This article is published in:

Quaternary International (2018)
in press

https://doi.org/10.1016/j.quaint.2018.03.001
Climate forcing and shifts in water management on the Northwest Arabian Peninsula (mid-Holocene Rasif wetlands, Saudi Arabia)

Christoph Zielhofer*, Kai Wellbrockb1, Amer S. al-Soulimanc-d, Manuel von Grafensteinb, Birgit Schneidera, Kathryn Fitzsimmonse, Andreas Stelef, Tobias Lauerg, Hans von Suchodoletza, Matthias Grottkerb, Hans Georg K. Gebelh1

* Chair of Physical Geography, Leipzig University, Leipzig, Germany
b Faculty of Civil Engineering, Lübeck University of Applied Science, Lübeck, Germany
c Hashemite University, Zarqa, Jordan
d Faculty of Humanities, Ferrara University, Ferrara, Italy
e Max Planck Institute for Chemistry, Mainz, Germany
f Institute of Geography, Osnabruck University, Osnabruck, Germany
g Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany
h ex oriente e.V., Freie Universität Berlin, Berlin, Germany

* zielhofer@uni-leipzig.de
1 These authors equally contributed to this study.

Abstract:

The mid-Holocene climate of Northwest Arabia is characterised by a significant increase in aridity which gave rise to changes in water management strategies including sophisticated techniques at later stages. The Rasif site, situated in Northwest Saudi Arabia, reveals a Late Neolithic society with multi-roomed domestic structures (1st phase, 6th millennium BCE, before the current era). At Rasif site the sediments of an endorheic basin (qa) show a minimum in salinity during this 1st phase. The 2nd phase is characterised by a pastoral ‘Chalcolithic’ watering and ‘Chalcolithic’ burial location of the 5th millennium BCE with wells, complex trough systems, and initial, probably coexistent grave structures. During this 2nd phase the qa deposits show already a slight increase in salinity. We have evidence for a sub-surface water-rich sand layer within the qa that was exploited by shallow wells. During the subsequent 3rd phase the number of pastoral ‘Chalcolithic’ D-shaped grave structures within the qa increased, probably co-existing with deepened wells and complex trough systems. At that time the qa is covered by an almost impermeable saline clay layer. The 4th phase is characterised by a culturally yet to identify pastoral post-‘Chalcolithic’ watering location with single small troughs. The final 5th phase represents a culturally unidentified pastoral post-‘Chalcolithic’ to sub-recent water harvesting location with complex dam systems, which were probably modified numerous times. The dam systems allowed to flooding the qas for several months, providing (sub-) surface water in the nowadays Northwest Arabian desert.
1. Introduction

Following an humid early Holocene climatic optimum (Engel et al., 2017), the relatively moist 6th-5th millennium BCE episodes of Arabia’s mid-Holocene provided still extensive grazing land (Dinies et al., 2015, 2016) to hitherto unknown complex shepherd cultures, occupying many parts of the Arabian Peninsula (Gebel and Mahasneh, 2012, 2013, Gebel et al., 2016). These ‘Chalcolithic to Early Bronze Age’ cultures consisted of groups of mobile pastoralists who dug wells into wadi floors and near lake shores, collected runoff water in drainage systems, and fed their flocks at built watering places that were operated by wells and troughs (al-Ghazzi, 2004; Wellbrock et al., 2012; Gebel et al., 2016).

However, these predominantly mobile pastoralists remained aceramic and thus poor in their material inventory. Furthermore, they hardly left geoarchaeological archives in the today’s deflated and arid desert landscape. Consequently, these cultures remained historically and archaeologically anonymous but most likely represent the origins of the Bedouin lifestyle that is the dominant cultural and economic tradition in the Arabian lands until today. Where local tabular bedrock sources allowed, their ritual and domestic architecture is executed by standing stones creating megalithic landscape sites (Gebel et al., 2016).

Archaeological excavations in the greater Qulban Beni Murra region (Fig. 1) in Southeast Jordan (Gebel and Mahasneh, 2012, 2013) and at Rajajil (Fig. 1) in Northwest Saudi Arabia (Gebel et al., 2016) revealed that standing stone sites with certain grave types are characteristic for the hitherto unknown 5.0 to 4.0 ka BCE pastoral occupations of Arabia, which co-existed with sedentary Chalcolithic cultures in more water-rich regions of the Fertile Crescent. A radiocarbon date provided an age of 4459-4346 cal. BC (Gebel et al., 2016) for the pastoral ‘Chalcolithic’ well structure at Qulban Beni Murra. Two OSL ages (4800-4400 BCE and 5040-4500 BCE) confirmed the 5th millennium BCE age of the well (al-Khasawneh et al., 2016). There is first evidence that standing stone sites were burial centres and locations of social identity and transaction in nowadays deserts, populated by mobile shepherds and characterised by watering places with wells and habitation structures.

However, although standing stone cultures are widespread on the Arabian Peninsula (al-Ghazzi, 2004), the knowledge about their land use and water management strategies, ritual life and social interaction remains fragmentary so far. This is caused by several basic obstacles: hardly datable sedimentary archives are preserved so that a chronological framework does not exist so far, the sites’ material culture is rather poor and insignificant, the horizontal stratigraphies of re-occupied sites are difficult to read, and many sites have been looted throughout all the periods including recent times.

In this study we focus on Rasif site (Fig. 1, Northwest Arabian Peninsula, Saudi Arabia) that might become a key site for the 5th millennium BCE pastoral well cultures besides Rajajil and Qulban Beni Murra. All three sites are linked by the Wadi Sirhan drainage system and certainly were part of the complex pastoral networks in Arabia’s 5th millennium BCE. In terms of geographical extension, variability of physiographic conditions, tasks and achievements of their long-distance exchange systems, etc., Arabia’s crossroads followed historically different principles and dimensions than the confined Chalcolithic/Early Bronze Age regional centres of the Fertile Crescent or the Nile Valley.

**Aims:**
Our study concentrates on the reconstruction of the Late Neolithic to Early Bronze Age palaeohydrological and archaeohydrological history of the Rasif site in Northwest Saudi Arabia. The study focuses on the unknown 5th to 4th millennium BCE mobile shepherd societies and shifts in their water management strategies. We distinguish between palaeohydrological and archaeohydrological approaches and arguments: palaeohydrology focuses on the supra-regional Holocene hydro-climatic history and its local hydrological impact while archaeohydrological research cares about water management techniques and strategies in the past.

With the focus on episodically flooded endorheic basins (local name: qas) and corresponding catchments at karstic Rasif site we aim to link archaeological (Gebel et al., 2016) and archaeohydrological survey data of burial fields, habitation and water management sites with geoarchaeological sounding data and palaeohydrological proxies. We aim to reconstruct changing water management strategies within the palaeohydrological transition from a mid-Holocene steppe landscape towards a late Holocene desert. Evidences of climate forcing and environmental changes will be detected by the interpretation of multi-proxy findings from qa deposits.

2. Geographical setting

Rasif (UTM 37N E633484 N3352570, 689.22 m above sea level [a.s.l.]) is located in the north-western part of the Arabian Peninsula at the edge of the greater Al Jouf oasis region (Fig.1). The area is part of a nowadays arid environment which exhibits annual evaporation rates of more than 1.700 mm per year (Trabucco and Zomer, 2009) and mean annual precipitation are in a range of 80-90 mm per year (Hijmans et al., 2005; Almazroui et al., 2012). As a consequence, natural vegetation is sparse and concentrated on the sandy wadi fills and depressions. For the study area annual recharges rates of 3 mm per year are assumed for the phreatic Saq aquifer (BRGM, 2008: 93).

Extensive investigation and modelling of the Saq aquifer and adjacent aquifers suggested a water head to be at approx. 670-680 m a.s.l. within the Jauf formation (BRGM, 2008), i.e. only 10-20m below Rasif area's surface (Fig. 1, Table 1). It is one particular unit of this formation, the Devonian Qasr limestone member (Wallace et al., 1997), which is supposed to be an aquifer of regional importance. The limestone of the Devonian Qasr member has a good permeability. The transmissivity is approx. $3.0 \times 10^{-3} \text{m}^2 \text{s}^{-1}$ where the aquifer is confined. In unconfined areas it is increased to about $1.1 \times 10^{-2} \text{m}^2 \text{s}^{-1}$. Accordingly, the storativity ranges from $2 \times 10^{-2}$ to $10^{-3}$ (Alsharhan et al., 2001). The thickness of the Devonian Qasr limestone member is about 15-20 m (Table 1). Below, the siltstone of the Sha’iba member represents an aquiclude and has a thickness of roughly 50 m (Table 1, Wallace et al., 1997).

Rasif is located in a large basin covered with Quaternary fills and calcareous crusts. Rasif study area itself is characterised by numerous endorheic depressions with small catchment/depression ratios (Fig. 2). According to Goudie (2010), these solutional depressions (dayas) are common in North African drylands and on the Arabian Peninsula.Locally, they are known as qas (Fig. 3) and they represent the most noticeable hydrological structures at Rasif.

Rasif study area reveals three sub-catchments with sizes of 11.2 km$^2$, 6.0 km$^2$ and 9.9 km$^2$ (Fig. 2). General flow direction is mainly from west/northwest to east/southeast. The topography is very gently sloping (mean surface slope is 0.5%) with the exception of inselbergs in the north-eastern and
northern part of the catchment that exhibit nearly vertical escarpments. Wadis of all three catchments today are taking course in a very small corridor of about 450m (at UTM37N E631600 N3353800, Fig. 2). Here, changing wadi courses and wadi capturing after single flash flood events might be possible. Hence, catchment sizes and runoff regimes affecting Rasif qas may vary at times. Today, only the sub-catchment I is draining to Rasif qas (Fig. 2) featuring a multiple cascade-like system (Fig. 3). Since vegetation is almost absolutely absent, runoff concentration during rainfall events is very fast after the surface is wetted. Rasif qas (01-05, Fig. 3) comprise a total size of c. 11.3 ha.

3. Recently published findings of autumn 2013 archaeological excavations

Findings of the autumn 2013 archaeological excavations at Rasif are presented in more detail in Gebel et al. (2016). Here, we provide a brief summary to introduce the reader in the archaeological context of Rasif site. According to the archaeological discoveries, Rasif is a functionally and stratigraphically complex, multi-period site occupied particularly during the 6th to 5th/4th millennium BCE featuring domestic, hydraulic, and sepulchral occupations, but also by different intensity until sub-recent times. The site's extension is still not yet determined. Depending on which of the area's surface structures are included, it can amount up to 1.5-2.0 km² (Figs. 2 and 3).

The relative-chronological framework of the site's chipped stone industries covers the Late Neolithic and the 'Chalcolithic/Early Bronze Age' (6th to early 4th millennium BCE). The latter's diagnostic fan scrapers are also attested with Rajajil and Qulban Beni Murra (Gebel et al., 2016). Aside from these, the unique rich unrolled quartzite heavy pick/cleaver industry (and related flakes) were reused tools to hack Rasif well shafts into bedrock.

The yet uncounted large structural inventory of Rasif occupations shows clear ground-plan types, but also a high structural variability of the various plan types, and differing statuses of preservation. The latter most likely is the result of reuse and stone looting of earlier structures.

The structure at Rasif Excavation 5 (Figs. 4a and 5) appeared to be a multi-roomed domestic unit, surrounded by a Late Neolithic flint industry. Full excavation revealed an ashlar-line structure (facing east) with three round spaces in its west in one of which a diagnostic piece of Late Neolithic pottery was found (Gebel et al., 2016). Most likely the structure is a variant of the 5th millennium BCE D-shaped graves, modified from a Late Neolithic (6th millennium BCE) domestic unit during the ‘Chalcolithic’.

Rasif Excavation 4 (Figs. 4b and 5) represents a partly preserved watering place consisting of a well with corbelling masonry for ist upper shaft and with ill-preserved multiple troughs due to stone looting.

Rasif Excavation 2 (Figs. 4c and 5) shows a partly excavated ‘classical’ ‘Chalcolithic’ D-shaped ashlar-line grave, so far with no evidence of bone preservation. The grave is founded within a clay-rich layer (similar with the clay rich layer III in Figs. 6 and 7), which represents the covering layer of the Rasif qa stratigraphy. Compared to the well/trough structure in Rasif Excavation 4, the grave seems to be somewhat younger, because it is only embedded in the uppermost clay-rich layer and not in the stratigraphically older, sandy layer (similar with layer II in Figs. 6 and 7).
Rasif Excavation 3 (Figs. 4d and 5) is a nicely preserved watering place and represents one of the numerous small rectangular paved single troughs with small wells at Rasif site (5th to 4th millennium BCE?). The trough is embedded in the uppermost clayey qa layer (similar with the clay rich layer III in Figs. 6 and 7). Archaeologically and by means of relative chronology, the absolute age of this type of structures cannot be determined. It belongs to a period after the 'Chalcolithic/Early Bronze Age'.

4. Methods

4.1. Topographical survey and mapping

In order to generate a high-resolution Digital Elevation Model (DEM) of Rasif key area DGPS-based surveying was applied with a Trimble rover and a ground-based reference station. Additionally, all archaeological structures in the key area have been recorded using this technique. Kite aerial photogrammetry has been applied for establishing a georeferenced high-resolution aerial photograph, which completed ground-based recording of archaeological findings. Rasif greater area catchment reconstructions bases on analysis of SRTM remote sensing elevation data. Particular hydrological features in the catchment like the positions of the qas and wadi courses were mapped also by means of DGPS. All maps and coordinates are in UTM zone 37N projected on the common WGS84 reference ellipsoid.

4.2. Electrical resistivity tomography (ERT)

Electrical resistivity tomographies (ERT) have been performed along 2D-profiles with equidistant spacing (1-4 m) of 80 ActEle electrodes using a multi-electrodes-apparatus 4 Punkt Light High Power of LGM Comp. Data handling and tomographic inversion were achieved by Geo-Test software applying Wenner Configuration. Several profiles were extended using the roll-on technique (Daily et al., 2004).

4.3. Flux gate magnetic survey

Within qa 01 (Fig. 5) a Bartington Grad601 fluxgate magnetometer was applied for a magnetic survey. Grid measurement was carried out using a Topcon HiPer II DGPS device. Wooden canes marked the corners of each grid. PE-cords with meter spacing indicated northern and southern grid baselines. Additional PE-cords equipped with meter distance marks were spanned between these two baselines and were used as an indicator for walking speed and position. For a higher resolution line spacing of 0.5 m and 4 measuring intervals per meter were selected resulting in a pixel size of 0.25 * 0.5 m. The logged data range was limited to 100 nT, resulting in a sensitivity of 0.03 nT (Zielhofer et al., 2014). Georeferencing and patching of magnetic survey grids were handled in ArcGIS 10. The findings of the magnetic survey were used to improve information about buried archaeological structures (e.g. wells).

4.4. Infiltration capacity and evaporation
The determination of the infiltration capacity of the surface soil was carried out according to the open-end-infiltration-test standard method for spherical flow field with zone coefficient of $C = 5.5r$, where $r$ is the semi diameter of the pipe. Calculation of infiltration capacity was conducted assuming unsaturated soil and variable head (USBR, 1974). For determination of infiltration capacity of the top layer during ponding, water level decrease was observed by means of a temporary gauge fixed in the flooded zone. Evaporation was measured by means of a small evaporation pan (diameter 20 cm).

4.5. Geoarchaeological survey

*Rasif qa* fillings appear to provide the best environmental archive at *Rasif* site but also in the broader region. Bulk samples from *Rasif* geoarchaeological soundings were taken in equidistant intervals (5 or 10 cm) to gain information about deposition and leaching processes and probable changes in sediment provenances.

Grain sizes were determined by sieving and X-ray granulometry (XRG). The sand fraction was determined by dry sieving. The sub-fractions of silt and clay were measured by XRG using SediGraph IIITM (Micromeritics) with MasterTech 052 AutosamplerTM (Zielhofer et al., 2014).

Measurements of mass-specific magnetic susceptibility ($\chi$) and frequency dependent magnetic susceptibility ($\chi_{fd}$) were performed using a Bartington MS3 magnetic susceptibility meter equipped with a MS2B dual frequency sensor. After softly grounding and densely packing the material into plastic boxes, volume magnetic susceptibility was measured with low (0.465 kHz, $\kappa_{LF}$) and high (4.65 kHz, $\kappa_{HF}$) frequency (Lauer et al., 2014). Normalizing $\kappa_{LF}$ with the mass of a sample yielded mass-specific magnetic susceptibility $\chi$.

For calculating total organic carbon (TOC) we measured total carbon by using an Elementar CNS analyser vario EL cube and determined inorganic carbon by Scheibler carbonate measurements (Hausmann et al., 2017). Total S is used as a proxy for the gypsum content (Bertrams et al., 2014).

*Qa* bulk samples were analysed with a Spectro Xepos X-ray fluorescence device. Measurements were conducted in a He gas atmosphere. For XRF sample preparation air-dried bulk sediment (4 g) is sieved with a 2 mm sieve. Subsequently, a homogenization of the sample is undertaken with a vibratory Retsch mill MM 200. Pressed pellets were prepared using a Vaneox press at 20 t for 2 min (Zielhofer et al., 2017a). According to Gasse et al. (1987) and Hoelzmann et al. (2001), the Mg/Ca ratio is a proxy of for palaeosalinity in karstic wetlands. We use this approach for the reconstruction of relative salinity changes within the *qa* stratigraphy at *Rasif* site.

4.6. Radiocarbon and luminescence dating

One humid acid sample from a slightly organic enriched *qa* layer was used for $^{14}$C AMS dating at Kiel AMS laboratory. The $^{14}$C age was calibrated using Calib 7.1 (Stuiver et al., 2017).

Two OSL samples were taken from *Rasif* Geoarchaeological Sounding 2. Approximately 500 g of additional sediments were collected from the same positions for analyses of moisture content and laboratory dosimetry measurements using gamma spectrometry. Sample preparation and measurement for OSL dating was undertaken in the luminescence dating laboratory of the Max...
Planck Institute for Evolutionary Anthropology. The coarse grain quartz fraction (180-212 mm) was isolated for measurement of the equivalent dose (De). Sample preparation was completed under subdued red light using published methods (Fitzsimmons et al., 2014). Equivalent dose (De) measurements were undertaken using automated Risø TL-DA-15 equipped with blue light-emitting diodes, and a Risø TL-DA-20 reader with single grain attachment containing a green laser emitting at 532 nm, for light stimulation of single aliquots and single grains respectively (Bøtter-Jensen et al., 2000). Irradiation was provided by calibrated $^{90}$Sr/$^{90}$Y beta sources (Bøtter-Jensen et al., 2000). The single-aliquot regenerative dose (SAR) protocol of Murray and Wintle (2003) was used to determine De. Small aliquots and single grain approaches were used (Supplementary Online Material).

5. Results and interpretation

5.1. DGPS based digital elevation model and archaeological survey

Our DGPS based digital elevation model provides a mapping basis for the hundreds of archaeological structures at the Rasif qa area (Fig. 5). In total, we identified more than 150 archaeological structures (i.e. more than 100 structures which likely are wells, more than 10 cairns etc.). Obviously, most of the visible archaeological remains (i.e. wells, cairns and others) are located within the local endorheic depression, i.e. mainly in qa 01, qa 02, and qa 04. On the other hand, qa 03 bears no structures at all. Generally, the relatively flat area is separated by a number of dams thus creating a series of qas which are placed in a cascade-like manner.

5.2. Geoarchaeological results

5.2.1. Rasif Geoarchaeological Soundings

Rasif Geoarchaeological Sounding 1 is located in the vicinity of an ancient well within qa 02 (Fig. 5). The stratigraphy can be distinguished in four sequences beginning from bottom to top:

Sequence 0 (0-10 cm, Fig. 6) consists of a compact carbonate crust. The following sequence Ila (10-40 cm, Fig. 6) reveals a fine to medium sandy texture. The reddish brown layer is rich in carbonate concretions and features some stones in the sediment matrix. No clear lacustrine or alluvial sediment structures are visible in the sandy layer. In the northern zone of the sounding an enrichment of fist-sized stones is visible. The stones are bedded on an ash-rich layer.

The subsequent sequence IIb (40-50 cm, Fig. 6) features a sandy layer. There is evidence for a hiatus between sequence Ila and laminated sequence IIb due to a distinct transition. Sequence IIb reveals a light reddish to ash gray colour and contains remnants of organic material. The well-laminated structure indicates episodic qa flooding.

Uppermost sequence III reveals a reddish laminated clayey layer (samples 52 to 60, Fig. 6). The transition from the lower sequence IIb is distinct, however, both sequences feature the same laminated structure due to episodic qa flooding.

Rasif Geoarchaeological Sounding 2 is also located within qa 02 some 50m east of Geoarchaeological Sounding 1 (Fig. 5). The sounding is located in an anomaly of the electrical resistivity tomography section (ERT 07 profile, Fig. 5) that indicates a vertical shaft within the bedrock and thick qa fillings.
The stratigraphy of the sounding can be distinguished in four sequences beginning from bottom to top:

Sequence 0 (0-20 cm, Fig. 7) consists of a carbonate rich (65.1%) layer with a crust-like structure. The stratigraphical transition to the upper sequence I is diffuse.

Sequence I (25-70 cm, Fig. 7) shows carbonate concretions with a decrease from the bottom to the top. The sequence is very compact and does not show hydromorphic features like redox colouring or Fe and/or Mn concretions.

The reddish brown sequence II (75-95 cm, Fig. 7) reveals an aggregated structure and a grain-size maximum in fine and medium sand. The sediment features some carbonate concretions but reveals only low carbonate contents in the sediment matrix. No laminated structures are visible in the sandy layer. From the lower and upper boundary layer of sequence II we have taken samples for luminescence dating (OSL 1 and OSL 2, Fig. 7). Although sequence II at Rasif Geoarchaeological Sounding 2 does not show a clear laminated structure, we assume that this sandy layer is in the same chronostratigraphical position as the sandy layer (sequence II) at Rasif Geoarchaeological Sounding 1.

Sequence III features a clayey layer between 100 and 140 cm (Fig. 7). Reddish sequence III is well laminated. We assume an aggradation of the sequence by episodic qa flooding. The transition from the lower sandy sequence II is distinct due to the different texture and structure. The sequence III corresponds with the sequence III at Rasif Geoarchaeological Sounding 1.

Rasif qaqs are surrounded by multiple hydraulic dam structures that feature slight elevations of the current surface and standing stone lines. (Figs. 5 and 8a). Rasif Geoarchaeological Sounding 3 represents archaeological Excavation 1 (Fig. 8b) and cuts one of Rasif’s dams that is located between qa 01 and qa 02 and shall clarify the dam’s stratigraphical position in relation to sounded qa layers in Figs. 6 and 7. The stratigraphy of the sounding can be distinguished in seven sequences beginning from bottom to top:

Sequence 0 (0-10 cm, Fig. 8b and c) features a carbonate crust that might provide the primary material for the dam’s standing stone lines.

Sequence C2 (10-20 cm) represents a clay layer with a subangular blocky structure. The clay layer is slightly sandy. Sequence C2 reveals a brown colour (slightly greenish to reddish) and does not show any organic remnants. Sequence C2 is poor in carbonates, only at the aggregate surfaces carbonates are detectable. Sequence C2 is poor in stones and seems to be an old (pre-Holocene?) basal layer.

Sequence C1 (20-30 cm) features a yellowish silty layer that is rich in carbonates. Sequence C1 reveals some stones (0.5-2 diameters), carbonate concretions, reddish iron and dark manganese precipitations. The yellowish layer ends at the eastern edge of the sounding. We assume a disturbance due to subsequent anthropogenic activity there. The transition from Sequence C2 to Sequence C1 is distinct. Sequence C1 reveals evidence for bioturbation with worm or insect burrows at the top. The calcified burrows are filled up with reddish material from the clayey Sequence AB at the top. The transition from Sequence C1 to the following Sequence AB is diffuse.

Sequence AB (30-37 cm) reveals a reddish brown layer with angular gravels and is weakly aggregated. Clayey Sequence AB is enriched in total organic carbon (Fig. 8c) and features carbonate nodules indicating former carbonate leaching processes. Hence, Sequence AB reveals evidence for a
terrestrial soil formation, indicating that the zone of Rasif Geoarchaeological Sounding 3 was initially not or only slightly influenced by qa deposition. This might be the result of the slightly elevated position in relation to the central qa deposition zones. The transition of Sequence AB toward Sequence Y is distinct.

Sequence Y (37-60 cm) features a reddish brown layer with multiple angular gravels (diameters between 2 and 4 cm). The loamy fine material is only weakly aggregated. Sequence Y represents the anthropogenic dam material. The standing stone lines are fixed within Sequence Y.

Sequence III (35-60 cm) is characterised by a reddish brown layer that is weakly laminated. Sequence III represents a qa layer that was deposited after the initial dam construction. Due to the characteristic fining-up pattern of sequence III (Fig. 8c), the 25 cm thick layer seems to correspond with the sequences III of Rasif Geoarchaeological Soundings 1 and 2. Accordingly, we postulate a covering of the dam material during the final qa deposition phase.

Sequence IV (60-75 cm) represents a medium sandy layer of sub-recent aeolian sand. As a result, Rasif Geoarchaeological Sounding 3 shows a hydraulic dam structure with standing stone lines that were founded outside the initial zone of thick qa deposition. The dam’s position is slightly enhanced and founded on a small and shallow watershed between the two isolated qas 01 and 02. The dam construction is significantly older than the onset of the final qa deposition phase (sequence III).

5.2.2. Radiocarbon and luminescence dating

The AMS humic acid dating of the bulk sample from sequence IIb (Rasif Geoarchaeological Sounding 1, Fig. 6) reveals a $^{14}$C age of $5980 \pm 25$ BP (KIA 48947). This corresponds with a calibrated age of 4936-4796 cal. BC (Table 2).

Since single aliquot measurements of the two OSL skewed equivalent dose distributions (Supplementary Online Material), single-grain dating was undertaken in order to identify outliers within the dose distribution, and to determine the final De values.

Prior to equivalent dose measurements, dose recovery tests were conducted. The dose recovery statistics are summarized in the Supplementary Online Material and the recovered dose distributions are shown in Fig. 9c and d.

The single quartz grains from Rasif rapidly decay, as is typical of quartz dominated by the fast component (Fig. 9a). IRSL signals as detected by the IR depletion ratio are negligible, indicating no feldspar contamination of the quartz signal.

Nevertheless, very few single grains were found to emit sufficient luminescence signal, and still fewer passed the selection criteria for equivalent dose determination (Supplementary Online Material). Consequently, since minimal material was available for analysis, the number of grains able to be used for De determination was fewer than the recommended 50 grains for robust statistical analysis (Rodnight, 2008).

Both samples yield Gaussian, if widely spread, distributions (Fig. 9e and f), with overdispersion values of 40%. Wide distributions may be attributed to proportionally high dose rate heterogeneity in sediments with low concentrations of radiogenic elements. Since there was no clear indication of
incomplete bleaching or mixing subsequent to deposition for the measured single grains, and the number of grains available for analysis were few, the Central Age Model (CAM) of Galbraith et al. (1999) was used for age calculation. The final age calculations, based on both single aliquot and single grain measurements, are summarized in Table 3.

Despite the less than ideal characteristics of the Rasif quartz, the results nevertheless indicate reproducibility and therefore reliability in the final calculated ages. Both single aliquot and single grain measurements yield rapidly decaying, if dim, OSL signals indicative of fast component dominance. IRSL signals are negligible indicating no feldspar contamination of the quartz and dose-recovery ratios lie within 10% of unity, irrespective of whether standard or “substitute” dose recovery tests are applied. The single aliquot and single grain results from both samples yield results within 2σ error of one another. However, the single aliquots consistently overestimate the age relative to the single grains. The most likely explanation for this lies in the dose distributions. The single aliquot results exhibit positive skewness towards older ages, and slightly older main peaks, whereas the single grain distributions are Gaussian and yield slightly younger peaks. The older peaks and positive skewness in the single aliquot results are probably derived from the incorporation of brighter, older individual grains onto the disc, thereby skewing the averaged signal of the aliquot towards an older age than was observed in the CAM peak for single grains. Given these arguments, the single grain ages must be taken as the final ages. OSL-1 is therefore 4900–3300 BCE and OSL-2 is significantly older at 14,800–9400 BCE.

5.3. Archaeohydrological results

5.3.1. Archaeohydrological interpretation of the well at Rasif Excavation 4

In March 2015 we excavated the well of Rasif Excavation 4 (Fig. 4b) to gain information about the depth of the well, the types of the former aquifers and their hydrogeological context. The uppermost part of the well shaft (part 1, 0–190 cm, Fig. 10) consisted of the well mouth's stones followed by corbelling dry stone masonry of tabular local limestone with inserted steps. The building pit was dug into sandy qa deposits, into which the corbelling masonry was set resting on the reached bedrock.

Part 2 (195–200 cm, Fig. 10) is characterised by an extremely hard, laminated calcareous crust of 3–9 cm thickness. The crust is uneven, slightly inclined, and features the uppermost part of a consolidated calcareous rock (belike bedded limestone).

Part 3 (200–215 cm, Fig. 10) consists of a bedded, chalk-like limestone. The in situ calcareous rock reveals a sandy to silty matrix with vertical fissures and is angularly fractured and partly scuffed.

Part 4 (215–480 cm, Fig. 10) consists of scuffed calcareous rocks. Well-bedded, protruding limestone 'rings' served as steps for climbing inside thewell. The steps are irregular and follows the hardness of the bedrock stratigraphy. The scuffed surfaces of the protruding bedrock layers indicate a long operation period of thewell in the past. The base of the well was not reached during the excavation.

5.3.2. Magnetic grids - archaeohydrological implications
Circular magnetic anomalies indicate buried well structures (Fig. 11). Furthermore, the magnetic grids point to relatively shallow magnetic anomalies. This might be an indication for changing redox conditions at the qa’s sub-surface probably indicating that the initially dug wells exploited a shallow aquifer at the beginning.

5.3.3. Water harvesting - operation mode of Rasif’s dam system

It is quite obvious that the dams are located in or adjacent to the topographic depression where today the sub-catchment I (Fig. 2) drains to. This depression is located at a level of less than 690 m a.s.l. (Figs. 3 and 5) and exhibits the qas 01 to 05. On the one hand, the dams’ construction type caused artificially an increased size of the catchment by diverting the surface runoff. For instance dam 10 (in the south of the Rasif qa area, Fig. 3), diverts the surface runoff of wadis 7 and 8 to the north in the direction of qa 01. Besides this artificial creek, which links qa 06 and qa 01, small dams on ist eastern bank were found. Those dams 8 and 9 likely have been used to avoid water to take course in (north-) eastern direction. Dams 5 and 6 in the north are preventing water to flow past the eastern mound (east of qa 03), Dam 11 likely was used to divert wadis 1, 2, and 3 entering the Rasif qa area from the west (Figs. 3 and 5).

On the other hand, some dams mainly where used rather to retain than to divert surface runoff. In particular dams 1, 2, 3 and 4 are likely to enclose temporal ponds in qas 1, 2, and 4. Consequently, the water depth is increased artificially once the site is flooded. At the same time the surface of temporal ponds is smaller thus evaporation losses are reduced.

The dams between the isolated qas possibly were altered several times. However, the recent operating mode of Rasif’s dam system became obvious with the heavy rainfalls on November 18th, 2013 (Fig. 3a). Of particular importance is dam 10 (Fig. 3b) south of Rasif qa area that enlarges the sub-catchment I (Fig. 2) substantially. After ponding of qa 06, surface runoff is bypassed into qas 01 and 02. Dams 8 and 9, both adjacent to wadi 6, prevent any runoff to enter eastern qa 03 (Fig. 5). This way, the amount of surface runoff directed to the well zone of qas 01 and 02 is significantly enlarged. Hence, the dams create a very shallow, cascade-like succession of hydrologically coupled pools, which represent the centre of a large-scale water harvesting system.

5.3.4. Spatial distribution of Rasif wells e archaeohydrological implications

It is remarkable that most wells are located in qas (Fig. 5) thus indicating the utilization of surface runoff rather than tapping groundwater. Even more, the wells are predominantly located only in some particular qas (qa 01, 02, and 04), where others are lacking any wells.

The ERT cross sections (Fig. 12) generally show a layer of several meter thickness at the top which has very little resistivity. This zone corresponds with Holocene and late Pleistocene qa deposits shown in Figs. 6 and 7. Below, we found a thick zone of multiple decametres with medium to high resistivity (300-800 Qm). Such resistivity values empirically can be linked to sand- or limestone, both generally suitable as aquifers.
The locations of wells in relation to the axes of the ERT profiles show an accumulation in zones of higher resistivity of app. 800 Ωm in deeper zones (Fig.12). At the same time, the wells are located in spots, where subsurface sediment layers seem to have biggest thicknesses. The subsurface sediment layers of the qas are divided in the uppermost clay-rich sequence III and the sandy sequence II (Figs. 6 and 7). Sequence III features a nearly impermeable infiltration capacity of about $k_f = 3.2 \times 10^{-8}$ m s$^{-1}$, Fig. 13a). However, the infiltration capacities of subjacent sandy sequence II reveal much higher values between $1.1 \times 10^{-7}$ and $2.6 \times 10^{-6}$ m s$^{-1}$ (Fig. 13b), according to the results of the open-end-tests. The useable pore volume of sequence II was determined to 24.4%. Therefore, subsurface sequence II was probably used as a shallow aquifer as indicated by the high well density in zones of thick occurrence of subsurface sequence II.

6. Discussion

6.1. Changing processes of qa deposition

The statistical key data of the principal component analysis are presented in Table 4 and Fig. 14. The 1$^{st}$ principal component reveals an eigenvalue of 9.69 and is characterised by high positive loadings of carbonates, medium silt and coarse sand. In arid environments it is typical that silty grains correspond with enhanced carbonate contents (Zielhofer et al., 2012). The 1$^{st}$ principal component shows high positive loadings in Ti/Al, Rb/Al, and K/Al. These silici-clastic ratios might be proxies for (three-layer) clay minerals (cf. Kylander et al., 2011). The strong coupling of carbonates with high Ti/Al, Rb/Al and K/Al indicate that carbonate contents in Rasif Geoarchaeological Soundings are predominantly the result of past qa aggradation processes with deposition of carbonates and specific silici-clastic minerals at the same time. Hence, we interpret changing carbonate contents as an almost synsedimentary process due to changing qa deposition processes or due to changing sediment provenances.

The 2$^{nd}$ principal component reveals an eigenvalue of 3.32 and shows high positive loadings for Zr/Al and Si/Al reflecting the presence of weathering resistant and quartz-rich minerals (cf. Kylander et al., 2011). These high loadings correspond with high loadings in fine sand and high negative loadings in fine silt, supporting the evidence for quartz in the fine sand fraction.

At Rasif Geoarchaeological Soundings 1 and 2 the Mg/Ca ratios show increasing values from the bottom to the top of the sequences. This might indicate increasing salinities in the upper part of the soundings as higher Mg/Ca ratios often corresponds with increased salinity in karstic wetlands (Gasse et al., 1987; Hoelzmann et al., 2001). Screenings of the sediments for the presence of ostracods were not successful. As ostracods are even present in temporary lakes the absence of ostracods points to relatively dry conditions for the entire qa stratigraphy or to postsedimentary carbonate solution and precipitation that destroy former ostracod valves (Steffen Mischke, personal communication).

Sequence II in Rasif Geoarchaeological Soundings 1 and 2 reveals maxima in sand contents (Figs. 6 and 7). Hence, sequence II reveals suitable conditions for a sub-surface aquifer fed by temporally qa flooding and exploited by shallow wells. The high density of wells within the qas (Fig. 5) can be explained by probable steep groundwater depression cones within this shallow subsurface aquifer.

At Rasif Geoarchaeological Soundings 1 and 2 we assume an aggradation of the laminated sequences IIb and III by episodic qa flooding. We have to emphasize that sequence II and III are no continuous
archives. There might be several chronological gaps within Rasif qa soundings. Sequence III contains no charcoal remnants and only few sharp-edged stones with diameters between 3 and 10 cm indicating a probable decrease in human activity.

6.2. Rasif occupation phases

The relative-chronological framework of the Rasif site’s chipped stone industries cover the Late Neolithic and ‘Chalcolithic/Early Bronze’ age (6th to early 4th millennium BCE). Recovered diagnostic pieces are similar to the industries at adjacent Rajajil site (Gebel et al., 2016). Although we are still at the onset of archaeological and geoarchaeological investigations at vast and complex Rasif site, first evidence allows us to speak of a water-favoured location during the mid-Holocene, probably providing at least seasonal ponds. ‘Chalcolithic’ water management systems at Rasif are generally well-preserved, whereas they are destroyed at close by well-known ‘Chalcolithic’ standing stone site of Rajajil (Gebel et al., 2016). Hence, ‘Chalcolithic’ wells and troughs at Rasif might mirror water management systems, which are representative for a broader zone of ‘Chalcolithic’ occupation in Northwest Arabia. So far, we are able to distinguish 5 occupation phases at Rasif, which corresponds with changing water management strategies (Table 5, Fig. 15).

6.2.1. Phase 1: Late Neolithic housing areas during the 6th millennium BCE

During mid-Holocene occupation phase 1 Late Neolithic domestic structures (Excavation 5, Fig. 4a) are located adjacent to local qa depressions (Figs. 3 and 5). The ashlar-line structure at Rasif Excavation 5 is surrounded by a Late Neolithic industry. The full excavation recovered a diagnostic piece of Late Neolithic pottery. The multi-roomed Neolithic house was most likely rebuild in the 5th millennium BCE into a D-shaped grave.

Relatively low Mg/Ca ratio indicates low salinity of the contemporaneous qa deposits (lower sequence II, Fig. 7). Therefore, we postulate higher rates of precipitation at Rasif that triggered a more frequent (maybe even perennial) shallow ponding area. Water was available at least seasonally without any technical or hydraulic installations. Furthermore, higher precipitation should provide a steppe landscape with favourable conditions for grazing. The 6th millennium BCE (Late Neolithic) corresponds with pollen zone 3 (6.0-4.3 cal ka BC) of the pollen-dated palaeo-environmental record at Tayma lake in Northwest Saudi-Arabia (Dinies et al., 2015, 2016). Pollen-dating improves the age model in karstic lake records as the hard-water effect can be significantly reduced (Fletcher et al., 2017). According to Dinies et al. (2015, 2016), pollen zone 3 is indicated by significantly drier conditions as during the early Holocene hydric optimum between 6.7 and 6.0 cal ka BC (pollen zone 2). However, pollen zone 3 reveals wetter conditions as the final pollen zone 4, starting approx. 4.3 cal ka BC, which indicates a further decrease in grassland pollen with the end of a perennial Tayma lake at ~2.8 cal ka BC.

6.2.2. Phase 2: Favoured pastoral ‘Chalcolithic’ watering location during the 5th millennium BCE
The partly-preserved pastoral watering place of Rasif Excavation 4 (Fig. 4b) corresponds with Rasif Holocene occupation phase 2 and reveals a lot of similarities with the ‘Chalcolithic’ well excavated in Qulban Beni Murra which belongs to the 5th Millennium BCE (Gebel et al., 2016). The well and troughs are partly embedded within the uppermost part of qa sequence II (Figs. 6 and 7). The qa sequence II reveals a $^{14}$C age of 4936-4796 cal. BC (Fig. 6, Table 2) and a OSL age of ~4900-3300 BCE (Fig. 7, Table 3). The latter represents the uppermost part of sequence II that reveals already a significant increase in Mg/Ca salinity proxy (Fig. 7).

Sequence II in Rasif Geoarchaeological Sounding 1 comprises charcoal remnants, sharp-edged stones with diameters between 3 and 10 cm and a quartzite artefact (Fig. 6) that indicate a ‘walking horizon’ and consequently a noticeable desiccation of the qa at that time. From the stratigraphical point of view sequence IIb (40-50 cm, Fig. 6) may belong to the period of human occupation in which the first wells and troughs were constructed. The laminated structure of sequence IIb points to multiple aggradation phases by episodic qa flooding. As the watering place of Rasif Excavation 4 is partly founded within the uppermost part of qa sequence IIb, we postulate an oldest stage of this multi-phase well/trough structure that corresponds with the 5th millennium BCE.

During Rasif occupation phase 2 shallow wells had been dug in order to tap interflow which was stored for a relatively long period in the sandy qa deposits once after surface runoff occurred. Deep percolation within these depressions is prevented by calcareous crusts located at 0.5-2.0 m below surface (Figs. 6 and 7). Hence, the sandy sub-surface qa sequences I and II (Figs. 6 and 7) could act as reservoir, which prevented evaporation and thus enabled the use of water long time after rainfall. Infiltration of surface runoff was possible at that time since the clayey top layer (Sequence III in Figs. 6-8) was not formed at this time. Generally, sequences I and II are not best but suitable for this type of water usage. Relatively low pore volume and infiltration capacity of about $10^{-6}$ ms$^{-1}$ likely triggered the digging of a big number of wells in order to increase total yield. The roughly estimated yield of each well was in the range of 50-200 L per day due to the limited infiltration rate and the low thickness of the shallow qa sandy aquifer. Consequently, we can assume that the troughs, allocated mostly adjacent to the wells (Fig. 4b), could have been charged once a day or every second day only. This fits to the mean capacity of the troughs which is 150-300 L.

6.2.3. Phase 3: Favoured pastoral ‘Chalcolithic’ burial location at the end of the 5th millennium BCE

The D-shaped ashlar-line grave (Rasif Excavation 2: Fig. 4c) is characteristic for ‘Chalcolithic’ grave types (5th millennium BCE), which are known from the north-western Arabia (Gebel et al., 2016). Note the original location of a cylindrical sandstone slab (Fig. 4c) among the cairn’s upper cover stones. The slab is similar in size and shape to slab excavated at ‘Chalcolithic’ Rajajil site (Gebel et al., 2016). The grave is embedded in the clay-rich qa layer III. The subjacent qa sequence II reveals in the uppermost part (Fig. 7) a single grain OSL age of 4900-3300 BCE (Table 3). Hence, we assume an age for the grave in Excavation 2 that belongs at the earliest to the end of the 5th millennium BCE.

The deposition of the uppermost clayey sequence III might be the result of progressive aridification and changing run off conditions within the qa catchment. Dinies et al. (2015, 2016) document the transition from pollen zone 3 to pollen zone 4 at 4.3 cal ka BC at Northwest Arabian Tayma Lake. Pollen zone 4 documents a progressive decrease in wood and grassland taxa. At Rasif, a lighting of the steppe vegetation cover due to increasing aridity could coincide with soil erosion in the
catchment and a contemporaneous supply of clayey particles into the qas. Hence, the resulting clayey top layer (sequence III, Figs. 6 and 7) of the qas led to a gradual decrease in infiltration capacity during phase 3. In combination with ongoing acidification, i.e. less precipitation, the site’s occupants faced progressive water shortage.

Many of the very distinctive well/trough structures (Excavation 3, Fig. 4d) appear to have been founded during the phases of final qa deposition that is represented by the clay-rich sequence III. The pavements of these well/trough structures are embedded in this final clay-rich sequence III. As mentioned above already, the subjacent qa sequence II reveals in the uppermost part a single grain OSL age of 4900-3300 BCE. Hence, we must assume a significantly younger age of the well/trough structure in Excavation 3. Probably, many of the distinctive well/trough structures of Excavation 3 type reveal post-‘Chalcolithic’ ages.

Due to the aggradation of the impermeable clay-rich qa sequence III, the functioning of the shallow qa wells tapping subsurface interflow was probably limited. However, we assume that surface runoff preferentially flowed into the open and numerous well shafts thus charging the subsurface reservoir of sequences I and II. This type of water management can be taken into account as artificial groundwater recharge.

6.2.4. Phase 4: Pastoral post-‘Chalcolithic’ watering location

In the course of progressive aridification, the application of shallow wells failed since surface runoff was further reduced after annual precipitation rate decreased. Additionally, rainfall probably did not occur as reliable as before. Consequently, some of the existing wells had been deepened or new wells had been dug in order to tap a deeper aquifer within the bedrock formation. Here, the Devonian Qasr limestone member (Table 1) exhibits a predominant aquifer that is currently present only 10-20 m below the surface (BRGM, 2008). Taking higher precipitation rates and higher groundwater recharge rates into account, the groundwater head was probably closer to surface during phase 4 than it is today.

Tapping a deep aquifer has decisive impact on the reliability of water supply in comparison to only tapping interflow or a shallow subsurface aquifer. Latter ones provide only a little yield or even exsiccate when rainfall was little or absent. Therefore the effort of digging deep wells into the bedrock (with depths of at least 5m, Fig. 10) has to be set into relationship to the benefits which one can anticipate. Generally, this archaeohydrological transition from shallow to deep wells might be an absolute condition for a sustainable domestication at that time. Generally, the idea and the technique of digging deep wells tapping (fossil) groundwater was known in this region at latest since Pottery Neolithic (Wellbrock et al., 2012).

For the subsequent millennia no general change in hydrological setting and in applied water management techniques can be deduced. Nevertheless, we assume a reduced groundwater recharge at Rasif due to enduring aridity with a contemporaneous and progressive decrease of regional-scale groundwater tables. However, as regional aquifers are supposed to be linked to one of the biggest and most sluggish ones of northern Arabia, any changes in hydro-climate and corresponding recharge rates will affect the groundwater table only after centuries or even millennia.
Consequently, we still consider the digging of wells with adjacent troughs in the 4th millennium BCE and afterward. Nevertheless, we assume the yield of the wells to decrease gradually.

6.2.5. Phase 5: Pastoral post-‘Chalcolithic’ to sub-recent watering location

Exploitation of groundwater became probably more and more difficult during a progressive post-‘Chalcolithic’ aridification. For this reason, at the latest in final phase 5 a large water harvesting system has been developed that concentrated surface runoff and significantly enhanced the water supply into Rasif qa area. Surface runoff was delineated and retained by means of several dams located adjacent to the natural qas (Figs. 2, 3 and 5). According to geoarchaeological observations (Fig. 8), parts of the dam system might be initially build-up already during the 5th millennium BCE while many of the visible dams should have a younger age than the ‘Chalcolithic’ graves, troughs and wells since they are not deeply embedded in upper qa deposits. We assume that the long use of the dams supports the ongoing aggradation of the uppermost clayey qa sequence III (Figs. 6-8) that is highly impermeable. Hence, Rasif qas do not represent solely natural endorheic basins that are seasonally filled by surface runoff with high suspension load but rather feature khabrats. A khabrat is the Bedouin term for an artificially barraged part of a shallow wadi system resulting in an episodic seasonal pool being the basis for temporary potable water supply. We assume that this water harvesting system was being modified and adapted during multiple millennia until sub-recent times.

6.3. Supra-regional climate forcing of Rasif water management strategies

On the supra-regional scale the major changes in the Holocene palaeohydrology are driven by alternating influences of monsoonal air masses due to insulation forces. Palaeoclimatic and palaeoenvironmental studies from the Arabian Peninsula (Sirocko et al., 1993; Arz et al., 2003; Fleitmann et al., 2003; Radies et al., 2005; Fuchs and Buertkert, 2008) as well as from the Western (Tierney et al., 2017; Zielhofer et al., 2017b) and Eastern Saharan region (Kuper and Kröpelin, 2006; Kröpelin et al., 2008; Francus et al., 2013) reveal more humid conditions during the early Holocene because of the northward shift of monsoonal air masses at that time. This early Holocene humid period with steppe/savannah-like environments in the nowadays hyperarid regions features a long-term aridity trend towards the mid-Holocene and was pronounced by sub-millennial phases of climatic deterioration (Fleitmann et al., 2004, 2011, Migowski et al., 2006; Weninger et al., 2006; Zielhofer et al., 2017b). These deterioration phases correspond with Rapid Climate Changes (RCC) of global scale (Mayewski et al., 2004; Fletcher and Zielhofer, 2013; Wanner et al., 2015). One of these RCC intervals started around 4.6 to 3.9 cal ka BC with a significant decrease in humidity in Mediterranean North Africa (e.g. Ibouhouten et al., 2010), the Eastern Mediterranean and Middle East (Bar-Matthews and Ayalon, 2011; Benito et al., 2015; Preston et al., 2015; Dines et al., 2016), enhanced Saharan (Zielhofer et al., 2017b) and Middle East (Sharifi et al., 2015) dust mobilization, the end of Eastern Mediterranean sapropel formation (Schmiedl et al., 2010), and with decreased population densities in the Southern Levant (Weninger et al., 2009) and the Arabian Peninsula (Staubwasser and Weiss, 2006).
At Rasif the onset of the clay-rich deposition (sequence III) started at the earliest around 4 ka BCE (Figs. 6 and 7). As deduced from our sedimentological and geoarchaeological findings the deposition of the uppermost clayey sequence III indicate a progressive aridification at Rasif site and many of the very distinctive well/trough structures (Excavation 3, Fig. 7) appear to have been founded during this phase of final qa deposition.

Reliable data on Holocene annual precipitation is very sparse for the Northwest Arabian Peninsula (Enzel et al., 2015, 2017, Engel et al., 2017). Palaeo-rainfall during the early Holocene (8-6.5 BCE) has been approximated by Wellbrock et al. (2011) and Engel et al. (2012) for the oasis of Tayma (340 km southwest of Rasif) to be about 150 ± 25mm per year and thus amounted to app. 200-300% of today's annual precipitation. New pollen data from the same region indicate a significant shift toward more arid conditions around 4.3 ka BCE (Dinies et al., 2016) that corresponds with the above mentioned climatic deterioration at supra-regional and with our own findings at Rasif local scale.

The essential study of Avner (2002) in the Negev and Sinai illustrates the level of variability we have to expect for mid-Holocene pastoral cultures in the Levant and North Arabia. The results of our archaeohydrological study at Rasif might help to get insight into the land use and water management strategies of Northwest Arabian mid-Holocene pastoral well cultures. The environmental knowledge of these palaeo-Bedouins, and the related hydrological competencies might have created the paradigms of adaptation and value systems that persisted in the sedentary oasis cultures of the nowadays arid to hyper-arid Arabian Peninsula (Gebel, 2013; Wellbrock et al., 2017).

7. Conclusions

At Rasif site in Northwest Arabia our multidisciplinary geoarchaeological and archaeohydrological study documents mobile well/trough/dam-based pastoral cultures sustaining on mid-Holocene moisture episodes. These partly megalithic cultures seems to be characteristic for land-use modes in the nowadays deserts in Northwest Africa and the Arabian Peninsula: their sites must have been meeting places for watering flocks, ancestor commemoration and social transaction in the former steppe environments, even allowing semi-permanent occupations at hydrologically favoured locations.

Rasif represents a vast site with multi-phased archaeohydrological phases. We reconstruct five different archaeohydrological phases at Rasif that correspond with an increasing water shortage due to climatic deterioration during the mid-Holocene.

Our data mainly point to a mid-Holocene water-favoured location. Lines of 6th millennium BCE domestic structures may indicate former shorelines of seasonal ponds or wetlands. Subsequent clayey qa deposits embedded the many 5th millennium and later wells with troughs, D-shaped and other graves. Finally, Rasif qa area was transferred by complex dam buildings into a system of interacting artificial pools since 5th millennium BCE times. This dam-based water harvesting system was most probably modified and enlarged during the post-‘Chalcolithic’ and was still functioning until sub-recent times.

Acknowledgements
Matthias Grottker and Christoph Zielhofer as principal investigators and Hans Georg K. Gebel as major cooperation partner thank the German Research Foundation for generous funding of the fieldwork and lab analyses (GR 1835/5-1, ZI 721/11-1). The authors are grateful to the Saudi Commission for Tourism and National Heritage for helpful support in field and in preparing the expeditions in February 2012, November 2013, February 2014, and March 2015. The authors are grateful to Armin Rauen for conducting ERT profiles, Martin Straub for supporting field work and to Wael Abu-Azizeh for performing the kite aerial photogrammetry of the site's core area. Also we gratefully acknowledge the numerous workmen. Finally, all authors are grateful to the guest editorial board and two anonymous reviewers for helpful comments and suggestions.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quaint.2018.03.001.

References


- Dinies, M., Plessen, B., Neef, R., Kürschner, H., 2015. When the desert was green: grassland expansion during the early Holocene in northwestern Arabia. Quaternary International 382, 293-302.


- Rodnight, H., 2008. How many equivalent dose values are needed to obtain a reproducible distribution? Ancient TL 26, 3-10.


Tables

Table 1

Regional lithostratigraphy of Rasif greater area (Wallace et al., 1997; BRGM, 2008).

<table>
<thead>
<tr>
<th>Period</th>
<th>Formation</th>
<th>Member</th>
<th>Lithology</th>
<th>Thickness</th>
<th>Hydrogeology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devonian</td>
<td>Jauf</td>
<td>Murayr</td>
<td>Djm</td>
<td>Siltstone and Shale&lt;br&gt;Cream to tan, hard, thin-bedded</td>
<td>30 m</td>
</tr>
<tr>
<td>Hammamiyat</td>
<td>Djh</td>
<td>&lt;br&gt;Interbedded, greyish, stromatolithic; tabular gypsum</td>
<td>120 m</td>
<td>possible aquifer</td>
<td></td>
</tr>
<tr>
<td>Subbat</td>
<td>Djsu</td>
<td>Shale</td>
<td>greyish-red, grayish-pink, purple; gray sanstone beds</td>
<td>120 m</td>
<td>aquiclude</td>
</tr>
<tr>
<td>Qasr</td>
<td>Djq</td>
<td>&lt;br&gt;Limestone&lt;br&gt;light grayish-brown to yellowish; argillaceaous; bioclastic limestone; stomatolite zone at the top of unit</td>
<td>15 - 20 m</td>
<td>possible aquifer</td>
<td></td>
</tr>
<tr>
<td>Sha'iba</td>
<td>Djsu</td>
<td>Siltstone and Shale&lt;br&gt;Interbedded gray to grayish-green; silty limestone; shale beds with gypsum plates</td>
<td>50 m</td>
<td>aquiclude</td>
<td></td>
</tr>
<tr>
<td>Tawil</td>
<td>Juraniyat</td>
<td>Dtj</td>
<td>Sandstone&lt;br&gt;Tan and light-gray; medium- to coarse-grained</td>
<td>60 m</td>
<td>braided aquifer</td>
</tr>
<tr>
<td>Tufayhah</td>
<td>Dtt</td>
<td>Sandstone&lt;br&gt;Tan, moderate-red nad grayish-red, medium- to coarse-grained</td>
<td>180 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ghuwar</td>
<td>Dtg</td>
<td>Sandstone&lt;br&gt;Tan, light-grayish-brown, medium- to coarse-grained</td>
<td>60 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Table 2**

Sediment sequence IIb radiocarbon dating (*Rasif* Geoarchaeological Sounding 1). Conventional $^{14}$C age was calibrated using Calib 7.1 (Stuiver et al., 2017).

<table>
<thead>
<tr>
<th>ID code</th>
<th>Sounding</th>
<th>Lab. No</th>
<th>Material</th>
<th>$^{14}$C [a BP] ± 1 sigma error</th>
<th>2 sigma [cal. BC]</th>
<th>$\delta^{13}$C (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural layer IIb</td>
<td><em>Rasif</em> 1</td>
<td>KIA 48947</td>
<td>Charcoal and humic acid</td>
<td>5980 ± 25</td>
<td>4936-4796</td>
<td>11.10 ± 0.11</td>
</tr>
</tbody>
</table>
Table 3

Age estimates, including dose rate data and De values. Single aliquot results are shown in plain text, single grain results in italics. The uncertainties of the final age estimates are given as 1σ.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{40}$K (%)</th>
<th>$^{238}$U (ppm)</th>
<th>$^{232}$Th (ppm)</th>
<th>$D_{\text{cosmic}}$ (Gy/ka)</th>
<th>$D_{\text{total}}$ (Gy/ka)</th>
<th>$D_e$ (Gy)</th>
<th>Age (ka)</th>
<th>Age BCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSL 1</td>
<td>0.61 ± 0.03</td>
<td>2.25 ± 0.11</td>
<td>12.3 ± 0.62</td>
<td>0.192 ± 0.02</td>
<td>1.98 ± 0.11</td>
<td>14.0 ± 0.7</td>
<td>7.0 ± 0.7</td>
<td>4900e-3300</td>
</tr>
<tr>
<td>OSL 2</td>
<td>0.86 ± 0.04</td>
<td>2.29 ± 0.11</td>
<td>11.1 ± 0.56</td>
<td>0.186 ± 0.02</td>
<td>2.12 ± 0.12</td>
<td>36.1 ± 3.1</td>
<td>17.0 ± 2.0</td>
<td>14800-9400</td>
</tr>
</tbody>
</table>
Table 4

Two principal components with cumulative variances, eigenvalues and loadings.

<table>
<thead>
<tr>
<th></th>
<th>PC1: 1st component</th>
<th>PC2: 2nd component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>9.69</td>
<td>3.32</td>
</tr>
<tr>
<td>Cumulative variance [%]</td>
<td>60.58</td>
<td>81.32</td>
</tr>
<tr>
<td>Fine sand, fS [%]</td>
<td>-0.471</td>
<td>0.850</td>
</tr>
<tr>
<td>P [mg/kg]</td>
<td>-0.771</td>
<td>-0.255</td>
</tr>
<tr>
<td>Ti/Al</td>
<td>0.800</td>
<td>-0.004</td>
</tr>
<tr>
<td>Si/Al</td>
<td>0.034</td>
<td>0.908</td>
</tr>
<tr>
<td>Zr/Al</td>
<td>-0.316</td>
<td>0.858</td>
</tr>
<tr>
<td>Nd/Al</td>
<td>0.832</td>
<td>0.020</td>
</tr>
<tr>
<td>Mn/Fe</td>
<td>0.830</td>
<td>0.159</td>
</tr>
<tr>
<td>Fine clay, fC [%]</td>
<td>-0.021</td>
<td>-0.890</td>
</tr>
<tr>
<td>Medium silt, mU [%]</td>
<td>0.831</td>
<td>-0.047</td>
</tr>
<tr>
<td>V/Al</td>
<td>0.929</td>
<td>-0.084</td>
</tr>
<tr>
<td>K/Al</td>
<td>0.863</td>
<td>0.263</td>
</tr>
<tr>
<td>Ca/Sr</td>
<td>0.952</td>
<td>0.146</td>
</tr>
<tr>
<td>Coarse sand, cS [%]</td>
<td>0.841</td>
<td>0.079</td>
</tr>
<tr>
<td>Ca/Al</td>
<td>0.976</td>
<td>0.109</td>
</tr>
<tr>
<td>Carbonates [%]</td>
<td>0.987</td>
<td>0.028</td>
</tr>
<tr>
<td>Rb/Al</td>
<td>0.958</td>
<td>-0.178</td>
</tr>
</tbody>
</table>
Table 5

*Rasif* occupation phases: Multidisciplinary interpretations (Phases 1-5).

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Late Neolithic housing areas 6th millennium BCE</th>
<th>Archaeological evidence</th>
<th>Archaeohydrological evidence and assumptions</th>
<th>Geoarchaeological evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alignments of multi-roomed domestic structures with polygonal rooms (Excavation 5), related open space structural features, basically aceramic</td>
<td>domestic structures next to local depressions (<em>qa</em>) indicating a more frequent flooded area</td>
<td>Low salinity in <em>qa</em> sediments (Sequences I and II)</td>
<td></td>
</tr>
</tbody>
</table>

| Phase 2 | Pastoral ‘Chalcolithic’ watering (and burial) location 5th millennium BCE | Wells with complex trough systems (and contemporary grave structures?), e.g. Excavation 4 | Intermediate flow (unconfined aquifer within Sequence II) tapped by shallow wells (infiltration capacity tested) | Age of sandy Sequence II: 4900-3300 BCE [OSL] Sequence II reveals a slight increase in salinity 14C age of ‘Chalcolithic’ occupation in the *qa*: 4936-4796 cal. BC |

| Phase 3 | Pastoral ‘Chalcolithic’ (watering and) burial location End of the 5th millennium BCE | Grave structures (mainly D-shaped, Excavation 2) founded in lower *qa* layers, still co-existing with ‘Chalcolithic’ wells/complex trough systems | Decreased mean annual precipitation caused more seldom a ponding of the *qas*; deceeding infiltration capacity of the *qa* surfaces due to the initial aggradation of Sequence III | Initial aggradation of the uppermost clay layer (Sequence III) Increase in salinity within the *qas* |

| Phase 4 | Pastoral Post-‘Chalcolithic’ watering location | Post-‘Chalcolithic’ deep wells with one small trough and other hydraulic features founded in upper *qa* layers (Excavation 3) | Gradually prevention of local infiltration causing exsiccation of shallow wells Consequently, deepening of (some) wells in order to increase yield and use of the wells for artificial groundwater recharge/storage (i.e. surface inlet) | Final aggradation of the uppermost clayey *qa* layer (Sequence III) Increase in salinity within the *qas* |

| Phase 5 | Pastoral (Post-) ‘Chalcolithic’ to sub-recent watering location | Dam systems, modified multiple times from the (Post-)Chalcolithic to sub-recent times (Excavation 1) | Water harvesting system applying dams for retaining and delineating surface runoff | Dams founded outside *Rasif qas* on local watersheds |
North-western Arabia: Location of Chalcolithic key standing stone sites with present-day isohyets in south-eastern Jordan and north-western Saudi Arabia (aquifer head: BRGM, 2008; isohyets: Hijmans et al., 2005; elevation data: SRTM3).
Figure 2

Rasif area: SRTM data based digital elevation model and reconstruction of modern catchments at Rasif site (primary data source: SRTM data, verified by field observations).
**Figure 3**

*Rasif qa area. A) Panoramic view one day after the heavy rainfalls of November 18th, 2013; B) Rasif major occupation areas/phases and the archaeohydrological model for the phase 5 water harvesting system.*
Figure 4

Rasif Archaeological Excavations (according to Gebel et al., 2016). A) Excavation 5: Late Neolithic domestic structure (6th millennium BCE) reused/rebuilt in the 5th millennium BCE as a D-shaped ashlar-line grave with 2–3 chambers; B) Excavation 4: Chalcolithic’ well structure (5th millennium BCE?) with partly preserved trough system. Upper well shaft was built by corbelling masonry; C) Excavation 2: Characteristic D-shaped ashlar-line cairn (5th millennium BCE) embedded in the uppermost clayey qa layer. Note the original location of a cylindrical sandstone slab among the cairn’s upper cover stones; D) Excavation 3: Unidentified Post-‘Chalcolithic’ well/trough structure, characteristic for many such structure embedded in the uppermost qa sequence III.
Figure 5

Rasif qa area: Locations of excavations, phases 1-5 structures, geoelectrical prospection lines (ERT), magnetic grids and geoarchaeological soundings mapped on a DGPS based digital elevation model.
Figure 6

Rasif Geoarchaeological Sounding 1 (location indicated in Fig. 5).
Figure 7

*Rasif* Geoarchaeological Sounding 2 (location indicated in Fig. 5).
Figure 8

Rasif Geoarchaeological Sounding 3 (location indicated in Fig. 5): a) hydraulic dam structure indicated by a slight surface elevation and standing stone lines, b) sketch of the sounding and c) geoarchaeological data.
Summary of single grain luminescence dating characteristics. A) OSL decay signal for representative grain of Saudi-OSL-2, showing rapid decay (dark shaded region corresponds to natural signal integral; paler band to background). B) Dose-response curve for the same grain of Saudi-OSL-2. C and D) Dose recovery test results for Saudi-OSL-1 and Saudi-OSL-2 respectively, illustrated as radial plots. The black line corresponds to the administered dose. E and F) Equivalent dose distributions for Saudi-OSL-1 and Saudi-OSL-2 respectively, illustrated as radial plots.
**Figure 10**

*Rasif Excavation 4: sections of the excavated ‘Chalcolithic’ well.*

---

**Rasif, Excavation 4**

*Interior Well Shaft Stratigraphy*

Rajajili|Standing Stones|J.A.P.: 2015

- Well mouth: dry stone masonry of tabular limestone, with steps (1), set/dug into qa-layers and sandy sediments
- “Crust”: layered, extremely hard, 3-5 cm thick (2)
- Bedrock layer with vertical fractures: angular fractured bedrock, partly dressed, soft/sandy/silty” (3)
- Dressed bedrock: hard and layered, convexly dressed and smoothed, with steps (4)
- Like (4), but layered bedrock is more soft and sandy “silty”, surface not completely exposed by excavation (4a)
- Position of radiocarbon sample (allocation of sediment samples not documented in drawing)
- Fallen fragm. of basalt “mace head” (Chalcolithic/EB; RJJ15.063)
- Animal bones
- Well fill: sand (silty)
- Well fill: sand with fallen stones
- Well fill: sand (silty), partly laminated roots (tiny)
- Ideal axis
- Well fill excavation limits (2015)

---

Figure 11

Magnetic grids 1 and 2 (location indicated in Fig. 5). A) Magnetic grid 1, B) Magnetic grid 2, C) aerial photo with magnetic anomalies of grid 1, and D) aerial photo with magnetic anomalies of grid 2. Note the red circle in magnetic grid 2 indicating a buried well structure that is not visible at the current qa surface.
**Figure 12**

*Rasif*: ERT profiles with allocation of wells (location of ERT lines: cf. Fig. 5).
Figure 13

Rasif: Determination of infiltration capacities (kf-values) of the Rasif qa layers. a) According to observation after flooding representing the top layer. b) According to the open-end-test for subsurface layers.
Figure 14

Biplots of the two principal components (PC): PC1 silty deposition proxy vs. PC2 sandy deposition proxy.
Figure 15

Schematic sketch of the site's water management strategies during the phases 1 to 5.