Res. 41, 248–159.

Ghazanfar, S.A., Fisher, M., 1998. Vegetation of the Arabian Peninsula. Kluwer, Dordrecht.

Ginau, A., Engel, M., Brückner, H., 2012. Holocene chemical precipitates in the continental sabkha of Tayma (NW Saudi Arabia). J. Arid Environ. 84, 26–37.

Goudie, A.S., Colls, A., Stokes, S., Parker, A.G., White, K., Al-Farraj, A., 2000. Latest Pleistocene dune construction at the north-eastern edge of the Rub al Khali, United Arab Emirates. Sedimentology 47, 1011–1021.

Groucutt, H.S., White, T.S., Clark-Balzan, L., Parton, A., Crassard, R., Shipton, C., Jennings, R.P., Parker, A.G., Breeze, P.S., Scerri, E.M.L., Alsharekh, A. Petraglia, M.D., 2015. Human occupation of the Arabian Quarter during MIS 5: evidence from Mundafan Al-Buhayrah, Saudi Arabia. Quaternary Sci. Rev. 119, 116–135.

Guagnin, M., Jennings, R., Eager, H., Parton, A., Stimpson, C., Groucutt, H.S., Drake, N.A., Pfeiffer, M., Stepanek, C., Alsharekh, A., Petraglia, M.D., 2016. Rock art imagery as a proxy for Holocene environmental change: a view from Shuwaymis, NW Saudi Arabia. Holocene, doi: 10.1177/0959683616645949.

Heim, C., Nowaczyk, N., Negendank, J., Leroy, S., Ben-Avraham, Z., 1997. Near East desertification: evidence from the Dead Sea. Naturwissenschaften 84, 398–401.

Herold, M., Lohmann, G., 2009. Eemian tropical and subtropical African moisture transport: an isotope modelling study. Clim. Dyn. 33, 1075–1088.

Hilbert, Y., White, T., Parton, A., Clark-Balzan, L., Crassard, R., Croucutt, H., Jennings, R., Breeze, P., Parker, A., Shipton, C., Al-Omari, A., Alsharekh, A., Petragila, M., 2014. Epipalaeolithic occupation and palaeoenvironments of the southern Nefud desert, Saudi Arabia, during the Terminal Pleistocene and Early Holocene. J. Archaeol. Sci. 50, 460–474.

Holm, D.A., 1960. Desert Geomorphology in the Arabian Peninsula. Science 132, 1369 –1379.

Jennings, R.P., Singarayer, J., Stone, E.J., Krebs-Kanzow, U., Khon, V., Nisancioglu, K.H., Pfeiffer, M., Zhang, X., Parker, A., Parton, A., Groucutt, H.S., White, T.S., Drake, N.A., Petraglia, M.D., 2015. The greening of Arabia: Multiple opportunities for human occupation of the Arabian Peninsula during the Late Pleistocene inferred from an ensemble of climate model simulations. Quatern. Int. 382, 181–199.

Kuper, R., Kröpelin, S., 2006. Climate-Controlled Holocene Occupation in the Sahara: Motor of Africa's Evolution. Science 313, 803–807.

Kuusisto, E., Hyvärinen, V., 2000. Hydrology of lakes. In: Heinonen, P., Ziglio, G., Van der Beken, A. (Eds.), Hydrological and limnological aspects of lake monitoring. John Wiley & Sons, Chichester, pp. 3–12.

Lambeck, K., 1996. Shoreline reconstructions for the Persian Gulf since the last glacial maximum. Earth Planet. Sci. Lett. 142, 43–57.

Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. J. Hydrol. 296, 1–22.

Lézine, A.M., Robert, C., Cleuziou, S., Inizan, M.L., Braemer, F., Saliège, J.F., Sylvestre, F., Tiercelin, J.J., Crassard, R., Méry, S., Charpentier, V., 2010. Climate change and human occupation in the Southern Arabian lowlands during the last deglaciation and the Holocene. Global Planet. Change 72, 412–428.

Mandaville, J.P., 1985. A botanical reconnaissance in the Musandam region of Oman. J. Oman Stud. 7, 9–28.

Matter, A., Neubert, E., Preusser, F., Rosenberg, T., Al-Wagdani, K., 2015. Palaeo-environmental implications derived from lake and sabkha deposits of the southern Rub' al-Khali, Saudi Arabia and Oman. Quatern. Int. 382, 120–131.

Matter, A., Mahjoub, A., Neubert, E., Preusser, F., Schwalb, A., Szidat, S., Wulf, G., 2016. Reactivation of the Pleistocene trans-ArabianWadi ad Dawasir fluvial system (Saudi Arabia) during the Holocene humid phase. Geomorphology 270, 88–101.

Mesquita-Joanes, F., Smith, A.J., Viehberg, F.A., 2012. The ecology of Ostracoda across levels of biological organisation from individual to ecosystem: a review of recent developments and future potential. In: Horne, D.J., Holmes, H., Viehberg, F., Rodriguez-Lazaro, J. (Eds.) Ostracoda as proxies for Quaternary climate change. Dev. Quat. Sci. 17, 265–281.

Meybeck, M., 1995. Global distribution of lakes. In: Lerman, A., Imboden, D.M., Gat, J.R. (Eds.), Physics and Chemistry of Lakes. Springer, Berlin, pp. 1–36.

Meyers, P.A., 1994. Preservation of elemental and isotopic identification of sedimentary organic matter. Chem. Geol. 114, 289–302.

Meyers, P.A., 2003. Applications of organic geochemistry to palaeolimnological reconstructions: a summary of examples from the Laurentian Great Lakes. Org. Geochem. 34, 261–289.

Mischke, S., Ginat, H., Faerstein, G., Porat, N., Braun, P., Rech, J., in press. Fossil-based reconstructions of ancientwater bodies in the Levantine deserts. In: Enzel, Y., Bar-Yosef, O. (Eds.), Quaternary Environments, Climate Change, and Humans in the Levant. Cambridge University Press.Neubert, E., 1998. Annotated checklist of the terrestrial and freshwater molluscs of the Arabian Peninsula with descriptions of new species. Fauna Arab. 17, 333–461.

Neugebauer, I., Plessen, B., Dinies, M., Engel, M., Tjallingii, R., Brauer, A., 2016. The early Holocene humid period in the Tayma palaeolake, NW Arabian Peninsula – A high-resolution micro-facies and geochemical approach. Geophys. Res. Abstr. 18, EGU2016-4396.

Parker, A.G., 2010. Pleistocene Climate Change in Arabia: Developing a Framework for Hominin Dispersal over the Last 350 ka. In: Petraglia, M.D., Rose, J.I. (Eds.), The Evolution of Human Populations in Arabia. Springer, Dordrecht, pp. 39 –49.

Parker, A.G., Goudie, A.S. 2007. Development of the Bronze Age landscape in the southeastern Arabian Gulf: new evidence from a buried shell midden in the eastern extremity of the Rub'al-Khali desert, Emirate of Ras al-Khaimah, UAE. Arab. Archaeol. Epigr. 18,132–138.

Parker, A.G., Goudie, A.S. 2008. Geomorphological and palaeoenvironmental investigations in the southeastern Arabian Gulf region and the implication for the archaeology of the region. Geomorphology 101, 458–470.

Parker, A.G., Eckersley, L., Smith, M.M., Goudie, A.S., Stokes, S., Ward, S., White, K., Hodson, M.J., 2004. Holocene vegetation dynamics in the eastern Rub al Khali desert, Arabian Peninsula: a phytolith and carbon isotope study. J. Quaternary Sci. 19, 665–676.

Parker, A.G., Goudie, A.S., Stokes, S., White, K., Hodson, M.J., Manning, M., Kennet, D. 2006a. A record of Holocene climate change from lake geochemical analyses in south-eastern Arabia. Quaternary Res. 66, 465–476.

Parker, A.G., Preston, G.W., Walkington, H., Hodson, M.J., 2006b. Developing a framework of Holocene climatic change and landscape archaeology for the lower Gulf region, southeastern Arabia. Arab. Archaeol. Epigr. 17, 125–130.

Parker, A.G., Preston, G.W., Parton, A., Walkington, H., Jardine, P.E., Leng, M.J., Hodson, M.J., 2016. Low-latitude Holocene hydroclimate derived from lake sediment flux and geochemistry. J. Quaternary Sci. 31, 286–299.

Pigati, J.S., Rech, J.A., Quade, J., Bright, J., 2014. Desert wetlands in the geologic record. Earth-Sci. Rev. 132, 67–81.

Pint, A., Frenzel, P., Engel, M., Plessen, B., Melzer, S., Brückner, H., 2016. Ostracoda and Foraminifera associated with macrofauna of marginal marine origin in continental sabkha sediments of Tayma (NW Saudi Arabia). Geophys. Res. Abstr. 18, EGU2016-7289.

Pointier, J.P., Delay, B., Toffart, J.L., Lefèvre, M., Romero-Alvarez, R., 1992. Life History traits of three morphs of *Melanoides tuberculata* (Gastropoda: Thiaridae), an invading snail in the French West Indies. J. Moll. Stud. 58, 415–423.

Preston, G.W., 2011. From nomadic herder-hunters to sedentary famers: the relationship between climate, environment and human societies in the United Arab Emirates from the Neolithic to the Iron Age. Ph.D Thesis, Oxford Brookes University.

Preston, G.W., Parker, A.G., Walkington, H., Leng, M.J., Hodson, M.J., 2012. From nomadic herder-hunters to sedentary farmers: the relationship between climate change and ancient subsistence strategies in South-eastern Arabia. J. Arid Environ. 86, 122–130.

Preston, G.W., Thomas,, D.S.G., Goudie, A.S., Atkinson, O.A.C., Leng, M.J., Hodson, M.J., Walkington, H., Charpentier, V., Méry, S., Borgi, F., Parker, A.G., 2015. A multi-proxy analysis of the Holocene humid phase from the United Arab Emirates and its implications for southeast Arabia's Neolithic populations. Quatern. Int. 382, 277–292.

Radies, D., Preusser, F., Matter, A., Mange, M., 2004. Eustatic and climatic controls on the development of the Wahiba Sand Sea, Sultanate of Oman. Sedimentology 51, 1359–1385.

Radies, D., Hasiotis, S.T, Preusser, F., Neubert, E., Matter, A., 2005. Paleoclimatic significance of Early Holocene faunal assemblages in wet interdune deposits of the Wahiba Sand Sea, Sultanate of Oman. J. Arid Environ. 62, 109–125.

Ramsar, 2016. An Introduction to the Convention on Wetlands. 5th ed., Ramsar Convention Secretariat, Gland, Switzerland.

Rosenberg, T.M., Preusser, F., Fleitmann, D., Schwalb, A., Penkman, K., Schmid, T.W., Al-Shanti, M.A., Kadi, K., Matter, A., 2011. Humid periods in southern Arabia: windows of opportunity for modern human dispersal. Geology 39, 1115-1118.

Singh, G., Wasson, R.J., Agrawal, D.P., 1990. Vegetational and seasonal climatic changes since the last full glacial in the Thar Desert, northwestern India. Rev. Palaeobot. Palynol. 64, 351–358.

Stokes, S., Bray, H., Goudie, A.S., Wood, W.W., 2003. Later Quaternary Paleorecharge events in the Arabian Peninsula. In: Alsharhan, A.S., Wood, W.W. (Eds.), Water Resources Perspectives: Evaluation, Management and Policy. Elsevier, Amsterdam, pp. 371–378.

Van Damme, D., 1984. The freshwater Mollusca of Northern Africa. Distribution, Biogeography and Palaeocology. W. Junk, The Hague, 164 pp.

Vogler, R.E., Núñez, V., Gutiérrez Gregoric, D.E., Beltramino, A.A., Peso, J.G., 2012. *Melanoides tuberculata*: The History of an Invader. In: Hämäläinen, E.M., Järvinen, S. (Eds.), Snails: biology, ecology, and conservation. Nova Science Publishers, New York, pp. 65–84.

Wellbrock, K., Voss, P., Grottker, M., 2011. Reconstruction of mid-Holocene climate conditions for north-western Arabian oasis Tayma. Int. J. Water Resour. Arid Environ. 1 (3), 200–209.

Whatley, R.C., 1988. Population structure of ostracods: some general principles for the recognition of palaeoenvironments. In: De Deckker, P., Colin, J.P., Peypouquet, J.P. (Eds.), Ostracoda in the earth sciences. Elsevier, Amsterdam, pp. 245–256,

Wood, W., 2011. Source of paleo-groundwater in the Emirate of Abu Dhabi, United Arab Emirates: Evidence from unusual oxygen and deuterium isotope data. Hydrogeol. J. 19, 155–161.

Figure captions

Fig.1: Overview of the Arabian Peninsula indicating key palaeolake sites (map based on SRTM30 data, provided by https://dds.cr.usgs.gov/srtm/version1/SRTM30).

Fig. 2: Maximum possible rainfall 8000 years ago over the Arabian Peninsula as simulated by Guagnin et al. (2016) using the Community Earth System Models (COSMOS) toolbox. See the original source for parameters and constraints of the simulation. See Fig. 1 for colour codes of lake sites.

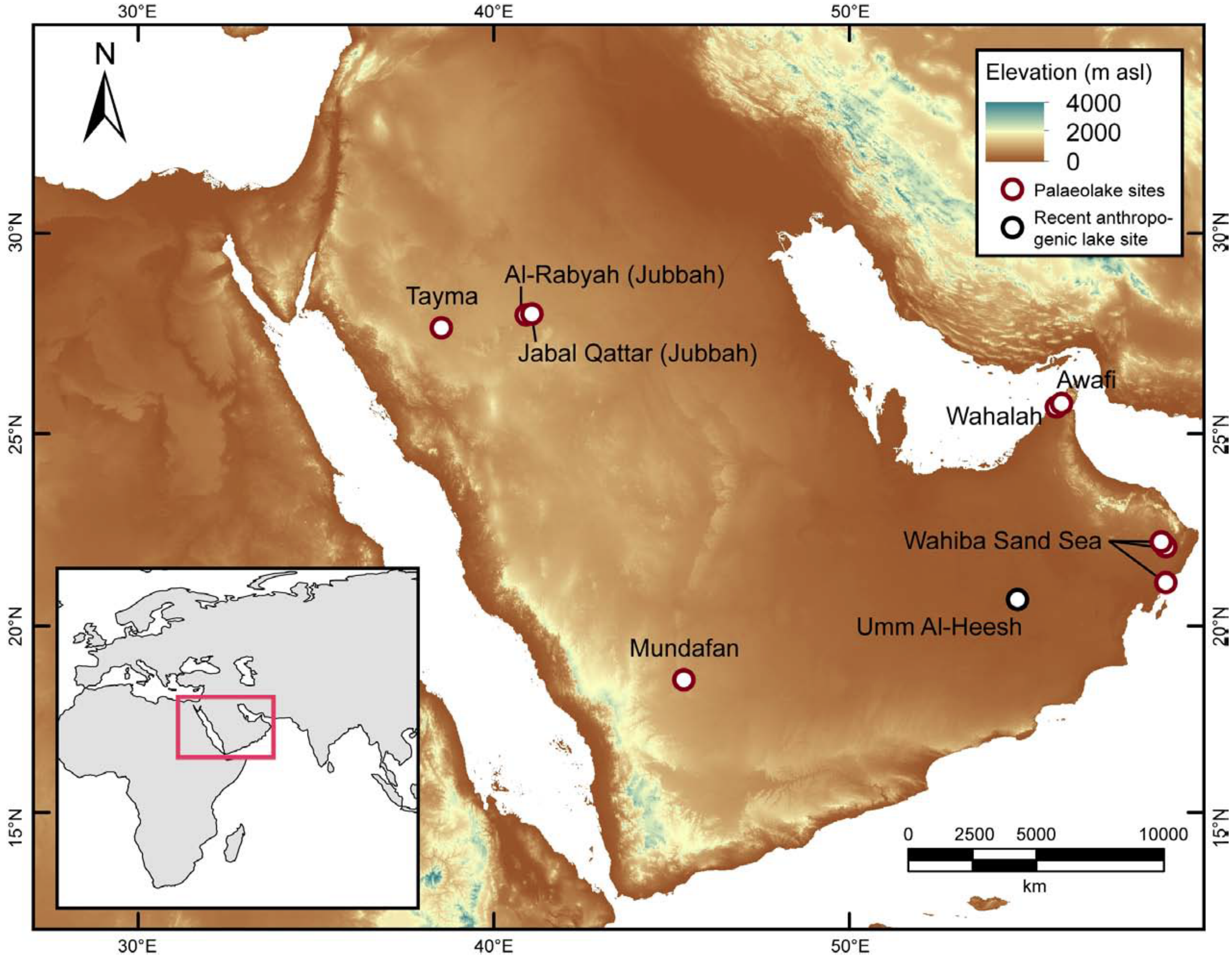
Fig. 3: a) Bioclastic shoreline deposits inclining towards the sabkha basin at Tayma (M. Engel, 2010). They mainly comprise shells and tests of gastropods, barnacles, ostracods and foraminifers and were dated to the early Holocene (Tay 177 in Engel et al., 2012; Pint et al., 2016). Some barnacles (*A. amphitrite*) are found in living position attached to proximally dislocated rock fragments from the nearby outcrop of Hanadir sandstone. (b) Remnants of barnacle colonies in living position attached to Hanadir sandstone. Saltating sand grains reflect strong sandblasting working against the

preservation of shoreline indicators (M. Engel, 2007). Both sites are located along the southwestern margin of the sabkha basin, approximately 16 m above the bottom of the Holocene palaeolake (Engel et al., 2016).

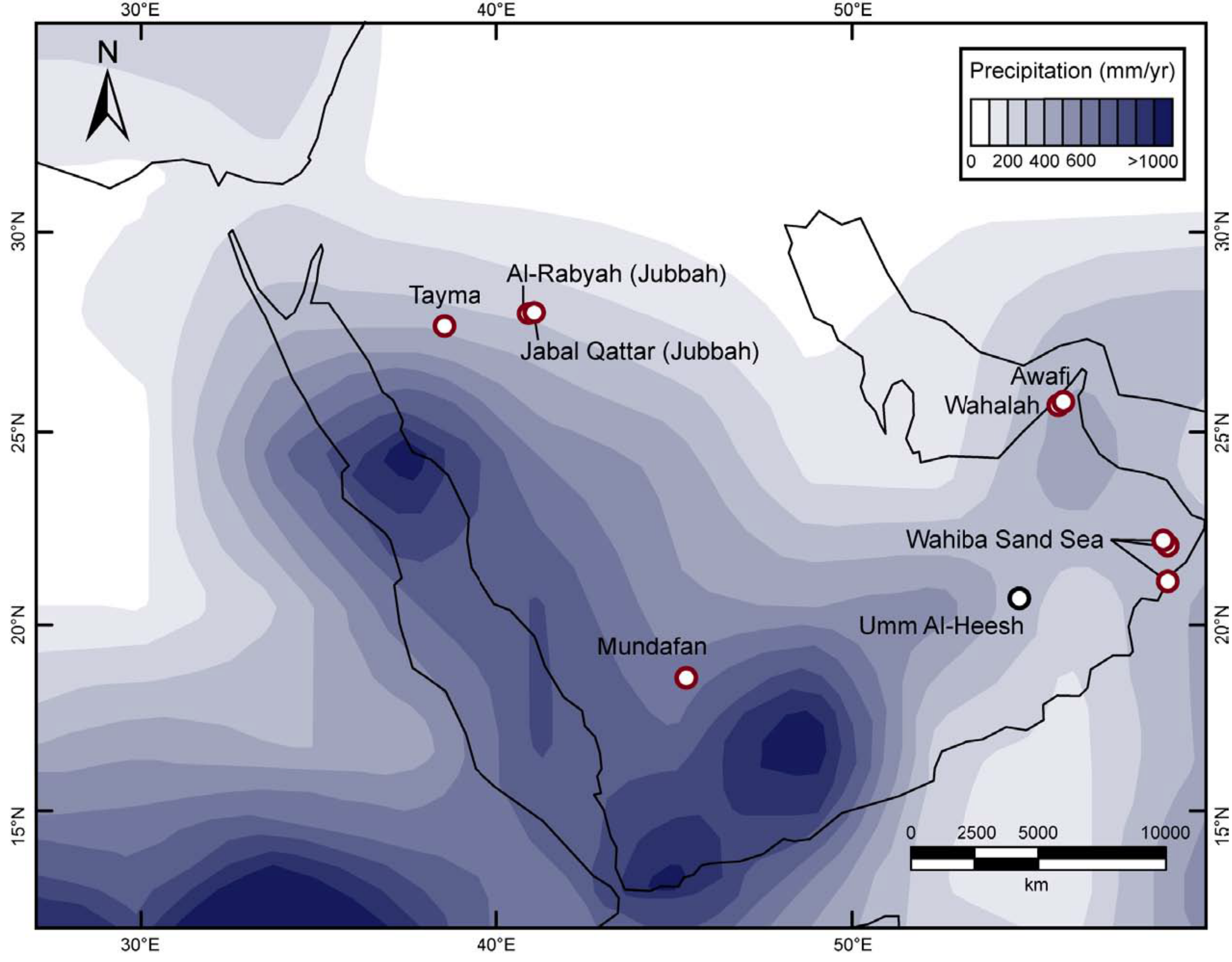
Fig. 4: (a) CORONA (1965), (b) Maps Geosystems (1980) and (c) Google Earth/Digital Globe (2013) imagery of Wahalah palaeolake.

Fig. 5: Photograph of Awafi palaeolake taken in 2005.

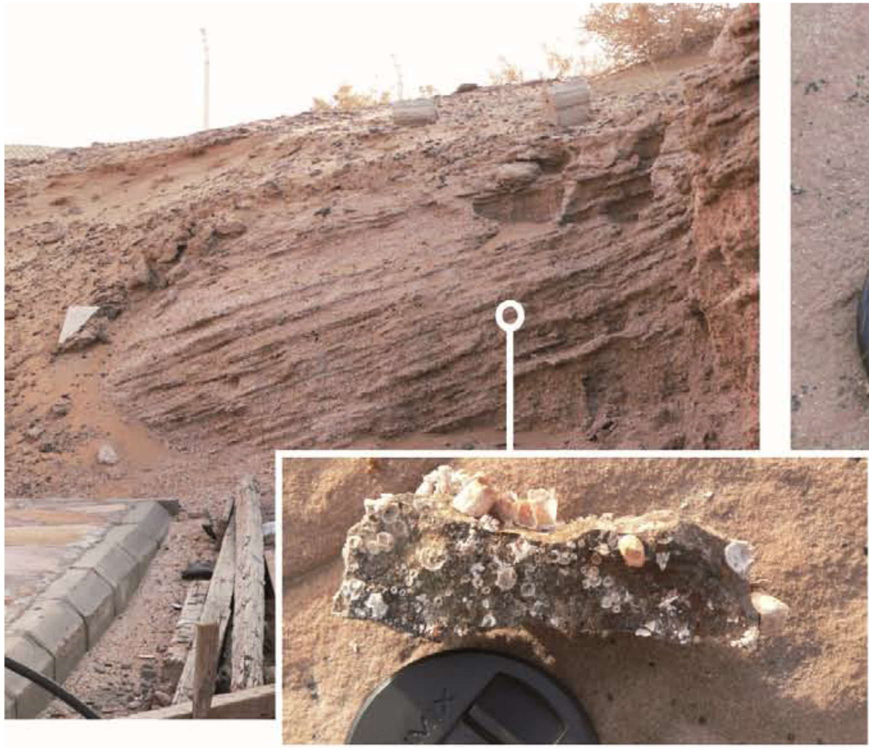
Fig. 6: Small interdunal lakes at Umm al-Heesh (Fig. 1) fed by a leaking oil well and likely representing a modern analogue of Pleistocene and Holocene lakes in the Rub' al-Khali.



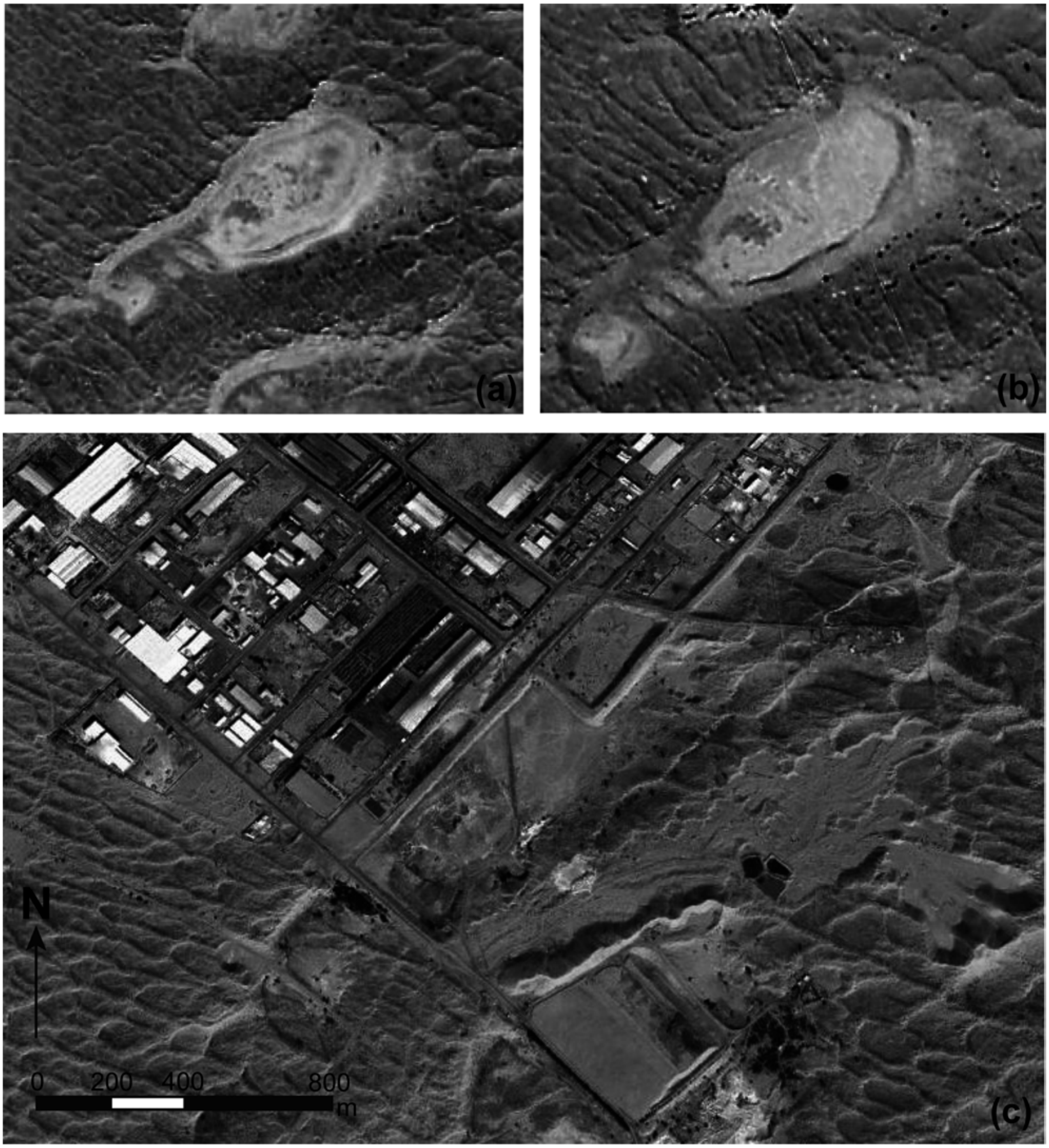
30°E
40°E
50°E
N
Elevation (m asl)
4000
2000
0
Palaeolake sites
Recent anthropo-
genic lake site
30°N
25°N
20°N
15°N
Tayma
Al-Rabyah (Jubbah)
Jabal Qattar (Jubbah)
Awafi
Wahalah
Wahiba Sand Sea
Umm Al-Heesh
Mundafan
0
2500
5000
10000
km



30°E
40°E
50°E
N
Precipitation (mm/yr)
0
200
400
600
>1000
30°N
25°N
20°N
15°N
Tayma
Al-Rabyah (Jubbah)
Jabal Qattar (Jubbah)
Awafi
Wahalah
Wahiba Sand Sea
Umm Al-Heesh
Mundafan
0
2500
5000
10000
km




LUMIX


(a)
(b)
N
0
200
400
800
m
(c)

Highlights

- Sedimentary lake records from Arabia were reinterpreted as wetlands by Enzel et al.
- Multiple evidence for Early to Mid-Holocene lakes missed by Enzel is compiled
- Increased African Summer Monsoon-related rainfalls charged aquifers, fed lakes