Quaternary Research

doi:10.1017/qua.2018.142

Geoarchaeology of Holocene oasis formation, hydro-agricultural management and climate change in Masafi, southeast Arabia (UAE)

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(Received January 26, 2018; Accepted November 13, 2018)

Abstract

Oases are subject to decreasing resources and changing human activities. Fully aware of their rich heritage, the United Arab Emirates (UAE) have undertaken work to preserve and revitalize these oases. However, there is a clear lack of understanding of the dynamic links between climate change, hydraulic and agricultural management, and socioeconomic activities. To clarify these links, our team conducted a systematic geoarchaeological, geophysical, spatial, and chronological study of the Masafi oasis, UAE. Results indicate the existence of a natural humid area as early as the late Pleistocene (~18 cal ka BP). These conditions persist during the early-mid Holocene with drainage activation and soil development (~12–6.3 ka). During the late Holocene, after the emergence of the "artificial" oasis around ~3250 cal yr BP, cycles of intense management suggesting water availability (~3250–2380 cal yr BP; 550 cal yr BP) alternate with episodes of fluvial detritism (~2380–1870 cal yr BP; >550 cal yr BP) and scattered evidence of farming activities with complex hydroclimatic signatures (~2300–550 cal yr BP). These results, together with regional environmental data, indicate that water and soil resources were available and exploited strategically throughout the Holocene despite adverse climatic conditions, and the oasis of Masafi could have acted as a desert *refugium*.

Keywords: Oasis; Agriculture; Soil; Water; Irrigation; Climate; Chronology; Geoarchaeology; United Arab Emirates; Masafi

INTRODUCTION

Oases are precious and unique anthropogenic landscapes in semi-arid and arid environments. Key socioeconomic nodes, places of residency and circulation, they are also intensively cultivated and irrigated spaces (Lacoste, 2014). While many oases are still exploited and managed in the world, they are considered today to be in critical condition. Less than 50 years ago, oases were the main elements of southeast Arabia's landscapes (United Arab Emirates [UAE] and Sultanate of Oman; Fig. 1), in the Al Hajar Mountains and along their piedmonts. Recent and fast development, drastic changes in population size, climate change, and consequent decreasing resources have led to the massive development of deep groundwater pumping (Mershen, 1998; Diener et al., 2003; Korn et al., 2004), at the expense of traditional agricultural practices and water management. In recent years, the UAE have implemented an active conservation program to preserve and revitalize some of these oases (al-Ismaily and Probert, 1998). To guarantee their successful preservation, however, it is essential to understand the interacting processes involved in their changes, not only the ones prevailing today, but also the long-term socio-environmental dynamics responsible for their formation, evolution, and current state (e.g., Garcier and Bravard, 2014; Charbonnier et al., 2017b). This study aims to better comprehend the coevolution of climate change, farming strategies (water and soil management), settlement patterns, and socioeconomic activities.

In southeast Arabia, the Holocene climate history has been mainly inferred from paleolacustrine records, eolian sediments,

Cite this article: Purdue, L., Charbonnier, J., Régagnon, E., Calastrenc, C., Sagory, T., Virmoux, C., Crépy, M., Costa, S., Benoist, A. 2019. Geoarchaeology of Holocene oasis formation, hydro-agricultural management and climate change in Masafi, southeast Arabia (UAE). *Quaternary Research* 92, 109–132.

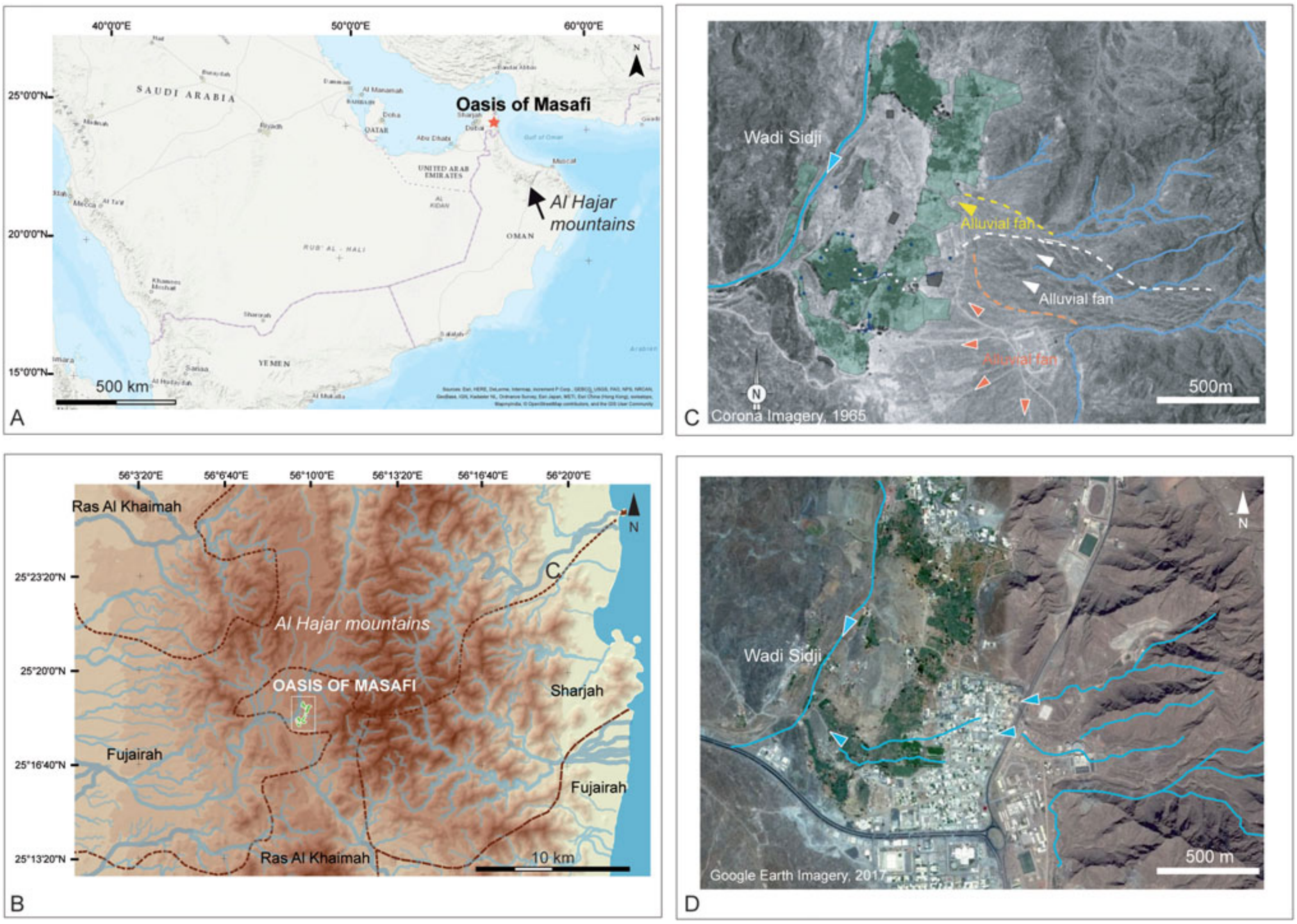

Figure 1. Geographical and hydrological background. (A) Location of Masafi in the United Arab Emirates. (B) The Masafi palm grove in the Emirate of Fujairah and the center of the Al Hajar Mountains. (C) Corona Image from 1965 and zoom on the palm grove and the eastern alluvial fans flowing in its direction. The arrows and dashed lines indicate the orientation of the flow and the spatial extent of the fans (yellow, white, and orange from the oldest fan to the most recent one). (D) Google Earth Image (2017) with the urbanization of Masafi and the incised streams in blue partly flowing towards the palm grove and Wadi Sidji. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

speleothems, and occasionally fluvial deposits. These archives have revealed that Arabia was a very different landscape during the early and mid- Holocene period (~10.6 to ~6.3 ka; Fleitmann and Matter, 2009). A progressive increase in precipitation favored by the northward migration of the Intertropical Convergence Zone (ITCZ) and the Indian Ocean monsoon system (e.g., Burns et al., 2001; Fleitmann et al., 2003a, 2007), or to the African monsoon expanding over Arabia (Jennings et al., 2015), provided favorable conditions for vegetation growth (e.g., Parker et al., 2004, 2006; Preston et al., 2012, 2015; Hilbert et al., 2014) and lake development (Parker et al., 2004). Climatic conditions change abruptly around 6.2 ka. A decline in summer rainfall, due to the southward retreat of the monsoon rain belt coupled with a reduction in winter rainfall, resulted in the widespread desiccation of lakes (Parker et al., 2006), the cessation of speleothem growth (Fleitmann et al., 2003a, 2003b), increased eolian activity (Atkinson et al., 2011), and peaks in aridity (between 5.4–5.1 ka; Preston, 2011). Beyond that date, there is a paucity of environmental records. Climatic data is mainly provided by cave speleothems highlighting humid periods between 4–2.7 ka (Fleitmann et al., 2007), 2.2–1.9 ka, and 450–350 yr (Fleitmann et al., 2003a). Regrettably, this data is often disconnected from terrestrial landscapes, human occupations, and land use. Fluvial archives, which could provide this missing link, are patchy and weakly dated (Berger et al., 2012). Indeed, they are rarely discovered in southeast Arabia, due to the presence of the Al Hajar mountain chain and its Pleistocene alluvial fans. One object of research that has been completely neglected and that could provide new and relevant information on climate change and land use are oases that appear around the fourth millennium BC. The structure and sediments composing them are archives of Holocene natural and artificial landscapes, which can provide direct data on hydroclimatic conditions prior to human interventions and indirect data via resource—soil and water—management and subsistence strategies (Charbonnier et al., 2017a).

Archaeological studies in southeast Arabia have highlighted the existence of many cycles of sedentism and land abandonment throughout the Holocene. Data is scattered for the early to mid-Holocene (Drechsler, 2009) but a decline in occupation is well-attested inland around ~ 5900 cal yr BP

https://doi.org/10.1017/qua.2018.142 Published online by Cambridge University Press

Table 1. Major chrono-cultural phases in Southeast Arabia (Magee, 1995, 1997) correlated with occupation at Masafi.

Cultural period	Sub-period	Chronology (BC–AD)	Chronology (cal yr BP)	Occupation in Masafi
Bronze Age	Early (Umm an-Nar)	2700–2000 BC	4650–3950	?
	Middle (Wadi Suq)	2000–1600 BC	3950–3550	Masafi 4
	Late	1600–1200 BC	3550–3150	Masafi 4 and 5
Iron Age	I	1200–1100 BC	3150–3050	Masafi 5
	II	1100–600 BC	3050–2550	Masafi 1–4
	III	600–300 BC	2550–2250	?
Late Pre-Islamic		300 BC–AD 350	2250–1600	?
Sasanian		AD 350–732	1600–1218	?
Islamic period	Early	AD 700–1000	1218–950	?
	Middle	AD 1000–1400	950–550	?
	Late	AD 1400–1900	550–50	Falaj/Fort/Residence

(Parker and Goudie, 2008). This "Dark Millennium" witnesses increasing occupation along coastal areas (e.g., Méry et al., 2009) and probably in refugia in the Al Hajar Mountains, where local resources could have been available (Presten and Parker, 2013). After ~4500 cal yr BP, on the onset of southeast Arabia's current climatic regime, phases of land conquest (4500–3600, 3050–2600, and 550–50 cal yr BP) resulted in the emergence and development of oases (Cleuziou, 2005) alternating with phases of population movements (3600–3250 and 2600–2300 cal yr BP) and periods for which we have very little data (2300–550 cal yr BP; Table 1). Between ca. 4500 to 2300 cal yr BP, the socioeconomic system was structured around the exploitation, transformation, and export of copper ingots from the Al Hajar mountain chain (Cleuziou, 1982, 1997, 1999, 2009), while later and current oases (550–50 cal yr BP) invested more in developing cash crops. The paleobotanical study of early oases has pointed out the cultivation of cereals (Tengberg, 2003) and date palms (e.g., Cleuziou and Costantini, 1980; Weisgerber, 1981; Willcox, 1995; Tengberg, 1998), which was also the case for more recent palm groves. Arabian farmers used and still use wells, cisterns, and channels to manage water but they also massively invested, probably from ~3050 cal yr BP (al-Tikriti, 2002), in underground galleries to distribute groundwater, a technology referred to as falaj in the UAE. Farmers would have coped with the Holocene aridification and decreasing levels of the aquifers by deepening their galleries and gardens. Based on the similarities between past and current water management and vegetation cover, and the disappearance of ancient gardens as a result of their digging progressively deeper, the study of oases has been hampered by the denial of their diachronic and dynamic dimensions (Power and Sheehan, 2011). Only very recent interdisciplinary studies in Arabia have refined our vision of the history of oases. Studies in the oasis of Tayma (Wellbrock et al., 2017), Al Ain (al-Tikriti, 2002; Power and Sheehan, 2011), Al-Madam (Córdoba, 2013), Bat (Desruelles et al., 2016), and Masafi (Charbonnier et al., 2017a, 2017b), the latter integrated into a larger project on multiple oases (Project ANR – Agence National de la Recherche OASIWAT, Director L. Purdue) have revealed that oases can be studied, and that they are dynamic, resilient, and mobile landscapes. Numerous questions remain, however, as we know very little about oasis agrosystems (soil and water management) and climate change.

In this paper, we aim to better comprehend and discuss oasis formation, management, and climate change, as well as their dynamic interactions during the Holocene, a period poorly documented in Arabia and for which sedimentary archives are scarce. Based on the systematic study of one oasis, the oasis of Masafi (Hajar Mountains, Emirate of Fujairah, French Archaeological Mission in the UAE), we are able to answer three major questions: What was the initial natural environment during the Holocene and when did the oasis system of production appear? How did this system evolve in the framework of long-term and abrupt climate changes? How does this system compare to other landscapes in southeastern Arabia? We propose here a diachronic reconstruction of the oasis landscape using the methods of agrarian geoarchaeology, hydraulic archaeology, spatial analysis, geophysics, chronology, and geomorphology. The combination of these methods in a well-dated archaeological environment and on thick sedimentary sequences have allowed us to provide new and unique data on water and agricultural strategies, provide new sedimentary archives of Holocene terrestrial dynamics, discuss the impact of Holocene climate change on Arabian communities, and rethink the environmental and landscape history of southeastern Arabian oases.

STUDY AREA

Climatic, geological, and hydrological background

The oasis of Masafi is located north of the Al Hajar Mountains (Fig. 1A). The mountain chain, which covers Northern Oman and the United Arab Emirates (UAE), is nearly 700 km long, 40 to 130 km wide, and 3000 m high in some areas. These mountains contain two scarce and precious resources: copper and water. Composed of superimposed sheets of Cretaceous limestone and ophiolites (gabbros, peridotite, serpentinite, and copper veins) as a result of subduction events during the Cretaceous and renewed uplift during the Oligocene, these geological formations are also fractured, enabling the recharge of most aquifers and the formation of springs. To the east and the west of the mountains, lying on top of the bedrock, old and recent Quaternary alluvial deposits (Tourenq et al., 2011) also contain the largest reserve of fresh groundwater aquifer (Rizk and El Etr, 1997; Brook et al., 2006). This supply in water has been crucial through time in the bimodal arid to hyper-arid climate of the Al Hajar Mountains (Böer, 1997). Temperatures in Masafi reach an annual average value of 28.4°C with average summer temperatures of 35.3°C (June to September) and 23°C in winter (December to March; http://worldweatheronline.com, 2009–2017 average). Annual average precipitation do not exceed 161 mm/year, with precipitation in summer (June to August) reaching an average of 0.6 mm and 30.7 mmm in winter (December to March; http://worldweatheronline.com, 2009–2017 average). The low amount of rainfall in winter (rainfall from the east coast of Africa, frontal storms from the Mediterranean, and southward advance of the westerlies) and during the summer months (Indian Monsoon convective storms and northward shift of the ITCZ), would have required the development of specific irrigation techniques and soil management.

The oasis of Masafi is located in a small depression at the border between the Emirate of Fujairah to the south (our area of study) and the Emirate of Ras al Khaimah to the north (UTM coordinates: 40 R, 415730 E, 2798920 N; Fig. 1B). This terraced palm grove covers nearly 50 ha in the upstream basin of Wadi Sidji (Fig. 1B and C). This intermittent and entrenched stream flows west-southwest through the Al Hajar Mountains and into the dunes of the Rub' al-Khali desert, 30 km downstream. While the oasis overlooks the wadi to the west, it is surrounded by high-sloped bedrock and Quaternary alluvial fans (Fig. 1C), composed of basic igneous bedrock part of the Ophiolite complex, mainly harzburgite and serpentinite with calcite veins. Lying on top of the bedrock are Quaternary deposits, comprised of boulders, cobbles, gravel, and sand, increasingly cemented in their lower part.

The study of satellite images (Fig. 1C and D) has highlighted the fact that Masafi is directly located in the trajectory of gullies located at the terminal end of alluvial fans originating 1 to 1.5 km to the east. These fans are composed of coarse gravel, stones, and blocks of harzburgite, as well as some blocks of limestone and finer material composed of light yellowish-brown silty sands, which correspond to weathered deposits and old pockets of eolian sands. Channeling these gullies could have provided both soil and water to agricultural fields but sheetflow erosion or uncontrolled water management could have led to soil erosion as well as the deposition of coarse sediments in cultivated areas of the palm grove.

Masafi has been the main producer of mineral water in the Gulf since 1976. Today, water is drilled into deep aquifers to irrigate the dominant date palms. Indeed, apart from a few mango and jujube trees, carrots, and onions, traces of agriculture are scarce in the palm grove.

Archaeological background

Archaeological excavations have been conducted in Masafi since 2007 (directed by A. Benoist 2007–2016 and J. Charbonnier since 2017) as part of the French Archaeological Mission in the United Arab Emirates (directed by S. Méry). These excavations have allowed for the discovery of five sites surrounding the palm grove and occupied since the Bronze Age (Masafi 1–5; Fig. 2A, Table 1; Benoist et al., 2012; Benoist, 2013). Masafi 4 and Masafi 5, located on small hills, are respectively dated from 3950–3550 cal yr BP (Middle Bronze Age) to 3050–2550 cal yr BP (Iron Age II), and 3550–3050 cal yr BP (Late Bronze / early Iron Age I). The three other sites, Masafi 1–3, were occupied between 3050–2550 cal yr BP (Iron Age II). Masafi 2 is a large fortified village erected on the rocky hill of Jebel Halyan. Masafi 1 is a large building with a pillared room, surrounded by a probable market 60 m to the south. Masafi 3 is a small shaped sanctuary where incense burners and copper snake figurines were discovered. In our current state of knowledge, the area of Masafi seems to have been abandoned around 2550–2550 cal yr BP (Iron Age III) and up until ~550 cal yr BP (Late Islamic period; Benoist et al., 2013). After that date, a mud brick fort and mosque were built south of the palm grove, while small stone structures and masonry houses were in use at the site of Masafi 2. The discovery of numerous Chinese and Japanese sherds suggests that Masafi was well integrated in an international trade network (Sasaki and Sasaki, 2006). During the first half of the twentieth century AD, the father of the current sheikh of Fujairah built his residence east of the oasis, above the ruins of Masafi 3 (Ziolkowski and al-Sharqi, 2005), underlining the persistent importance of the oasis through time.

MATERIAL AND METHODS

Mapping the spatial and vertical extension of the palm grove and its watershed

To understand the spatial extension of the palm grove, its structure, and main components, the current oasis was placed within its microregional to regional archaeological and geomorphological context. Data were extracted from the Shuttle Radar Topography Mission (digital elevation model [DEM] with a 90-m resolution) and from topographic maps at a scale of 1/25000 published in 1976 and kindly provided to us by the Fujairah Municipality. In the perspective of a regressive approach, the oasis structures (terrace boundaries and slope changes), hydraulic constructions (canals, wells, and cisterns), and houses were mapped. This survey was conducted using mainly a differential GPS (DGPS) in more open areas and a total station in densely vegetated areas. In parallel, and in order to cover the largest area possible, kite views were taken using a camera fixed on a kite. These vertical views, replaced in a geo-referenced frame located using the DGPS and/or total station, were used to build a DEM (Fig. 2A and B) by photogrammetry and orthographic pictures using Agisoft Photo Scan Pro. These data (DGPS, total station, photogrammetry) were combined using the GIS software (Arcgis 10.2), allowing us to obtain a model

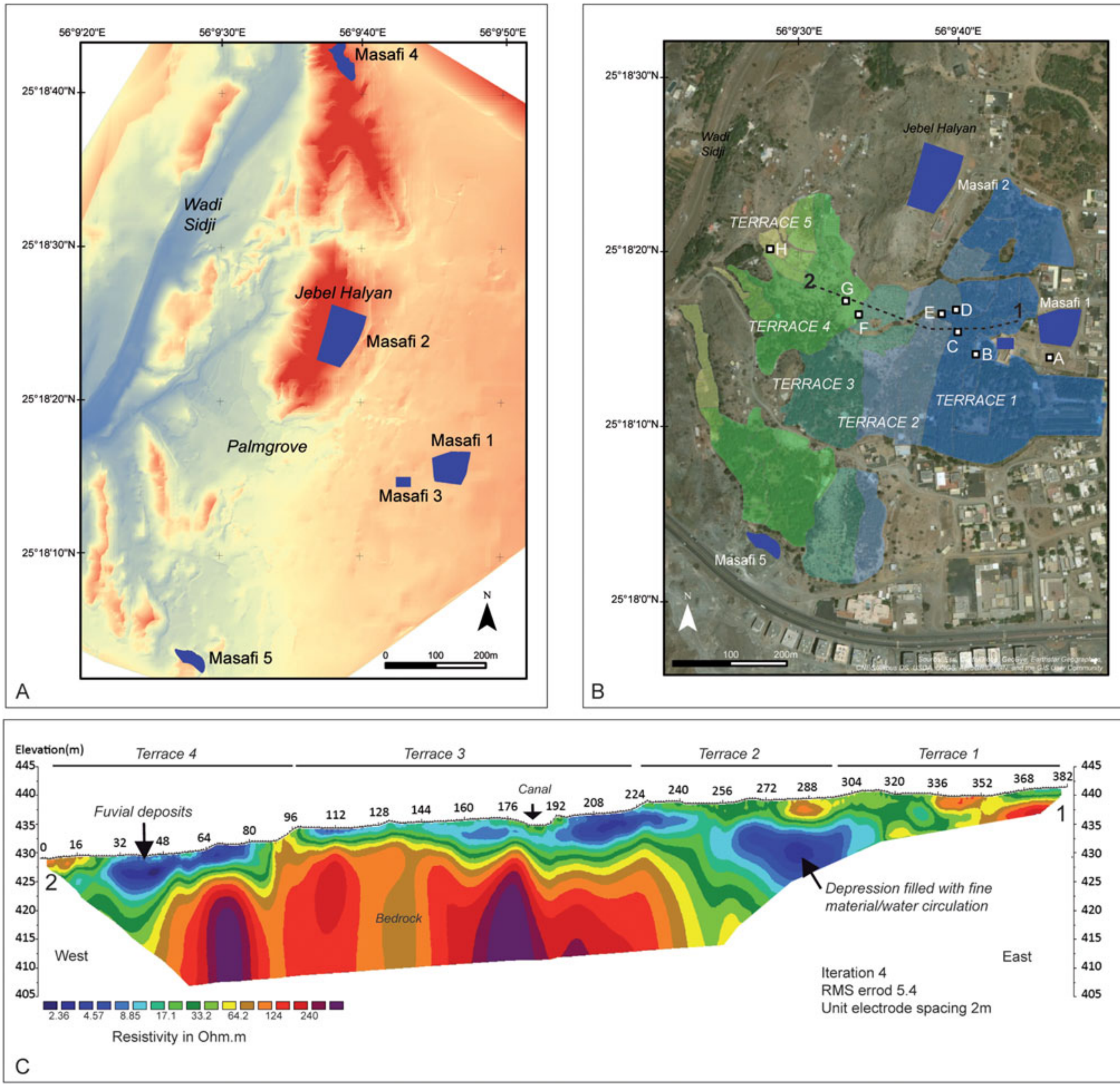

Figure 2. (color online) The Masafi palm grove. (A) Digital elevation model of the palm grove and location of the main archaeological sites. (B) Location of the five main terraces and the eight test pits studied. The dashed line corresponds to the geophysical transect. (C) Results of the electrical resistivity tomography (ERT) geophyical profile.

covering a 10 × 10 m dot grid (Fig. 1B and 2A), as well as providing information on the excavations. The surface covered by this detailed mapping comes to 29 ha with a resolution ranging from 10 cm under the palm trees to 5 cm in open spaces.

In order to understand the paleotopography of the palm grove, we conducted in 2017 a geophysical survey involving two-dimensional electrical resistivity tomography (ERT). ERT was carried out with a Wenner-Schlumberger array and the device used a multi-electrode system Abem Terrameter LS with 64 electrodes. An electrode spacing of 2 m allowed us to investigate 382 m, following an east-west transect, at a depth of nearly 12 m. Data inversion and interpretation were carried out using the Res2dinv software (Loke and Barker, 1996), which uses a least-square inversion technique to get a subsurface model from apparent resistivities measured in the field. Less than five iterations allowed us to get a RMS error below 5%, which is considered as satisfying (Fig. 2C).

Agrarian geoarchaeology and hydraulic archaeology

In order to understand the formation and evolution of the palm grove, we decided to pursue a systematic study of the

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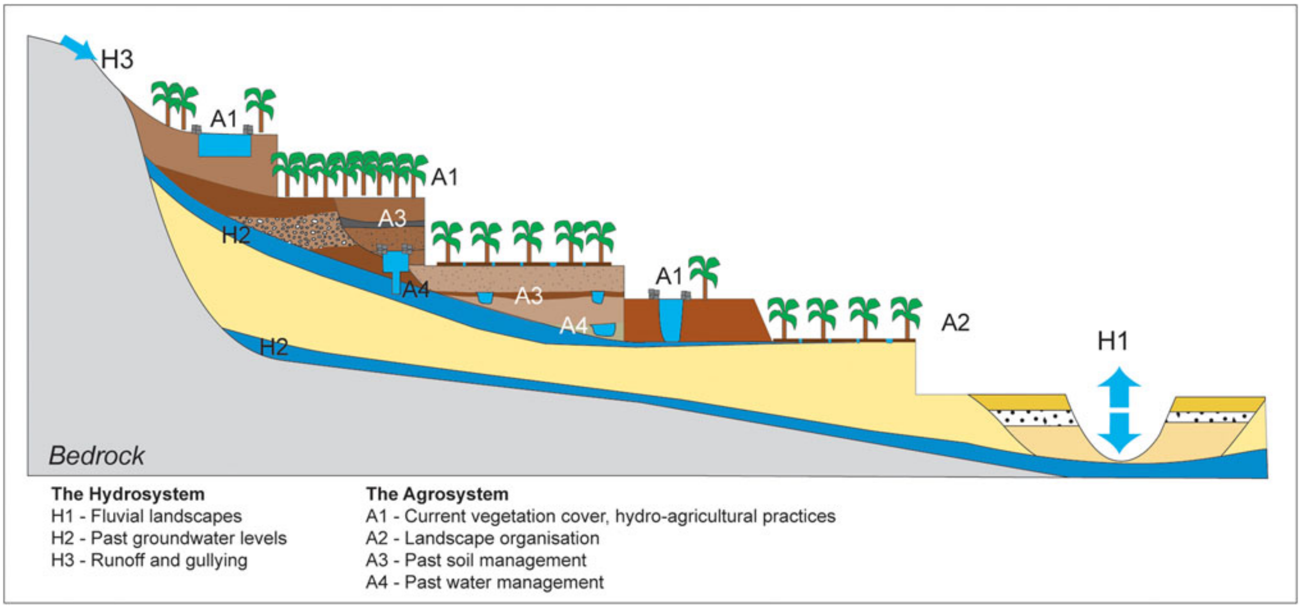

Figure 3. (color online) Principle and objectives of the geoarchaeological study of oases to reconstruct the long-term dynamics of the hydrosystem and the agrosystem.

agricultural terraces to identify irrigated fields and connected hydraulic structures. The approach and methods adopted are based on the ones of geoarchaeology, archaeology, agronomy, chronology, and taphonomy of hydraulic and agricultural systems (Fig. 3; Berger and Jung, 1996; Purdue and Berger, 2015). Eight test pits (TP) were dug between 2011 and 2016 (east-west transect) in the framework of the excavation of Masafi 1 (TP A) and directly in the palm grove to understand the past and current organization of the terraces (TP B–H; Fig. 2B). Each stratum was defined based on its texture, color, structure, stratigraphic boundaries, as well as the presence of macroremains (e.g., charcoal and shells), artifacts (sherds), and pedological features (e.g., secondary carbonates, iron oxides, and bioturbation). The precise description of the strata allowed us to create a typology of the deposits encountered and classify sterile layers, agricultural soils, eolian deposits, and major phases of erosion, as well as hydraulic structures such as canals and wells. Due to the high number of strata identified, this typology is key to chronostratigraphical correlations throughout the palm grove.

Radiocarbon, optically stimulated luminescence (OSL), and ceramic dating

Agricultural environments and terraces are very difficult to date, even more so when they are constantly reworked and modified (e.g., Acabado, 2009; Kinnaird et al., 2017). Dating the Masafi terraces was obtained by four means. First, accelerator mass spectrometry dating was conducted when in situ burning events were visible or layers of charcoal were identified in agricultural deposits or hydraulic structures. In this situation, sampling was made directly in the profile. More often, however, charcoal and large macroremains were obtained after sieving 10 L of bulk sediments and sorting under binoculars. Samples were identified when possible prior to their dating. Fifteen radiocarbon dates were processed at the Poznan Radiocarbon Laboratory (Table 2). The protocol consists in a chemical pre-treatment (Brock et al., 2010), followed by the combustion and graphitisation of the sample (Czernik and Goslar, 2001). The ^{14}C content was measured by a "Compact Carbon AMS" spectrometer (Goslar et al., 2004) and the ^{14}C age calculated (Stuiver and Polach, 1977) and calibrated using INTCAL 13-calibration curve (Reimer et al., 2013) on the OxCal ver. 4.2 software (Bronk Ramsey and Lee, 2013).

The second method used at Masafi is OSL dating, which provides dates in briefly used structures (Berger, 2003; Huckleberry and Rittenour, 2013). Two dates were processed at the Oxford Dating Luminescence Laboratory. The protocol is based on the luminescence measurement of sand-sized quartz, extracted and measured in a Lexsyg Smart luminescence reader (Richter et al., 2015) using a single aliquot regenerative post-infrared (post-IR) blue OSL measurement protocol (Wintle and Murray, 2006). One further sample was dated at the University of Freiburg using the same device. The fine-grained (silty) sample, however, did not deliver enough quartz grains and a post-IR infrared stimulated luminescence protocol was applied, using a stimulation temperature of the second measurement at 225°C. Dose-rate calculations were obtained using DRAC (Durcan et al., 2015) and are based on the concentration of radioactive elements derived from elemental analysis (Oxford, ICP-MS/AES; Freiburg, high-resolution gamma spectrometry). The paleodose determination and rate calculations are based on Aitken (1985) and integrate attenuation factors (Mejdahl, 1979), dose rate conversion factors (Guerin et al., 2011), and an absorption coefficient for the water content (Zimmerman,

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Table 2. Radiocarbon dates obtained in the test pits studied. All the dates were calibrated using INTCAL 13-calibration curve (Reimer et al., 2013) and Oxcal ver 4.2 software (Bronk and Lee, 2013).

Sites and excavation year	Terrace	Test pit	Stratigraphic unit	Material dated	Laboratory code	Age ^{14}C BP	±1 σ (95%)	Calibrated age cal yr BP 2 σ (95.4%)	Status
MSF 11	1	A	45	Microcharcoal	Poz-53975	2680	30	2847–2752	Accepted
MSF 14	1	B	35	*Ziziphus* sp.	Poz-64519	2945	35	3211–2989	Accepted
MSF 14	2	C	7	Microcharcoal	Poz-64517	2520	35	2745–2490	Accepted
MSF 14	2	C	25	Microcharcoal	Poz-64518	1545	30	1525–1371	Accepted
MSF 15	2	D	37	*Ziziphus* sp.	Poz-77512	2475	35	2721–2381	Accepted
MSF 15	2	D	12	Microcharcoal	Poz-77434	2000	35	1858–1874	Accepted
MSF 15	2	D	15	Microcharcoal	Poz-77435	630	30	663–551	Accepted
MSF 11	2	E	10	Microcharcoal	Poz-53976	3315	35	3637–3463	Debated
MSF 11	2	E	3	Microcharcoal	Poz-53977	850	80	923–671	Debated
MSF 14	3	F	3	Microcharcoal	Poz-64515	375	30	504–317	Accepted
MSF 14	3	F	9	Microcharcoal	Poz-64515	465	30	540–485	Accepted
MSF 14	3	F	11	Microcharcoal	Poz-64590	325	30	471–306	Accepted
MSF 14	3	F	15	Microcharcoal	Poz-64591	330	30	473–307	Accepted
MSF 16	2	OTHER	2	Organic matter	Poz-80588	14720	110	18,210–17,621	Debated
MSF 16	2	OTHER	2	Charcoal	Poz-90232	110	0.29	257–31	Rejected

1971). The contribution of cosmic radiation to the total dose rate was based on data by Prescott and Hutton (1994), and rely on latitude, altitude, and burial depth (Tables 3 and 4).

The third method used is ceramic dating. Sherds were systematically sampled during the excavation of the TP (Table 5) and identified by A. Benoist and M.-P. Pellegrino. Ceramics were found in primary or secondary position. Most of the sherds encountered, rounded and eroded, and probably in secondary position, were dated between 3250–2600 cal yr BP (Iron Age I and II) or 1218–500 cal yr BP (Islamic period; Magee, 1996; Benoist, 2000; Kennet, 2004), and might have originated from Masafi 1 and 3. Indeed, these sites to the east were subject to erosion and gullying (Charbonnier et al., 2017a) and some of these gullies seem to have found their way to the gardens (Fig. 1C). Some sherds could also have been brought with displaced soils or with fertilizers (waste is often spread in the fields). The sherds therefore mainly provide us with a terminus post quem. What is significant here is that only Iron Age sherds were encountered in the Iron Age cultivation layers, strengthening the results of absolute dating.

Last, chronostratigraphical control based on the definition of sedimentary facies was used as relative dating on terraces for which similar paleosoils or phases of agricultural use were encountered.

RESULTS

The spatial organization and (paleo)topography of the palm grove

Field surveys, the DEM, and the geophysical transect provide extremely relevant information on the current and past organization of the palm grove, which is difficult to perceive and

Table 3. Optically stimulated luminescence (OSL) dates conducted on quartz grains at the Luminescence Dating Laboratory of the University of Oxford (J.-L. Swenniger). The year of processing is 2016.

Sites and excavation year	Terrace	Test pit	Depth (cm)	Stratum	Lab. code	Water content (%)	Paleodose Q (Gy)	Dose rate (Gy/Ka)	OSL estimate (ka before 2016)
MSF 14	2	C	235	16	X66-77	5.96	2.6 ± 0.17	1.22 ± 0.07	2.32–1.95
MSF 14	1	B	205	3	X6964	5.58	12.26 ± 0.9	1.22 ± 0.04	10.19–9.17

Table 4. Optically stimulated luminescence (OSL) date conducted on feldspar grains at the University of Freiburg (F. Preusser). The year of processing is 2016.

Site and excavation year	Terrace	Test pit	Depth (cm)	Stratum	Lab. code	Water content (%)	DeIR-50 (Gy)	De pIR-225 (Gy)	Age IR-50 (ka before 2016)	Age pIR-225 (ka before 2016)
MSF 11	2	E	210	4	FR-0186	5.96	19.51 ± 0.71	24.79 ± 2.08	7.07–6.33	9.23–7.41

https://doi.org/10.1017/qua.2018.142 Published online by Cambridge University Press

https://doi.org/10.1017/qua.2018.142 Published online by Cambridge University Press

Table 5. Ceramics extracted from the test pits during their excavation and chronology. *, sherds that can be associated with certitude with a specific stratigraphic unit; Terr, Terrace; TP, Test Pit; SU, Stratigraphic unit; Undat., Undated; dep., deposition; P, primary; S, secondary.

Sites /excavation year	Terr.	TP	SU	Numb. of sherds	Preserved shapes	Iron Age II sherds	Late Islamic sherds	Un dat.	Context of dep.	Type of deposit	Cultural period	Absolute chronology (^{14}C and OSL)
MSF 14	1	B	8*	1				1	?	Plantation Hole		3211-2989 cal yr BP
MSF 14	1	B	12*	4		4			P.	Cultivated Layer	Iron Age	
MSF 14	1	B	26*	1		1			P.	Occupational level	Iron Age	
MSF 14	1	B	27*	3		3			P.	Occupational level	Iron Age	
MSF 14	2	C	8*	7	1IA	7			P.	Cultivated Layer	Iron Age	2745-2490 cal yr BP
MSF 14	2	C	9*	1		1			P.	Well		
MSF 14	2	C	10*	1		1			P.	Well		
MSF 14	2	C	15–16*	25	3IA	25			S.	Cultivated Layer	Iron Age	2.32.1.95 ka
MSF 14	2	C	17–18*	3		3			S.	Gully		
MSF 14	2	C	22*	2		2			S..	Cultivated Layer		
MSF 14	2	C	24*	21		21			S.	Gully		
MSF 15	2	D	1–37	6		5		1	P..?	Cultivated Layer	Iron Age	2721–2381 cal yr BP
MSF 15	2	D	3–6	13		13			S.	Gully	Iron Age	
MSF 15	2	D	7–19	8	1IA	8			S..	Cultivated Layer?	Islamic	1858–1874 / 663–551 cal yr BP
MSF 15	2	D	20–22	13	3IA	13			S.	Gully	Islamic	
MSF 15	2	D	23–27	14		12		2	S.	Cultivated Layer	Islamic	
MSF 15	2	D	28	1			1		P.?	Cultivated Layer	Islamic	
MSF 14	3	F	11a	1			1		S..	Canal fill	Late Islamic	471–306 cal yr BP
MSF 14	4	G	38–48	1			1		S..	Pit	Late Islamic	

map under the dense vegetation cover (Fig. 2A–C). Five main terraces, sloping to the west, were distinguished. Three main terraces (T1–3), lying on the eastern side of the oasis, present a homogeneous surface: T1, 250 m wide, lies at an elevation slightly above 440 m; terrace T2, 70 m wide, around 437 m; and terrace T3, 160 m long, at 435 m. The uppermost one, T1, lies 23 m above the bottom of Wadi Sidji, located about 600 m to the west. It is currently urbanized, while T2 is cultivated and irrigated for palm trees and T3 is partly abandoned. The topography is more irregular on T4 and T5, which contain abandoned parts of the palm grove and the recent constructions of small terrace walls and agricultural plots. The slope gently decreases from 433 m at the base of T3 to 429 m on T4, 30 m wide, and to 425 m on T5. The bottom of Wadi Sidji, overlaid by T5, lies 417 m above sea level. The eight TP studied are representative of all the terraces, with TP A and TP B on T1, TP C–E on T2, TP F on T3, TP G on T4, and TP H on T5.

The ERT profile allows us to characterize more precisely the composition and thickness of these terraces (Fig. 2C). Terraces 1 and 2 present average to high resistivity values, with even higher values in localized areas (>64.2 ohm·m), which could reveal the existence of embedded agricultural terraces with different lithologies or the presence of ancient gullies filled with gravels. Terrace 3 and 4, on the contrary, are composed of much finer material, visible directly on the surface due to its erosion. The terraces are indeed composed of very fine cemented silts, which remind one of eolian sediments. Of particular interest is the paleotopography revealed by this profile. West of the palm grove, the metamorphic bedrock was identified close to the surface, while the very eastern part of the oasis is composed of fractured harzburgite. In the middle, ca. 5 m below T1 and 2, we can identify less resistant material filling a 10-m-deep, 50-m-wide depression, in contact with these two substrata, and outcropping to the west. This depression must be a fault depression, which could explain why Masafi has benefited from good water supply for millennia, but also why the oasis has acted as a sediment trap that provides a unique paleoenvironmental record.

Identification and classification of the agricultural and hydraulic deposits

Due to the depth of the TP, the thickness of the deposits, and the high number of stratigraphic units identified, we defined six pedo-sedimentary facies (Table 6) that were encountered both in agricultural deposits and in the fills of canals, wells, and/or cisterns. Facies 1 and 2 correspond to Pleistocene and Holocene deposits. While Facies 1 is composed of well-sorted white to beige silts more-or-less pedologically developed (Facies 1 a and b), Facies 2 is composed of weakly sorted clayey silts, rich in blocks, stones (Facies 2a), and local gravel of harzburgite (Facies 2b). Facies 3 is composed of gravelly sediments. Facies 4 is comprised of five subfacies (a–e) characteristic of agricultural deposits, which differ in color (reddish-brown to greyish-beige) and inclusions (charcoal, ashes, and shells). Facies 5 is typical of backfill or slope-wash deposits (stones, blocks, and sand), while Facies 6, composed of well-sorted white silts, is interpreted as eolian or abandonment sediments. The presentation of the lithostratigraphy of the TP will directly refer to these facies.

Lithostratigraphy

The stratigraphical results obtained from the eight TP are presented per terrace following an east-west transect (Fig. 2B). As many strata were identified in each TP, they were grouped in Facies (presented in Table 6) and are presented by phase.

T1, TP A

The archaeological excavation of Masafi 1 has allowed for the digging of a large north-south trench and the description of about 1.4 m of stratigraphy (referred to as the North Trench in Charbonnier et al., 2017a; Fig. 4A). We have identified 3 different phases. Phase 1 is composed of archaeological occupation soils. Above, Phase 2 is comprised of small earthen canals (10–20 cm wide), part of a runoff water-channeling system (Charbonnier et al., 2017a) connected to cultivated deposits. The latter are composed of light-brown silts (Facies 4e) dated from 2847–2752 cal yr BP. These deposits are eroded and buried under 80 cm of alluvial fan gravel (Facies 3).

T1, TP B

The stratigraphy exposed measures 2.3 m, which allowed us to distinguish four major phases of deposition (Fig. 4B). Phase 1 is composed of cemented light-beige to white silts, with a little gabbro gravel (Facies 1b, strata 1 to 3). An OSL date indicates deposition between 10.19–9.17 ka. These silts are buried under cultivated deposits (Phase 2) (Facies 4b and c; strata 5, 6, 12 and 15) On top of Stratum 6, we discovered a well-preserved tree planting hole (diameter = 1.5 m, depth = 90 cm) in which burnt fragments of Ziziphus sp. (Herveux, L, personal communication, 2016) were dated from ~3211–2989 cal yr BP. During Phase 3, these deposits are eroded by gravel from the reactivation of eastern alluvial fans (Facies 3, Strata 16–30), and forming sheetflow deposits as well as sinuous shallow gullies. Phase 4 is composed of backfill deposits and a wall (Strata 30–33, Facies 5).

T2, TP C

Located less than 50 m west of TP B (Fig. 2B), TP C was opened in the middle of T2. A depth of 4.5 m was reached before identifying the substratum (Facies 2a), indicating a substantial drop in the topography. Five different phases have been identified (Fig. 5). Phase 1 is composed of stones and blocks of gabbro in a cemented green matrix (Facies 2a) buried under 80 cm of dark-orange silty clays (Stratum 1, Facies 2b). The latter correspond to the less-resistant material identified in the ERT profile (Fig. 2C). Phase 2 is indicative

Table 6. Pedo-sedimentary typology of the natural/cultivated deposits encountered in the test pits of the Masafi palm grove and first interpretation

Facies	Sub-facies	Texture	Color	Inclusions	Sorting	Structure	Iron features	Secondary CaCo3 features	Bioturbation	Chronology	Interpretation
Facies 1	1a	Silts	White	Gravels (<0.5 cm)	+++	Massive	No	Cemented matrix	No	early–middle Holocene	Cemented deposits (eolian)
	1b	Silts to sandy silts	Light beige to brown	Gravels (0.5 cm)	+++	Polyhedric	No	Filaments, nodules (<mm)	Root traces	early–middle Holocene	Pedologically evolved (eolian) sediments (facies 1a)
Facies 2	2a	Stones, gravels and blocks of gabbro in clayey matrix	Green to dark brown	Gravels (cm)	+	Massive	Mottled reduced/ oxidized areas	No	No	Pleistocene	Quaternary deposits
	2b	Silty clay	Brown to orange brown, to light green west of the oasis	Gravels (mm to < cm)	++	Massive to prismatic	Mottled reduced/ oxidized areas	Occasional nodules (<mm)	Root traces	Pleistocene / Holocene	Pedologically evolved quaternary deposits (paleosoil)
Facies 3		Gravels (3 mm–5 cm) / gravels in a sandy matrix	Dark brown to greyish-brown	Eroded sherds	No	Massive	No	No	No	late Holocene	Sheetflow or gully deposits
Facies 4	4a	(Fine) silt	Dark brown to (dark) reddish-brown	Charcoal, ash (2–3 mm)	+++	Polyhedric	Hematite	No	Root traces	late Holocene	Paleosoil, agricultural layer with in situ burning and soil rubefaction
	4b	Silt	Light yellowish-brown	Shells, brown soil aggregates, occasional insect pupae	+++	Massive to polyhedric	No	No	Root and faunal traces	late Holocene	Bioturbated agricultural deposits with mix between the A and AB horizons. Also identified in irrigation canal fill.
	4c	Sandy silt	Greyish-beige	Charcoal, ash, shells, silt aggregates	+++	Massive	No	Nodules and carbonated silt aggregates	No	late Holocene	Agricultural layer with ashes—no in situ burning
	4d	Silts to sandy silts	Brown to greyish-brown	Small gravels (<0.5 cm), some charcoal	++	Weakly developed polyhedric	Occasional filaments	Few filaments	Roots	late Holocene	Agricultural layer with ashes and in situ weathered organic matter—no in situ burning. Also identified in drainage canal fill.
	4e	Sands and sandy silts	Light brown	Gravels (<cm), microcharcoal, insect pupae	+ / ++	Massive to polyhedric	No	Numerous filaments, nodules < mm	Roots and rootlets, insects	late Holocene	Agricultural layer. Also identified in irrigation canal fill.
Facies 5		Stones, gravels, blocks, sand	White to dark brown	Sherds	No	No	No	No	No	late Holocene	Backfill deposits/anthropic structures
Facies 6		Silts to sandy silts, occasionally laminated	Light beige	Rare microcharcoal	+++	Massive	Diffuse oxidized mottling	No	No	late Holocene	Eolian, abandonment deposits, irrigation canal fill

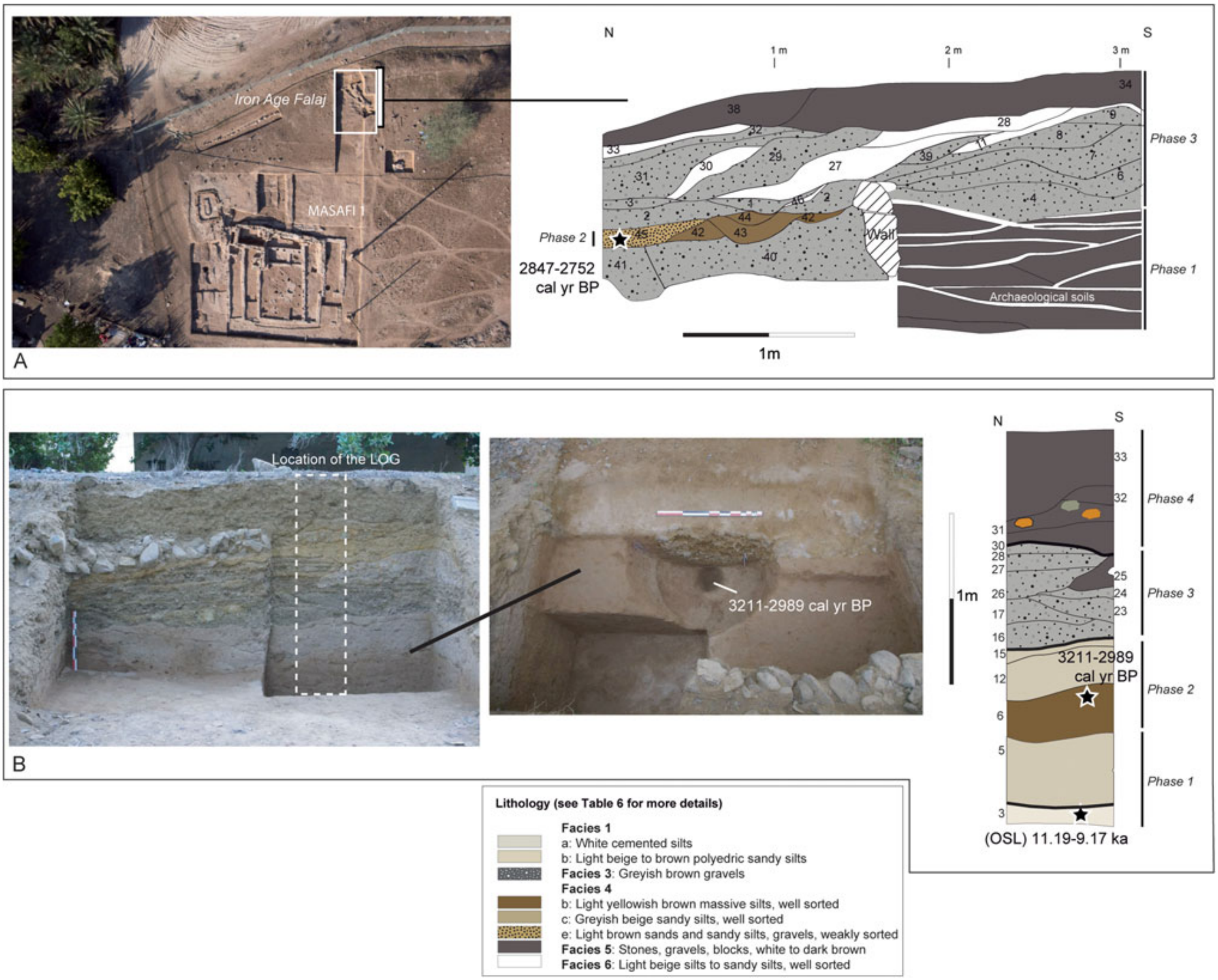

Figure 4. (color online) Terrace 1. (A) View from above of the site of Masafi 1 and lithostratigraphy of Test Pit A, Iron Age Period. (B) View from the west of Test Pit B and view from above of the tree plantation hole (Ziziphus sp.) identified in the pit (stratum 6) with a presentation of the lithostratigraphy (Iron Age to the Islamic Period). Facies are described in detail in Table 6.

of the first management of the palm grove, as two hydraulic structures have been identified. The first one is a small canal filled with greyish-brown clayey silts (Stratum 2b, Facies 4d) (Fig. 5). The texture, dark color, and weak organization of the deposits in the canal suggest its use as a drainage structure. Just above, dark-brown to reddish fine silts (Strata 7 and 8, Facies 4a), indicative of in situ burning, were dated from 2745–2490 cal yr BP. A well (Strata 9–11, Facies 5) was dug directly into them. During Phase 3, these agricultural deposits are covered by harzburgite gravel and coarse sands, rich in weathered sherds, alternating with fine hard carbonated silts of about 1 m (Strata 12–20, Facies 6 and 3). An OSL date obtained in Stratum 16 indicates deposition between 2.23–1.95 ka. Phase 4 is indicative of a probable return to agriculture, with the occurrence of brown silts (Strata 23, 25, and 26, Facies 4b), dated from 1525–1371 cal yr BP in Stratum 25. The last phase encountered is composed of 1.25 m of beige bioturbated silts and sands, which correspond to the more recent palm tree environment (Strata 27-31, Facies 4e) (Phase 5).

T2, TP D

Test pit D was opened also on T2, less than 50 m north of TP C (Fig. 2B). We reached the bedrock at a depth of 4.8 m (Fig. 6). Seven distinct phases can be proposed. Phase 1 is composed of stones and blocks of gabbro cemented in an orange matrix (Stratum 39, Facies 2a), buried under nearly 0.9 m of brown structured silty clayey deposits, presenting traces of in situ vegetation development (Strata 38–36, Facies 2b). Stratigraphic correlations with a nearby TP (not presented here) provided a date of 18,210–17,620 cal yr BP for the lower part of these deposits. This paleosoil also corresponds to the less-resistant material discovered thanks to the ERT profile (Fig. 2C). Phase 2 is composed of rubified brown silts rich in charcoal (Strata 37, 1, and 2, Facies 4a and c), dated from 2721–2381 cal yr BP. Above, Phase 3 deposits are comprised of

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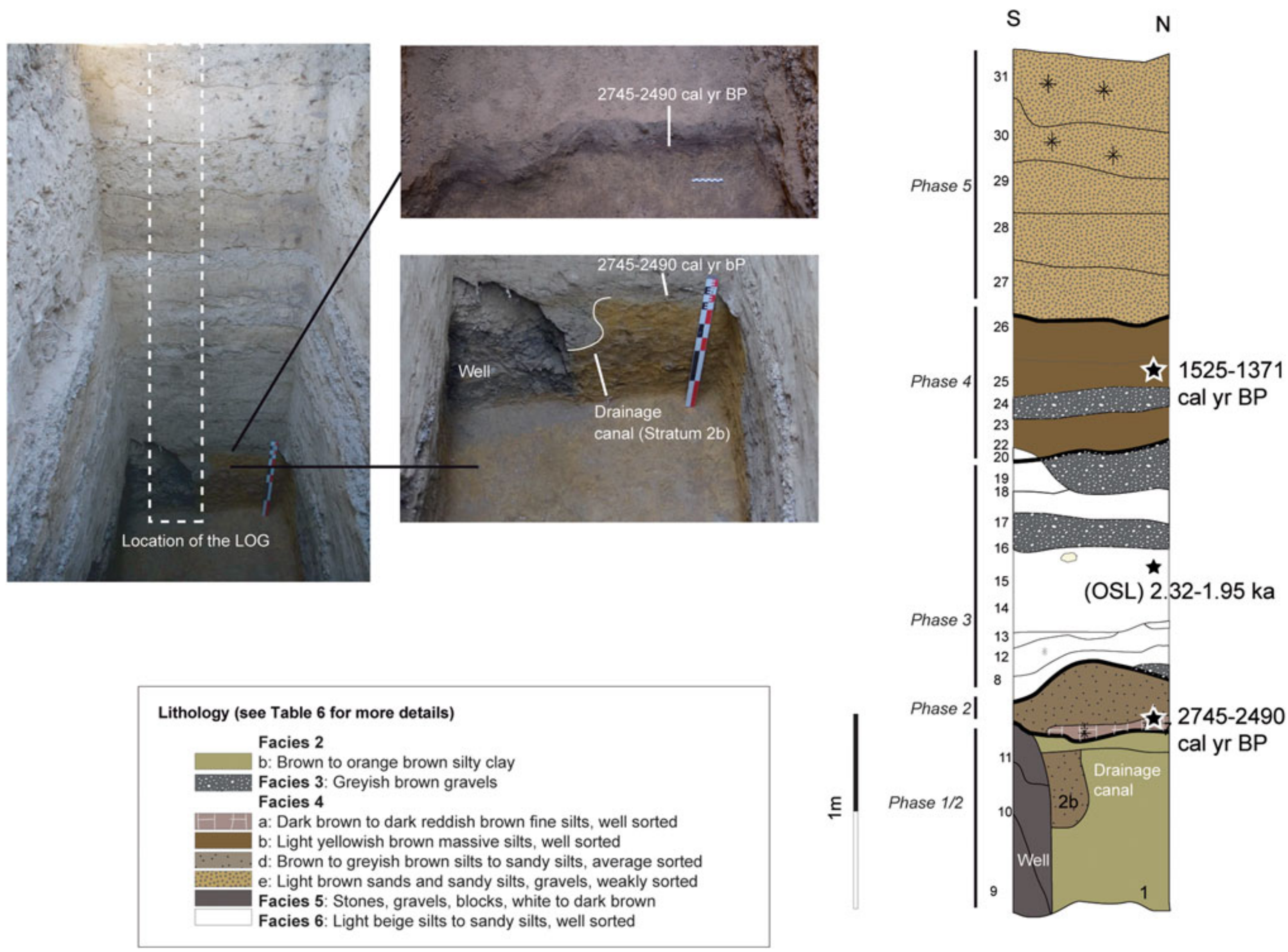

Figure 5. (color online) Terrace 2. View from the east of Test Pit C with a zoom on an in situ burnt agricultural layer (Stratum 7) (Top image), and on an Iron Age drainage canal dug in the perched groundwater table and recut by a well (Bottom image); presentation of the lithostratigraphy (Iron Age Period until today). Facies are described in detail in Table 6.

fine, hard, carbonated silts alternating with gravel from sheetflow or shallow gullies in which sherds dated from the first millennium BC (Table 4) were discovered (Strata 5–10, Facies 3 and 6). A probable return to agricultural practices characterizes Phase 4 (Strata 11–13), with the deposition of greyish-beige sandy silts containing ashes and soil aggregates (Facies 4c and d) dated from 1858–1874 cal yr BP (Stratum 12). Above (Phase 5), traces of in situ burning, ashes, and soil aggregates still indicate agricultural activities, but during later periods (663–551 cal yr BP). These deposits are buried under gravel and light-beige massive silts (Strata 18-23, Facies 3 and 6) (Phase 6). The last dynamic (Phase 7) is composed of 1.25 m of beige bioturbated silts and sands, which correspond to the more recent palm tree environment (Strata 27–31, Facies 4e).

T2, TP E

Test pit E is located 50 m west of TP C (Fig. 2B) and corresponds to the natural exposure of T2. A total height of 3.3 m of stratigraphy allowed for the identification of four different phases (Fig. 7). Phase 1 is composed of very fine, greenish cemented silts, mottled green/orange in their upper part (Strata 1–4, Facies 2b), on top of which we identified a unique polyhedric to granular brown soil (Stratum 4). These deposits, similar to those in TP C and D, correspond to the less resistant sediments identified in the ERT profile (Fig. 2C). Multiple dates were processed in this soil: microcharcoal were dated from ~920–670 cal yr BP, while an OSL date processed on feldspar grains (no quartz available) indicates probable deposition between 9.23–7.41 ka (Age pIR-225) to 7.07–6.33 ka (Age IR-50). We suspect the recent ^{14}C date to result from contamination along the cross section due to regular burning, and we favor the Neolithic date. Above (Phase 2), we encountered a succession of six dark-brown soils (Strata 4–14, Facies 4b, 4d, and 4e) with two small earthen irrigation canals. Stratum 10 provided a date of 3637–3463 cal yr BP. While this date could be coherent, we suspect that, due to the texture and weak sorting of the deposits, their location close to the surface, chronostratigraphic comparison with other close-by TP, and the total absence of Bronze Age sediments in the palm grove, that these deposits could result from the voluntary reworking and displacement of ancient agricultural sediments to build this terrace. Moreover, OSL dates currently studied at

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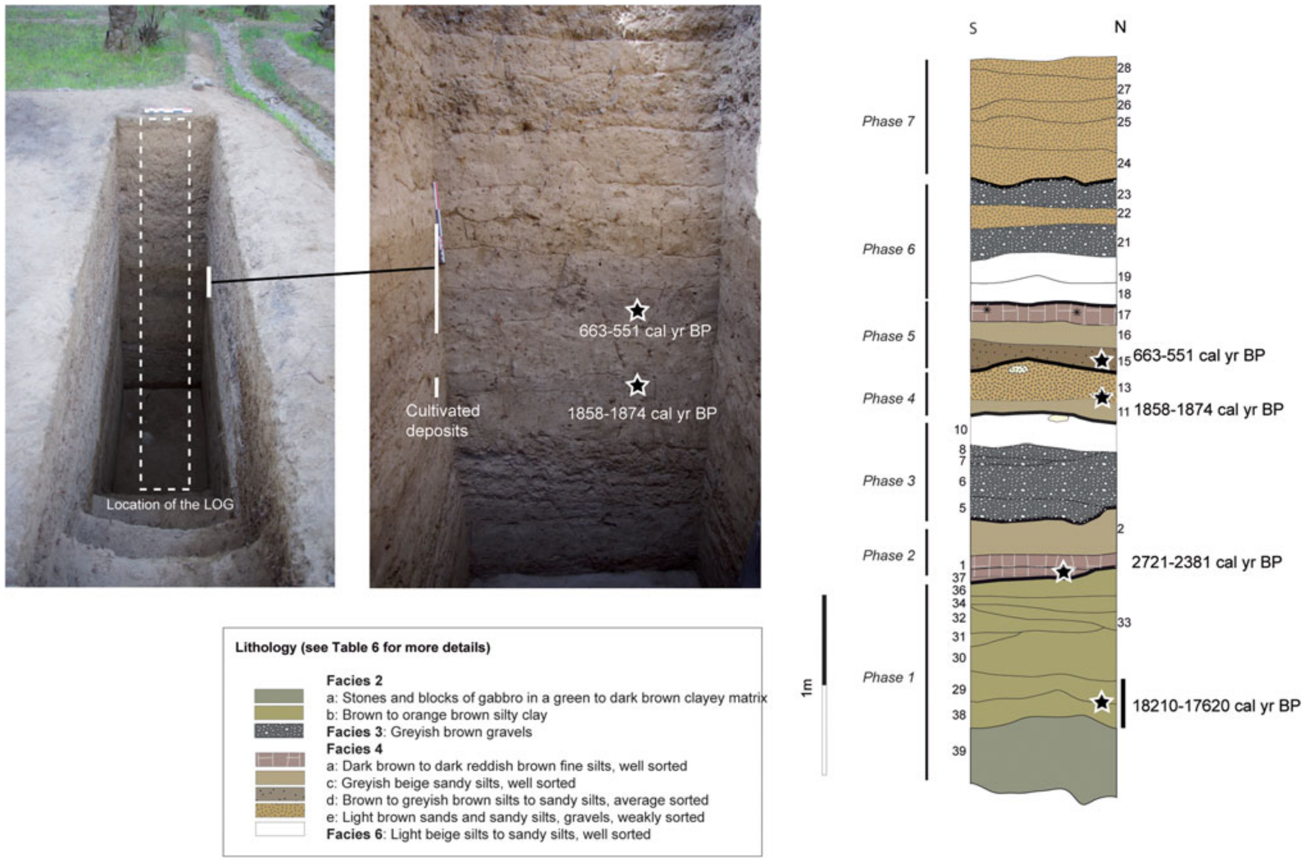

Figure 6. (color online) Terrace 2. View from the east of Test Pit D and zoom on the central cultivated deposits (Phase 4 / 5) with a presentation of the lithostratigraphy (Iron Age Period until today). Facies are described in detail in Table 6.

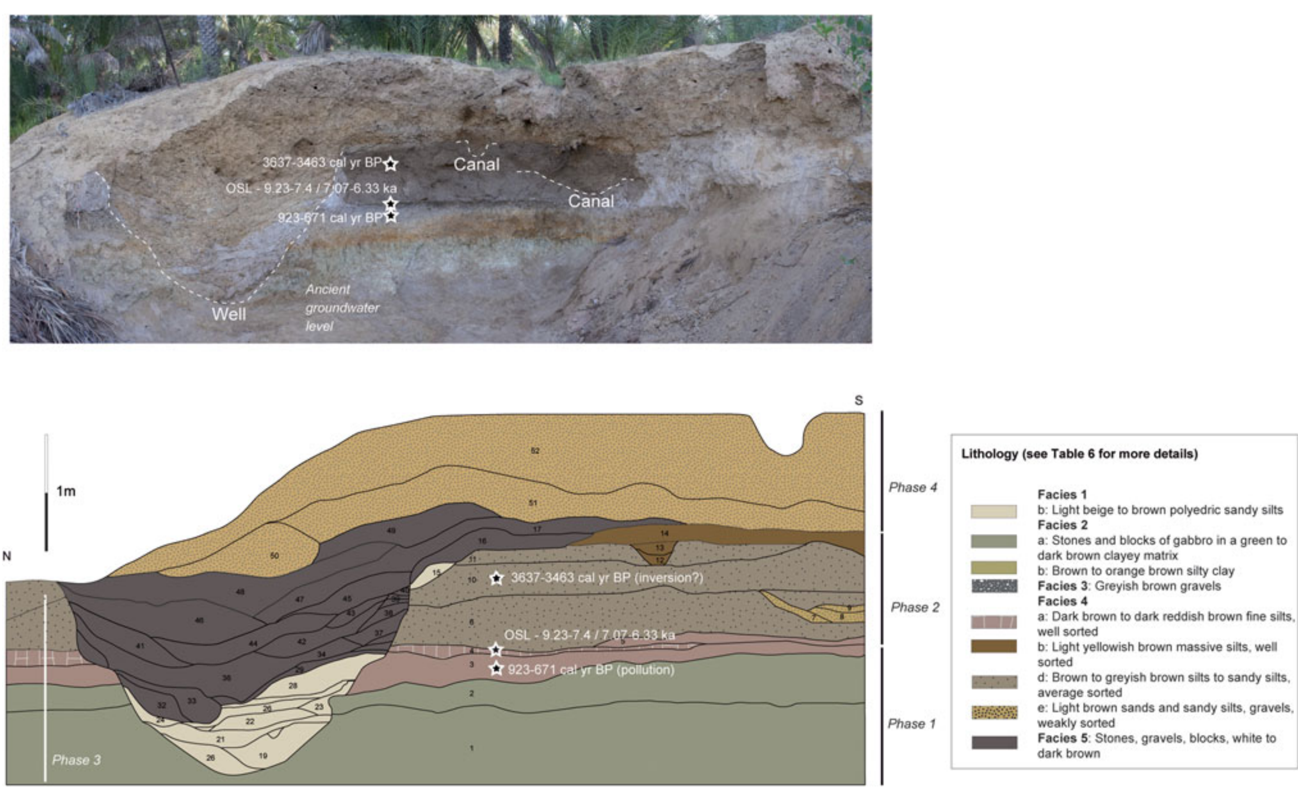

Figure 7. (color online) Terrace 2. View from the west of Test Pit E and lithostratigraphy (Neolithic Period until today). Facies are described in detail in Table 6.

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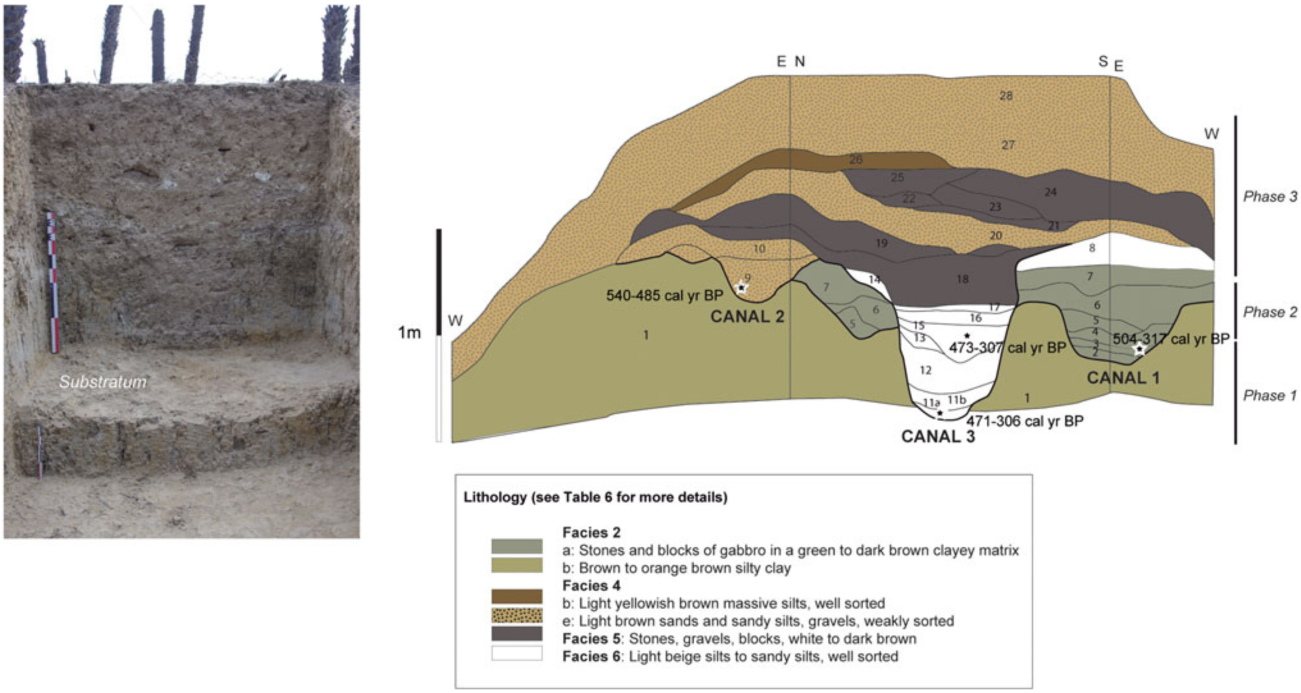

Figure 8. (color online) Terrace 3. View from the west of Test Pit F and lithostratigraphy (Islamic Period). Facies are described in detail in Table 6.

Durham University suggest that the deposition of these sediments might have occurred around the turn of the era (Late Pre-Islamic period; Kennedy, L.S., personal communication, 2016).

Above, Phase 3 corresponds to the digging of a well filled with fine light-grey silts (Strata 19–28, Facies 1b) and backfill deposits on top (Strata 32–49, Facies 5). Phase 4 corresponds to beige bioturbated silts and sands (Strata 50–52, Facies 4e) identified in all the upper parts of the palm grove (Test Pits C and D).

T3, TP F

Test pit F is located 136 m west of TP E, on the western edge of T3 (Fig. 2B). The stratigraphy exposed measures 1.94 m and comprises three superimposed hydraulic structures (Fig. 8). Three phases were identified. Phase 1 is composed of fine greenish to orange cemented silts (Stratum 1, Facies 2a) with traces of soil development on its surface (cf. ERT profile; Fig. 2C). Phase 2 is comprised of irrigation Canals 1– 3. Canal 1 is filled with laminated gravel of harzburgite and serpentinite (Strata 2–7, Facies 2a). Its base was dated from 504–317 cal yr BP. Canal 2 is filled with dark-brown silts (Strata 9 and 10, Facies 4e) and was dated from 540–485 cal yr BP. Canal 3 is much deeper than the previous ones and is filled with fine beige laminated silts and sands. Its base was dated from 471–306 cal yr BP (Stratum 11a) and central part from 473–307 cal yr BP (Stratum 15). Phase 3 is composed of anthropogenic and backfill deposits (Strata 19–25, Facies 5), while the upper part of the TP is comprised of about 60 cm of light-brown gravelly silts (Strata 20, 27, and 28, Facies 4e).

T4, TP G

This very shallow TP, opened less than 50 m west of TP F, on the edge of T4 (Fig. 2B), revealed the presence of fine cemented silts directly at the surface (Strata 1-4, Facies 2 and b; Fig. 9) (Phase 1). A pit was dug in these deposits

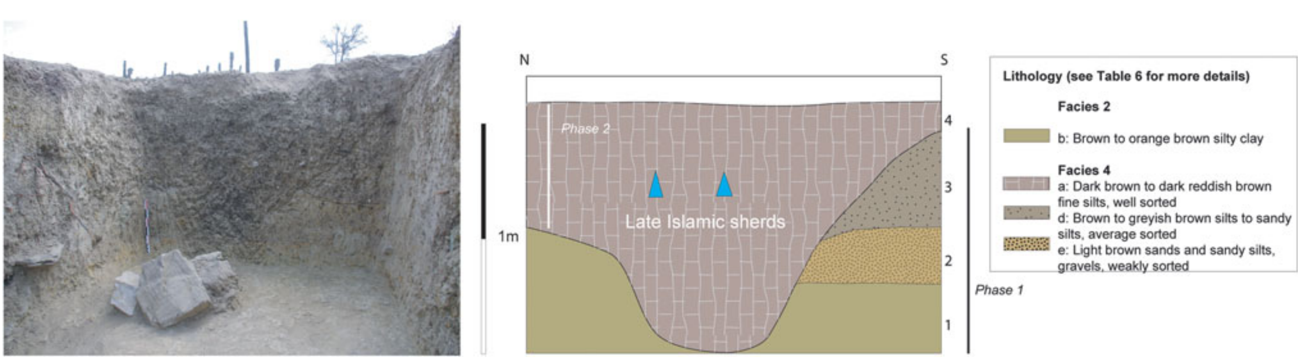

Figure 9. (color online) Terrace 4. View from the west of Test Pit G and lithostratigraphy (Late Islamic Period). Facies are described in detail in Table 6.

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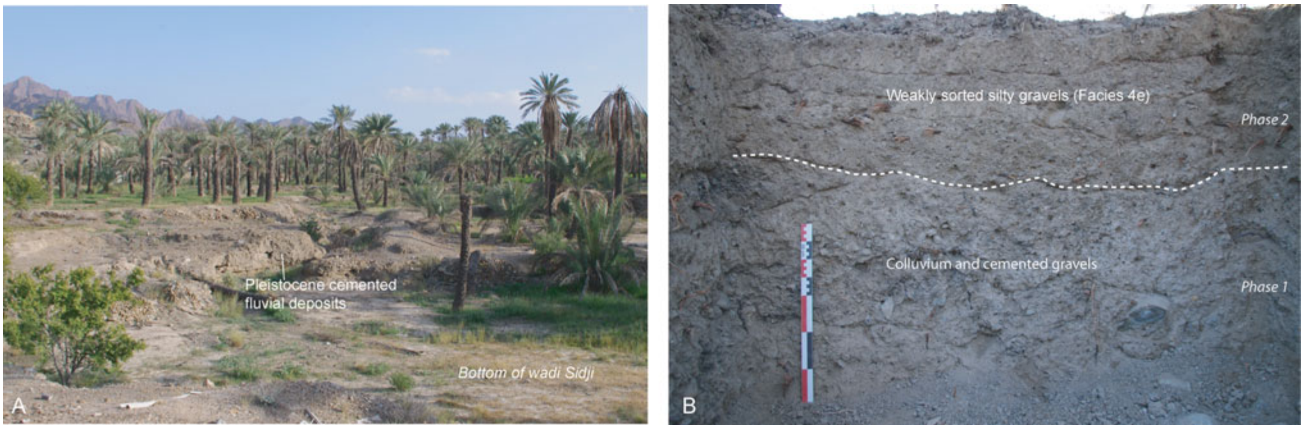

Figure 10. (color online) Terrace 5. (A) View from the west of Wadi Sidji, terrace 5 and the junction between cultivated deposits, (B) Zoom on the ancient cemented fluvial deposits and weakly sorted gravel of Test Pit H (Pleistocene to Late Islamic Period).

and was filled with homogeneous blocky dark-brown clay, indicating water stagnation, in which a Late Islamic sherd (550–50 cal yr BP) was found (Phase 2).

T5, TP H

Terrace 5 is located at the western end of the palm grove (Fig. 10). Two phases were identified. Phase 1 is composed of laminated gravel and cobbles in a white cemented carbonated matrix. Due to their location close to Wadi Sidji, these deposits correspond to Pleistocene fluvial deposits. Above, gravels in a silty matrix were encountered with no visible and datable material (Facies 4e, Phase 2).

INTERPRETATION

The geoarchaeological, geophysical, and spatial study of the oasis of Masafi was used to reconstruct a nearly 20-ka-long landscape record. Chronostratigraphical correlations are presented in Figure 11. Final phases were defined and designated

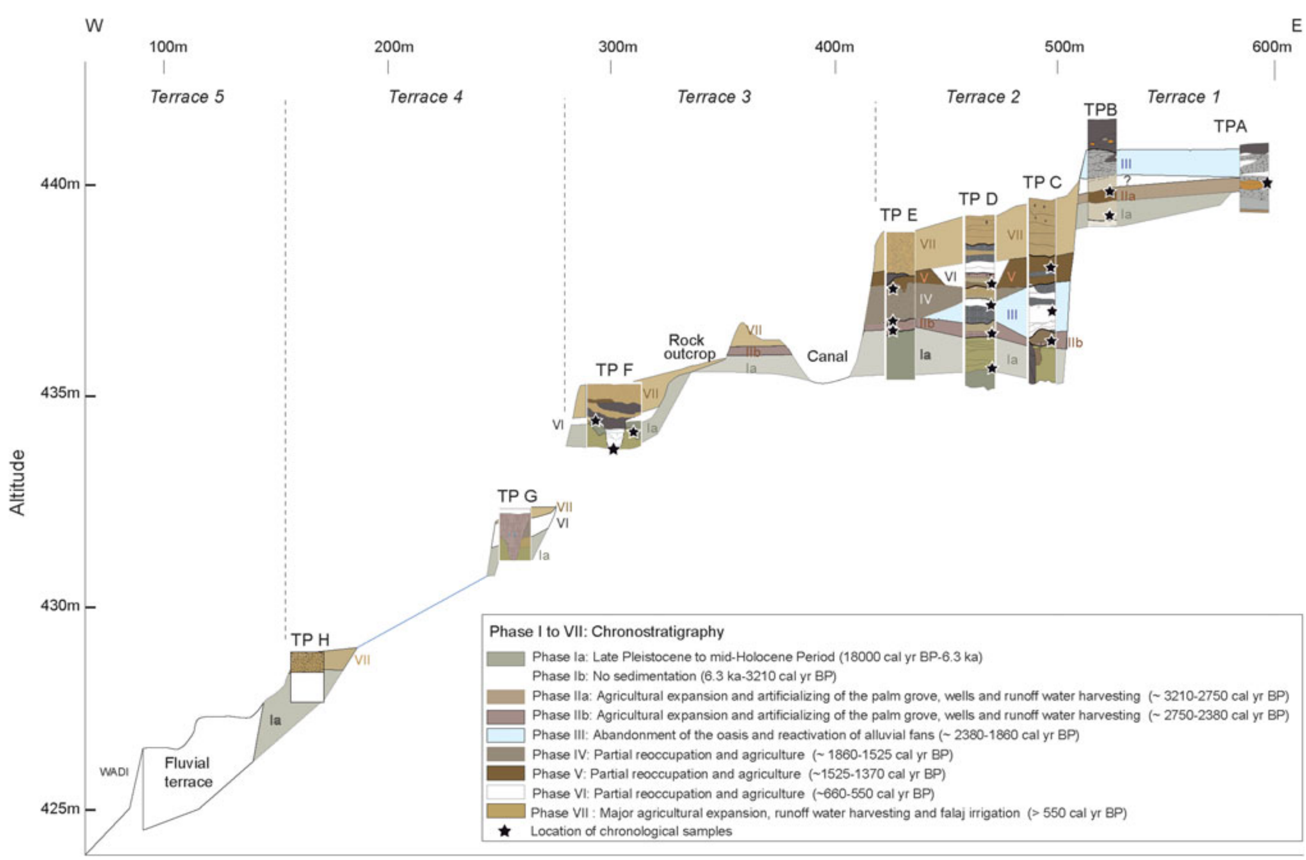

Figure 11. (color online) Chronostratigraphical correlation between the test pits studied and proposed phasing. Final phases are mentioned in Roman numerals (I to VIII).

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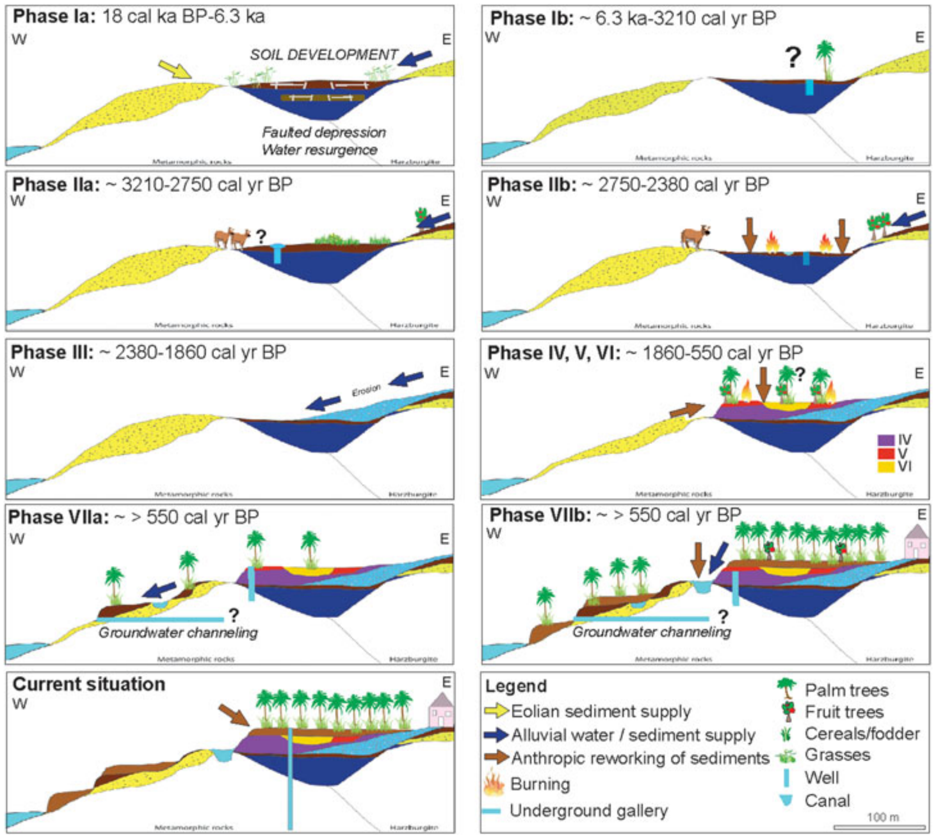

Figure 12. (color online) Sketch of the paleo-geographical and hydro-agricultural evolution of the oasis of Masafi from the late Pleistocene to the late Holocene.

with Roman numerals (Phase I to VII). Diachronic paleogeographical sketches of the oasis are presented in Figure 12.

Phase I: the "natural" existence of the oasis (18–6.3 cal ka BP; late Pleistocene to mid-Holocene period)

At the center of the palm grove (T2), 5 m below the surface, the base of the TP is composed of nearly 1 m of orange/greenish clayey silts (Phase Ia, Facies 2b). As revealed by the ERT profile, these deposits correspond to the upper part of the fill of a fault depression (Fig. 2C). Their fine texture and homogeneous sorting indicate eolian deposition, while their color is due to an ancient perched aquifer. They can be followed to the west, where they naturally and progressively outcrop. Two distinct preserved paleosoils have been encountered within them. The oldest one (TP D), is composed of well-sorted brown prismatic silty clay with root prints, indicating vegetation development and humid conditions during the late Pleistocene (18210–17620 cal yr BP). This date, however, was obtained on bulk organic matter. We processed a ^{14}C date on charcoal, which provided modern results and was therefore rejected (Table 2). The second paleosoil identified is located at the base of TP E. Composed of dark-brown blocky silty clay with well-defined iron features, this soil was dated between 9.23–7.41 and 7.07–6.33 ka (OSL). Upstream and to the west on T1, the base of TP B is composed of fine, white, and homogeneous silts containing small gravel of serpentinite that have been dated from the Early Holocene (11.15–9.23 ka, OSL). Their fine homogeneous texture and sorting suggest eolian deposits but the local gravel inclusion indicate their secondary removal and their initial existence as sand pockets upstream of the watershed, east of the palm grove.

Late Pleistocene to mid-Holocene deposits are directly overlaid by late Holocene deposits. There is a sedimentary gap between ~6.3 ka and ~3210 cal yr BP (Bronze Age, Phase Ib). To the eastern edge of the palm grove, at a higher elevation on T1, erosion processes could have removed soils or sedimentation rates could have decreased during that period. In the fault depression, we suspect that sedimentary archives are no longer available in situ due to the voluntary displacement of sediments during Phase II, which served as perfect agricultural soils.

Phase II: agricultural expansion and artificializing of the palm grove, wells, and runoff-water harvesting (~3210–2380 cal yr BP; Iron Age period)

The first attested and in situ traces of agricultural development in the oasis reveal the existence of three different hydro-

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agricultural strategies. First (Phase IIa), tree plantation holes with the exploitation of Ziziphus were identified east of the palm grove on T1 (TP A) and dated from ~3211–2989 cal yr BP (Iron Age I/early Iron Age II). Water was supplied on this high terrace by a well-developed runoff-water channeling system definitely in use between 2847–2752 cal yr BP (Iron Age II). Slightly after that period (Phase II B), around 2720–2380 cal yr BP (Iron Age II), we observe on T2 a major phase of agricultural restructuration and management. Traces of this activity are located about 5 m below the archaeological site of Masafi 1, and erode parts of the Neolithic paleosol of Phase I. This suggests the voluntary digging of the oasis to reach the perched aquifer and exploit it. In TP B, a small drainage canal suggest the voluntary evacuation of excess water. This strategy has been noticed in many modern contexts in the framework of the creation of palm groves (Ruf, T., personal communication, 2015). Drainage waters could have been used downstream for the production of fodder crops (Daoud, 2011). The burnt sediments on top of this drainage structure, identified in TP C and D, are indicators of voluntary swidden agriculture to prepare the palm grove for massive agriculture. Finally, a well was dug directly into these sediments (TP B). As it is not very deep, it also suggests the existence of a nearby aquifer during the Iron Age.

Phase III: abandonment of the oasis and drainage activation (~2380–1860 cal yr BP; Iron Age III and late Pre-Islamic period)

This phase is well attested in Masafi. On T1, the agricultural deposits of Masafi 1 (TP A), as well as the urban and public areas were abandoned and buried under gravel in gullies and sheetflow. On T2, small gullies less than 1 m wide have been encountered in TP D, suggesting a concentrated flow in some areas that eroded the Late Pleistocene paleosoil. In TP C, very well-sorted silty to sandy silts, light-beige to white, occasionally laminated, resemble eolian or temporary abandonment deposits. No traces of gullying have been encountered west of T2, suggesting their removal at a later period.

Phase IV–VI: partial reoccupation and agriculture (~1860–550 cal yr BP; late Pre-Islamic, Sasanian, and Middle Islamic periods)

These three phases are scattered in the oasis. Although there is no archaeological evidence of human occupation during these periods, our findings indicate the contrary. Late Pre-Islamic period deposits dated from after 1858–1874 cal yr BP and prior to 1525–1371 cal yr BP have been identified mainly on T2 (TP C and D, phase IV; Fig. 11 and 12). Light-beige laminated silts indicate the absence of agriculture in the western part of T2 (TP C), while deposits in TP D contain traces of ashes, charcoal, and soil aggregates resulting from bioturbation, soil ploughing, or fertilization. Based on stratigraphic correlation and similar soil signatures, the area around TP E was probably also used at that time. Traces of hydraulic activity have been attested, with the digging of a very large well, filled at its base with light-beige to greyish sediments and slopewash deposits. We suspect that the sediments used during this period correspond to the reworking of soils located west of the palm grove.

The palm grove shows evidence of being in use between 1525–1371 cal yr BP (Sasanian period, TP C and probable TP E based on chronostratigraphic correlations, phase V; Fig. 11). The succession of deposits belonging to Facies 4b suggest soil development and possible agriculture, but their occurrence could also result from more humid conditions associated with vegetation development. The soil composing this terrace could find its origin in the remobilization of ancient soils located initially to the west of the palm grove.

Similarly, the succession of three soils (rich in organic matter and with traces of in situ burning) in TP D indicate a return to agriculture at ~663–551 cal yr BP (Middle Islamic period, phase VI; Fig. 11). Interestingly however, these deposits stand in a lower elevation than the older ones, indicating a phase of voluntary digging in the palm grove, which confirms its probable use during that period. No traces of hydraulic management were noticed however, nor archaeological traces of occupation.

Phase VII: major agricultural expansion, drainage activation, runoff-water harvesting, and falaj irrigation (~ >550 cal yr BP; Late Islamic period)

The Late Islamic period witnesses a major agricultural expansion in Masafi (Phase VIIa). On T3 and 4, agricultural soils directly overly early Holocene deposits. On T3 (TP F), three superimposed irrigation structures dated from ca. ~540–306 cal yr BP suggest the irrigation of the western part of the palm grove. The fills of the irrigation structures, mainly their texture and grading, suggest: the use of runoff harvesting techniques and available water to do so; intense erosion, as indicated by the rapid fill of the hydraulic structures; and the will to irrigate and cultivate all the available areas of the palm grove. Slightly to the west, the pit identified in TP G and also dated from the Late Islamic period suggests the existence of small humid areas or ponds. The discovery of a falaj gallery south of the palm grove, in which a well-preserved sixteenth century vessel was encountered, reveals the exploitation of underground water supplying large areas of the palm grove.

Above these deposits, we encountered 1 m of light-brown silts throughout the oasis (Phase VIIb, TP C–K). Rich in gravel and weakly sorted, they indicate the restructuration of the palm grove. One remaining question is the origin of the sediments, as both the mixed silts and gravel content indicate eolian and local sediments. Two hypotheses can be put forward: (1) the natural erosion of small pockets of sand from the eastern watershed of the palm grove; and (2) the removal and remix of Bronze Age to Islamic soils from the western part of the palm grove, totally deprived of soil to create this artificial landscape. Currently, though, we have noticed that the palm grove is supplied with marine sand.

DISCUSSION

Three questions were raised in the introduction: what was the initial natural environment during the Holocene and when did the oasis system of production appear? How did this system evolve in the framework of climate change? How does this system compare to other landscapes in southeastern Arabia? To answer these questions, unravel the forcing drivers of changes (climatic versus social and regional versus local), and measure the extent to which oases can be used as new environmental records for the Holocene, we relate our results to regional paleoenvironmental records (Fig. 13).

A new terrestrial record for the late Pleistocene and Holocene Pluvial period in the Al Hajar Mountains

The existence of a fault depression in the center of the oasis of Masafi provides a new and rare record of environmental conditions during the late Pleistocene and early–middle Holocene period. Research in both Oman and the UAE for the late glacial period indicate arid conditions, reduced precipitation, cessation of speleothem growths (Fleitmann et al., 2003a, 2003b), and lack of lacustrine sediments (Burns et al., 2001; Parker et al., 2006; Fuchs and Buerkert, 2008). Recent research (Preston et al., 2015) suggests that dune accumulation could also reflect reduced wind speed and the progressive transition to more humid periods. Soil development and vegetation growth in Masafi between 18210–17620 cal yr BP do not support these results. New chronological data should be obtained before suggesting that Masafi could have been an isolated case in the Al Hajar mountains.

The early to mid-Holocene period (10.5 to 6.2 ka) is recorded in many lacustrine, fluvial, and speleothem records throughout Arabia. The onset of the Holocene humid period is estimated at ~ 11–10 ka due to monsoonal incursions (Fleitmann et al., 2007; Cheng et al., 2009; Fleitmann and Matter, 2009; Farrant et al., 2015), increased winter rains from Mediterranean cyclones (Schulz and Witney, 1986; al-Farraj, 1995; Enzel et al., 2015), or the expansion of the African Monsoon over Arabia (Jennings et al., 2015). In southeast Arabia, the oldest fluvial archives have been dated from ~11.1–10.5 cal ka BP on the piedmont of the Al Hajar mountains in the UAE (Gebel et al., 1989; Dalongeville and Besançon, 1997) and in northern Oman (Fuchs and Buerkert, 2008). The formation of gravel terraces 20 km west of the oasis of Masafi (Dalongeville and Besançon, 1997) is coherent with the phase of drainage activation and soil erosion we identified and dated from 11.1–9.2 ka in Masafi. This confirms an early onset of wetter conditions in the UAE. This occurs in parallel with dune emplacement in the northern UAE between 12.5 and 10 cal ka BP (e.g., Goudie et al., 2001; Parker et al., 2006; Preston and Parker, 2013) and a regional upwelling record of the Arabian sea (e.g., Sirocko et al., 1993). Coastal erosion due to higher sea levels formed transgressive dunes that carried carbonate sand inland (Hadley et al., 1998 in Parker and Goudie, 2008). In Masafi, the accumulation of fine eolian carbonated silts on the slopes of the Al Hajar Mountains is in accordance with these processes.

A maximum level of humidity is reached between ~9 and 7 cal ka BP (Berger et al., 2012). In southeast Arabia (UAE,

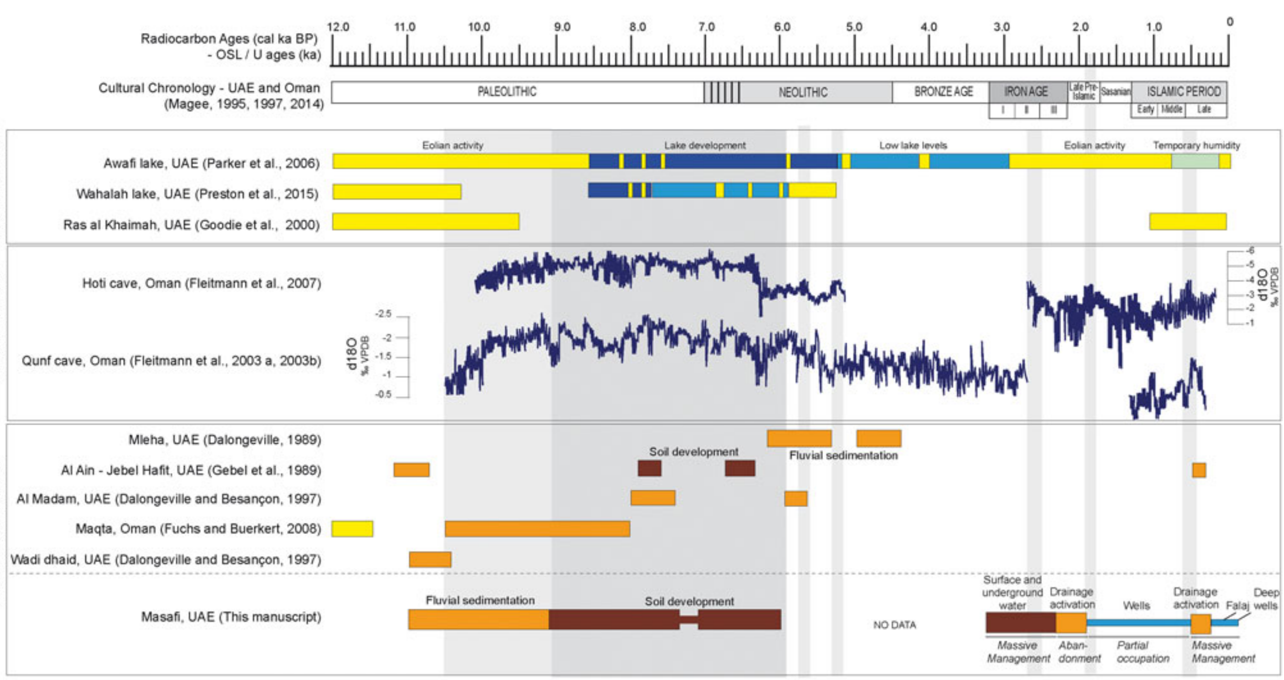

Figure 13. (color online) Comparison of the results obtained in Masafi with regional lacustrine, terrestrial, speleothem, and eolian records in the United Arab Emirates and northern Oman.

https://doi.org/10.1017/qua.2018.142 Published online by Cambridge University Press

Oman), evidence of the Holocene humid phase is suggested by the development of lacustrine conditions (Parker et al., 2006; Preston et al., 2015), increasing detritism between ∼8 and 7.6 cal ka BP (Dalongeville and Besançon, 1997) and soil development between ∼6 and 5.6 cal ka BP (Gebel et al., 1989). Results in Masafi provide a new record of these conditions with the identification of a well-developed paleosoil with probable marshy conditions between 9.2–7.4 and 7–6.3 ka. While we have no evidence of occupation in Masafi, coastal archaeological sites have been discovered in the UAE and Oman. We suspect the oasis to have been a place of circulation at that time.

The onset of regional aridity gradually appeared in northern southeast Arabia around 7.7 cal ka BP (Parker et al., 2015) up until 5.9 cal ka BP (Neff et al., 2001; Uerpmann, 2003; Parker et al., 2004, 2006). Increased eolian activity (Goudie et al., 2000; Atkinson et al., 2001; Parker and Goodie, 2008) and cessation of speleothem growth in northern Oman between ∼6.3–5.2 ka (Fleitmann et al., 2003a, 2003b) have been widely attributed to the southward retreat of the monsoon rain belt (Neff et al., 2001) with a decline in summer rainfall and the shift to dominant northern moisture (Fleitmann and Matter, 2009). Interestingly, these events occurred simultaneous to the progressive decline of human presence in Arabia for nearly a millennium beginning around 5800 cal yr BP. During this "Dark Millennium" (Uerpmann, 2003), populations migrated to the southern coasts of Oman (Biagi, 1994). In southeast Arabia (UAE), fluvial archives suggest drainage activity on the piedmont of the Al Hajar mountains until ∼4.2 cal ka BP. Lacustrine deposits (Parker et al., 2006) do indicate decreasing lake level around ∼5.2 cal ka BP, but they persist at lower levels until ∼3.0 cal ka BP. In Masafi, we have a sedimentary gap during the mid-Holocene shift to aridity and early portion of the late Holocene, between ∼6.3–3.2 cal ka BP (Neolithic and Bronze Age). Archaeological evidence of permanent occupation starting at ∼ 4–3.6 cal ka BP (Table 1, Masafi 4), however, indicates the presence of farmers and local resource availability. We suspect erosion or the voluntary displacement of sediments during later periods to have removed sedimentary archives dated from that period. Further studies in Masafi might allow us to fill this gap but other oases should be also be studied for comparison.

An environmental and human record for the late Holocene arid period

Evidence of climate conditions during the mid–late Holocene is very scarce, but most records show regional drying beyond ∼4.2 ka. Indirect data are provided by an increasing number of archaeological sites and climate data can be obtained from speleothems in Oman and marine cores from the Indian Ocean. Masafi provides a new terrestrial record of the hydro-sedimentary dynamics that have prevailed for the last three millennia in southeast Arabia, from ∼3.2 cal ka BP to today. Between ∼3.2–2.3 cal ka BP, archaeological data record a real increase in settlement patterns in various ecological zones (Benoist, 2000; Magee, 2014). The establishment of a socioeconomic system structured around agricultural production and the export of copper ingots from the Al Hajar Mountains to the Near East and Indus Valley (Benoist, 2000), could explain a renewed occupation. Two major technological innovations could have at least partly contributed to this demographic increase: the domestication of the camel around 1200 BC and the introduction (or development) of underground water supply as a response to decreasing resources (al-Tikriti, 2002; Córdoba and Del Cerro, 2005; al-Tikriti, 2010; Córdoba, 2013). Results obtained in the oasis of Masafi and presented in this manuscript and in recently published papers (Charbonnier et al., 2017a, 2017b) suggest runoff-water channeling and a high, exploitable, and drained aquifer between ∼3–2.5 cal ka BP (Iron Age). While we suspect farmers to have lowered their gardens to exploit this groundwater, maybe as a result of reduced surface water around ∼2.7 cal ka BP, this suggests available water and precipitation in the Al Hajar mountains despite regional aridification. Indirect evidence of similar conditions at Al Ain is provided by al-Tikriti (2017), who also suggests a higher ground-water level during that period. After ∼2.6 cal ka BP and until 2.3 cal ka BP (Iron Age I), a majority of sites, Masafi included, are abandoned (Benoist, 2000), possibly as a result of regional decreasing resources (Del Cerro and Córdoba, 2005; Mouton, 2010; Córdoba, 2013) and/or conflicts between groups, as suggested by traces of major fire events or weapons (Benoist, 2000, 2013). In Masafi, we witness a period of concentrated and sheetflow deposition between ∼2.3–1.8 cal ka BP, probably following the abandonment of the hydraulic system and indicating drainage activation and soil erosion. These wetter conditions reveal that water depletion is unlikely to explain the abandonment of Masafi, which is in contradiction with previous studies that stressed the role of ground-water drawdown and water depletion in the desertion of Iron Age settlements (Boucharlat, 2003; Córdoba and Del Cerro, 2005; Córdoba, 2013). This understated period of humidity framed between ∼ 3.2–1.8 cal ka BP, with a phase of increased detritism between ∼2.3–1.8 cal ka BP, is partly recorded in speleothems between ∼ 2.7–2.4 ka (Fleitmann et al., 2003a, 2003b) and at ∼1.8–1.7 ka in marine pollen records (Gupta et al., 2003). This short and poorly recorded period of humidity would be related to a short-term intensification of winter rainfall in our area of study, while a moderate instability of the Southwest monsoon could explain the more meridional signatures (Chauhan et al., 2009).

Following this period, between ∼1.8–0.5 cal ka BP, data on oasis economy, resource availability, and climate change are even more scattered in southeast Arabian. This period of time coincides with a record of precipitation minimum in the northeastern Arabian sea (von Rad et al., 1999 in Parker and Goudie, 2008), a cessation of speleothem growth (Fleitmann et al., 2003b) and major dune sand accumulation at ∼1 ka in the UAE (Goudie et al., 2000; Stokes et al., 2003). Between ∼1.8–1.6 cal ka BP (late Pre-Islamic period) and

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~1.6–1.2 cal ka BP (Sasanian period), only a couple of sites are known to have been occupied north of the Al Hajar Mountains (e.g. Mouton, 2010; Kennet, 2013). The economic foundation seems to have been agriculture (dates, cereals, and fruit trees) and long-distance trade through the caravan road. Similarly, we only suspect the presence of villages, field systems, and falaj between 1.2–0.5 cal ka BP (Early to Middle Islamic period), despite a regional boom in Indian trade related to agriculture and mining (Potts, 2012). In Masafi, the lack of settlements for these three periods but evidence of hydro-agricultural management does suggest human occupation. The scale of this activity is unknown, however. Masafi probably benefited from more resources than other sites and could have played the role of a refugium during that period.

Regional archives are more abundant after 550 cal yr BP. Slightly more humid conditions are recorded between 550–450 yr in speleothems (Fleitmann et al., 2003a, 2003b) and in δ18O measurements and pollen records from marine cores in the Indian Ocean between ~ 650–450 yr (e.g., Gupta et al., 2003; Chauhan et al., 2009; Miller et al., 2016). Other records, however, indicate that areas located close to the ITCZ northern limit became drier as a result of cooling waters (e.g., Fleitmann et al., 2004). Terrestrial records in the UAE do suggest wetter conditions and drainage activation (Gebel et al., 1989). We also have records of alluvial fan activation at ~500 cal yr BP in Masafi, based on irrigation-canal fills composed of surface deposits. While this indicates the exploitation of available runoff water and precipitation, the progressive and first development of falaj irrigation around the sixteenth to seventeenth century AD could point to a progressively decreasing ground-water level. This major technological investment is indicative of perennial occupation. This is in accordance with a regional agricultural expansion (export of dates to India; Mershen, 2001; Power and Sheehan, 2012), which occurred after the Portuguese conquest and the establishment of an Omani Empire. This could also explain the progressively decreasing resources we witness in Masafi and the investment in electric pumping during the mid-twentieth century.

CONCLUSION

This study of the Masafi palm grove in the UAE is one of the first that simultaneously provides information on sedimentary dynamics, erosion processes, resource management, and environmental change in the Al Hajar Mountains from the late Pleistocene to the late Holocene. The results allow us to identify and describe the natural environment of the oasis during the Holocene and the appearance of the oasis system of production around 3250 cal yr BP. In parallel with climate change, this system evolved with cycles of intensive agriculture (investment in cash crops) versus seasonal or opportunistic cropping. The sedimentary record suggests that the oasis was a humid area during the late Pleistocene–early Holocene periods. Eolian sedimentation and increased erosion during the middle Holocene supplied soils for future agriculture. During suspected arid periods, Masafi provided evidence of available surface water and perched aquifers (~3210–2380 cal yr BP), while increased erosion and reactivation of alluvial fans was recorded between ~2380–1870 cal yr BP and after ~550 cal yr BP. Our results indicate decreasing water availability through time, but not necessarily drier conditions during the Holocene, as has always been thought to be the case in the area. Moreover, the occurrence of surface water and its exploitation up to the twentieth century in the palm grove do suggest a regular water supply despite global climatic change. Compared to other landscapes in Arabia, the oasis of Masafi seems to have developed independently from regional climatic trends, taking advantage of local conditions, such as orogenic precipitation, in periods of regional adverse climatic conditions. While oases are resilient witnesses of socio-environmental changes and key recorders of human adaptations and practices, more studies throughout Arabia and the Al Hajar Mountains will allow us to determine if Masafi is a unique case and has acted as a refugium for Arabian herders and farmers from the Neolithic onwards.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Fujairah Tourism and Antiquities Authority, and especially Ahmed al-Shamsi, Saeed al-Semahi, and Salah Ali Hassan for their support, which enables us to carry out our study of the Masafi oasis. We would also like to thank the French Ministry of Foreign Affairs and International Development (MAEDI) for its financial support as well as the French Agence National de la Recherche (ANR), under grant ANR-16-CE27-0008 (Project OASIWAT). We deeply thank Frank Preusser (University of Freiburg, Institute of Earth and Environmental Science) and Jean-Luc Schwenniger (Luminescence Dating Laboratory, University of Oxford) for their collaboration and advice on the OSL dating. Last, we thank Dr. T. Faith and two anonymous reviewers for their comments and help to improve this paper.

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