The palaeoenvironmental potential of the eastern Jordanian desert basins (Qe'an)

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Abstract

This paper presents a summary of work undertaken by the authors and their teams on a series of Qe’an (plural of Qa’), in the Badia of eastern Jordan. These basins are foci for settlement in the region, with the sites described here (Shubayqa, Wisad and the Qa’ Qattafi) edged by archaeological sites dating from the late Epipalaeolithic (ca. 14,500 - 11,600 cal BP) and the Neolithic (ca. 11,700 - 6100 cal BP), and in areas still used by people today as seasonal wetlands for watering animals and growing cereal. We assess here the potential for the Qe’an sediments to provide what would be rare continuous palaeoenvironmental records for this part of SW Asia. The paper presents the first dates from the Qe’an of this region and the outline sedimentology. Much of the fill is of Holocene age, which leads to discussion of climate and landscape change over the last 15,000 years, particularly due to the close geographical relationship between these basins and archaeology. Our optically stimulated luminescence and radiocarbon dating of the basin fill suggests that there was significantly more space in the landscape for water storage in the early Holocene, which may have therefore provided this resource for people and their livestock or game for a longer duration each year than that seen today. Linked to this are hypotheses of a more vegetated landscape during this time period. Given the environmentally marginal nature of our study area subtle changes in landscape and/or climate, and human exploitation of these resources, could have led to significant, and likely detrimental for its inhabitants, environmental impacts for the region, such as desertification. Our data are suggestive of desertification occurring, and sets up a clear hypothesis for testing by future work in the region.

Keywords: Jordan Badia Holocene Epipalaeolithic Neolithic

1. Introduction

The dryland environments in the eastern Badia of Jordan (Al-Homoud et al., 1995; Allison et al., 2000) contain multiple archaeological sites spanning the late Quaternary (e.g. Maher and Macdonald, 2020; Meister et al., 2017; Nowell et al., 2016). Water availability was an important factor for enabling this human occupation. However, without the technological possibilities of bringing water from substantial depths underground, as it is today, questions are raised about how past societies maintained habitations in these areas. It is likely that environments were considerably different in the past, with increased rainfall, or increased surface water retention supporting people and the plants and animals they exploited for survival.

Natural archives, such as lake sediments and speleothems, that can produce continuous time series of past climatic and environmental conditions, and that have provided important similar information elsewhere in southwest Asia (e.g. Jones et al., 2019) don't exist in the Badia, so alternative approaches to environmental reconstruction have to be taken. Local palaeoenvironmental archives are important for helping to understand local archaeological sites (e.g. Jones et al., 2016a, b), and the climatic gradients in the region today, including within Jordan itself (Fig. 1), highlight the difficulties in relying on archives from further afield, even within the region, for understanding past environmental conditions.

There are depositional basins in the Badia, locally known as *Qa'* (plural *Qe'an*), that although in the present day do not contain lakes, do hold water for small periods of the year following winter rains, sometimes having travelled substantial distances through the normally dry wadi systems. These basins contain sediment, and as part of ongoing work we have been evaluating these as potential palaeoenvironmental archives, including providing the age estimates for this basin fill. Little work of this kind has been previously published from the eastern Badia (but see Al-Tawash, 2007), beyond the major drainage centre of Azraq (e.g. Ahmad and Davies, 2017).

Here we present the preliminary results of our work at three Qe'an; at Shubayqa, Qattafi and Wisad (Fig. 1). Our preliminary results show that these archives do hold useful palaeoenvironmental information that warrants further study. In addition the relatively consistent Holocene ages of the upper sediments of these basins lead to interesting, and archaeologically and palaeoclimatically important, hypotheses about the Badia over the last 15,000 years.

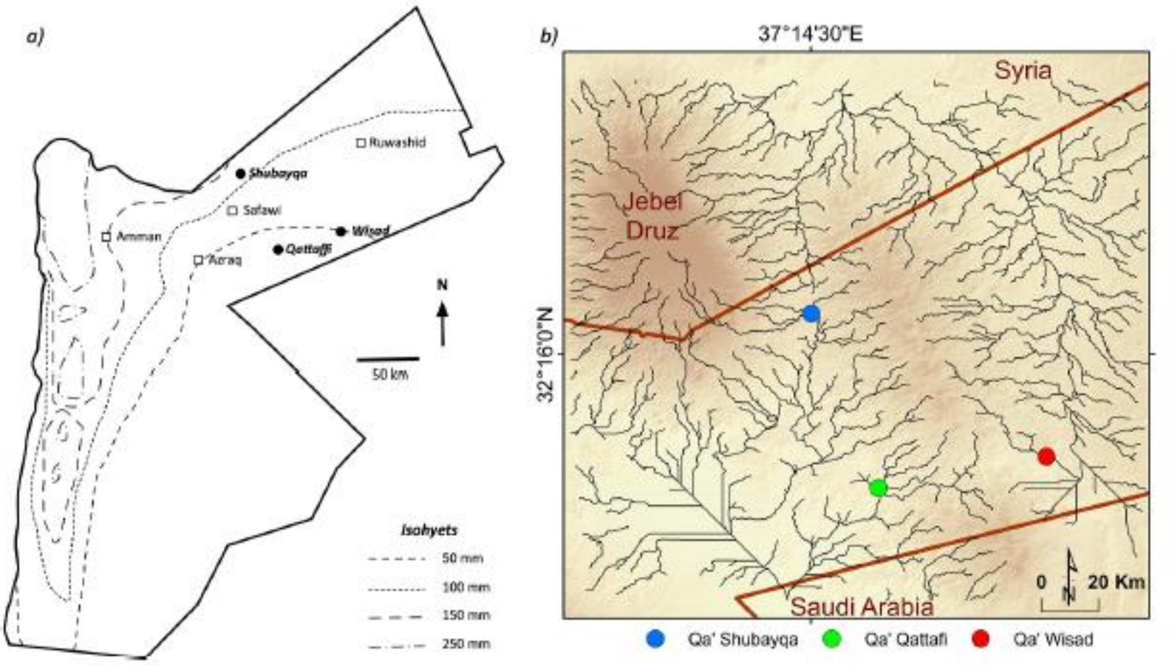

Figure 1 a) Map of Jordan showing the study sites (and selected present day occupation centres) with the rainfall isolines b) primary wadi drainage in the eastern Jordanian Badia. The drainage network was produced using the SRTM v3 (30 m pixel) Digital Elevation Model (DEM) and the Hydrology Toolset in ArcMap v.10.3.1.

2. Regional setting

Much of the region discussed here lies in, or at the edges of, the basaltic desert of the eastern Jordanian Badia. The basalts are late Neogene to Quaternary in age and lie above a series of Cenozoic limestones (Bender, 1968; Ibrahim, 1993; Rabba, 2000, 2005, 2005). Our study region spans a semi-arid steppe zone in the most northern reaches, that receives less than 200 mm of mean annual rainfall, to a hyper-arid zone in the south, where rainfall is less than 50 mm per year (Fig. 1). Rainfall is not only low on average, but also, especially in the southern region, usually falls in only one or two events during the rainy season, which usually occurs from October through May. This paper focuses on the study of three Qe'an, all located near to ongoing archaeological excavations.

2.1. Shubayqa

The Qa' Shubayqa is situated *c*. 20 km north of the modern town of Safawi (Fig. 1). The Qa' covers approx. 12 km^2 (Fig. 2) and consists of an extensive alluvial fan that merges into a playa. The alluvial fan is the culmination within the Qa' of the Wadi Rajil, that enters from the west, and whose drainage basin starts on the southern flanks of the Jebel Druze in southern Syria (Fig. 1; Whitehead et al., 2008). A secondary wadi system drains into the north east corner

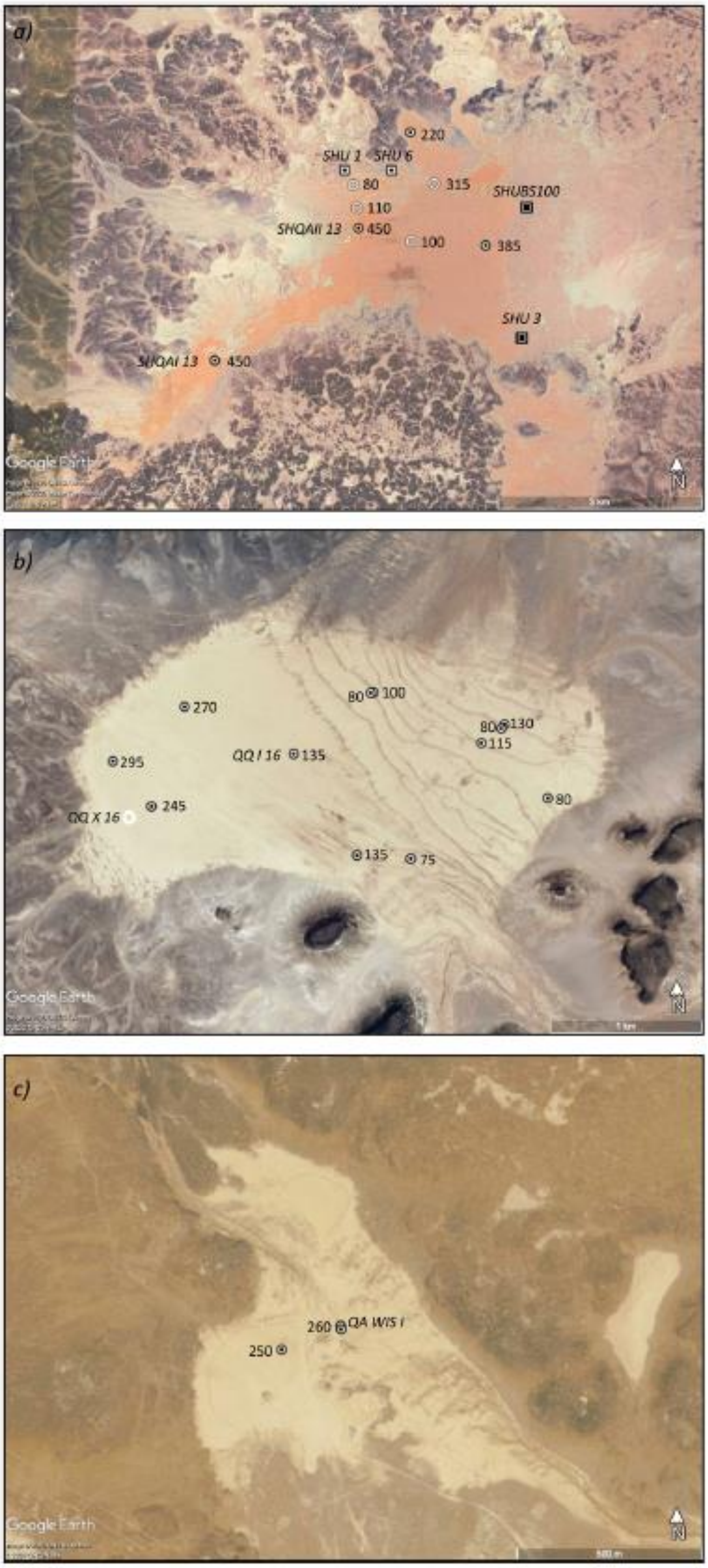

Figure 2 The three sites Qa' Shubayqa (a), Qa' Qattafi (b) and Qa' Wisad (c) showing measured sediment depths (m), sampled sections referred to in the text are named. Key archaeological sites around Qa' Shubayqa (a) are marked (squares) and open circles mark partial sediment depths for this site.

of the Qa' through the Wadi Selma. Water transport through the wadi systems causes seasonal flooding of the Qa', which can be extensive and rapid.

Following earlier fly-overs by Aurel Stein, evidence for the human occupation of and around the Qa' Shubayqa was first reported by Alison Betts (1998). Betts reported the presence of a number of prehistoric sites in this area, including late Epipalaeolithic occupations at Shubayqa 1 and 3. In 1996 she conducted a brief test-excavation at Shubayqa 1. The site was re-excavated between 2012 and 2015 as part of the Shubayqa Archaeological Project, accompanied by the landscape survey and geomorphological sampling of the Qa' reported in this paper (Richter et al., 2014, 2016a, b, 2017; Richter, 2014, 2017a, 2017b). In addition, extensive excavations were carried out at the late Epipalaeolithic - Pre-Pottery Neolithic A site Shubayqa 6 between 2014 and 2018 (set to continue in the future) and test excavation at a small number of other late Epipalaeolithic and early Neolithic sites in the area.

At present, apart from one locality that has produced heavily patinated and abraded Middle Palaeolithic artefacts, there is little evidence for human occupation in the area pre-dating the Late Epipalaeolithic.

Shubayqa 1 sits atop a c. 3 m high natural mound to the immediate north of the Qa' Shubayqa (Fig. 2). A scatter of chipped and ground stone artefacts extends over ca. 3000 m^2 across the top of the mound. Several later constructions have resulted in a dense accumulation of basalt boulders across the mound. Amongst these boulders are several that were used as mortars by the late Epipalaeolithic inhabitants of the site. Excavations have revealed seven occupational phases that can be grouped into three major occupational episodes. In addition to many artefacts, several buildings were excavated. The different occupational phases are discriminated on the basis of 27 Accelerator Mass Spectrometry (AMS) C14 dates, coupled with stratigraphic observations and archaeological finds. The three major occupational episodes date from the Early Natufian ~14,400 - 14,200 cal BP, Late Natufian ~13,300 -13,200 cal BP and Late/Final Natufian ~12,100 - 11,800 cal BP (Richter at el. 2017). The earliest occupation immediately overlies archaeologically sterile sediment deposits. Archaeobotanical evidence indicates the presence and exploitation of wetland tubers (*Bolboschoenus glaucus*), cereals (*Hordeum spontaneum, Triticum* spp.), various trees and shrubs (*Tamarix* sp.*, Chenopodiaceae* and *Vitex agnus-castus*) andother plants (e. g. *Heliotropium* sp.*, Buglossoides* sp.) (Arranz-Otaegui et al., 2018). The presence of large amounts of wetland plant tubers strongly suggests that there was a substantial wetland in the Qa' Shubayqa during the late Pleistocene. The last occupational episode is contemporary with the last stage of the Younger Dryas, and zooarchaeological evidence suggests that localised water availability may have become less reliable just prior to the beginning of the Younger Dryas (Yeomans and Richter, 2018).

Situated ca. 900 east of Shubayqa 1, the site of Shubayqa 6 (Fig. 2) forms a low mound ca. 2.5 m in height that is composed entirely of anthropogenic material (i.e. a settlement mound). A scatter of chipped stone artefacts extends across ca. 5000 m^2 around the mound, which itself measures about 3500 m^2. Excavations have led to the discovery of a series of buildings and occupations that can be grouped into four phases: late/final Natufian, dated to ~12,300 - 11,800 cal BP; Early PPNA, dated to ~11,900 - 11,200 cal BP; Late PPNA, dated to ~11,090 - 11,970 cal BP; and late Chalcolithic, dated to ~5700 - 5600 cal BP. This sub-division is based on combined observations from stratigraphy, finds and 24 ^{14}C AMS dates. The late Chalcolithic occupation consists of an elaborate funerary monument that encompasses several burial cairns enclosed by a circular wall. The LPPNA phase has several small oval buildings with trodden floors, while the EPPNA phase is associated with two large round structures with stone paved floors accompanied by a series of smaller oval structures. The Natufian occupation has thus far only been clearly identified in a sondage, but some of the structures in the main excavation area may have started during this phase. In addition to large amounts of worked stone artefacts, the excavations have recovered a large faunal assemblage, as well as botanical remains. Both are currently undergoing detailed analysis.

Walkover surveys along the margins of the Qa' Shubayqa and adjacent areas have produced a rich record of archaeological sites, many of which date to the Late Pleistocene and early Holocene. Some of these are substantial habitation sites, such as Shubayqa 3 to the southeast of the Qa' (Fig. 2), while others appear to have been the locus of more ephemeral or specialised activity. The density of late Pleistocene and early Holocene sites in the Qa' Shubayqa area suggests comparatively large seasonal aggregations of hunter-gatherer-cultivators.

Later occupation around the Qa' is also attested, but less well understood. Salvage excavations at a looted cairn on the western edge of the Qa' Shubayqa (SHUBS100; Fig. 2) produced late Neolithic material culture (Richter, 2014). Sporadic late Neolithic material culture was also found during excavations at Shubayqa 1 and 6. There are hundreds of other known sites located in the vicinity of the Qa', including desert kites, 'wheel houses', numerous cairns, wall lines and later Islamic tombs. At least some of these sites can be expected to date to the late Neolithic, Chalcolithic and Bronze Age, although hardly any of these have to date been investigated in detail. There are also several localities with many Safaitic, Thamudic and Arabic inscriptions, as well as rock art. In addition, Shubayqa 1 and 6 are located at the edge of an extensive abandoned early medieval village, Khirbet Shubayqa, that attests to significant settlement at that time. This evidence suggests that the Qa' Shubayqa was frequently and at times intensively occupied throughout the past 14,000 years.

2.2. Wisad

Wisad Pools is a narrow landscape feature at the eastern edge of the basalt fields known as *Harrat al-Sham*, approximately 105 km east of Azraq (Fig. 1). The pools (Rollefson et al. 2010, 2011, 2011) are located in the short (1.5 km) Wadi Wisad that leads from a generally level plain at c. 660 masl southwards to the small Qa al-Wisad at 645 masl (Fig. 2).

The nearby archaeological site is extensive. The "core" of the site, where structures were concentrated, extended over ca. 2.8 km2 and contain over 500 structures, not including animal pens. Lower Palaeolithic artefacts are rare, as was evidence of Middle and Upper Palaeolithic, Epipalaeolithic, and Early Neolithic visits except for one small looted area near Pool #1 that exposed a relatively dense concentration of Late PPNB lithics (late 8th millennium BCE). Except for a handful of potsherds from a few pot-breaks, the great bulk of surface artefacts reflect repeated Late Neolithic (7th through 6th millennia BCE) visits to the site.

Three Late Neolithic buildings at Wisad have produced good evidence for the subsistence economy, long-distance exchange networks, and paleoenvironment. Hunting (especially gazelle) and herding provided meat for the diet, and charcoal suggest that the numerous and massive grinding stones may have involved the processing of starchy foods such as acorns and *Typha* sp. roots. Many sherds of Yarmoukian pottery reflect contact with the arable region of the southern Levant (e.g. Rollefson et al., 2013), and marine shells include Mediterranean and Red Sea species. Rare obsidian comes from Meydan Dag, Anatolia (Rowan et al., 2015), and some shaped stone objects in the small finds invoke contacts with the Mesopotamian region.

2.3. Wadi al-Qattafi

Wadi al-Qattafi is a complex drainage system consisting of three sub-parallel arms (called the north, central, and south Qattafi wadis by Bedouin of the area) that initiate in the south-central part of the basalt fields of eastern Jordan (Fig. 1). After an aerial distance of approximately 25 km southwest of the sources, the sinuous parts of the drainage system merge about 5 km north of the Qa' al-Qattafi, a broad playa of c. 10 km^2 in area (Fig. 4) about 60 km ESE of North Azraq. The drainage continues out of the Qa' to the south in a straighter course for ca. 10 km before beginning a slow curvilinear path some 18 aerial km to the west and south, emptying onto a plain about 43 km southeast of Azraq.

Archaeologically, the section of the wadi system to the northeast of the Qa' has only isolated hunting/pastoral camps and special activity burin sites, but south of the Qa' the situation changes abruptly. For the 10 km N-S wadi section, there are 22 basalt-topped mesas (ghura in Arabic) on the sides of the wadi (Supplementary Fig. 1). On top of each mesa are one or two "tower tombs" commemorating the death of important personages dating to the Late Prehistoric period (Early Bronze Age, possibly Iron Age) and often reused by 2nd century BCE to 4th century CE Safaitic herders/traders (e.g. Macdonald, 2020). The bed of this wadi section directly south of the Qa' is dense with Anabasis shrubs and to a lesser extent by Atriplex sp. that Musil (1927) identified with the local Bedouin name "qattaf", thus the name of the wadi.

At the foot of most of the mesas there is an impressive number of structures. Recent reanalysis of aerial photos taken by the APAAME group (http://www.apaame.org/) has revealed a minimum of 800 residential huts of circular to oval shape at the bases of the mesas, mostly on southern slopes. Numbers of huts at each mesa vary considerably, with only 5–10 on some of the slopes to 100 at Mesa-1 (M-1) and M-15 and up to 278 surrounding M-7. Animal enclosures are numerous. At least 11 kites (hunting traps, principally for gazelle) occur at the base of or between mesas (one kite occurs on the summit of M-2), although an additional 30 mesas have been located within the area. "Wheels" of elaborate design (Kennedy, 2011) number more than 25.

Rare surface artefacts demonstrate that the wadi was exploited to an unknown degree by Late Acheulian and Levantine Mousterian hunters, and there are several Middle and Late PPNB chipping stations, one on the summit of M-3 and three on the southern slope of M-4 (Rowan et al., 2014). Most of the rest of the archaeological material ranges from the Late Neolithic of early and late 7th millennium to the Early Bronze Age of the late 4th millennium BCE, with a major gap in settlement until the Safaitic period. One dwelling on the southwest slope of M-4 dated to 5480-5320 cal BCE (Wasse et al., 2012), and another on the south slope of M-7 yielded four radiocarbon dates of 6455 to 6236 cal BCE (Rollefson et al. 2016, Rollefson et al., 2017). Atop Mesa 4 there are 262 structures (not included in the 800 total), although these include tombs and animal pens/farming enclosures as well as dwellings; it is probable that many of them are Early Bronze Age in date (mid-fourth millennium BCE). Excavations of two of the huts produced no datable material, but floor plans and construction techniques are identical to huts at Tulul al-Ghusayn about 90 km northeast of M-4 that date to the mid-4th millennium BC (Rowan et al., 2014; Müller-Neuhof, 2016).

Evidence for the Late Neolithic subsistence economy comes from faunal remains, artefacts, and charcoal. Hunting was a mainstay for obtaining meat and skins, particularly gazelle at ca. 50% of the bones; smaller mammals (hare, fox) were also important as were caprines, which made up perhaps 10% of the faunal inventory. Other mammals including an equid were hunted but played a lesser role in the diet. Grinding equipment was not particularly numerous, but plant resources (all probably wild) were likely a major food source. Late Neolithic charcoal included oak, indicating a landscape and climatic regime that was different to present, and one charred fragment of a fig also points to a wetter local habitat (Rollefson et al., 2016).

3. Material and methods

3.1. Fieldwork

Field work took place over a number of field-seasons between August 2013 and June 2016. At each site the Qa' sediments were previously unstudied, so preliminary work concentrated on understanding the subsurface shape of the basins and taking preliminary samples to understand the potential of these sites for further work.

The depth of Qa' sediment, to bedrock, was measured by using a hand auger. To take samples trenches were dug into the Qe'an by hand where possible, such that a clean face could be used for collecting dating and sedimentology samples. Samples below the hand-dug trenches were taken using the auger, ensuring that all peripheral material was removed before sampling. At Wisad, deep holes, to bedrock, had been dug into the Qa', presumably by a bulldozer or equivalent to attempt to store more of the winter rains, and the side of one of these holes was used to clean a section for sampling. At SHQA13 (Fig. 2a) recent flow through the Wadi Rajil had cut some sections and these were used to sample the upper sediments.

3.2. Chronology

Samples for Optically Stimulated Luminescence (OSL) age estimates were taken using opaque cylinders at least 20 cm in length hammered into cleaned sections.

OSL analyses were undertaken at the University of Gloucestershire Luminescence Dating Laboratory. Samples were prepared under controlled laboratory illumination (Encapsulite RB-10 red filters). Material was dried at 40 ∘C and moisture content evaluated. Each sample was then subjected to acid and alkaline digestion (10% HCl, 15% H_2O_2) to attain removal of carbonate and organic components respectively. Fine silt sized (5–15 µm) quartz, along with other mineral grains of varying density and size, was then extracted by sample sedimentation in acetone (<15 µm in 2 min 20 s, >5 µm in 21 min at 20 ∘C). Feldspars and amorphous silica were then removed from this fraction through acid digestion (35% H_2SiF_6 for 2 weeks, Jackson et al., 1976; Berger et al., 1980). Following addition of 10% HCl to remove acid soluble fluorides, grains degraded to <5 µm as a result of acid treatment were removed by acetone sedimentation. Where available, fine sand sized (125–180 or 180–250 µm) quartz was isolated in place of fine silts through a process of acid digestion (40% HF, 60 min), resieving and density separation at 2.68 g cm^{-3}.

For each sample, 19 multi-grain aliquots (10 mm Ø, 1 mg for fine silts; 8 mm Ø, 4–5 mg for fine sands) of quartz were mounted on aluminium discs. Equivalent Dose (De) values were quantified using a single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle 2000, 2003, 2003) facilitated by a Risø TL-DA-15 irradiation-stimulation-detection system (Markey et al., 1997; Bøtter-Jensen et al., 1999). Preheat treatments were led by the outcome of Dose Recovery tests (Murray and Wintle, 2003). The success of OSL sensitivity correction was monitored through low and high dose repeat ratios. The presence of any feldspar contamination was evaluated using the post-IR OSL depletion ratio (Duller, 2003). Given the use of multi-grain aliquots, geometric mean De values and their inter-aliquot variation beyond that attributable to counting statistics (% overdispersion) were calculated using the Central Age Model (Galbraith et al., 1999).

Lithogenic dose rate (D_r) values were defined through measurement of U, Th and K radionuclide concentration within a 50 g sub-sample of sediment using an Ortec GEM-S high purity Ge coaxial detector system. These concentrations were converted into α, β and γ D_r values (Adamiec and Aitken, 1998), accounting for Dr modulation forced by grain size (Mejdahl, 1979), present moisture content (assumed ±25% uncertainty; Zimmerman, 1971) and, where D_e values were generated from 5 to 15 µm quartz, reduced signal sensitivity to α radiation (a-value 0.050 ± 0.002). U-disequilibrium was evaluated through $^{226}Ra/^{238}U$ ratios. Cosmogenic D_r values were calculated on the basis of sample depth, geographical position and matrix density (Prescott and Hutton, 1994).

One bulk sediment sample from Qa' Shubayqa was analysed for ^{14}C by Beta Analytic.

3.3. Sedimentology

To begin to quantify sediment change in our study basins through time, and support field observations, samples were analysed at the School of Geography, University of Nottingham. Loss on Ignition (LOI) was undertaken following standard methods using c. 1 cm^3 of sample (Dean, 1974; Heiri et al., 2001). Magnetic susceptibility was analysed using air dried and gently ground, using a porcelain mortar, sediments placed in a 10 cm^3 plastic box, that were full for these analyses. Samples were analysed using a Bartington MS2B single sample dual frequency sensor at 0.1 sensitivity range (0.46 kHz).

Laser particle size analysis was undertaken using a Beckman Coulter LS 13,320 particle size analyser providing a grain size data for a size range from 0.041 to 2000 µm. Prior to analyses sediment samples were sieved at 2 mm and the finer fraction placed in hydrogen peroxide in a water bath at 80 ∘C for 5 h to remove any organic material. 10% Calgon (sodium hexametaphosphate and sodium bicarbonate) was then added to the washed samples to ensure that the samples are well dispersed for analysis.

Air dried and sieved (<2 mm) samples, ground using an agate pestle and mortar, were used for XRF analyses. The samples were analysed in the School of Geography at the University of Nottingham, using a PANalytical Epsilon3XL X-ray fluorescence spectrometer with high resolution Si drift detector.

4. Results

4.1. Fieldwork

The auguring of the qe'an has provided preliminary information on the amount of sediments these basins contain, and the shape of the basins prior to their filling by the sediments. Qa' depth more or less follows Qa' surface area in size. Qa' Shubayqa has a maximum measured depth of 4.5 m (Fig. 2a), Qa' Qattafi c. 3 m (Fig. 2b) and Qa' Wisad has a maximum depth of c. 2.5 m (Fig. 2c), although a basin wide auguring programme hasn't been undertaken here like at the other two sites.

At Shubayqa the shape of the basin, from the data currently available, suggests that the basin sides are relatively steep with the similar sediment depths at SHQAI13 and SHQAII13 (Fig. 2) suggesting a relatively flat bottom. The present day Qa' surface dips gradually (c. 0.5 m/ km) to the northeast (in a surveyed section south of Shubayqa 6). Qa' Qattafi is substantially (c. 3 m compared to c 1 m in the east of the basin) deeper in the western part of the basin (Fig. 2b). The eastern side is, more directly, part of the larger Wadi Qattafi system. The NW-SE trending lines running across the surface on the east side of the basin (Fig. 2b) are today more vegetated ridges, standing c. 0.5 m above the Qa' floor.

Field descriptions of the sediments only noted significant changes in sediment characteristics, as generally sediments were homogenous at all three sites. Sediments in Qa Shubayqa were described as reddish brown silts and fine sands. The images of the qe'an (Fig. 2) provide a good representation of the sediment colour at Shubayqa and at the other sites, and the sediment colour does not change significantly with depth at any of the sites, unless otherwise noted. At SHQAI13 it was notable that 1.5 cm diameter, rounded basalt pebbles appeared in the sediments from 430 cm depth. Sampling of SHQAI13 started 45 cm below the surface of the sediments as the upper sediments were cracked and full of roots. At SHQAII13 field descriptions noted that sediments were finer, containing more clay, below 200 cm depth. Not all auger holes reached bedrock as the sediments were often too hard to get through with a hand auger.

from Qa Wisad were sampled in the 2014 season. Two sub-sections were dug into the side of a pre excavated hole in the qa as described above, to aid access. The upper sediments, sampled in section QAWISIa, were very light brown silts, samples began at 10 cm depth to avoid the more recently disturbed upper sediments. The top of sub-section QAWISIb was stratigraphically level with 110 cm in QAWISIa. The top 30 cm of sub-section Ib contained sand sized sediment in clear layers, between 30 and 90 cm depth the sediments are massive very light brown silt as in Ib. From 90 cm depth to the base (270 cm from the qa surface) sediments became much courser with increasing proportions of basalt clasts. Sampling stopped at 230 cm depth as the bottom 40 cm of the section was largely basalt gravel.

Some initial auguring into Qa Qattafi was undertaken on a preliminary visit in 2013, with most sampling being undertaken in the 2016 season. The very light brown to light yellow silts and clays changed little with depth in auger and section samples. Sediments from a shallow trench, to 60 cm, at QQI16 (Fig. 2b) suggested a general coarsening upwards pattern to the sediments, with clays below 50 m and silts in the upper sediments. Most auger holes in the Qa Qattafi reached bedrock, which was particularly soft limestone under the vegetated ridges in the north-east of the qa (Fig. 2b).

4.2. Chronology

OSL age estimates are summarised in Table 1 (see the Supplementary Table for underpinning data). Generally, the range of diagnostics deployed to help evaluate the reliability D_e and D_r are without issue. There are three areas to highlight; firstly, the D_e values for samples GL14061 and GL15063 exceed $2D_0$ (86% saturation of the OSL signal) and thus can be considered no more than minimum age estimates. Secondly, $^{226}Ra/^{238}U$ ratios for samples GL15064 and GL19086 may indicate excessive (>50%) U disequilibrium at the time of sampling. However, each ratio is accompanied by a large uncertainty. Thirdly, the overdispersion of De values for fine sand samples GL14061 and GL15065 exceeds 20%, which may signify substantial inter-grain variation in De values forced by extrinsic factors beyond microdosimetric variations in β radiation. The sedimentary history of all samples would have involved in-wash to basins and an aeolian input, but deflation likely dominated prior to burial which would have promoted resetting of the OSL signal. Thus, inter-grain D_e scatter is unlikely rooted in partial bleaching. There is also little evidence in section of either anthropogenic or biogenic reworking. At Qa' Wisad, it is possible that the basal sediments comprise weathered basalt bedrock. Given the relatively old age estimate for sample GL14061, D_e overdispersion likely originates from cross-sampling bedrock and superficial geology. However, the source of the overdispersion in GL15065 remains unclear.

*Table 1 Summary of age estimates, largely OSL, from the three study sites. * Samples from beneath floors of archaeological structures. The radiocarbon age from Qa Shubayqa was calibrated using Intcal09 (Reimer et al., 2009).*

Section	Depth (cm)	Lab Code	Total D_r (Gy.ka^{-1})	D_e (Gy)	Age (ka)
Qa Qattaffi					
QQ I 16	60	GL19087	2.40 ± 0.09	14.3 ± 0.7	5.9 ± 0.4
QQ X 16	65	GL19086	2.74 ± 0.10	19.5 ± 1.0	7.1 ± 0.5
	95	GL19085	2.81 ± 0.10	27.1 ± 1.1	9.6 ± 0.5
Qa Wisad					
WIS IA (55cm)	65	GL15064	2.18 ± 0.13	17.3 ± 1.2	7.9 ± 0.7
WIS IB (35cm)	145	GL19088	2.51 ± 0.10	29.7 ± 1.1	11.8 ± 0.6
WIS IB (135cm)	255	GL14061	1.53 ± 0.11	405 ± 64	>265
Wisad Pools					
WIS80 076 81 *		GL15063	0.55 ± 0.05	333.1 ± 20.2	>605
WIS66 subfloor *		GL15065	1.43 ± 0.08	26.6 ± 3.6	19 ± 3
Qa Shubayqa					
SHQA II	115	GL13008	2.24 ± 0.13	4.8 ± 0.2	2.1 ± 0.2
SHQA Is	137	GL13007	2.15 ± 0.09	12.0 ± 0.4	5.6 ± 0.3
Shubayqa 1					
Context 197 *	65	GL16131	2.55 ± 0.11	210.9 ± 9.5	82.5 ± 5.1
	120	GL16132	2.61 ± 0.12	226.3 ± 9.6	86.8 ±5.3
Qa Shubayqa					
			Measured radiocarbon Age (BP)	$\delta^{13}C$	
SHQA Ia	195	Beta 367336	5430 ± 40	-20.9	6.31 ± 0.09

The majority of the age estimates from the Qa' sediments presented are Holocene in age. Sedimentation patterns appear similar at Wisad and the deeper, western part of Qa' Qattafi, with age estimates at 65 cm in both at 7.9 ± 0.7 and 7.1 ± 0.5 ka respectively, and sedimentation rates to the older dates of c. 50 and 80 yrs cm^{-1}. The age estimate at 145 cm in Qa' Wisad dates these sediments to the start of the Holocene. Sedimentation rates appear faster at Shubayqa (c. 12–18 yrs cm^{-1}), although this assumes a recent date for the top of SHQAII13 and confidence in both the OSL and ^{14}C age estimate from SHQA113. At Shubayqa the equivalent sediments, by depth, appear to be older in the western samples than in the more central SHQAII13, which seems sensible if the basin filled in from the west, the source of most material washing down the Wadi Rajil.

4.3. Sedimentology

The sedimentological summaries of the three sites (Figs. 3 and 4) show subtle variations around the themes that would be expected from the general field descriptions of these fine-grained filled basins as described above. Sediment organic content is much higher in Qattafi than the other two sites, and carbonate higher in Wisad and Qattafi. The latter reflects the closer location of these sites to the limestone that underlies the basalt and that dominate in the Shubayqa catchment.

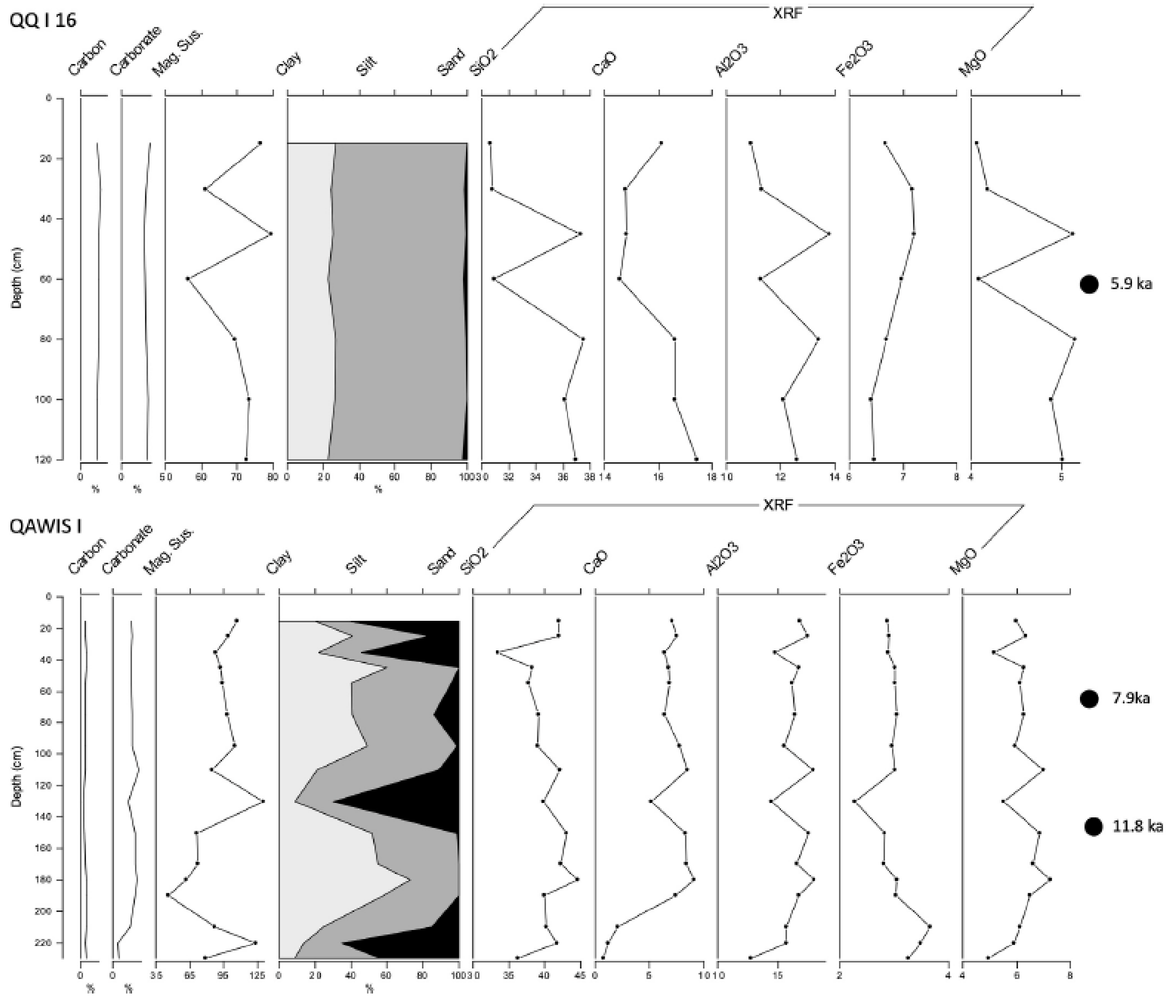

Figure 3 Sediment analyses from Qa' Qattafi and Qa' Wisad, showing changes through an example section from each site. Estimates of percentage carbon and carbonate from LOI, magnetic susceptibility, percentage of clays, silts and sands from the grain size analyses and key elemental compositions from XRF.

There is little change with depth in the sediments from QQI16 (Fig. 3), whereas those from Wisad and Shubayqa show clear down-section variability (Figs. 3 and 4), particularly in changes in grain size, that suggest change in the energy of water flowing into these Qe'an. The courser levels in Qa Wisad described in section QAWIS Ib are evident in the grain size analyses

(Fig. 3) as are the courser sediments at the base of SHUQA I 13 (Fig. 4) described in the field. At these two sites the sediment chemistry also generally changes with the grain size, such that Ca and Mg increase from the lower sections that contain more bedrock material, with corresponding reductions in Si and Fe up section.

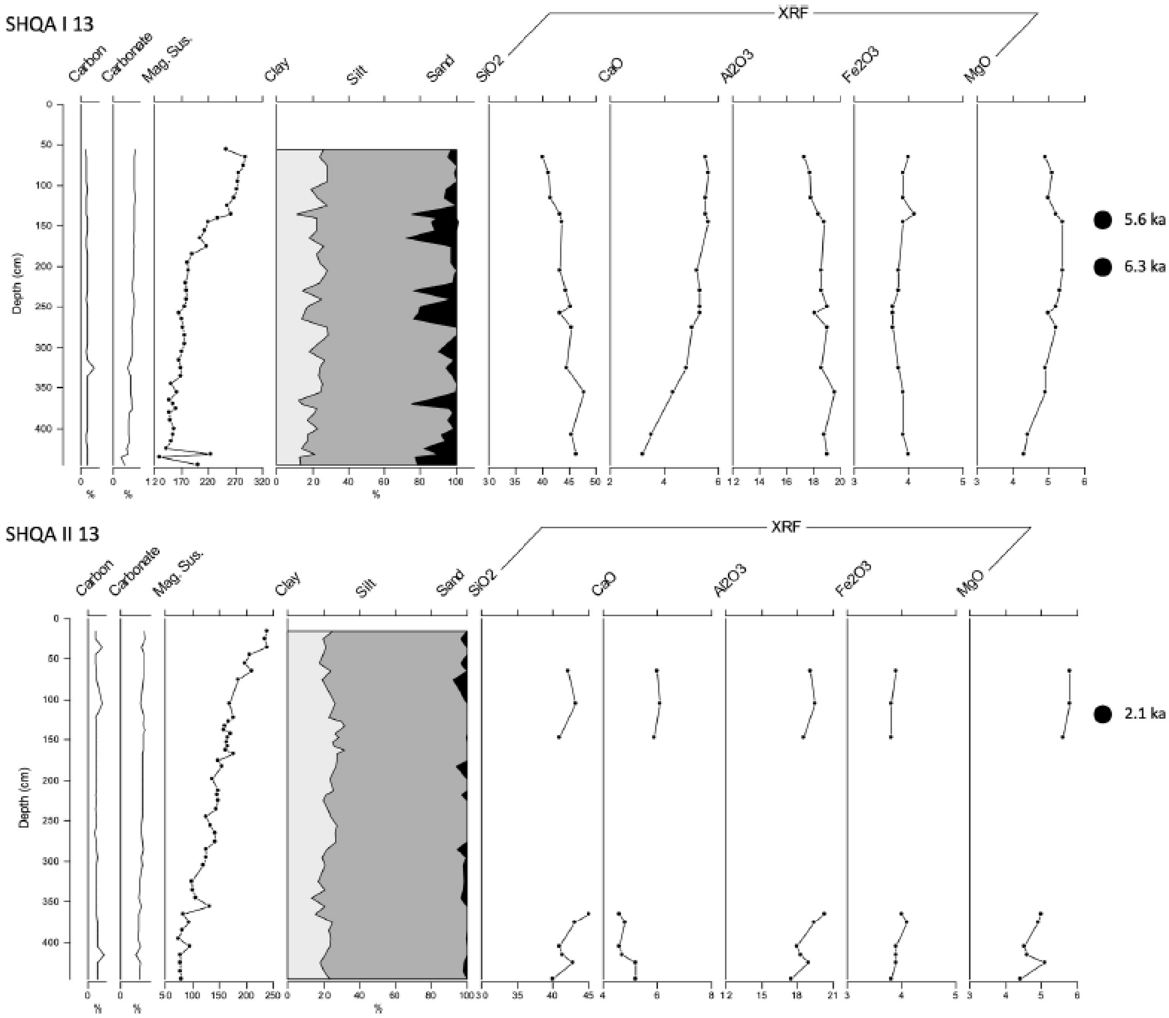

Figure 4 Sediment analyses from Qa' Shubayqa, showing changes through two sections section from the site. Estimates of percentage carbon and carbonate from LOI, magnetic susceptibility, percentage of clays, silts and sands from the grain size analyses and key elemental compositions from XRF.

Preliminary work from Wisad and Shubayqa has also shown that pollen is preserved in countable quantities at these sites. The grain size and organic content of the Qattafi sediments also suggests that pollen preservation is potentially good here. The taphonomy of pollen, likely washed and blown in, in these systems will be complex (e.g. Campbell and Campbell, 1994) and may sample large areas of the Badia, but given the little information currently available this is an exciting find, especially for comparison with the archaeobotanical finds described in section 2, and we look forward to furthering work in this area in the near future.

5. Discussion

The results presented here show that the Qe'an sediments of the eastern Badia of Jordan hold a potentially useful paleoenvironmental archive. OSL age estimates are able to provide sensible chronologies and sediments change in time. Although detailed work on each of the basins discussed here is still to be undertaken, and the dating resolution on individual basins and sampling resolution precludes paleoclimate interpretations at this stage, the preliminary results presented allow a number of hypotheses regarding the region to be discussed, with more evidence than has been previously possible.

5.1. A green early Holocene Badia?

There is evidence for green, or greener, environments in the early Holocene, or for increased precipitation at this time, for much of the wider region surrounding the eastern Badia, from the Sahara (e.g. Kuper and Kr¨opelin, 2006; Bunbury et al., 2020; Van Neer et al., 2020), Arabia (e.g. Petraglia et al., 2020), Turkey (e.g. Jones et al., 2007) and from southern Jordan (Henry et al., 2016). These include areas that are hyper-arid at present. The lack of lacustrine sediments yet found in the study region of this paper is therefore notable and suggests early Holocene rains may not have pushed as far north, from the Indian Monsoon system, or east from North Africa or the Mediterranean, as the present day Jordanian Badia. However there are many basins yet to be investigated. The amount of early Holocene rain, and its seasonality, is a key part of understanding the desertification hypotheses outlined in section 5.2.

The dating of the sediments reported here does suggest that all three basins had the capacity to hold more water in the early Holocene, given approximately a third of the present day basin fill in Wisad and Qattafi, and almost a half at Shubayqa, would have yet to have been deposited. All other things being equal, particularly evaporation rates, the larger capacity for the Qe'an to hold water at this time would have led to more water being available for local inhabitants, likely for longer amounts of time than it stays in the Qe'an in current climatic and geomorphological conditions. In the Wadi Qattafi, the archaeobotanical finds do suggest wetter conditions at this time (Section 2.3), and the archaeobotanical and zooarchaeological data from Shubayqa (Section 2.1) suggests that in the late Pleistocene, when the Qa' Shubayqa likely had even further capacity to hold water than in the early Holocene, the basin did hold substantially more water than it does following winter rains in the present.

The sediments and results described in this paper cannot yet attest to a greener, or more watered, landscape, but the sediments span the early Holocene time period and the hypothesis of a greener Badia is therefore one target for future study for these sites, alongside the archaeological evidence.

5.2. Desertification? And if yes, when?

The dating of the sediments described here raises questions about landscape change in the Badia through time, particularly when combined with the ages of the archaeological sites near the Qe'an and the archaeologically sterile sediments these structures sit upon. As part of this work these sterile deposits have also been dated at Wisad and Shubayqa (Table 1). The sediments underneath the structures at Shubayqa 1 and Wisad 66 and 80, all comfortably predate the archaeology which sits upon them, substantially so in the case of Wisad 80.

The sediments underlying the archaeological structures are similar in colour and grain size to those found in the nearby Qe'an and yet little such material is seen on the surface of the rocky desert today, certainly not sitting in raised positions like observed at Shubayqa 1 and at Shubayqa 6. It can therefore be hypothesised that this material has washed and/or blown into the basins from relatively local positions at some point following the building of the structures. It has been observed elsewhere in the badia that archaeological sites (e.g. Kharaneh IV; Jones et al., 2016a,b) can preserve Quaternary sediments from deflation and the relative ages of the substructure sediments, the structures themselves and the Qe'an fill do not disprove a desertification hypothesis. Linked to questions around early Holocene rainfall (Section 5.1) a key question to investigate would be if early Holocene sedimentation rates increased due to more inwash of catchment material, or slowed, perhaps to a degree soil horizons could develop within the Qe'an sediments, if a wetter, and warmer environment led to a restabilised, more vegetated landscape.

Based on the age estimates and sedimentation rates that can be taken from them for these sites, it is likely that the basins began to fill in the late Pleistocene. Although there are not enough age estimates yet from these sites to discuss further, a late Pleistocene or early Holocene start of a desertification story for the Badia would be substantially earlier than that proposed for southern Jordan, around 5.6 ka (Henry et al., 2016). The potential causes of the apparent desertification also require further investigation within the potentially complex interactions between climate, vegetation, and people and (their) animals through the late Pleistocene - Holocene transition. The results presented here show that the Qa' sediments have the potential to provide direct information on the former two of these factors, in close proximity to evidence for the third.

6. Summary

Preliminary work to understand the Qa’ sediments of eastern Jordan presented here shows that they are a potentially useful palaeoenvironmental archive containing proxies to begin to test hypotheses of landscape and climate change in the region over the last 15,000 years. This work will add further to recent developments in the understanding of the Quaternary of Jordan (e.g. Abu-Jaber et al., 2020; Al-Saqarat et al., 2020). Importantly these basins provide the opportunity to provide local archives of environmental change to many archaeological sites in the region and can be used with the botanical and faunal evidence from these sites to build comprehensive pictures of the past environments of the Badia.

Author contributions

Matthew D. Jones, Tobias Richter, Gary Rollefson, Yorke Rowan: Conceptualisation, Methodology, Investigation, Writing- Original Draft, Writing- Review and Editing, Supervision, Funding acquisition **Joe Roe:** Methodology, Validation, Investigation, Writing- Review and Editing **Phillip Toms:** Formal Analysis, Investigation, Writing-Original Draft, Writing- Review and Editing **Jamie Wood:** Formal Analysis, Investigation **Alexander Wasse:** Investigation, Writing-Original Draft, Writing- Review and Editing **Haroon Ikram:** Investigation **Matthew Williams:** Investigation **Ahmad AlShdaifat**: Investigation, Visualization, Writing-Original Draft **Patrick Nørskov Pedersen**: Investigation, Writing- Review and Editing **Wesam Esaid:** Investigation, Project administration, Writing- Review and Editing.

Data availability

All data not available in the manuscript are available from the corresponding author on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.
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