OPENQUATERNARY

Karstic Aquifers and Climate Refugia: A Preliminary Outline History of Water-Management Strategy in Bronze and Iron Age Southeast Arabia

RESEARCH PAPER

]u[ubiquity press

MICHEL DE VREEZE
DEREK KENNET
WILLIAM M. DEADMAN

*Author affiliations can be found in the back matter of this article

ABSTRACT

This paper attempts to set out a preliminary narrative of changing water exploitation and settlement in Southeast Arabia from the Umm an-Nar period to the Iron Age, with a particular focus on the 4.2ka event. It argues for long-term cultural and adaptive trends that are only now becoming apparent and are relevant to understanding local adaptation strategies to climatic events such as the 4.2ka event. In setting out this narrative, we also aim to show the value of Southeast Arabian data to regional discussions relating to human adaptation to climate change. We argue that lower ground water availability related to aquifer structures would have been a problem for Bronze Age (Umm an-Nar) communities, in particular those living in Central Oman around the Hajar Mountains and would have affected settlement viability in certain climatic conditions, leading to decline in the number and size of settlements after c. 2000BC. We suggest that late Umm an-Nar (2200–2000BC) settlement and agricultural activity over-extended in this area, a development paralleled in Harappan and Mesopotamian communities. These changes would have affected already ancient traditions, for example in relation to the communal ritual monuments. By contrast, for the Northern Emirates karstic aquifers were a crucial factor supporting settlement continuity after the 4.2ka event, in particular in the western coastal areas of Ras al-Khaimah and the area around Dibba on the east coast. It is argued that the distribution of these aquifers is key to understanding the cultural and economic changes associated with the ensuing Wadi Suq period (2000–1600BC). Other processes strengthened the pattern, such as changing interregional exchange patterns and associated overland and maritime routes. By the Iron Age (starting c 1300 BC), it appears that rainfall patterns changed again and settlement density in Central Oman began once again to exceed that of the Northern Emirates. We suggest that this is at least partly linked to the resilience of local communities in dealing with another climate event (3.2ka event) that potentially necessitated the management of climatic patterns that may have included periods of higher and lower rainfall including irregular flooding. Whilst some of the ideas set out here are still quite speculative, they are set out in the belief that further understanding of these changing patterns is crucial for our understanding of long-term adaptation to climate change in this region.

CORRESPONDING AUTHOR:
Michel de Vreeze
Honorary Research Fellow at Durham University, UK
michel.de-vreeze@durham.ac.uk

KEYWORDS:
Climate change; Aquifers; South East Arabia; Settlement change; Local Resilience; 4.2ka event

TO CITE THIS ARTICLE:
de Vreeze, M, Kennet, D and Deadman, WM. 2024. Karstic Aquifers and Climate Refugia: A Preliminary Outline History of Water-Management Strategy in Bronze and Iron Age Southeast Arabia. *Open Quaternary,* 10: 5, pp. 1–16. DOI: https://doi.org/10.5334/oq.144

INTRODUCTION

Human adaption to climate change has been one of the dominant topics in recent archaeological research. Particularly major aridification events, such as the 4.2ka event, have long been associated with cultural change and human response in terms of settlement strategies, agricultural regimes and water management (Cullen et al. 2000; Weiss et al. 1993; Weiss 2016; 2017; Petrie et al. 2017; Petrie 2019; Riehl 2009; Riehl et al. 2014; Kaniewski et al. 2018; Cookson et al. 2019; Carolin et al. 2019; Dee 2017; Palmisano et al. 2021; Lawrence, Palmisano and de Gruchy 2021). Human responses to climatic events remain a major concern in studying cultural change, particularly in arid regions such as Southeast Arabia (Terry et al. 2022). Building resilience to climate change is a major current concern and examining how past societies managed this, both socially and technically, for instance when facing aridification and access to crucial water resources, can be insightful when observing modern events, particularly when looking at longer term developments and regional forms of adaptation. Southeast Arabia, which formed part of an interregional network of Bronze Age cultures that were in contact with Mesopotamia and the Indus Valley, has not received the same level of archaeological attention compared to the urbanised regions in discussion of the effect of aridification events such as the 4.2ka. However, as a semi- to hyper-arid region, Southeast Arabia shows a pertinent and unique archaeological record in relation to human strategies in managing access to water resources, which is important within the current debate on adaption to climate change.

PART 1: THE 4.2ka EVENT IN THE NEAR EAST

The effect of the 4.2ka event on human societies in the Near East has been much discussed (Cullen et al. 2000; Weiss et. al. 1993; Weiss 2016; 2017; Petrie et al. 2017; Petrie 2019; Riehl 2009; Riehl et al. 2014; Kaniewski et al. 2018; Cookson et al. 2019; Carolin et al. 2019; Dee 2017; Palmisano et al. 2021; Lawrence, Palmisano and de Gruchy 2021). Aridification in Southeast Arabia has been noted in coring of paleolakes (Parker et al. 2006; Goudie & Parker 2011). The effects might show regional variation (Lawrence, Palmisano & de Gruchy 2021, 6). A consensus exists that diminishing westerlies which would have been linked to a rapid decrease in seasonal winter rains caused aridity, in many areas including the Arabian Gulf (Cookson et al. 2019; Parker et al. 2006, 473), whilst also being associated with a weakening monsoonal system that regulates summer precipitation for the region, including parts of Southeast Arabia (Giesche et al. 2023, 8).

MULTIPLE WAYS OF RESPONDING TO CLIMATE CHANGE

The importance of climate proxies, cultural data, and chronology all being of high resolution has been made (Palmisano et al. 2021; Cleuziou 2009, 736). Recent studies also highlight human resilience to climate changes, including cultural adaption such as communal storage and adaptations in agricultural and settlement systems (Palmisano et al. 2021; Sołtysiak, A., & Fernandes 2021; Giesche et al. 2023; Petrie et al. 2017; Riehl 2009). Due to problems with absolute dating in Southeast Arabian archaeology, particularly for the late 3rd millennium including the Late Umm an-Nar: c. 2200–2000BC, and especially the ensuing Wadi Suq period (2000–1600BC), the precise effects of the 4.2ka event are not fully explored. However, with Southeast Arabia being a semi- to hyper-arid region, human populations would have been more susceptible to sudden aridification of the sort suggested by local records (Cullen et al. 2000; Parker et al 2006; Goudie & Parker 2011). The effect of the event on subsistence patterns has been argued by isotopic studies of human remains (Gregoricka 2016; Gregoricka 2021).

We should be wary of simplistic causation (Middleton 2017, 5; Cleuziou 2009, 726) in relating climate to cultural change, but neither can we shy away from the broader theme of climate related cultural change that is investigated for nearby regions, particularly due to the high susceptibility to climatic shifts in arid regions. It therefore seems most useful to address patterns in settlement and look at multiple factors in which such events might have played a role.

THE 4.2ka ARIDIFICATION AS MULTIPLE EVENTS

Recent studies show that the 4.2ka might not have been a single event (Giesche et al 2023, 6). Oxygen, carbon and calcium isotopes from a speleothem records in a cave system, the DHAR-1 system in India, shown that the 4.2ka was made up of a series of dry spells that occurred from 4.2ka to 3.97ka, ca. 2250–2020 cal BC, and lasted for 25–90 years each over this ca. 230 year period. As Giesche and colleagues (2023: 6) suggest, this should allow for a temporal resolution of human decision making. Equally crucial, the more pronounced effects would have occurred around the 'final and longest 90-year drought peaking at 4.02 ka BP' or ca. 2070 cal BC (Giesche et al 2023, 6). If this pattern can be transferred c 1,500 km west to Southeast Arabia, then this longest drought would date to ca. 2120–2020 BC and coincide with the final years of the Umm an-Nar period and the earliest of the Wadi Suq period (de Vreeze forthcoming). Thus, the strongest effects of the 4.2ka event would have played out at the end of the Umm an-Nar period and preceded the transition from Umm an-Nar to Wadi Suq at c. 2000 BC. This means that to understand societal adaption to aridification, we must examine cultural practices during the final Umm an-Nar period (c. 2200–2000BC) but also realise that its most pertinent consequences might have become visible at the start of the Wadi Suq period.

DELAYED HUMAN RESPONSES TO CLIMATE EVENTS

Human societies might not have immediately responded to climatic events due to the inherent conservatism of traditional practices. Moreover, people respond to the change in perception but not necessarily to the change in the environment itself that can go unnoticed for some time (McIntosh et al. 2000). This delayed social response was argued by Portugali (1996, 17: Fig. 2; see also Greenberg 2002, 114–115). It is therefore possible that worsening climatic conditions during the last two centuries of the Umm an-Nar period might not have sparked an immediate large-scale cultural response and may have had no visible effect on the archaeological record. In such a scenario, Umm an-Nar society may have over-extended exploitation of resources, whilst unsustainable settlement growth of the type that has been suggested in contemporary Mesopotamia (Palmisano et al 2021, 22) and the Indus Valley (Petrie 2019, 122) could also have occurred here, rendering settlement fragile when hit by repeated aridification. Additionally, the Umm an-Nar settlement system was never urban (see Deadman et al. 2022, 78). Umm an-Nar society might have had some inbuilt resilience to climate change due a more flexible social structure of settlements that could remain functioning as smaller self-sufficient units along heterarchical lines. There are several avenues to look at the potential effects of aridification during the Umm an-Nar period, foremost the changes in monumental traditions of tower building discussed below.

PART 2: LATE UMM AN-NAR SETTLEMENTS IN CENTRAL OMAN UNDER STRESS

‘TOWERS’ AND DITCHES – A MILLENNIA-OLD RITUAL MONUMENT TRADITION IN CRISIS

Water management and agriculturally viable areas are crucial for Southeast Arabian settlement (Beuzen-Waller et al. 2018, 195; Nathan & Harrower 2023; Velde 2009, 63; Kennet et al. 2025; Al-Jahwari 2009; Deckers, Döpper & Schmidt 2019, 1). With a largely agricultural basis dependent on available groundwater but preceding the introduction of *falaj* irrigation, agriculture would probably have relied on seasonal runoff irrigation and the use of groundwater wells. Availability of water and water management were therefore foremost concerns. The regulation of access to water was likely administered in the way that has been demonstrated for more recent periods (e.g. Wilkinson 1977). From related contemporary societies, such as Mesopotamia, we know water could be an integral part of the religious underpinning of society and associated with one of the main gods (Enki/Ea) (Black and Green 1992, 27). Without textual evidence or clearly identified religious structures, this ritual concern with water is less obvious in Bronze Age Southeast Arabia. However, one could argue that the investment in monumental towers might precisely reflect the ritual and communal concern for water management. These towers are monumental constructions built both in mudbrick and stone, mostly circular in shape, but occasionally rectangular and often featuring internal divisions and central wells (Kluge 2021). They often feature ditches surrounding the tower and can have complicated phasing of construction and reconstruction showing that they are long-lived monuments. Much has been written about towers, surrounding ditches and their function (see Cable 2012, Cable and Thornton 2013; Döpper 2018; Kluge 2021; Swerida & Thornton 2019, Mortimer and Thornton 2018). Initially these were seen as defensive (see discussion Kluge 2021, 36–37; Cable 2012, 50), but more recent work has stressed the ritual and performative nature (Cable 2012, 55; Cable & Thornton 2013; Swerida & Thornton 2019; Orchard & Orchard 2007).

Towers can be seen as major investments in ritual monumentality during the Bronze Age, the second being collective tombs. As Miller (2021) has argued, ritual monumentality would have been essential not only in the establishment of cooperate labour groups, but also in maintaining such groups in ‘small-scale’ societies, which were lacking other communal obligations related to hierarchically-organised societies. Hafit and Umm an-Nar period towers might therefore be seen to represent this cooperate ritual monumentality. According to this view, during the Umm an-Nar period, towers would have become the ritual focal points of cooperate groups, such as kin-groups or neighbours, within larger agglomerative settlements that could have multiple organisational nuclei (Deadman et. al 2022, 76). Spatially, they follow social principles that are similar to multiple hubs of settlement and associated religious structures such as temples, as has recently been argued for south Mesopotamian towns (Hammer 2022).

TOWERS AND WATER MANAGEMENT

Nathan and Harrower (2023) highlight the consistent association of towers with high water flow accumulation. Indeed, many towers are concentrated within alluvial plains or directly along wadi beds as, e.g. at sites such as Bat, Khasbah, Tikha, Bidyah, Hili and Salut (Cable 2012, 57; Schmidt et al. 2021, 73; Deadman et al. 2022, 54; al-Tikriti 1989, 108–109; Cleuziou 2009, 731; Degli-Esposti 2014, 665). Figure 1 shows how towers in general cluster consistently along the ophiolite piedmont aquifer systems in associated with major stream catchment areas. Often featuring wells that are not always centrally placed, and

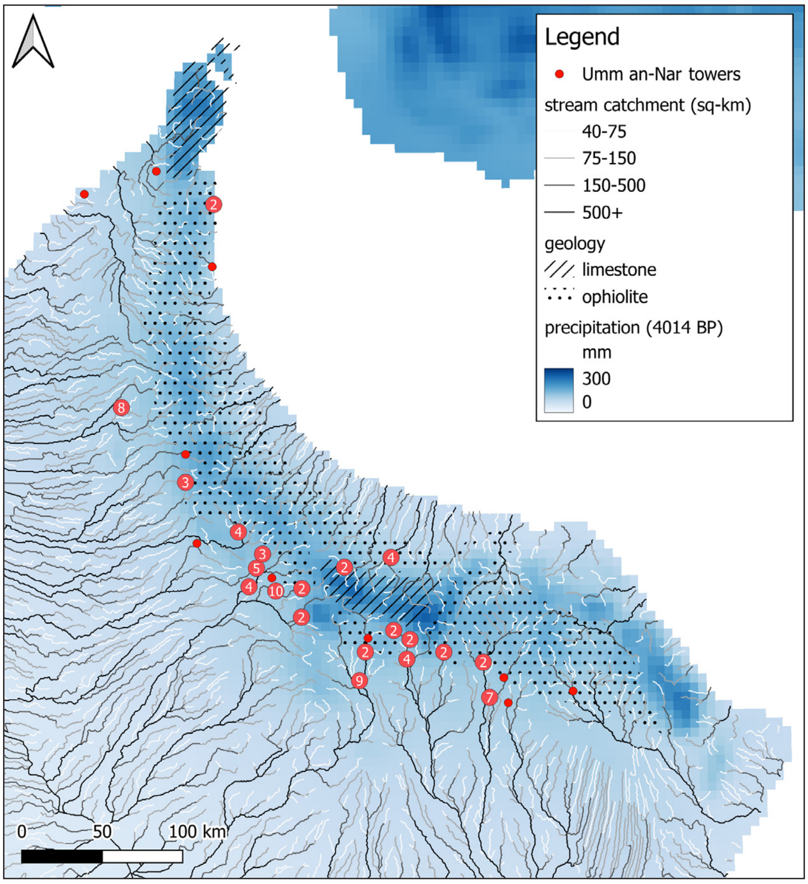

Figure 1 The distribution of towers in red (number of towers), major drainage channels and precipitation (ca. 4014BP). Ophiolite and limestone geology, with their associated aquifers, indicated with dots and diagonal hash respectively. See 'data availability' for data sources. The towers mainly cluster along significant stream catchment areas fed by ophiolite aquifers.

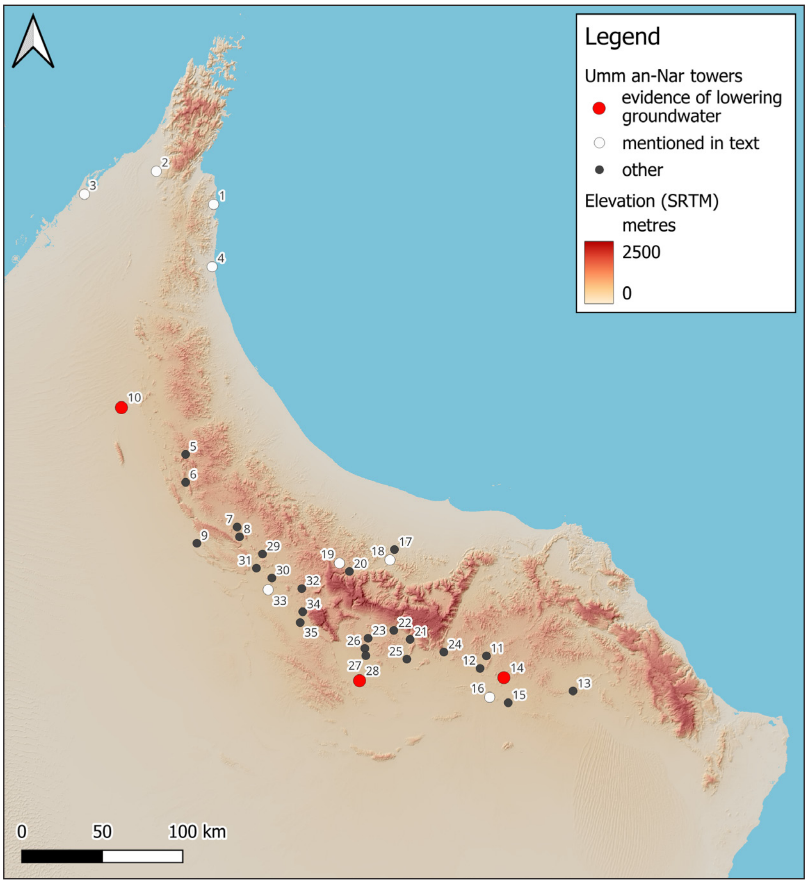

Figure 2 Map of the tower sites shown in Figure 2 with associated site names in table. Towers sites mentioned in the text are highlighted in white, those with evidence of lowering groundwater mentioned in the text are highlighted in red.

SITE nr.	SITE NAME	TOWERS	SITE nr.	SITE NAME	TOWERS
1	Bidiyah	2	**19**	Maidan	1
2	Nud Ziba	1	**20**	Yika	1
3	Tell Abraq	1	**21**	Nizwa	2
4	Kalba	1	**22**	Tanuf	2
5	Ajran	1	**23**	Bahla – Ghubra	1
6	Qumayra	3	**24**	Izki	2
7	Abu Suwaih	2	**25**	Firq	4
8	Safri	2	**26**	Wihi al-Murr	1
9	Shukur	1	**27**	Sufayha	1
10	Hili	8	**28**	Bisya/Salut	9
11	Ghoryeen	1	**29**	Khadil	3
12	Khadra Bani Dafa'a	1	**30**	Bat al-Zebah	1
13	Ibra	1	**31**	al-Hasi	5
14	Maysar	1	**32**	Banah	2
15	Fath	1	**33**	Bat	14
16	Khashbah	7	**34**	Amlah	1
17	Falaj al-Shrah	1	**35**	al-Ligma	1
18	al-Tikha	3			

Table 1 Tower sites with toponyms and number of towers used for Figures 1 and 2. Tower date partially updated from Mortimer 2019.

surrounding ditches and canals (Cable 2012; Cleuziou 2009), a key feature of many towers would have related to seasonal water management. Ditches surrounding towers equally needed collaborate labour and have been suggested to have various functions related to irrigation, defence, or seasonal flood water management (see Döpper 2018 for an overview). The relation to floodwater management is highlighted as most relevant for towers surrounded by ditches (Döpper 2018: 129). To understand the purpose of towers, it is important to stress their prolonged social relevance. They were constructed for over a millennium, evolving from their first attestation during the Hafit period around 3100 cal BC (Khasbah Building V: Kluge 2021, 61; 62). Less often, the ditches surrounding towers have been seen as a formative stage in the construction. The earliest mudbrick towers (Hili-8; Cleuziou 2009; Khashbah Building I; Schmidt and Döpper 2017; and towers at Bat: Thornton, Cable and Possehl 2017, 22) were most likely built by first excavating a ditch to extract the mudbrick material for the construction of these towers and would have evolved into an essential feature. Towers are often associated with well-constructed central wells (Cable 2012, 210; Kluge 2021, 66) -although wells have not been attested for all towers, at least partially because many examples remain unexcavated. Ditches surrounding the towers would have accumulated water in a process where seasonal runoff and higher groundwater could accumulate due to the permeable gravel layers the ditches cut through, sandwiched between less permeable deposits such as compact marls (Döpper 2018, 129 previously argued for the capacity to flow off water, rather than collect it). At Hili 8, the ditch had various stages of use and canals could feed additional water into it (Cleuziou 2009, 731–732: Fig. 5). Wells and cisterns were dug inside ditches at Khasbah I, whilst Salut illustrates their use to access lower groundwater (Döpper & Schmidt 2019, 266; Degli-Esposti 2014, 670–672; Fig. 4).

With higher intensity water flow after winter rains — the towers, as communal ritual monuments, might have played a role in ritually dividing water resources between parts of the community. The interior rooms of the Khafaji tower were packed with sterile mud packing (Swerida & Thornton 2019, 160) and could have allowed for temporal water storage during the wet season. Similar compartments in other towers, although subsequently filled, would have had capacity for water storage; for example Hili 1 (Frifelt 1975, 369) where the rooms were filled in with cemented gravel with half a meter of space left at the top. At Hili-8, Cleuziou (1989: 64) observed small openings connecting the compartments. This might suggest that water could, potentially, have flowed from one compartment to the next before the rooms were filled in. Additionally, towers were also the focus of communal labour after being built, as is shown at Khashbah Building V through evidence of copper working (Schmidt & Döpper 2017, 5; Döpper & Schmidt 2019).

LOWERING WATER TABLES AND THE DEMISE OF MONUMENTALITY AND ITS RITUAL COHESION

The large-scale end of tower construction in Central Oman at the end of the Umm an-Nar period, with minor re-use in the Wadi Suq period, exemplifies major changes to the organization of corporate groups. Construction and the upkeep of towers involved communal labour. Their association with water access and management and the social sanctioning of water rationing, might have been one of the reciprocal acts involved with the building and use of these towers. The 4.2ka effect on available water would not have directly affected the use of rainwater, as will be argued further below. Following Nathan and Harrower (2023: S53), the rain itself was important as sub and surface flows of water, and crucially, the recharge of aquifers and wells.

The wells of towers have demonstrated lowering water tables (Figure 2). At Hili-8, a second well, no longer in the centre of the tower, needed to be continuously dug down with an increasing depth of 4.5 m below the level of the original well (Cleuziou 2009: 730). Similarly, the well of Maysar-25 was continuously deepened, apparently due to the lowering water table, up to an eventual depth of 15 m, but possibly with little success (Weisgerber 1981, 203). At Salut, wells were dug through the marl floor of the canals to access lowering water tables at the end of the 3rd millennium BC (Degli-Esposti 2014: 672). There is thus evidence of increasing difficulties with getting access to water around these towers. Miller (2021) stresses that reciprocity was one of the key aspects which engaged people with ritual monumentality. The loss of a key aspects of reciprocity, in the form of shared water management, would potentially have negatively affected investment in communal buildings. Hili, Maysar and Salut might illustrate a wider phenomenon associated with the repeated arid spells of the 4.2ka, which grew in intensity peaking around 4.02ka (Giesche et al. 2023). These show that dropping water tables became a pressing issue during the last two centuries of the Umm an-Nar period. This seems to have led communities to abandon the building and upkeep of such monuments, although there is evidence of scant re-use in subsequent centuries (Kluge 2021, 62).

When we turn to the Northern Emirates region (Figure 2) it seems that towers were not a consistent feature of Umm an-Nar settlements. The northern-most towers are found at Kalba (Schwall et al. 2024), Tell Abraq (Potts 1990; 1991), Bidyah (al-Tikriti 1989: 107–109) and at Nud Ziba at Khatt (Kennet and Velde 1995; See Kluge 2021, 36: Fig. 39). Despite numerous surveys, they are absent at the large settlement area of Shimal (Velde 2009).

PART 3: NORTHERN RAS AL-KHAIMAH AS A SETTLEMENT HUB AND ITS FAVOURABLE ENVIRONMENT

In general, the nature of settlement during the Wadi Suq period in Southeast Arabia is difficult to define (Velde 2003, 102–103; Velde 2009, 60; Righetti 2015, 77; Döpper 2021, 315; 319). Wadi Suq settlements are much rarer in Central Oman than their Umm an-Nar predecessors (Döpper 2021; Righetti 2015, 77). In the Northern Emirates, settlements are also rare and known mainly from the re-use of Umm an-Nar towers at sites such as Tell Abraq (Potts 1990; 1991) Kalba (Eddisford Phillips 2009; Schwall et al. 2024) and Nud Ziba (Kennet and Velde 1995) with the unusual settlement at Shimal, which is mainly Late Bronze in date (Vogt and Vogt 1987).

More illustrative of settlement continuity is the evidence of associated funerary traditions. There is a marked difference in the dominance of monumental communal tombs in the north versus the predominance of smaller cist tombs in Central Oman, although sometimes in large concentrations (Kennet et al. 2025, Fig. 3). Particularly in the Sir and Jiri plains of northern Ras al-Khaimah, the Wadi Suq period is represented through small of large cemeteries of monumental surface-built, collective tombs burials that are unparalleled in Central Oman (Righetti 2015, 57–58; Velde 2009; Kennet et al. 2025). Shimal is the best-known example, (with 110+ such tombs) forming one of the largest prehistoric cemeteries in Southeast Arabia, but others are equally impressive, such as Qarn al-Harf, (16 tombs), Dayyah (14 tombs), Ghalilah (10), and Khatt (53 tombs) (see Kennet et al. 2025 for an overview). These show continuity in monumental tomb traditions in the Northern Emirates, with transitional tombs such as Qarn al-Harf 6 and Idhn IN5 carrying on traditions inherited from Umm an-Nar tomb building (Kennet et al. 2025; Vogt 1998). These monumental tombs, constructed by communal labour and used for multiple burials of possibly extended familial lineages, dramatically contrasts with the archaeological record in Central Oman. The density of monumental tombs seems paralleled only in the Dibba area, on the east coast of the Musandam, where many such monumental tombs are being discovered, although mainly subterranean, suggesting similar activity continued into the Late Bronze and Iron Age, often obscuring their original Wadi Suq construction (Pellegrino et al. 2019, 4; Genchi 2023). This evidence is in contrast to Central Oman, where the tradition of monumental collective tombs of the Umm an-Nar period largely disappears with the Wadi Suq period (Döpper 2021; Kennet et al. 2025).

TOMBS AND THE SPLITTING OF COMMUNITIES

Monumental funerary architecture shows a similar development to towers in the south, in that it broadly illustrates reduced communal labour investment. Here, after a tradition of monumental tomb building that was one of the hallmarks of Umm an-Nar culture (Magee 2014, 100), funerary architecture becomes dominated by smaller cist tombs (Figure 3). Although cemeteries of these cist tombs can be extensive, for instance at Wadi Suq (Düring 2015: 97), Samad ash-Shan (Yule 2001) and Buweiten (Döpper 2021, 319). These might have developed by adding tombs over time, and these smaller tombs would have mostly contained individual burials with exceptions containing several individuals, for instance individual burials attested at Bilad al Shuhum (Gernez et al. 2023, 60) and up to three individuals at Samad ash-Shan (Yule 2001, 374). Crucially, the building of these tombs would not have necessitated the same cooperative labour as building the larger monumental tombs. The dominance of the smaller tombs in Oman, although with the potential to grow into several larger clusters of these smaller tombs, reflect the splitting up of Umm an-Nar communities living in large agglomerative settlement systems (Deadman et al. 2022, 54), potentially more mobile and spread within a wider landscape in smaller groups that added individual tombs to cemeteries over time (Cleuziou 1981, 292).

CERAMIC EVOLUTION AND THE MOVE TOWARDS THE NORTH

Wadi Suq ceramics show continuation in manufacturing tradition and style from the preceding Umm an-Nar period, but with the addition of novel shapes and elaborately painted decoration (de Vreeze 2016). Ceramics are the clearest marker of a Wadi Suq presence in the region. They are most often, but not exclusively, associated with tombs. Ceramics show a noticeable focus on spouted jars and beakers (Velde 2003). There is also a clear evolutionary trajectory in Wadi Suq ceramics (Velde 2003; Righetti 2015; de Vreeze forthcoming). These developments can be traced across Central Oman and the Emirates and demonstrate a gradual retraction of settlement towards the north (de Vreeze forthcoming; Fig. 4). The idea of a contraction of settlements towards the Northern Emirates has been argued previously (Carter 1997, 72–75; Righetti 2015, 44–45). When the changes in ceramic fabric and shape are viewed on a distribution map in chronological stages (Figure 4), based on sequential data at sites such as Qarn al-Harf, and other dated archaeological assemblages, a clear chronological development is evident, The widest distribution is across Southeast Arabia at the start of the Wadi Suq (Type 1) a time when elaborate decoration and simple shaped beakers and cups were common. There is then an increasingly narrow focus on the Northern Emirates as time passes and there is a trend towards Type 2 and 3 beakers with simplified decoration and wheel-thrown production (de Vreeze forthcoming).

These developments point to the exceptional nature of the Northern Emirates region and its unusual settlement dynamics which developed only during and after the 4.2kya period into the Wadi Suq period. It has an unusually high settlement density, based largely on tomb data and on the ceramic developments mentioned above, it is clear that activity slowly concentrates into this area during the latter part of the 3rd and early part of the 2nd millennium. The reason for this development, it can be argued, is its unique environment and continuing availability of ground water, which gave it a crucial edge over Central Oman during periods of reduced precipitation.

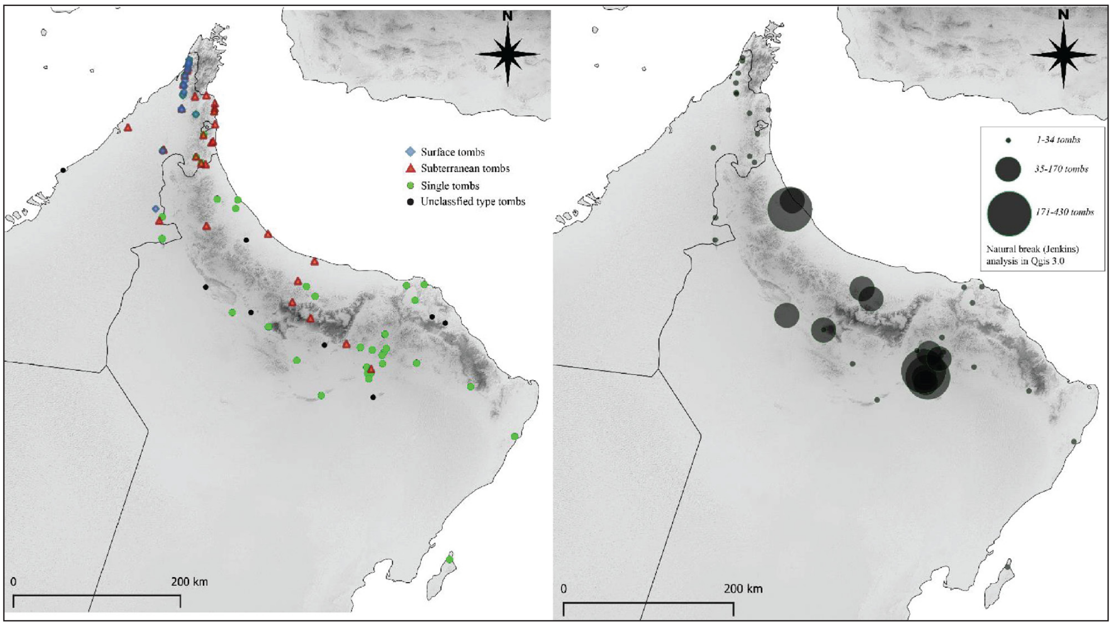

Figure 3 Single cist burials from the Wadi Suq period dominate the south vs monumental tombs in the north. On the right, the large single cist cemeteries (after Kennet et al. 2025).

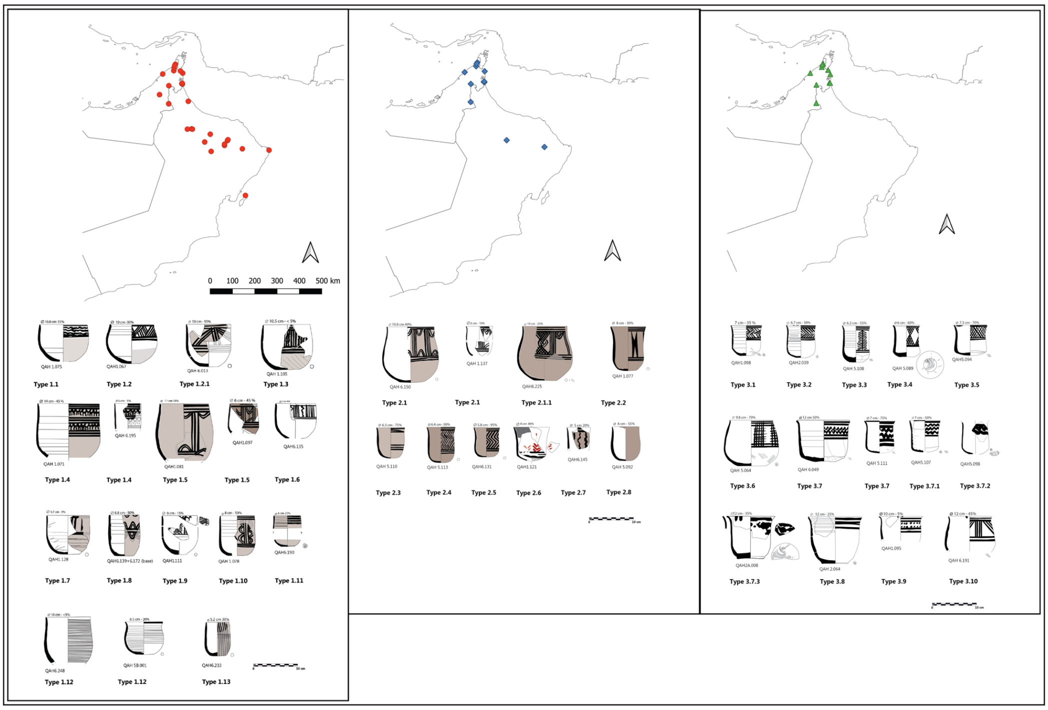

Figure 4 Chronological development and distribution of Type 1 (earliest) to Type 3 (latest) beakers and cups, making clear the increased focus on the north (after de Vreeze forthcoming).

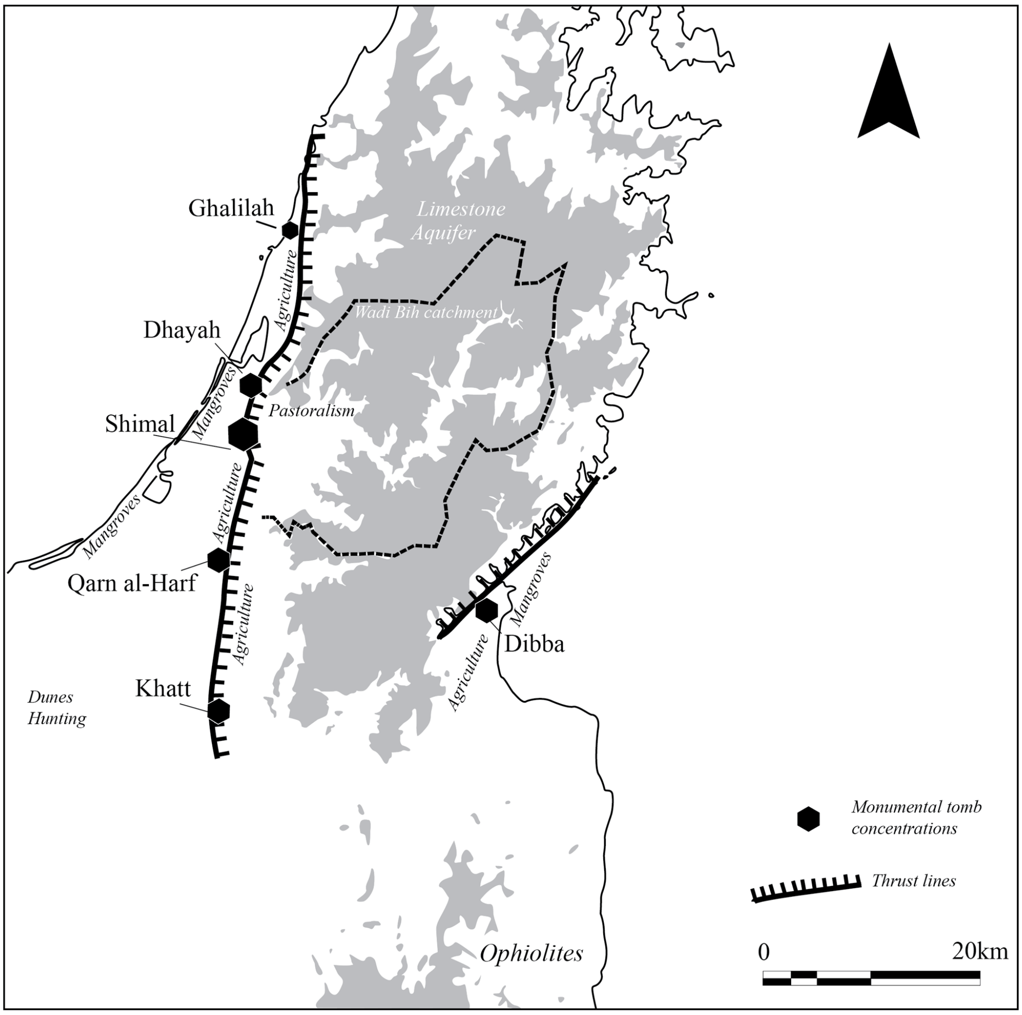

Figure 5 Shows the Karstic aquifers of the northern Emirates in association with major Wadi Suq settlement hubs represented by their monumental cemeteries. Economic niches, such as coastal mangroves, are indicated. From de Vreeze (forthcoming; based on the geological mapping of Phil Macumber in Kennet et al. 2025).

KARSTIC AQUIFERS AND THE DIFFERENCE BETWEEN NORTH AND SOUTH

Irrigation, prior to the large scale adoption of *falaj* irrigation in the Iron Age at around 1300BC, was based on runoff irrigation and the use of wells. Groundwater levels were crucial, and the accessibility of water is determined by local geology as well as water flow and supply. Groundwater has traditionally been the main source of water for agriculture in Central Oman and the United Arab Emirates (UAE) (El Mahmoudi and Sherif 2004). Northern Ras al-Khaimah, in particular, has marked hydrological advantages. In general, two karstic aquifer systems have been highlighted for Southeast Asia (Chen et al. 2017). One is linked to the limestone Hajar mountains of the Northern Emirates, which we will discuss further, whilst the second system relates to the southern Hajar mountains (Chen et al. 2017), with the main recharge area being the Jebel Akhdar (Weyhenmeyer 2000) (Fig. 1 & Fig. 5). Karstic aquifers are crucial for water reserves across the globe and are estimated to supply 20–25% of the global population (Chen et al. 2017, 772). The continuation of settlements in association with karstic aquifers during the 4.2ka aridification has been argued for in other areas the Near East (Manning et al. 2021: 2).

Although the limestone massifs of Southeast Arabia had the largest formation volumes, they were not equally suitable for water storage, and for Central Oman, the most significant storage of water relied on the ophiolite piedmont alluvium (Stanger 1986, 330; Fig. 1; Fig. 2). The nature of the Central Omani aquifers and their potential to sustain water tables in lower habitation areas throughout time, might have been much lower (Gerner, Schütze and Schmitz 2012, 4). The towers mostly relate to the ophiolite piedmont aquifers, with the higher karstic aquifers of the central Hajar mountains not readily exploitable (Figure 1). Lowering precipitation and groundwater accessibility would therefore have affected the tower-related ritual water management disproportionately.

The idea that the Northern Emirates and Omani Musandam might have provided better groundwater supply has previously been suggested (Carter 1997, 243). In contrast to the Central Omani aquifer system, settlement on the narrow coastal Sir and Jiri plains of Northern Ras al-Khaimah was able to take advantage of higher groundwater as they lie adjacent to the western Hajar mountains which here consist of the highly permeable northern limestone making up the Northern Limestone Aquifer (Sherif et al. 2021, 6) (Fig. 1 and 5). This is the most sustainable aquifer in the UAE, with the Wadi Bih catchment the largest in the UAE (Rizk 2015). Moreover, the coastal strip yielded access to lagoons and mangroves (Vogt 1998; Kennet et al. 2025). Precipitation would also have favoured the Northern Emirates (Hewett et al. 2022, supplementary data used in our Fig. 1–2; Kennet et al. 2025; Dreschler 2008, 20–24; Preston 2011, 54–56) (Figure 1).

Groundwater therefore occurred in the plains of Northern Ras al-Khaimah at relatively shallow depths, placing it within relatively easy access of both runoff and well irrigation (Kennet et al. 2025 for a detailed analysis; Halcrow & Partners 1965: 8–11; Bowen-Jones et al. 1967: 17). Two main aquifers are important for this groundwater, the above-mentioned higher, karstic northern limestone aquifer of the mountains; the Wadi Bih, and the lower western gravel aquifer of the plains (Kennet et al. 2025). The limestone aquifer is recharged from the westerly winter rainfall over the Musandam which gradually percolates into the gravels of the plain and thus maintains the water table, with the coastwards-flowing groundwater recharging the gravel aquifers in the plains which were the main focus of agriculture (Rizk & Alsharan 2003:257; Kennet et al. 2025). Crucially, the Haqab Thrust fault, at the boundary between the Sir and Jiri plains (Figure 5) allowed for inter-aquifer flow, which also gave rise to springs— most famously at Khatt — where evidence of a major early Wadi Suq settlement hub is found (Kennet and Velde 1995). The relatively narrow nature of the Sir and Jiri plains is somewhat paralleled at Dibba on the west coast. This would have confined the area of water flow and maintained relatively high-water tables ideal for agricultural exploitation through wells (Figure 5).

To sum up, the 4.2ka event would have affected westerly winter rainfall (Parker et al. 2006, 474), but the potentially high rainfall in the north combined with the better capacity of the karstic limestone would have provided a significant buffer during this event, certainly in comparison with Central Oman. This might have been exacerbated by the gradual retreat southwards of the ICTZ, which began around 8ka (Fleitmann et al. 2003: 1738). The northern limestone aquifers would also have fed aquifers in the Dibba plain on the western coast west of the Musandam. The situation differed in Central Oman due to lower rainfall caused by diminishing westerlies and the geological nature of the dominant ophiolites, which were not as effective in retaining water as the limestone formations (Figure 1).

THE HABITATION HALO AROUND THE DISTAL END OF THE AQUIFER SYSTEM

In effect, the Wadi Suq settlements clustered in a halo around the distal ends of these aquifer systems along the Haqab Thrust fault. The Wadi Suq presence, most clearly marked by the monumental collective tombs in various locations, and including settlements at Nud Ziba (Kennet and Velde 1995) and Shimal (Vogt and Franke-Vogt 1987) at both ends of this zone, follow this line from Khatt in the south to Ghalilah in the north. Equally, Dibba has a remarkable presence of monumental collective tombs, many of which are constructed during the Wadi Suq but continue in use during the Late Bronze and Iron Age (Pelegrino et al. 2019; Genchi 2023). With the exception of Shimal, which is largely if not exclusively Late Bronze in date, these tombs so far lack associated settlements (Vogt and Franke Vogt 1987), but clearly represent high population density. These areas bordered the Rub al-Khali desert to the south and the mangrove and lagoon areas in the north and were thereby able to take advantage of multiple ecological niches, including mountains for grazing, alluvial plains for agriculture, mangrove lagoons and desert (Kennet et al. 2025; de Vreeze forthcoming; see Figure 5). Besides favourable water access, additional factors also therefore made the Northern Emirates a settlement niche in the early 2nd millennium BC.

DIVERSITY IN SUBSISTENCE: SHELL MOUNDS AND TEREBRALIA

Wadi Suq settlements would have been dispersed across the Sir and Jiri plains in association with suitable agricultural land and the exploitation of marshy areas and mangroves (Velde 2009; Vogt 1998; Kennet et. al 2025, de Vreeze forthcoming). In the Northern Emirates, the exploitation of maritime resources, foremost mangrove lagoons, will have been a crucial adaptation to climatic challenges. The continuation of larger sites at Tell Abraq and Kalba has been attributed to the potential to exploit these resources (Potts 2001, 44; Schwall et al. 2024). For the area of Shimal, Dhayah and Ghalilah, numerous shell mounds have accumulated over time showing continuity in this period. Particularly the exploitation of mangrove whelks (*Terebralia palustris*), might have been key to sustaining high population densities (Vogt 1998; Glover 1998; de Vreeze forthcoming). This would suggest a climate-resistant economic adaptation with a mixed economy based on agriculture, pastoralism (Von den Driesch 1994; Potts 2001, 44) and mangrove exploitation.

CHANGING ROUTEWAYS AND 'CUTTING OFF' THE SOUTHERN COPPER ROUTE

Besides changes in economic strategies and settlement locations, 4.2ka associated climate change might also have affected mobility and trade routes. For instance, one of the key routeways across the desert taking copper from al-Ain/Buraimi might have become less viable due to dune formation associated with the 4.2ka event (de Vreeze forthcoming; Kennet et al. 2025). Rapid dune formation has been associated with this event (Parker and Goudi 2007; Atkinson et al. 2011). Around 6 km northwest of Hili, a staging post of copper transport from the Northern Batinah to the west coast, saw the accumulation of 7 m of dunes at c. 4.3ka (Atkinson et al. 2011, 102). Dune formation would have complicated donkey transport across the desert by covering harder gravel deposits suitable for donkeys with less suitable loose sand dunes. As a consequence, maritime trade might have shifted northwards from Umm an-Nar island to Tell Abraq (see Carter 2003, 37; also Kennet et al. 2025; de Vreeze forthcoming). This in turn would have meant that the chain of major settlement sites such as al-Aridh, Bat, Bisyah, Salut and al-Khashbah, along the western Hajar mountains, which were involved in copper trade (Kluge 2021, 36; Fig. 39), would have been cut off from the major transport hub of Hili/al-Ain, limiting access to the west coast. This illustrates the potential for aridification to influence economic structures at various levels, with a combined effect that caused stress to a previously well-established Umm an-Nar period settlement and exchange system.

PART 4: 'REVERSING THE ODDS' AND THE EARLY IRON AGE REVIVAL IN OMAN?

It is useful to look at cultural changes in Southeast Arabia within a longer time frame as it can show how climatic events continued to be factors in cultural and economic changes that helped to improve resilience. Repeated disturbance, both social and environmental, has been seen to enhance overall resilience among human populations (Riris et al. 2024). In this case, resilience would have grown among Southeast Arabian populations who, over extended periods of time, had to repeatedly find solutions to water management in the face of changing climate conditions. In the light of repeated disturbances, it is helpful to consider another 'megadrought' event at 3.2ka (ca, 1250BC) and explore briefly what effects this event might have had and whether societies in Southeast Arabia changed their strategies, particularly in relation to water management. In Southeast Arabia, the evidence of the effect of the 3.2ka event is not straightforward. In the Near East this period is generally perceived as one of marked aridification but with more regionalised responses than the 4.2ka event (Palmisano et al. 2021, 11; 22; Kaniewski & Van Campo 2017). During this general period of aridification in the region there are also indications of periods of intense rainfall which have left evidence in the geomorphological record (Beuzen-Waller et al 2022, 234; Purdue et al. 2019). These might have been episodic heavy rains, similar to those observed recently in the region (Terry et al. 2022, 8; see also the April 2024 floods in the region: Farrell 2024). It is reasonable to suggest that the development of the *falaj* system may have been a response to an environment with continually unpredictable levels of rainfall. It has already been suggested that *falaj* irrigation corresponds to a notable increase in population and settlement density, despite apparently declining rainfall (see also Palmisano et al. 2021, 22 for *falaj* technology as a key development). By tapping groundwater and aquifer systems through these carefully engineered subterranean galleries or tunnels, Iron Age populations took an approach that was different and more interventionist than the towers and ditches of the Umm an-Nar period. In this way, it could be argued that *falaj* irrigation systems extended monumental, communal water management over a larger part of the landscape. The introduction of *falaj* irrigation would have made seasonal water supply more predictable and would have quickly become necessary to maintaining consistent exploitation of agricultural fields.

In terms of settlement data, we are aware of a marked lack of evidence for Late Bronze settlement in Central Oman, which compares to evidence for an equally clearly marked continuation of settlement in the Northern Emirates (Carter 1997; Velde 2003; Döpper 2021). However, following this period, there does appear to have been a dramatic reversal of the picture during the very early stages of the Iron Age in this region, most clearly shown at sites such as Salut (Avanzini and Degli Esposti 2014), with evidence of monumental architecture and technologically advanced ceramic industries that can be compared to the less technically advanced ceramics of the Northern Emirates. This counters the picture of the Iron Age I in the Northern Emirates where a lowering technical standard in, for instance, ceramic technology has been suggested (Magee 2014, 192). This could indicate that in Central Oman, after a period of relatively dispersed communities with possibly high mobility and low density, the picture was dramatically turned towards larger permanent settlement systems in the Iron Age. It is not unlikely that communities in Central Oman developed communal resilience strategies for dealing with the climatic event of 3.2ka. Communal investment in *falaj* irrigation would potentially have arisen as a method of controlling seasonal water supply by creating a supply of subsurface water, which provided the basis for increased settlement density. This Iron Age reversal of the regional picture of settlement towards Central Oman, illustrates an initial difference in cultural adaptation and resulting settlement densities between the Northern Emirates and Central Oman archaeological record of Southeast Arabia.

CONCLUSION

This paper has attempted to set out a broad narrative for the key trends in water management and exploitation from the Umm an-Nar to the Iron Age, focussing on developments surrounding the 4.2ky event that are particularly crucial in the region. Although much key evidence is still lacking, in particular on runoff irrigation (Purdue et al. 2021) and well irrigation, and some data is preliminary in nature, we consider it useful to set out this narrative at this point in order to move to a clearer understanding of the degree to which water management developed and the degree to which those developments affected the cultural, social, economic and, so far as is possible, the political development of the region. Looking at the broader picture, groundwater levels providing water for agriculture seem crucial in adapting to environmental stress. It is possible to argue that the 4.2ka event caused lowering groundwater levels and reduced water availability, causing stress to the Umm an-Nar settlement system and its unique social structure including ritual monuments. As argued, a delayed response in cultural behaviour, typical for human adjustment to relatively rapid climate events, might have caused an overextension of resources in the last century of the Umm an-Nar period (c. 2100–2000BC), which led to a break recognized as the onset of the Wadi Suq period. Northern communities, taking advantage of karstic aquifers and favourable water availability, found ways to counter this development creating a northern settlement niche which contrasts with quite drastic settlement decline in the south. This pattern was seemingly reversed during the early Iron Age, when communal water management evolved that could partially be through adaptation to another climatic event in need of further research.

DATA ACCESSIBILITY STATEMENT

For Figure 1 the data is freely available: Stream network courtesy of HydroSHEDS; geology (geo2bg) courtesy of USGS and precipitation data from Hewett et al. 2022. Elevation data for Figure 2 is SRTM, courtesy of NASA. Tower database of Figures 1, 2 and Table 1 Is partially based on Mortimer (2019). For Figure 3, data is available in Kennet et al. 2025. For Figure 4 data from de Vreeze forthcoming with key geological information on by Phil Macumber in Kennet et al. 2025.

ACKNOWLEDGEMENTS

We would like to acknowledge the support of the Department of Antiquities and Museums, Government of Ras al-Khaimah, in particular Ahmed Obeid Alteneiji, General Director, and Christian Velde, Chief Archaeologist and Researcher, for their support with the Qarn al-Harf excavations and related data collection.

FUNDING INFORMATION

Part of the research on the Northern Emirates from which this paper developed was funded by the Department of Antiquities and Museums, Government of Ras al-Khaimah in relation to the Qarn al-Harf excavations. No other funding was received.

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

MdV devised the concept, MdV and DK contributed data and wrote the paper. WD co-wrote some parts of the paper, collected data and created Figures 1 and 2.

AUTHOR AFFILIATIONS

Michel de Vreeze orcid.org/0000-0002-0001-2525
Honorary Research Fellow at Durham University, UK

Derek Kennet orcid.org/0000-0002-4179-3516
Howard E. Hallengren Professor in Arabian Peninsula and Gulf States Archaeology, Institute for the Study of Ancient Cultures, University of Chicago, US

William M. Deadman orcid.org/0000-0002-5860-9551
Department of Archaeology, Durham University, UK

REFERENCES

Al-Jahwari, NS. 2009. 'The agricultural basis of Umm an-Nar society in the northern Oman peninsula (2500–2000 BC)'. *Arabian Archaeology & Epigraphy*, 20: 122–133. DOI: https://doi.org/10.1111/j.1600-0471.2009.00315.x

Al-Tikriti, WY. 1989. 'The Excavations at Bidya, Fujairah: the 3rd and 2nd millennia B.C. culture'. *Archaeology in the United Arab Emirates*, 5: 101–114, Plates 59–97.

Atkinson, OAC, Thomas, DSG, Goudie, AS and **Bailey, RM.** 2011. 'Late Quaternary chronology of major dune ridge develop, ent in the northeast Rub' al-Khali, United Arab Emirates'. *Quaternary Research*, 76: 93–105. DOI: https://doi.org/10.1016/j.yqres.2011.04.003

Avanzini, A and **Degli Esposti, M.** 2014. *Husn Salut and the Iron Age of South East Arabia*. Rome: L'Erma di Bretschneider.

Beuzen-Waller, T, Desruelles, S, Marrast, A, Giraud, J, Gernez, G, Forman, S, Beshkani, A, Bonilauri, S, Lemée, M, Nacarro, H and **Fouache, E.** 2022. 'Late Pleistocene-Holocene fluvial records of the Wadi Dishshah: hydro-climatic and archaeological implications (Southern piedmont of the Hajar Mountains, Oman)'. *Géomorphologie: Relief, Processus, Environnement*, 28(4): 223–239. DOI: https://doi.org/10.4000/geomorphologie.17247

Beuzen-Waller, T, Giroud, J, Gernez, G, Courault, R, Kondo, Y, Cable, CM, Thornton, C, Desruelles, S and **Fouache, É.** 2018. 'L'émergence des territoires protooasiens dans les piémonts du Jebel Hajar. Approche géoarchéologique multicritère et comparative'. In: Purdue, L, Charbonnier, J and Khalidi, L (eds.) *From Refugia to Oases: Living in Arid Environments from Prehistoric Times to the Present Day*. Antibes: APDCA, pp. 179–204.

Black, J and **Green, A.** 1992. *Gods, Demons and Symbols of Ancient Mesopotamia: An Illustrated Dictionary*. London: The British Museum Press.

Bowen-Jones, H, Fisher, WB, Stevens, J, Smith, K, Scott, IA, and **Stimpson, JG.** 1967. *Survey of Soils and Agricultural Potential in the Trucial States. December 1966/January 1967*. The Trucial States Council/Sir William Halcrow & Partners: Department of Geography, University of Durham.

Cable, CM. 2012. *A Multitude of Monuments: Finding and defending access to resources in third millennium BC Oman*, Unpublished thesis (PhD). Michigan State University. DOI: https://doi.org/10.25335/2tqn-bd73

Cable, CM and **Thornton, CP.** 2013. 'Monumentality and the Third-millennium "Towers" of the Oman Peninsula'. In: Abraham, S, Gullapalli, P, Raczek, TP and Rizvi, UZ (eds.) *Connections and Complexity. New Approaches to the Archaeology of South Asia*. London: Routledge, pp. 339–375.

Carolin, SA, Walker, RT, Day, CC, Ersek, V, Sloan, RA, Dee, MW, Morteza, T and **Henderson, GM.** 2019. 'Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change'. *Proceedings of the National Academy of Sciences of the USA,* 116: 67–72. DOI: https://doi.org/10.1073/pnas.1808103115

Carter, R. 1997. *Defining the Late Bronze Age in Southeast Arabia: ceramic evolution and settlement during the second millennium BC*. Unpublished PhD dissertation, University College London.

Carter, R. 2003. 'Restructuring Bronze Age trade: Bahrain, southeast Arabia and the copper question'. In: Crawford, H (ed.) *Proceedings of a seminar held on Monday 24th July 2000 to mark the exhibition 'Traces of Paradise' at the Brunei Gallery,* SOAS, London. Oxford: BAR International Series 1189, pp. 31–42.

Chen, Z, Auler, AS, Bakalowicz, M, Drew, D, Griger, F, Hartmann, J, Guanghui, J, Moosdorf, N, Richts, A, Stevanovic, Z, Veni, G and **Goldscheider, N.** 2017. 'The World Karst Aquifer Mapping project: concept, mapping procedure and map of Europe'. *Hydrogeology Journal*, 25: 771–785. DOI: https://doi.org/10.1007/s10040-016-1519-3

Cleuziou, S. 1981. 'Oman Peninsula in the Early Second Millennium B.C'. In: Hartel, H (ed.) *South Asian Archaeology 1979* (SAA). Berlin: Dietrich Reimer, pp. 279–293.

Cleuziou, S. 1989. 'Excavations at Hili 8: a preliminary report on the 4th to 7th campaigns'. *Archaeology in the United Arab Emirates*, 5: 61–87.

Cleuziou, S. 2009. 'Extracting wealth from a land of starvation by creating social complexity: A dialogue between archaeology and climate?'. *Geoscience*, 341: 726–738. DOI: https://doi.org/10.1016/j.crte.2009.06.005

Cookson, E, Hill, DJ and **Lawrence, D.** 2019. 'Impacts of long-term climate change during the collapse of the Akkadian Empire'. *Journal of Archaeological Science*, 106: 1–9. DOI: https://doi.org/10.1016/j.jas.2019.03.009

Cullen, H, deMenocal, PB, Hemming, S, Brown, FH, Guilderson, T and **Sirocko, F.** 2000. 'Climate Change and the Collapse of the Akkadian Empire: Evidence from the Deep Sea'. *Geology*, 28(4): 379–382. DOI: https://doi.org/10.1130/0091-7613(2000)28<379:CCATCO>2.0.CO;2

de Vreeze, M. 2016. 'The social significance of ceramic change at the start of the Wadi Suq period. Rethinking ceramic continuity and change based on recent evidence from the tombs at Qarn al-Harf'. *Proceedings* *of the Seminar of Arabian Studies*, 46: 63–80. https://archaeopresspublishing.com/ojs/index.php/PSAS/article/view/1244.

de Vreeze, M. Forthcoming. *The Wadi Suq ceramics from Qarn al-Harf: tracing social change through technical developments in ceramic during the early 2nd millennium BC*. Qarn al-Harf Excavations II. Archaeopress: Oxford.

Deadman, W, Kennet, D, de Vreeze, M and **al-Jahwari, NS.** 2022. 'The nature of 3rd-millennium settlement: the example of al-Tikha (Rustaq) an Umm an-Nar site on the Batinah coast of Oman'. *Arabian Archaeology and Epigraphy*, 33(1): 49–83. DOI: https://doi.org/10.1111/aae.12218

Deckers, K, Döpper, S and **Schmidt, C.** 2019. 'Vegetation, Land, and Wood Use at the Sites of Bat and Al-Khashbah in Oman (Fourth–Third Millennium BC)'. *Arabian Archaeology and Epigraphy,* 30: 1–14. DOI: https://doi.org/10.1111/aae.12123

Dee, MW. 2017. 'Absolutely dating climatic evidence and the decline of Old Kingdom Egypt'. In: Höflmayer, F (ed.) *The late third millennium in the ancient Near East: chronology, C14, and climate change (Oriental Institute Seminars 11)*. Chicago: THe Oriental Institute, pp. 323–331.

Degli-Esposti, M. 2014. 'Excavations at the Early Bronze Age Site «ST1» near Bisya (Sultanate of Oman): Notes on the Architecture and Material Culture'. *Proceedings, 9th ICAANE, Basel 2014*, 3: 665–678. DOI: https://doi.org/10.2307/j.ctvc76zz7.52

Döpper, S. 2018. 'Towers and Ditches in Third Millennium BC Eastern Arabia: A view from Building II at Bat, Sultanate of Oman'. *Paléorient*, 44(1): 119–131. DOI: https://doi.org/10.3406/paleo.2018.5789

Döpper, S. 2021. 'The Middle and Late Bronze Age in Central Oman: New Insights from Tawi Said, Al-Mudhairib and the Wilayat al-Mudhaybi'. *Arabian Archaeology and Epigraphy,* 31(S1): 313–327. DOI: https://doi.org/10.1111/aae.12181

Döpper, S and **Schmidt, C.** 2019. 'A Hafit Period Copper Workshop at Al-Khashbah, Sultanate of Oman'. *The Journal of Oman Studies*, 20: 265–274. https://archaeopresspublishing.com/ojs/index.php/PSAS/article/view/350.

Düring, B. 2015. 'Revisiting the Suhar hinterlands: the Wadi al-Jizi archaeological project'. *Proceedings of the Seminar of Arabian Studies,* 45: 93–106. https://archaeopresspublishing.com/ojs/index.php/PSAS/article/view/1271.

Eddisford, D and **Phillips, C.** 2009. 'Kalbā in the third millennium (Emirate of Sharjah, UAE)'. *Proceedings of the Seminar of Arabian Studies*, 39: 99–112. https://archaeopresspublishing.com/ojs/index.php/PSAS/article/view/261.

El Mahmoudi, A and **Sherif, M.** 2004. 'Geomorphological and Geological Setting of Selected Wadis in the Northern Emirates'. *The Fifth Annual U.A.E. University Research Conference*, pp. 11–22.

Farrell, J. 2024. *Flash floods wash through Oman and Dubai*. 16 April 2024. Available at: https://www.washingtonpost.com/video/local/weather/flash-floods-wash-through-oman-and-dubai/2024/04/16/8b428b25-b8ee-4a95-8993-1a29e1408677_video.html [last accessed 5 September 2024].

Fleitmann, D, Burns, SJ, Mudelsee, M, Neff, U, Kramers, J, Mangini, A and **Matter, A.** 2003. 'Holocene Forcing of the Indian Monsoon Recorded in a Stalagmite from Southern Oman'. *Science*, 300: 1737–1739. https://www.science.org/doi/10.1126/science.1083130.

Frifelt, K. 1975. 'On prehistoric settlement and chronology of the Oman Peninsula'. *East and West*, 25: 359–324. https://www.jstor.org/stable/29756093.

Genchi, F. 2023. 'The Collective Corridor-Shaped Tombs of The Daba Al Bayaah Necropolis (Musandam: Oman): The Origin and Spread of A Funerary Structure Based On Evidence From South-East Arabia'. *Journal of Oman Studies*, 24: 19–46.

Gerner, A, Schütze, N and **Schmitz, GH.** 2012. 'Portrayal of fuzzy recharge areas for water balance modelling – a case study in northern Oman'. *Advances in Geoscience*, 31: 1–7. DOI: https://doi.org/10.5194/adgeo-31-1-2012

Gernez, G, al-Ghafri, W and **Ciesielski, E.** 2023. 'A Wadi Suq Necropolis in the mountains. Rescue Excavations at Bilad Ash Shuhum'. *Journal of Oman Studies*, 24: 47–77.

Giesche, A, Hodell, DA, Petrie, CA, Haug, GH, Adkins, JF, Plessen, B, Marwan, N, Bradbury, HJ, Hartland, A, French, AD and **Breitenbach, SFM.** 2023. 'Recurring summer and winter droughts from 4.2-3.97 thousand years ago in north India'. *Communications. Earth and Environment*, 4: 1–10. DOI: https://doi.org/10.1038/s43247-023-00763-z

Glover, E. 1998. 'Mangroves, molluscs and man: Archaeological evidence for biogeographical changes in mangrove around the Arabian peninsula'. *Abiel II*, 63–78.

Goudie, AS and **Parker, AG.** 2011. 'Paleoenvironments and Prehistory in the Holocene of SE Arabia'. In: Martini, IP and Chesworth, W (eds.) *Landscapes and Societies. Selected Cases*. Dordrecht: Springer, pp. 109–120. DOI: https://doi.org/10.1007/978-90-481-9413-1_7

Greenberg, R. 2002. *Early Urbanizations in the Levant. A Regional Narrative*. London and New York: Leicester University Press.

Gregoricka, LA. 2016. 'Human response to climate change during the Umm an-Nar/Wadi Suq transition in the United Arab Emirates'. *International Journal of Osteoarchaeology,* 26: 211–220. DOI: https://doi.org/10.1002/oa.2409

Gregoricka, LA. 2021. 'Aridity and Adaptation among Arabian Bronze Age Communities. Investigating mobility and climate change using isotope analysis'. In: Robbins Schug, G (ed.) *The Routledge Handbook of the Bioarchaeology of Climate and Environmental Change*. London: Routledge, pp. 431–452. DOI: https://doi.org/10.4324/9781351030465-28

Hammer, E. 2022. 'Multi-centric, Marsh-based Urbanism at the early Mesopotamian city of Lagash (Tell al-Hiba, Iraq)'. *Journal of Anthropological Archaeology*, 68: 1–21. DOI: https://doi.org/10.1016/j.jaa.2022.101458

Hewett, Z, de Gruchy, M, Hill, D and **Lawrence, D.** 2022. 'Raincheck: A new diachronic series of rainfall maps for Southwest Asia over the Holocene'. *Levant*, 54(1): 5–28. DOI: https://doi.org/10.1080/00758914.2022.2052660

Kaniewski, D, Marriner, N, Cheddadi, R, Guiot, J and **van Campo, E.** 2018. 'The 4.2 ka BP event in the Levant'. *Climate of the Past*, 14: 1529–1542. DOI: https://doi.org/10.5194/cp-14-1529-2018

Kaniewski, D and **Van Campo, E.** 2017. '3.2 ka BP Megadrought and the Late Bronze Age Collapse'. In: Weiss, H (ed.) *Megadrought and Collapse: From Early Agriculture to Angkor*. New York: Oxford Academic. DOI: https://doi.org/10.1093/oso/9780199329199.003.0005

Kennet, D, et al. 2025. *The Bronze Age Collective Graves of Qarn al-Harf, Ras al-Khaimah (UAE), Southeast Arabia at the dawn of the second millennium*. London: Oxbow.

Kennet, D and **Velde, C.** 1995. 'Third and early second-millennium occupation at Nud Ziba, Khatt (U.A.E.)'. *Arabian Archaeology and Epigraphy*, 6: 81–99. DOI: https://doi.org/10.1111/j.1600-0471.1995.tb00078.x

Kluge, J. 2021. 'Die Türme'. In: Schmidt, C, Döpper, S, Kluge, J, Petrella, S, Ochs, U, Kirchhoff, N, Maier, S and Walter, M (eds.) *Die Entstehung komplexer Siedlungen im Zentraloman. Archäologische Untersuchungen zur Siedlungsgeschichte von Al-Khashbah*. Oxford: Archaeopress Publishing, pp. 36–92. DOI: https://doi.org/10.2307/jj.14638155.12

Lawrence, D, Palmisano, A and **de Gruchy, MW.** 2021. 'Collapse and continuity: A multi-proxy reconstruction of settlement organization and population trajectories in the Northern Fertile Crescent during the 4.2kya Rapid Climate Change event'. *PLOS one*, 16(1): e0244871 DOI: https://doi.org/10.1371/journal.pone.0244871

Magee, P. 2014. *The Archaeology of Prehistoric Arabia. Adaptation and Social Formation from the Neolithic to the Iron Age*. Cambridge: Cambridge University Press. DOI: https://doi.org/10.1017/CBO9781139016667

Manning, SW, Lorentzen, B, Welton, L, Batiuk, S and **Harrison, TP.** 2021. 'Beyond megadrought and collapse in the Northern Levant: The chronology of Tell Tayinat and two historical inflection episodes around 4.2ka BP, and following 3.2ka BP'. *PLoS ONE*, 15(10): e0240799. DOI: https://doi.org/10.1371/journal.pone.0240799

McIntosh, RJ, Tainter, JA and **McIntosh, SK.** 2000. 'Climate, history and human action'. In: McIntosh, RJ, Tainter, JA and McIntosh, SK (eds.) *The way the wind blows*. New York: Columbia University Press, pp. 1–44.

Middleton, GD. 2017. *Understanding collapse: ancient history and modern myths*. Cambridge: Cambridge; Cambridge University Press. DOI: https://doi.org/10.1017/9781316584941

Miller, GL. 2021. 'Ritual, Labor Mobilization, and Monumental Construction in Small-Scale Societies. The Case of Adena and Hopewell in the Middle Ohio River Valley'. *Current Anthropology*, 62(2): 164–197. DOI: https://doi.org/10.1086/713764

Mortimer, AE. 2019. List of Umm an-Nar round towers compiled between 2011 and 2015. Unpublished report.

Mortimer, AE and **Thornton, CP.** 2018. 'Bronze Age towers and the control of water: New evidence from Bāt, Oman'. *The Journal of Oman Studies*, 19: 65–84.

Nathan, S and **Harrower, MJ.** 2023. 'Mapping spatial patterning of Bronze Age towers in Oman according to water flow accumulation'. *Arabian Archaeology and Epigraphy*, 34(S1): S51–S60. DOI: https://doi.org/10.1086/713764

Orchard, JC and **Orchard, JJ.** 2007. 'The third millennium BC oasis settlements of Oman and the first evidence of their irrigation by Aflaj from Bahla'. *Proceedings of the International Symposium: Archaeology of the Arabian Peninsula through the ages*. Muscat: Ministry of Heritage and Culture, pp. 143–173.

Palmisano, A, Lawrence, D, de Gruchy, MW Bevan, A and **Shennan, S.** 2021. 'Holocene regional population dynamics and climatic trends in the Near East: A first comparison using archaeo-demographic proxies'. *Quaternary Science Reviews*, 252: 106739. DOI: https://doi.org/10.1016/j.quascirev.2020.106739

Parker, AG and **Goudie, AS.** 2007. 'Development of the Bronze Age landscape in the southeastern Arabian Gulf: new evidence from a buried shell midden in the eastern extremity of the Rub' al-Khali desert, Emirate of Ra's al-Khaimah, U.A.E'. *Arabian Archaeology and Epigraphy*, 18: 132–138. DOI: https://doi.org/10.1111/j.1600-0471.2007.00278.x

Parker, AG, Goudie, AS, Stokes, S, White, K, Hodson, MJ, Manning, M and **Kennet, D.** 2006. 'A Record of Holocene Climate Change from Lake Geochemical Analyses in Southeastern Arabia'. *Quaternary Research*, 66: 465–76. DOI: https://doi.org/10.1016/j.yqres.2006.07.001

Pellegrino, MP, Degli Esposti, M, Buta, M, Tagliamonte, E and **Hassan, SA.** 2019. 'Grave-goods from the long chamber tomb "Dibba 76/1" (Fujairah, UAE): a first inventory'. *Arabian Archaeology and Epigraphy*, 30(1): 1–43. DOI: https://doi.org/10.1111/aae.12120

Petrie, CA. 2019. 'Diversity, variability, adaptation and 'fragility' in the Indus Civilization'. In: Yoffee, N (ed.) *The evolution of fragility: setting the terms*. Cambridge: McDonald Institute for Archaeological Research, (McDonald Institute for Archaeological Research, 2019), pp. 109–133. DOI: https://doi.org/10.17863/CAM.40701

Petrie, CA, Singh, RN, Bates, J, Dixit, Y, French, CAI, Hodell, DA, Jones, PJ, Lancelotti, C, Lynam, F, Neogi, S, Pandey, AK, Parikh, D, Pawar, V, Redhouse, DI and **Singh, DP.** 2017. 'Adaptation to Variable Environments, Resilience to Climate Change Investigating Land, Water and Settlement in Indus Northwest India'. *Current Anthropology*, 58(1): 1–30. DOI: https://doi.org/10.1086/690112

Portugali, J. (ed.) 1996. *The Construction of Cognitive Maps*. Dordrecht: Kluwer Academic Publishing.

Potts, DT. 1990. *A Prehistoric Mound in the Emirate of Umm al-Qaiwain*, U.A.E. Excavations at Tell Abraq in 1989. Copenhagen: Munksgaard.

Potts, DT. 1991. *Further Excavations at Tell Abraq. The 1990 Season*. Copenhagen: Munsgaard.

Potts, D. 2001. 'Before the Emirates: an Archaeological and Historical Account of Developments in the Region c. 5000 BC to 676 AD'. In: Al-Abed, I and Hellyer, P (eds.) *The United Arab Emirates: A New Perspective*. London: Trident Press, pp. 28–69.

Preston, GW. 2011. *From Nomadic herder-hunters to sedentary farmers: the relationship between climate, environment and human societies in the United Arab Emirates from the Neolithic to the Iron Age*. Unpublished thesis (PhD), Oxford Brookes University. DOI: https://doi.org/10.1016/j.jaridenv.2011.11.030

Purdue, L, Kennet, D, Garnier, A, Parton, A, Djerbi, H, Botan, S, Herveux, L, Davtian, G, Carré, A, Moger, D and **al-Jahwari, NS.** 2021. 'Ancient agriculture in Southeast Arabia: A three thousand year record of runoff farming from central Oman (Rustaq)'. *CATENA*, 204: 105406. DOI: https://doi.org/10.1016/j.catena.2021.105406

Purdue, L, Charbonnier, J, Régagnon, E, Calastrenc, C, Sagory, T, Virmoux, C, Crépy, M, Costa, S and **Benoist, A.** 2019. 'Geoarchaeology of Holocene oasis formation, hydro-agricultural management and climate change in Masafi, southern Arabia (UAE)'. *Quaternary Research*, 92: 109–132. DOI: https://doi.org/10.1017/qua.2018.142

Riehl, S. 2009. 'Archaeobotanical evidence for the interrelationship of agricultural decision-making and climate change in the ancient Near East'. *Quaternary International*, 197: 93–114. DOI: https://doi.org/10.1016/j.quaint.2007.08.005

Riehl, S, Pustovoytov, KE, Weippert, H, Klett, S and **Hole, F.** 2014. 'Drought stress variability in ancient Near Eastern agricultural systems evidenced by d^{13}C in barley grain'. *PNAS*, 111(34): 12348–12353. DOI: https://doi.org/10.1073/pnas.1409516111

Righetti, S. 2015. *Les cultures du Wadi Suq et de Shimal dans la péninsule omanaise au deuxième millénaire avant notre ère. Évolution des sociétés du Bronze moyen et du Bronze récent*. Unpublished thesis (PhD), Université Paris 1, Paris Sorbonne.

Riris, P, Silva, F, Crema, E, Palmisano, A, Robinson, E, Siegel, PE, French, JC, Jørgensen, EK, Maezumi, SY, Solheim, S, Bates, J, Davies, B, Oh, Y and **Ren, X.** 2024. 'Frequent disturbances enhanced the resilience of past human populations'. *Nature*, 629: 837–842. DOI: https://doi.org/10.1038/s41586-024-07354-8

Rizk, ZE. 2015. 'Why Wadi Al Bih Limestone is the Most Sustainable Aquifer in the United Arab Emirates?'. *International Journal of Sustainable Water & Environmental Systems*, 7(1): 21–28. DOI: https://doi.org/10.5383/swes.7.01.003

Rizk, ZE and **Alsharhan, AS.** 2003. 'Water resources in the United Arab Emirates'. In: Alsharhan, AS and Wood, WW (eds.) *Water Resources Perspective: Evaluation, Management and Policy*. Elsevier: Amsterdam, pp. 245–264. DOI: https://doi.org/10.1016/S0167-5648(03)80022-9

Schmidt, C and **Döpper, S.** 2017. 'The development of complexity at third-millennium BC al-Khashbah, Sultanate of Oman: results of the first two seasons, 2015 and 2016'. *Proceedings of the Seminar for Arabian Studies*, 47: 215–226. https://archaeopresspublishing.com/ojs/index.php/PSAS/article/view/1232.

Schmidt, C, Döpper, S, Kluge, J, Petrella, S, Ochs, U, Kirchhoff, N, Maier, S and **Walter, M.** 2021. *Die Entstehung komplexer Siedlungen im Zentraloman. Archäologische Untersuchungen zur Siedlungsgeschichte von Al-Khashbah*. Oxford: Archaeopress Publishing. DOI: https://doi.org/10.2307/jj.14638155

Schwall, C, Brandl, M, Börner, M, Lindauer, S, Deckers, S, David-Cuny, H, Yousif, E and **Jasim, SA.** 2024. 'Kalba: research on trade networks of a prehistoric coastal community on the Gulf of Oman, United Arab Emirates'. *Antiquity*, 98(399): 1–8. DOI: https://doi.org/10.15184/aqy.2024.45

Sherif, M, Sefelnasr, A, Ebraheem, AA, Al Mulla, M, Alzaabi, M and **Alghafli, K.** 2021. 'Spatial and Temporal Changes of Groundwater Storage in the Quaternary Aquifer, UAE'. *Water*, 13(6): 864. DOI: https://doi.org/10.3390/w13060864

Sir William Halcrow & Partners. 1965. Trucial States Hydrological & Groundwater Survey. HM Political Agent, Dubai. (The National Archives, Kew FO 1016/840 Pt 2 of 2, see also FO 1016/841). https://www.agda.ae/en/catalogue/tna/fo/1016/840/n/39.

Sołtysiak, A and **Fernandes, R.** 2021. 'Much ado about nothing: Assessing the impact of the 4.2 kya event on human subsistence patterns in northern Mesopotamia using stable isotope analysis'. *Antiquity*, 95(383): 1145–1160. DOI: https://doi.org/10.15184/aqy.2021.117

Stanger, G. 1986. *The hydrogeology of the Oman Mountains*. Unpublished thesis (PhD), The Open University. https://oro.open.ac.uk/57011/112/377781_vol1.pdf.

Swerida, J and **Thornton, CP.** 2019. 'al-Khafaji reinterpreted: New insights on Umm an-Nar monuments and settlement from Bat, Oman'. *Arabian Archaeology and Epigraphy*, 30: 157–172. DOI: https://doi.org/10.1111/aae.12131

Terry, JP, Al Ruheili, A, Almarzooqi, MA, Almheiri, RY and **Alshehhi, AK.** 2022. 'The rain deluge flash floods of summer 2022 in the United Arab Emirates: Causes, analysis and perspectives on flood risk reduction'. *Journal of Arid Environments*, 215: 105013. DOI: https://doi.org/10.1016/j.jaridenv.2023.105013

Thornton, CP, Cable, CM and **Possehl, GL.** (ed.) 2017. *The Bronze Age Towers at Bat, Sultanate of Oman Research by the Bat Archaeological Project, 2007–12*. Pennsylvania, P.A.: University of Pennsylvania Press. DOI: https://doi.org/10.9783/9781934536070

Velde, C. 2003. 'Wadi Suq and Late Bronze Age in the Oman Peninsula'. In: Potts, DT, al-Naboodah, H and Hellyer, P (eds.) *Proceedings of the First International Conference on the*

Archaeology of the UAE. Abu Dhabi: Trident Press, pp. 102–113.

Velde, C. 2009. 'The Landscape of the Middle Bronze Age in the UAE – Where did people live?'. *Proceedings of the International History Conference on New Perspectives On Recording UAE History*, National Centre for Documentation and Research, Abu Dhabi, pp. 61–74.

Vogt, B. 1998. 'State, problems and perspectives of second millennium B.C. funerary studies in the Emirate of Ras al-Khaimah (U.A.E.)'. In: Phillips, C, Potts, D and Searight, S (eds.) *Arabia and her neighbours: Essays on prehistorical and historical developments presented in honour of Beatrice de Cardi*. Leiden: Brepols. pp. 273–290.

Vogt, B and **Franke-Vogt, U.** (ed.) 1987. *Shimal 1985/1986. Excavations of the German Archaeological Mission in Ras al-Khaimah, U.A.E. A Preliminary Report*. Berlin: Dietrich Reimer Verlag.

Von den Driesch, A. 1994. 'Viehhaltung, Jagd und Fischfang in der bronzezeitlichen Siedlung von Shimal bei Ra's al-Khaimah/U.A.E.' In: Calmeyer, P, Hecker, K, Jakob-Rost, L and Walker, CBF (eds.) *Beiträge zur altorientalischen Archäologie und Altertumskunde: Festschrift für Barthel Hrouda zum 65. Geburtstag*. Wiesbaden: Harrassowitz, pp. 73–85.

Weisgerber, G. 1981. 'Mehr als Kupfer in Oman'. *Der Anschnitt*, 33: 174–263.

Weiss, H. 2016. 'Global megadrought, societal collapse and resilience at 4.2e3.9 ka BP across the Mediterranean and west Asia'. *Past Global Changes Magazine*, 24(2): 62–63. DOI: https://doi.org/10.22498/pages.24.2.62

Weiss, H. 2017. '4.2 ka BP Megadrought and the Akkadian collapse'. In: Weiss, H (ed.) *Megadrought and Collapse: from Early Agriculture to Angkor*. Oxford: Oxford University Press, pp. 93–160. DOI: https://doi.org/10.1093/oso/9780199329199.003.0004

Weiss, H, Courty, M-A, Wetterstrom, W, Guichard, F, Senior, L, Meadow, R and **Curnow, A.** 1993. 'The genesis and collapse of third millennium north Mesopotamian civilization'. *Science*, 261(5124): 995–1004. DOI: https://doi.org/10.1126/science.261.5124.995

Wilkinson, J. 1977. *Water and Tribal Settlement in South-East Arabia. A Study of the Aflaj of Oman*. Oxford: Clarendon Press.

Weyhenmeyer, C. 2000. *Origin and Evolution of Groundwaters in the Alluvial Aquifer of the Eastern Batinah Coastal Plain, Sultanate of Oman*. Unpublished thesis (PhD), University of Bern.

Yule, P. 2001. *Die Gräberfelder in Samad al Shān (Sultanat Oman) Materialien zu einer Kulturgeschichte*. Rahden: Deutsches Archäologisches Institut.

TO CITE THIS ARTICLE:
de Vreeze, M, Kennet, D and Deadman, WM. 2024. Karstic Aquifers and Climate Refugia: A Preliminary Outline History of Water-Management Strategy in Bronze and Iron Age Southeast Arabia. *Open Quaternary,* 10: 5, pp.1–16. DOI: https://doi.org/10.5334/oq.144

Submitted: 27 June 2024 **Accepted:** 10 September 2024 **Published:** 27 September 2024

Open Quaternary is a peer-reviewed open access journal published by Ubiquity Press.