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First contribution of the excavation and chronostratigraphic study of the Ruways 1 Neolithic shell midden (Oman) in terms of Neolithisation, palaeoeconomy, social-environmental interactions and site formation processes

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The NeoArabia project tries to understand how environmental, social, economic and technological factors work in concert to influence settlement and abandonment along a latitudinal transect of 1200 km from UAE to southern Oman. This region was affected by wide north–south variations in the Indo-Arabian monsoon, marine upwelling activity and eustatic variations in the Mid-Holocene. On the local settlement scale, this transect is based on fine stratigraphic excavations and permits the reconstruction of the site formation processes and site catchment analysis. A large number of studies have been conducted on the Ruways-1 site, focusing on a deep stratified sequence corresponding to three millennia of occupation. These studies include on-site climate-environmental signal analysis, local palaeogeography and environmental reconstruction, reservoir effect studies, typo-technological studies, palaeoeconomic strategies, anthropological studies, sclerochronological studies and, finally, site formation processes, the understanding of which makes it possible to explain the potential and limits of the archaeological excavation. The first results

confirm the richness of these archaeological archives for documenting the socio-environmental dynamics, but also the richness of its complex sedimentary structure and the importance of conducting fine and multidisciplinary excavations to answer questions about the rhythms and functions of occupations and the causalities of socio-environmental changes.

KEYWORDS
Coastal Neolithic, geoarcheology, shell midden, site catchment, site formation processes, Sultanate of Oman

1 | INTRODUCTION

The French Agence nationale de la recherche (ANR) NeoArabia research project is an international multidisciplinary and multiscalar project that questions whether climatic and environmental changes could be an explanation for Neolithic cultural developments (c. 6500–2800 yr BC), and whether the populations of eastern Arabia developed specific modes of adaptation to increase their resilience to mid-Holocene climatic variability. In this perspective, a contextual and interdisciplinary work is being conducted in the search to construct a viable Neolithic coastal fisher-gatherer-pastoral model. This work is based on the excavation of fine sedimentary units and a broad interdisciplinary practice combining archaeosciences (geoarchaeology, archaeozoology, archaeobotany, and geochronology) and the analysis of material culture. Nevertheless, little is known of the characteristics of the coastal sites, the spatial pattern of mobility of the populations, and the activities they practised. Indeed, in the world of Arabian archaeology, few excavations have been planned from the perspective of environmental archaeology and site formation processes, with the main effort most often focusing on the study of material culture and its diffusion, especially economic and ritual aspects (tombs).

The Ruways-1 (RWY-1) shell middens excavation stimulated several themes of complementary analyses on a vast mid-Holocene stratified archaeological archive of 8 ha, and we will present the spectrum of these ongoing studies in this paper. The RWY-1 site, located between the Oman Sea and a vast paleo-lagoon supplied by several wadis from the Jabal Safran, was occupied over nearly three millennia (from the end of the seventh to the fourth millennium yr BC). It provides an opportunity to better understand the development of the Arabian Neolithic through its long sequence of occupation, its sedimentary strength (2–3-m depth), and the presence of a very old Neolithic level at the base of the site (6300–6100 yr BC), whose status and cultural characterisation are still under discussion in the absence of lithic fossil-directors. The combination of stratigraphic excavation and a large geoarchaeological study of the entire site allows us to understand the site formation process and the spatial distribution of the occupations according to cultural periods (helped by the presence of many artificial stratigraphic sections created by the exploitation of a quarry).

We here summarise the different tasks in progress on the current RWY-1 excavation and attempt to draw up their main contributions to the practice of multidisciplinary and integrated environmental archaeology. We discuss the impact of the site formation processes for the analysis of archaeological archives, and their contribution to the elaboration of a socio-environmental discourse on the coastal Neolithic resiliency of Eastern Arabia.

2 | NEOLITHIC ARABIAN COASTAL ARCHAEOLOGY CONTEXT AND STATE OF THE ART

Along the Oman coast, the concept of a "Neolithic package" is questionable, pottery is absent and evidence for sedentism is poor (Crassard & Dreschler, 2013); only the presence of domesticated animals in archaeozoological assemblages, the lithic and beads technics and network developments and a certain vision of the socio-environmental space permits the labelling of these groups in Arabia as Neolithic. Coastal environments and marine resources were an important factor in Neolithic development, notably because they presented an apparent resilience to climatic variations. The explanation of cultural changes under climato-environmental constraints has been the subject of numerous academic debates, particularly since the advent of the processual approach (Binford & Binford, 1968; Cleuziou & Tosi, 2000; Renfrew & Bahn, 2013) and the recent theorisation of a deterministic explanation of cultural changes (Clare et al., 2008; Cullen et al., 2000; Weiss et al., 1993), which have recently been modulated by hypotheses favouring more societal adaptation and bifurcation processes (Berger & Guilaine, 2009). Several archaeology-related studies have since been dedicated to the production of specific data on societal vulnerability and adaptation during the early–mid-Holocene (Berger et al., 2016; Borrell, Junno, & Barceló, 2015; Flohr et al., 2016). However, few of them have been concerned with the Arabian

Peninsula and the context of coastal areas (Parker & Goudie, 2008; Preston et al., 2012). As environmental variability has to be considered an integral part of the historical process (Butzer, 2012; Le Roy Ladurie, 1981), the confrontation between human and climato-environmental trajectories is becoming imperative, although the chronology of both is often approximate, which then complicates a robust discussion of causalities. Some environmental systems are more resilient than others to anthropogenic or climatic changes and their cascading feedbacks (Butzer, 2012). The determination of a precise lagoon, estuary and mangrove ecosystems history is ongoing along the eastern Arabian coast, and the progressive disappearance or reduction in these habitats will soon be documented, allowing the detection of new keys to discuss societal-environmental interactions. There is little doubt that the presence of mangrove swamps played a fundamental role in the selection of areas where settlements were established. Many of the Neolithic sites lie at the mouth of wadi deltas or estuaries that supplied fresh water, and were therefore subject to rapid coastal sedimentation (Berger et al., 2013; Biagi & Nisbet, 1999; Woodroffe, 1983). As a consequence, their subsistence economy was often based, almost exclusively, on the exploitation of marine and mangrove swamp resources (Biagi & Nisbet, 2006; Munoz, 2017; Zazzo, Munoz, & Saliège, 2014; Zazzo et al., 2016). The Arabian Sea mangroves can be considered to have been highly productive on many levels for the prehistoric subsistence economies (Berger et al., 2013; Biagi & Nisbet, 2006; Tengberg, 2005).

The interaction between humans and their environment operates over a number of different spatial and temporal scales, and evidence for these is apparent in eastern Arabia, where the sub-arid to arid zone was subject to rapidly changing environmental conditions after the onset of the humid period around 7000 yr BC (Parker & Goudie, 2008). Firstly, the region is located in the frontier zone between dry and wet tropical systems where the monsoon has reduced its activity and gradually shifted southward (Yemen) since the middle Holocene (Fleitmann et al., 2007, Lézine et al., 2017), and it has constantly been impacted by the dynamics of the vast marine upwelling off Oman (regional scale of the system). The NeoArabia ANR project is based on the consideration that the shell midden archives of the eastern Arabian coast allow us to explore through time the modes of societal adaptability in stress conditions in an intra-site-specific context (local scale). Nevertheless, the understanding of their spatial organisation and their mode of accumulation must be well understood beforehand.

Regional chronocultural patterns defined by cumulative probability density function (CPDF) techniques often appear insufficient for characterising socio-environmental relationships with climate and environmental changes (Berger et al., 2016; Flohr et al., 2016). With extensive application of stratigraphy, as well as spatial analysis at the site scale, the in-site approach aims to reveal continuity/discontinuity in occupation and cultural changes with sensitive timing. Systematic intra-site stratigraphic, taphonomic, and geochronologic evaluations should reveal more robust data to verify whether site abandonment or abrupt decreases in occupation density are real, and not artificially created by insufficient control of the site formation processes or poor control of absolute chronology (Berger, Metallinou, & Guilaine, 2014; Lespez et al., 2016; Marciniak et al., 2015). It was with this in mind that a stratigraphically controlled excavation at RWY-1 was decided on, facilitated by the presence of numerous artificially created sedimentary stratigraphies created during quarrying works. This combined approach of archaeological surveys and systematic chronostratigraphic studies should provide extensive knowledge on the site's occupation, facilitating comparisons with off-site studies of the coastal archives.

3 | GEOMORPHOLOGICAL, ARCHAEOLOGICAL AND STRATIGRAPHICAL CONTEXTS OF THE RWY-1 SITE

The Neolithic RWY-1 shell midden (governorate of al-Sharqquiyah, Sultanate of Oman) is located in the centre of a wide open and flat north-east–south-west coastline combining many wadi estuaries with vast sabkhas, many kilometres in size, which are largely invaded by a system of barchanoid dunes (Fig. 1a). Previous works showed that large mid-Holocene lagoons and sedimentary mangrove archives were preserved under the surface of these recent sabkhas, with these having being fed by more perennial and powerful wadis under monsoon control (Berger et al., 2013). The surface of the RWY-1 shell midden is estimated to be nearly 8 ha, and its height in relation to the sabkha that borders it to the west and the current marine beach to the east is about 8–10 m (Fig. 1b). This site has been prospected on the surface for 20 years by the "Ja'alan-Dhofar" French Archaeological Mission in the Sultanate of Oman, to characterise the age and potential duration of occupation (sixth–fourth millennia yr BC). It has now been excavated over the past 3 years in the context of the NeoArabia ANR project, in collaboration with the Ministry of Heritage and Culture of Oman. The site was heavily damaged at the beginning of 2010 by bulldozers obtaining ballast for public works. This destruction of nearly half of the site surface has presented the opportunity to observe long continuous stratigraphic sections. The front of the ballast quarry has created an observable semi-circular stratigraphic section nearly 80 m in length and 3 m in height in the eastern part of the shell midden (Fig. 1b). Around 90% of the western part of the site has been destroyed, but we were able to observe, record and sample its stratigraphy in 2013–2014, before its near total destruction.

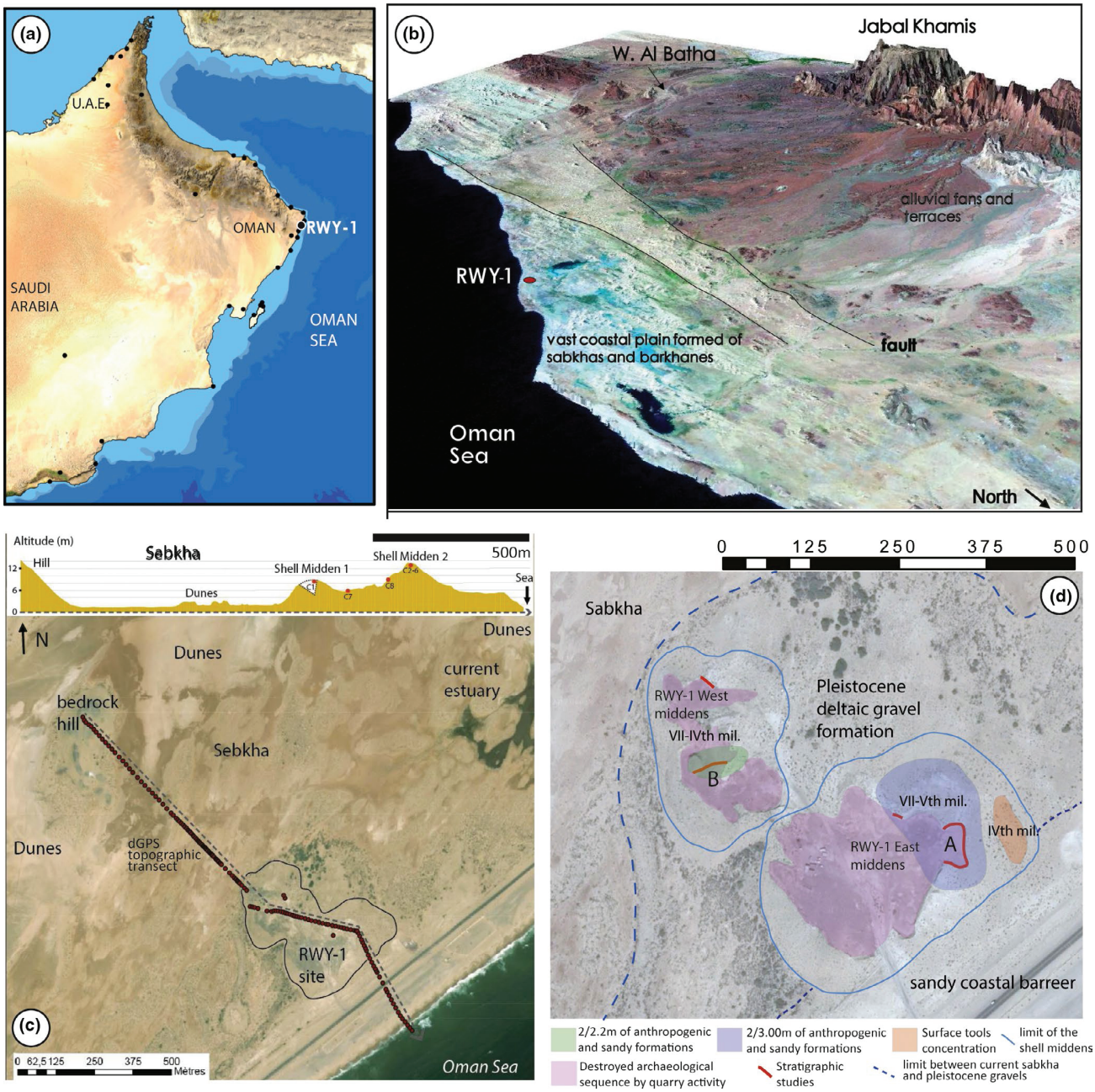


FIGURE 1 (a) Location of the RWY-1 site in the eastern Arabian region with the main archaeological sites studied in the NeoArabia Project (black circles). (b) 3D view of Ja'alan from the north-east with the main geological units, the geological faults, the current coastal sabkhas and the site of RWY-1. (c) Zoom-in of a Google Earth satellite image with the trace of the RWY-1 site and the position of a topographical dGPS transect between the Oman Sea and the bottom of the sabkha. The yellow topographic profile at the top reveals the presence of two successive shell middens (SM1 and SM2), culminating at 10 and 12 m respectively. (d) A focus on the spatial organisation of the RWY-1 shell midden, located on a cemented Pleistocene gravelly alluvial formation, shown on a Google Earth framework with the locations of the main stratigraphic studies (see a and b in Fig. 2) and archaeological formations dated by millennium [Colour figure can be viewed at wileyonlinelibrary.com]

Zooming in on the appropriate google images allows the current situation of the site to be observed, showing the heavy impact from the recent extension of a gravel quarry, which destroyed more than half of the initial surface of the site (see the pink areas; Fig. 1d). The area in blue contains archaeological remains from the seventh to fifth millennium yr BC, the green area remains from the seventh to fourth millennium yr BC, and the orange area a concentration of remnants from the fourth millennium, mainly identified on the surface.

This type of systematic stratigraphic approach, associated with a geochronological study, is very rarely addressed by

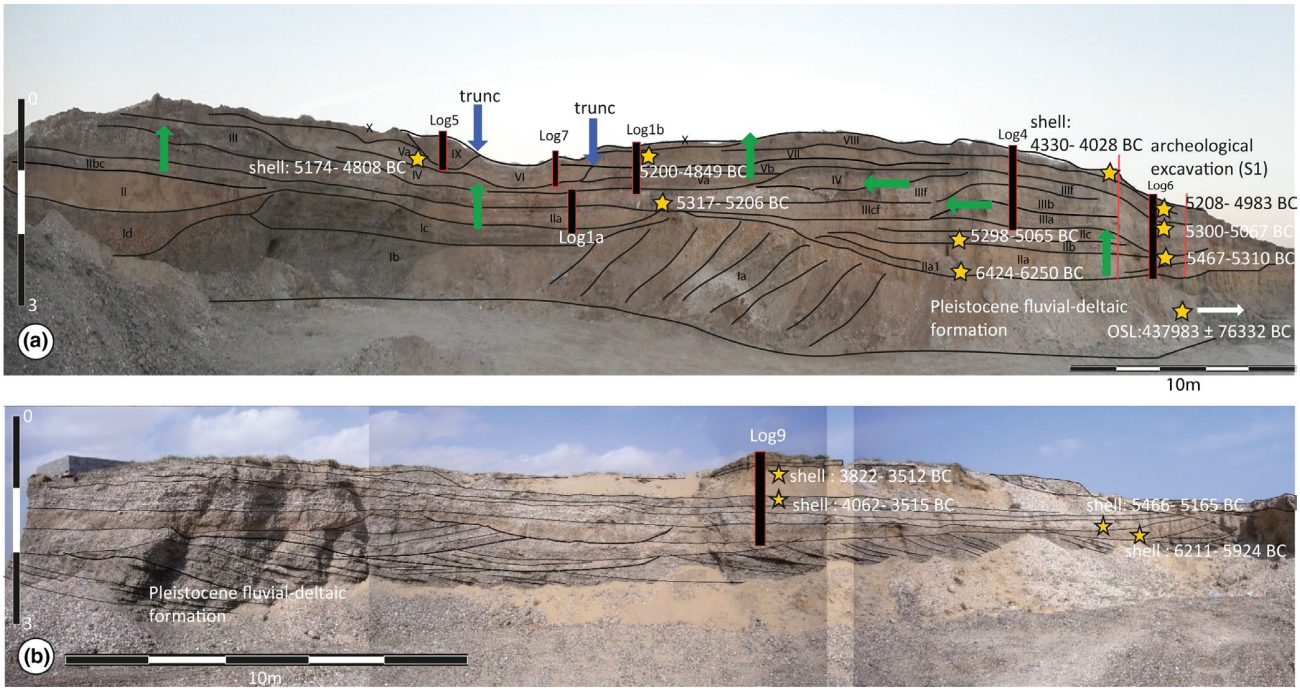


FIGURE 2 The two main stratigraphies of the RWY-1 site. (a) Eastern stratigraphy of the site (60 m) with the location of the main sedimentary units, the geologically analysed sequences (log), and a part of the radiocarbon dating series in cal yr BC age (mainly on charcoal, except those noted as being from shell). The vertical green arrows indicate a vertical aggradation, the horizontal arrows a lateral aggradation, and the blue arrows a truncation process (versus deflation corridors). (b) Western part of the site (30 m) with the same data and a clear bi-partition between ^{14}C dates of the seventh–sixth millennia yr BC and those of the fourth millennium yr BC. No radiocarbon dates from the fifth millennium were recorded in this sequence (this could be due to either absence or destruction of the archaeological sequence) [Colour figure can be viewed at wileyonlinelibrary.com]

Arabian Neolithic archaeology, because of the often small size of the excavations, which are often constrained by very thick and complex archaeologically stratified sequences. Indeed, few excavation areas larger than 10 m^2 exist (Borgi et al., 2012; Cavulli & Scaruffi, 2012) outside the preventive archaeology context (Marcucci, Badel, Genchi, Munoz, Todero, & Tosi, 2014; RAA, Usai, 2006), and most of the studies conducted in Ja'alan over the past 40 years are one-off surveys of less than 5 m^2 and are too punctual (Charpentier, Blin, & Tosi, 1998; Charpentier et al., 2013). Unfortunately, such contexts do not make it possible to ensure that the excavations carried out were properly representative. This has been the case on very rare occasions, and for more recent periods and contexts with significantly reduced sedimentary thicknesses more favourable to extensive archaeological stripping (Azzarà, 2013; Cattani et al., 2019; Cavulli & Scaruffi, 2012).

The overall plan is to conduct an excavation strictly modelled on the previously detailed stratigraphic sequence for analysis of the continuous rhythmicity of occupation from the many visible sedimentary strata (passes of 3–5 cm), with a view to determining, as soon as possible, the socio-environmental strategies developed by the Neolithic populations, revealing the technical and economic variations of their occupation through the analysis of material culture, wildlife and ecofact remains that are present at a very high chronological resolution (from 25 to 5 years). The aim is to enable a comparison with off-site palaeoenvironmental data documenting the evolution of the environment and climate in nearby palaeo-lagoon-archives, to reveal the causes of socio-environmental phenomena. The precision of the excavation depends mainly on the sedimentation rate, and the equilibrium between the speed of aeolian sedimentation and that of anthropogenic deposition. In RWY-1, time controls were made from the scale of the site to that of the complex micro-laminated structures of some fire pits (Fig. 1c). Stripping and sampling of layers 1–2 cm thick, strictly in accordance with the sedimentary structure, were favoured, to permit analysis of the rhythmicity and temporality of the deposits (annual and seasonal).

4 | SITE FORMATION PROCESSES

Understanding the process of formation and post-depositional evolution of these complex sites is accessible thanks to the presence of numerous stratigraphical sections artificially dug in the quarry, and a chronostratigraphic framework based on many ^{14}C and optically stimulated luminescence (OSL)

dates. The effects of natural agents are particularly pronounced in the arid context, where the protecting vegetation is very sparse and strong winds are very frequent and intensive. We know by analysis of pollen from the mid-Holocene that ecological conditions were different, being less arid and closer to an arboreal steppe with the presence of mangrove ecosystems in the intertidal areas of deltas and estuaries (Lézine et al., 2002). Atmospheric agents such as rain then had a more significant and regular impact, particularly through flooding of estuarine areas. In the shell middens, we therefore have to consider the combined effects of anthropogenic agencies and aeolian processes of deposition, with the shell midden being the product of these two main sedimentary factors. The thickness and frequency of fire-floor surfaces (in clay fire soles or in pebbles) or pure anthropogenic accumulation from the detritus of consumed products (shells, fish, ashes and charcoal) reflects the density of Neolithic occupation. These accumulations clearly show the structuring of the intra-site space under the effect of human activities, which can only be partially understood during punctual excavations such as ours, but which can be tracked on continuous stratigraphic transects such as quarry fronts. Sequential and chronostratigraphic analysis of these transects reveals the rhythmicity and time frame of the occupations. Lateral sedimentary progradation can be observed during the densest occupation phases, indicating an extension of the occupied surface. Time is then no longer recorded only vertically, but also laterally (Fig. 2a). Natural post-depositional alterations are also observed, with reprecipitated salts (gypsum) or calcium carbonates from evaporation of rain being punctual in these semi-arid regions. These are mainly observed on the most ashy facies, which sometimes appear compacted, and are associated with the formation of small millimetric $CaCO_3$ nodules during moister episodes.

Ten main sedimentary units were observed and dated from the bottom of a shell midden represented by cemented gravels of a Pleistocene fluvial-deltaic sequence (>400 ka BP by OSL dating; Fig. 2a). The Neolithic occupation represented by the eastern main shell midden developed between 6300 and 4600–4400 yr BC. The first horizons of occupation are located in Pleistocene relictual palaeochannels filled by yellow aeolian sands (6300–5800 yr BC). The sedimentation of the shell midden shows vertical and lateral aggradation phases, especially in sections relating to the second part of the sixth millennium yr BC, where the anthropogenic deposits are dense. The fifth millennium yr BC is illustrated as being subject to more energetic and destructive aeolian processes, which result in truncation phases to some of the older anthropogenic formations (Fig. 2a). Erosion by the wind continued until recent times (eighteenth–nineteenth century AD) based on OSL dating (see Section 9). The western shell midden, now totally destroyed by quarrying activity, illustrates a long hiatus between the seventh–sixth millennium yr BC and the fourth millennium yr BC, whose mainly sandy sedimentary formations were deposited following a truncation covering more than a millennium (Fig. 2b).

The impact of wind on sedimentation is almost permanent (a mixture of consumption of debris or charcoal with deposition of wind-driven sand), and appears to show fluctuations in intensity (the size and density of particles and of remobilised artifacts). In phases of greater stability, the effects of the wind appear only in the form of small discontinuous sorted sand beds (perhaps the result of storms?) within otherwise purely anthropogenic formations. During phases of almost continuous wind activity, regular beds of well-sorted horizontal or oblique small shell debris or fish bones are observed between sandy accumulations. Truncation by wind action is sometimes observed, from the micro-local scale (decimetric-sized deflation bowls) to the local scale (deflation corridors over several meters that permanently weaken the shell midens; Fig. 2a). In the second case, these probably correspond to hyper-arid periods (cf. unit VI around 5000–4800 yr BC), and the destruction of a large part of the previous formations over several meters is observed. These phenomena complicate the stratigraphic interpretation of the site.

5 | PALAEOECONOMIC AND SITE CATCHMENT ANALYSES

The multi-proxy analysis (charcoal, charred seeds, pollen, marine molluscs, crustaceans, fish, turtles, birds, land and marine mammal bones) provides a preliminary reconstruction of the subsistence strategies. The faunal remains collected during the 2017 and 2018 excavations are currently being studied at the laboratory of archaeozoology and archaeobotany at the National Museum of Natural History in Paris, using the modern comparative osteological collections for the taxonomic identification of the remains. The results of the archaeomalacological study show that the marine shells are mainly culinary waste (Fig. 3), with the main species being the clam *Marcia recens* (syn. *Marcia marmorata*). Several other species were also collected for food on a smaller scale, such as oysters (Ostreidae), the clam *Callista umbonella* (syn. *Amiantis umbonella*), brown mussel *Perna perna* (syn. *Perna picta*), crowned turban shell *Lunella coronate*, and cowry *Cypraea* sp. The main environment exploited was the muddy sand from the lagoon, used for the gathering of *Marcia recens*. Marine shells were also used as raw materials for manufacturing objects like decorative elements, tools, and fishing hooks.

The ichthyological study revealed thousands of small vertebrae belonging to small fish species or juvenile specimens, which can take refuge in the pneumatophores of the mangrove to hide from predators. This illustrates a subsistence activity mainly oriented towards exploitation of the lagoon

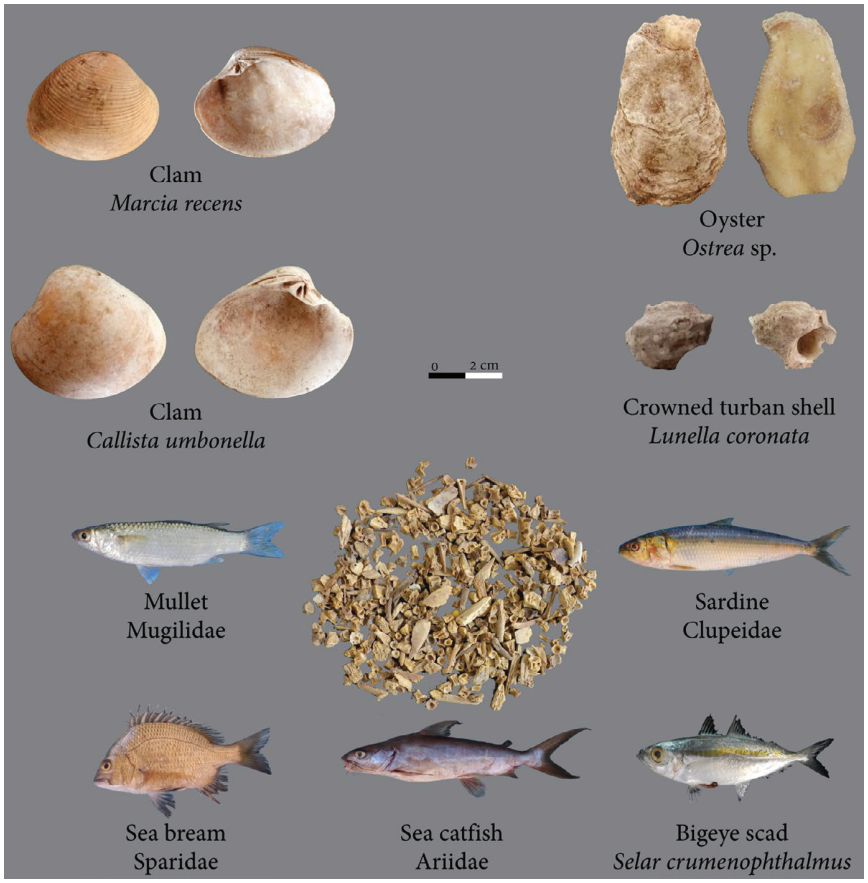


FIGURE 3 Illustration of the main shellfish and fish taxa identified in the first RWY-1 studies. Seashell photographs: archaeological specimens from RWY-1. Fish photographs: fresh fish from the MNHN osteological collection of fish for the Indo-Pacific area [Colour figure can be viewed at wileyonlinelibrary.com]

and mangrove swamps (Fig. 3), with the presence of many mullet (Mugilidae), bigeye scad (*Selar crumenophthalmus*), and sardines (Clupeidae), as well as many juvenile sea bream (Sparidae) and sea catfish (Ariidae). Neolithic people from RWY-1 probably used fishing nets with small meshes.

These preliminary results of the study of marine resources show that the Neolithic populations of RWY-1 had a subsistence activity mainly focused on exploitation of the lagoons, which were probably very extensive in the western part of the site (see Section 11). RWY-1 appears to be a fishing station where Neolithic communities were able to exploit the entire intertidal zone to collect bivalves, and also to have access to lagoon waters where they could lay their fishing nets, as is the case on other sites on the Ja'alan coast such as SWY-1 (Marrast, Béarez, & Charpentier, 2020; Martin, 2005).

In general, the preservation of vertebrate remains is poor because of the loss of organic material and high fragmentation. Besides fish, the vertebrate assemblage of Ruways 1 is composed of a few mammalian and reptilian remains (Fig. 4). The mammalian remains belonged to ovicaprids, and in some cases it was possible to identify the bones to the level of the species. This is the case for a talus allocated to a goat (Fig. 4: 1). In other cases, it was not possible to distinguish between sheep and goat (Fig. 4: 2). Ruways 1, like other Neolithic sites in Oman, is remarkable for the presence of canid bones among the faunal assemblages. A complete calcaneus of a dog (Fig. 4: 3) and a distal part of a humerus (Fig. 4: 4) were recovered from the site, and highlight once more the importance of these taxa for consumption in this part of the world. Other mammals exploited in Ruways are dolphins, a single vertebra of which was recovered practically complete (Fig. 4: 5). Finally, marine turtle bones are also present in the remains, as demonstrated by a relatively large shell that was consolidated before removal (Fig. 4: 7). This shell belonged to a green sea turtle, common in most of the coastal sites of Oman. Study of the turtle remains is still ongoing.

Analyses of the floral macro-remains have also been performed, specifically the different types of fuelwood obtained from local vegetation communities, with these fuelwood remains being very frequent in the numerous fireplaces or ashy layers of the site. Despite the still partial data, the charcoal remains reveal that the mangrove environment, which has nowadays disappeared, was present at least until the end of the fifth millennium yr BC. After two seasons of study (2017–2018) and the analysis of two-thirds of the RWY-1 sequence, with more than 1000 charcoal fragments having been analysed, a similar pattern emerges in the relative presence of taxa, though with some differences (*Avicennia* occurring in 87% of the samples, Rhizophora in 53%) in relation to Chenopods. The very limited range of species at the anthracological level

FIGURE 4 RWY-1 faunal remains, 1: C2 US18. Capra, talus. 2: B2 US18. Caprini mandible fragment of the articulation. 3: A2 US18. Canis sp. Calcaneus. 4: S1 A2 US6B distal humerusCanis sp. 5: B3 US13b dolphin vertebra. 6: B2 US12a long bone (humerus) shaft of a medium-sized ungulate. 7: B2 US11b marine turtle shell [Colour figure can be viewed at wileyonlinelibrary.com]

is surprising, given that the other Neolithic sites for which charcoal analyses have been performed generally present a more varied situation (cf. Ras al Hamra 5–6; Biagi & Nisbet, 1999). This would suggest that mangroves were the only source of timber and firewood for the local groups over a period of several centuries.

The remarkable presence of Rhizophora cf mucronatais of note; it is a species no longer growing along the coasts of the Arabian Sea (refuges are found in more humid tropical areas). Avicennia sp., known to be the most tolerant in terms of environmental conditions, were observed in the region until at least the Early Bronze Age (Cartwright, 2004), and are now present in the Khor al Jaramah (north Ja'alan), where they were recently reintroduced. Their presence confirms results from the pollen assemblages (see Section 10), the frequent presence of mangrove-adapted species like the gastropod Terebralia palustris, and the exploitation by Neolithic peoples of the two arboreal species of mangrove. Further research should provide details on the origin, evolution and death of the local mangroves, which probably locally disappeared at different times and for different reasons (climatic changes and human pressure).

FIGURE 5 Illustrations of the RWY-1 lithic material (from the upper part of the archaeological sequence between 5200 and 4600 yr BC). 1. Net sinkers in sandstone and calcareous rock from the levels 5–6. 2. Arrow heads: a, b, c: bifacial points from levels 6–10d, e: trihedral points from levels 8 and 9 (pressure retouches, around 5100–5200 yr BC). 3. A large scraper. 4. Production of bladelets from a great variety of flint material, with a soft striking debitage (some of them are probably imported in the form of finished products). 5. Presentation of drill points on various flint materials from levels 5–6 [Colour figure can be viewed at wileyonlinelibrary.com]

6 | TYPO-TECHNOLOGICAL STUDIES

The 16 current levels studied (from 5 to 20) from the 3 m^2 S1 excavation of the Ruways shell midden have already delivered 2728 lithic objects (excepted sketches). These include knapped flint pieces, shaped or crushed sandstone or limestone pebbles, and net sinkers; the whole being associated with numerous beads, faunal remains (including several polished bone objects), and a large mass of marine shells, including some used as scrapers.

Throughout the sequence, the Ruways 1 site is characterised by intense craftworking activity, as we were able to identify the presence of a workshop for the manufacture of drills and net sinkers, and most probably a workshop for the processing of beads (which are quite common along the coast of the

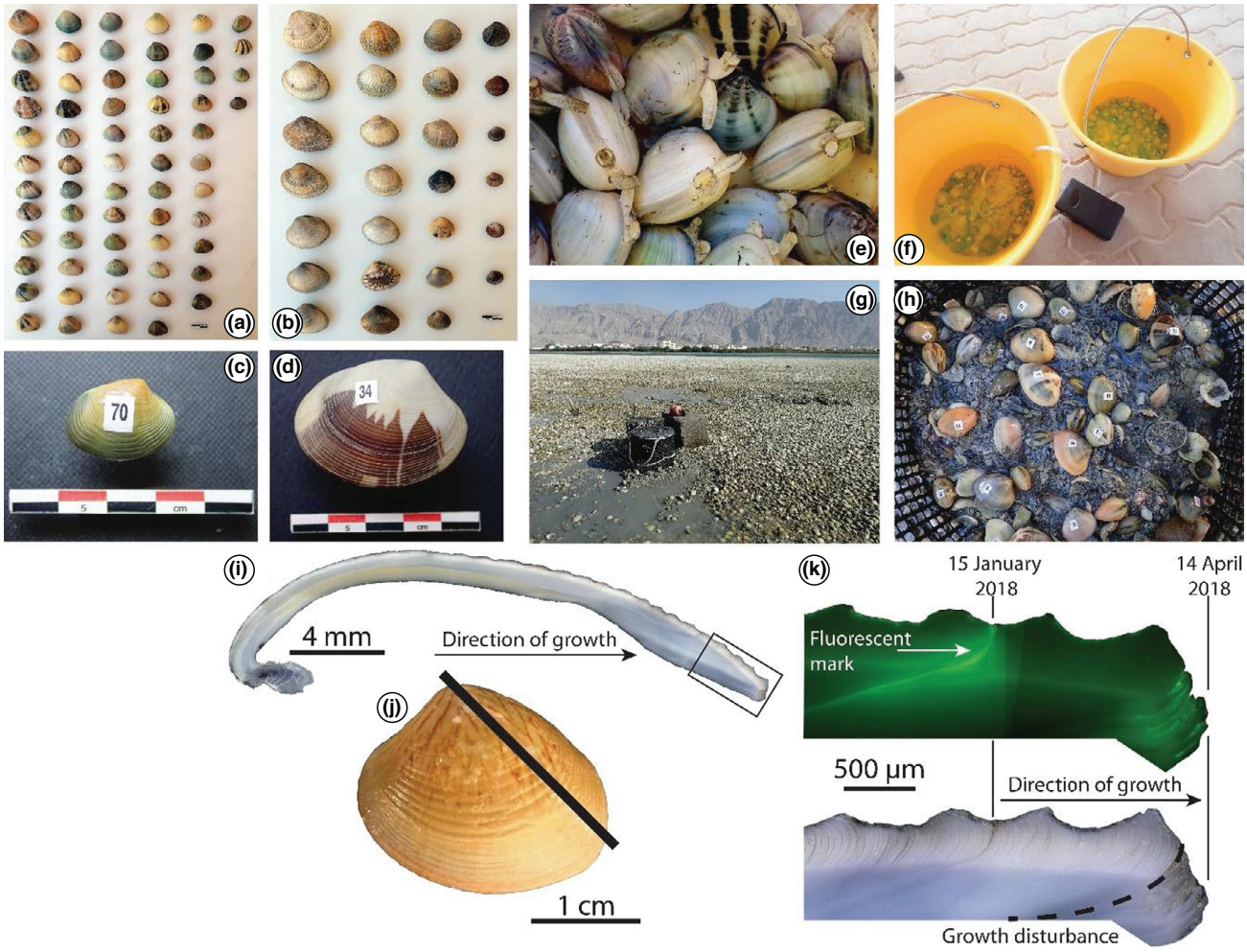


FIGURE 6 Different steps of the marking experiment (a–h) and observation of the growth increment and chemical marking from the thin section of a shell of Marcia recens (#M.68 from the non-broken cage) marked on 15 January 2018, and taken out of seawater on 14 April 2018 (i–k). (a and b) Size, colour and form diversity among Marcia recens and Circenita callypiga species. (c and d) Each of the caught bivalves were tagged, sized and weighed. (e) Bivalves were kept alive in seawater with a compressor system for aeration. (f) Marking was performed in oxygenated seawater with the chemical tag (Calcein) being mixed in and the specimens being exposed to it over 4 h. They were finally rinsed in clear seawater and then kept in oxygenated seawater for an additional 8 h. (g and h) The marked specimens were taken back to their original place of growth and split into two cages where they grew for 89 days. (i Thin section of a shell demonstrating its birth (umbo, left side) to its death (pallial margin, right side). (j) Left valve of #M.68. The black line shows the cutting line as well as the piece of shell used to make the thin section. (k Detail of the end of the growth of specimen #M.68 (pallial margin) under fluorescent light (upper right panel) and reflected light (lower right panel). The black dotted line shows the beginning of the disturbed growth period [Colour figure can be viewed at wileyonlinelibrary.com]

Arabian Sea) (Brunet, 2015). The site also presents records of many domestic activities related to fishing, hunting and most likely gathering (the presence of a circular cup anvil). Several fireplaces have been identified during the excavations, and these attest to culinary activities. At the same time, the den sity of shaped flint suggests that it was knapped on site, and the fragmentation rate from production, particularly of blades, leads us to consider a high utilisation rate (Fig. 5).

In addition, analysis of the raw materials and economic strategies of the Ruways trimmers' workings revealed the presence of the production of different blanks, particularly in early phases around 5200 yr BC. Moreover, although the great majority of the production remained rudimentary (chips, bladelet chips, small irregular blades), some isolated blades attest to a high degree of expertise and are in sharp contrast with the rest of the shaping industry (Fig. 5). These latter items could testify to importations from specialist workshops at the micro-regional scale.

7 | SCLEROCHRONOLOGICAL STUDY OF BIVALVE SHELLS AND SEASONALITY OF OCCUPATION

Among the zooarchaeological remains found at RWY-1, mol - luscs are a well-represented taxon in terms of biodiversity,

as well as in quantity, forming the so-called "shell middens". Among the bivalve taxa, the Veneridae dominate, with *Marcia recens*, *Callista umbonella* and *Circenita callipyga*. These three species could have been gathered from the intertidal zone at the edge of the mangrove environment. Similar to dendrochronology, sclerochronology is the study of the testaceous part of biological organisms, such as the shells of molluscs. Growth line patterns and the chemical composition of these shells can provide information on the biology of the species, as well as on the environment in which they grew (Buddemeier, 1978; Gosselin, Lazareth, & Ortlieb, 2013; Jones, 1983; Schöne, 2008; Wanamaker et al., 2011). In an archaeological context, periods of human residence in coastal settlements can be deduced via determination of the season of the mollusc catch and paleo-climatic parameters, such as inferred sea surface temperatures (Andrus, 2011). For this purpose, a preliminary calibration study on living specimens was implemented during the winter of 2017–2018 to characterise the growth patterns (e.g. rhythm and variation of growth) of the three bivalve species (Fig. 6: a–h).

The first results of the marking experiments in Oman and UAE provide insights into the respective time frameworks of the three species. *M. recens*, *C. umbonella* and *C. callipyga* show a common tidal growth rhythm. After a period of about one month, *M. recens* and *C. callipyga* were disturbed in their growth by an environmental event that may have been related to a punctual winter flood (Fig. 6: i–k). Further research on bivalve shells will provide knowledge on the seasonality of occupation sites and paleo-environments, which will be cross-referenced with the other information gathered during this interdisciplinary study.

A regular pattern of Neolithic transhumance between the inland regions and the west coast of what is now the United Arab Emirates has not been proved by analyses of $^{87}Sr/^{86}Sr$ ratios of Neolithic skeletons (Kutterer & Uerpmann, 2017). The pattern of animal exploitation at UAQ2 (Mashkour et al., 2016) also documents a year-round residency on the coast. Mobility to the interior seems to be more associated with herder or hunter pathways than with the general population. For the fourth millennium Ja'alan communities, a micro-regional seasonal nomadism model is proposed, comparing the different scales of movement with both the territory and resources (Cavulli & Scaruffi, 2013). The cross-discipline approach used for the RWY-1 data (fauna, sclerochronology, pollen, geoarchaeology) should provide answers to these essential questions, allowing an understanding of the status of sites and Neolithic strategies within the East Arabic region.

8 | MIDDLE NEOLITHIC HUMAN REMAINS AND BURIALS AT RWY-1

During the last survey and excavation season at RWY-1, several human remains were brought to light, most of which were related to burials partially or totally damaged by the quarry extraction works carried out in the shell midden during recent years. In total, three graves, including three adult individuals and one child aged 4 ± 1 years, were recognisable from human bones cut by the north-western and south-eastern sections in the quarry. A few other scattered human remains were also found in the quarry debris, but these could not be linked to graves in the section. These finds are of considerable interest, because their stratigraphic position shows that they belong to the middle Neolithic period, during the second half of the sixth millennium yr BC, for which no other human remains or burial evidence has yet been recovered in Oman. Findings of the most ancient human remains have so far come from the UAE at Faya 10 (Kutterer, 2012), Marawah 11 (Beech et al., 2008) and in the large Neolithic cemetery at Jebel Buhais (de Beauclair, 2008; Uerpmann, Uerpmann, & Jasim, 2006), with contexts dating from the seventh to fifth millennium yr BC. Although the graves documented at RWY-1 share common characteristics with those known from later sites (pit graves, accompanied by ornaments and faunal remains; see Bortolini & Munoz, 2015; Marcucci et al., 2014; Salvatori, 2007), some are unique in the position of the individuals. Indeed, in two graves the subjects were placed in a lying position on their backs, which is totally unparalleled in the region. The ongoing anthropological study should provide valuable information on dietary practices and the health status of individuals.

9 | ABSOLUTE CHRONOLOGY AND RESERVOIR EFFECT STUDY

Sequential analysis has concentrated on the central part of the shell midden, which is highly anthropogenic and about 30 m long (Fig. 2a). Ruways 1 is already an exceptional site according to the absolute chronological data, as the first Neolithic occupation is very old (late centuries of the seventh millennium yr BC), being confirmed in three parts of the site by two distinct radiocarbon dates on the same level in the log2 sequence (6378–6069 on shellfish with a small average delta R value still temporary in RWY-1 (28,625 ± 58 years) and 6424–6250 on charcoal), and by three OSL dates immediately posterior to this oldest occupation (6323 ± 485 yr BC to 5725 ± 583 yr BC, Richard et al., submitted). The site is more than 6–7 centuries older than the other oldest dates obtained regionally (SWY-1, SWY-11 and SWY-20) (Charpentier, 2008), and five centuries older than the known chronology of Ras dah SM-10 (Masirah Island) (Charpentier et al., 2012).

The second goal in RWY-1 is to develop a specific study on the reservoir effect of the stratified shell accumulations

dated by the radiocarbon method (with the radiocarbon laboratory of the University of Lyon and the Artemis National Planning), combining on the same levels the dating of samples of lagoon and marine shells and terrestrial charcoals. The complementarity of the OSL method was tested in the sandiest parts of the archaeological sequence, where no charcoal was preserved because of an unfavourable environment (Richard et al., submitted). In order to complete the chronology of the site, sediments (n = 12) were sampled in phases I, II, VII, VIII and IX. Ten of these samples were dated using OSL applied to quartz grains; for the two remaining samples, the quartz signal reached or was close to saturation, therefore feldspar grains were dated using their infrared stimulated luminescence signal. The age obtained at the base of the sequence (phase I) indicates a deposition time during the Middle Pleistocene, before 437 ka. For the later phases, luminescence ages indicate that the site was occupied from 6323 ± 485 yr BC (phase II) to 3225 ± 275 yr BC (phase VIII) (Richard et al., submitted). OSL ages obtained for phase IX range from 1389 ± 186 yr BC to the modern period (1764 ± 15 to 1917 ± 9 AD), suggesting that the sediment from the top of the sequence was recently reworked by wind activity in this area.

For a given region, the difference between the local marine ^{14}C age and the global model marine ^{14}C age is given by ΔR, whose estimation is necessary to calibrate the ^{14}C ages of marine samples. This offset in the local marine ^{14}C ages from the global modelled mean can be determined from the ^{14}C dating of terrestrial material (charcoal, seeds) and marine shell pairs collected from the same stratigraphic horizon. For the moment, our study is based on 12 dates using combined values from the ubiquitous shells of *Marcia recens* and charcoal, and 12 dates using the more marine shell *Lunella coronata*, which are being analysed at the radiocarbon laboratory of Lyon. Preliminary results with low values of ΔR (50–150 years) strongly oscillate between the seventh and sixth millennia yr BC; these are very different from previous estimations proposed for the mid-Holocene period (240–720 years) (Staubwasser et al., 2002; Uerpmann, 1991), but closer to the robust calculations made in an archaeological context for the mid-sixth and the mid-fifth millennium cal yr BC at Ra's al-Hamra 6 where ΔR values range from 99 ± 27 to 207 ± 43 ^{14}C yr (Zazzo et al., 2016), for the forth millennium at Ra's al-Hamra 5 (ΔR= 255 ± 55 ^{14}C yr; Zazzo et al., 2012; 2014) or for the third millennium yr BC (Early Bronze Age) : 210 ± 15 years (Saliège, Lézine, & Cleuziou, 2005). The forthcoming results should make it possible to decide on dates for almost the entire Neolithic period.

10 | IN-SITE CLIMATE AND ENVIRONMENT SIGNALS

The Ja'alan coast is today associated with an arid tropical desert with sudanian to sub-sudanian vegetation. However, pollen (Lézine et al., 2002, 2017) and geoarchaeological studies suggest that the mid-Holocene conditions were different (Berger et al., 2013). Conditions along the eastern Arabian coast have changed, with past latitudinal monsoon circulation changes through time (Fleitmann et al., 2007; Parker & Goudie, 2008). Local variation in climatic change is still too rarely attested to archaeological sites or continental river archives close to sites occupied by the first Neolithic communities of the eastern Mediterranean (Berger & Guilaine, 2009; Berger et al., 2016; Lespez et al., 2016; Zielhoffer et al., 2012). The inferences for climatic impacts are most often indirect, being derived from glacial, marine or continental archives like speleothems (Cremaschi et al., 2015; Cullen et al., 2000; Fleitmann et al., 2007; Staubwasser et al., 2003). One of the purposes of the RWY-1 excavation was to identify climatic signals recorded in different forms in the sedimentary sequence (by sedimentological, geochemical, palynological, and anthracological techniques).

The fine analysis of anthropogenic and environmental records in the stratigraphies of the shell middens are associated with coherent sedimentological and geochemical signals recovered by studies of sequential sedimentations. Eight sequences have been selected from the east to west part of the site along the artificial stratigraphies, to document all the sedimentary processes with the most precision. We have chosen to discuss two of them (log 1ab and log 2), to demonstrate their promising potential (Fig. 2a and Fig. 7). Coincidental high bromine/titanium ratios (an indicator of organic matter), high magnetic susceptibility values (an indicator of fire and fireplaces with production of maghemite oxide), total organic matter (loss-on-ignition), and sulphur, characterise the anthropogenic deposits. These show strong correlations with potassium/titanium ratios, which probably represent local increases in soil weathering (more atmospheric humidity favourable to anthropogenic deposits in periods of low wind input). Aeolian accumulations by wind activity (in yellow hatching) appear in inverse correlation with anthropogenic indicators (Fig. 7). They are associated with a high rubidium/titanium ratio, and high D50 (median) and D99 (superior unipercentile) grain size indicator values, which infer an increase in sediment size and wind energy, and together with high values of calcium carbonates indicate carbonates as the main source of the aeolian dust. Two main arid phases are recorded, the first between 6200 and 5300–5200 yr BC, and the second between 5000–4900 and 4200 yr BC. The main anthropogenic production is centred on the period 5300–5200 to 5000 yr BC. This diagram also shows the sedimentary contraction of the fifth millennium yr BC in this part of the site, which is better documented in other parts of the site.

Intra-site palynological analysis is used on the same sequences to determine the evolution of the vegetal landscape, the climatic conditions, and in-site anthropogenic activities. In this case, this study is particularly interesting

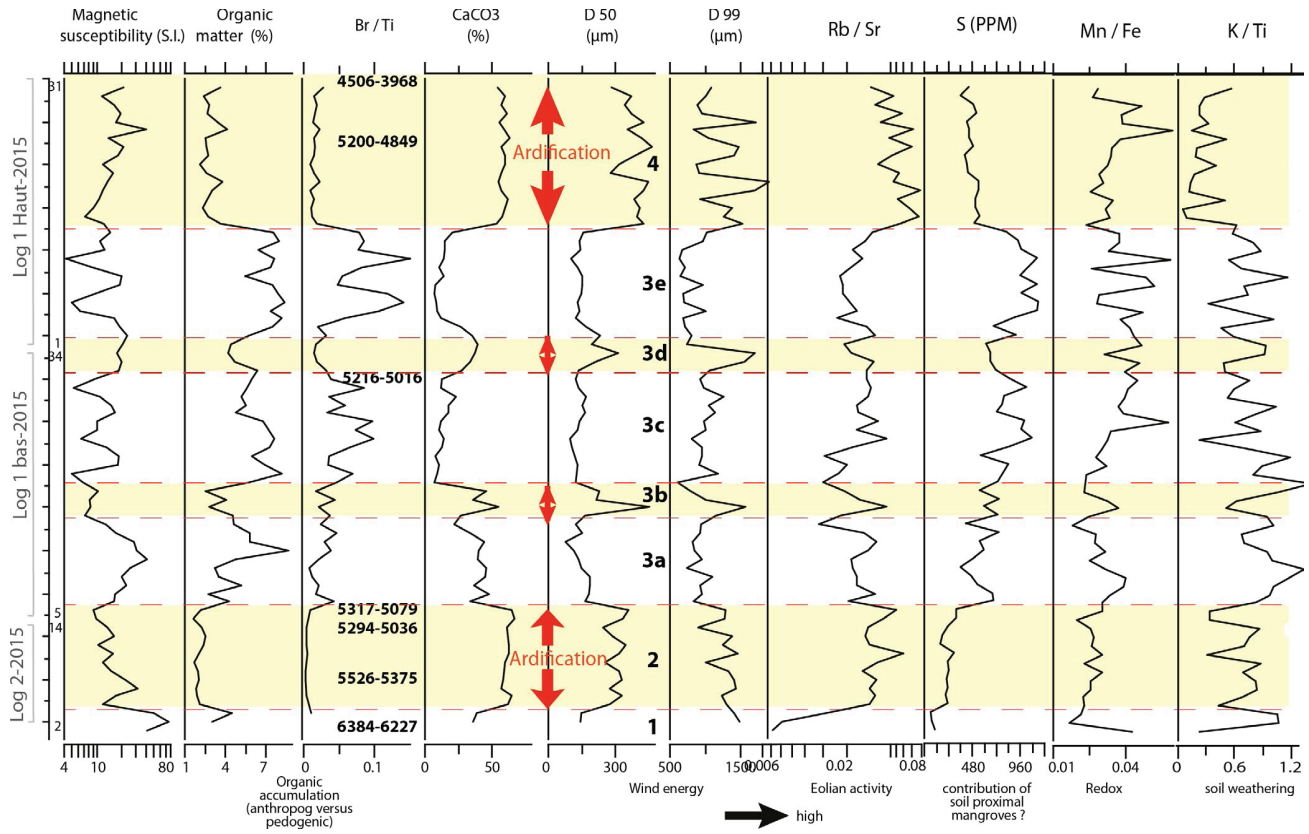
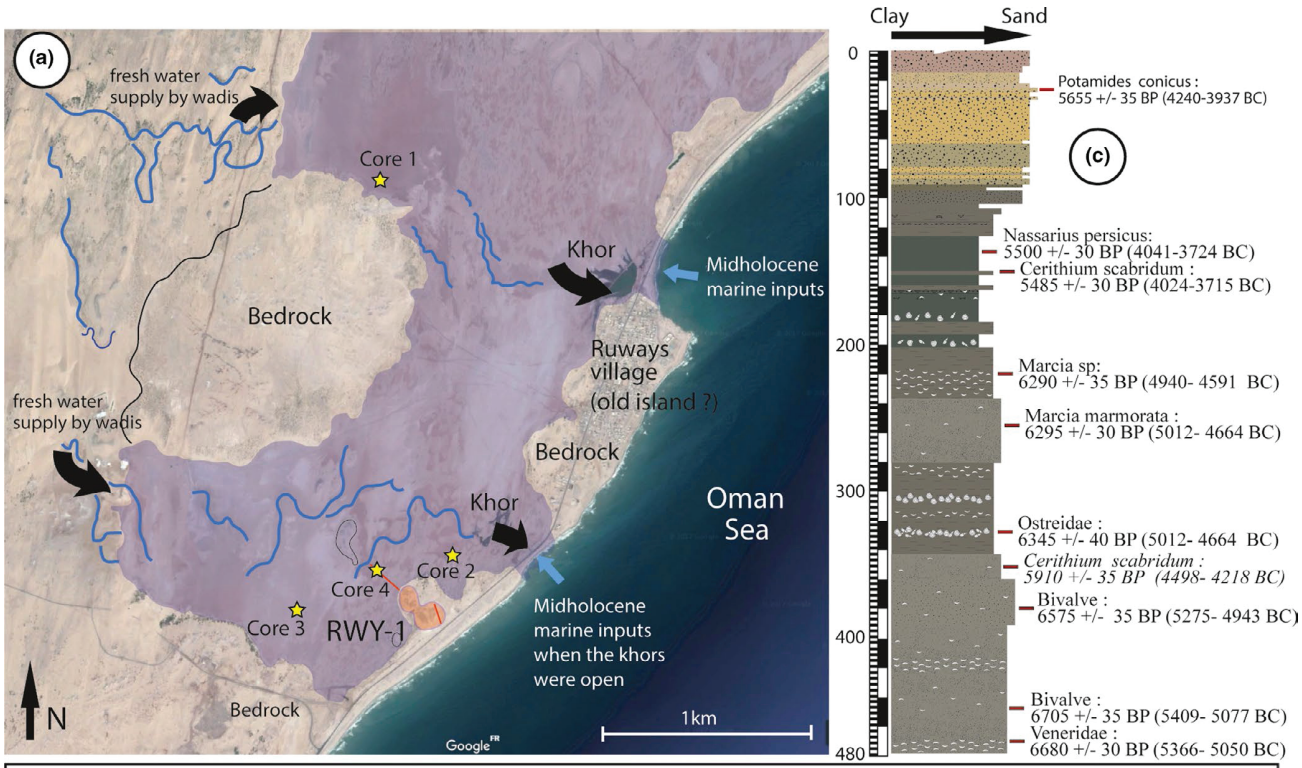


FIGURE 7 Sedimentological and geochemical diagram of log 1a/b and 2 (western RWY-1 stratigraphic section). Dates are in cal. yr BC [Colour figure can be viewed at wileyonlinelibrary.com]

because of the great scarcity of palynological analysis in the region in relation to global changes, coastal ecosystems (lagoons, mangroves), fluctuations in marine upwelling and population concentrations (Lézine et al., 2002). The first results from Ruways 1 (log 1ab and 2) show different taxa from 5500 yr BC, which can be grouped into five ecological groups. One includes the two mangrove taxa (Avicennia and Rhizophora), another the wetland taxa including Cyperaceae,Typha and Tamarix, that is, plants related to a high water table and little salinity in the water. There are a whole series of local and semi-desert taxa (Acacia, Aizoaceae, Artemisia, Asteraceae, Calligonum, Chenopodiaceae, Combretaceae, Ephedra, Poaceae, Prosopis, Tribulus and Ziziphus), although Chenopodiaceae may also be related to high concentrations of salt on the surface. There is also a group of regional taxa from the Omani mountains located in the north-east of Ja'alan (Dodonaea, Olea europaea type, Podocarpus, Juniperus type, Myrica and Ericaceae), and finally there are the non-pollen palynomorphs of a coprophile nature (Cercophora, Chaetomium, Sordaria and Sporoemiella), which confirm the presence of faunal pastoral remains. Regarding evolution, the base of the sequence (log 2) represents a time when the mangroves were much more abundant than today, reaching their maximum (both Avicennia and Rhizophora). In log 1a and log 1b, the mangroves are reduced, but they are still important, almost always with high values. In the top of log 1b (fifth millennium yr BC), the mangroves show an abrupt reduction, at the same time as an increase in wetland taxa, Chenopodiaceae, Poaceae and Artemisia, and especially the coprophilous fungi.

11 | LOCAL PALAEOGEOGRAPHY AND ENVIRONMENT RECONSTRUCTION

Palaeogeographic parameters are affected by physical forces such as sea-level changes, climate and tidal amplitude and duration, as well as the quantity of fresh water inflow associated with monsoon systems, which have determined and impacted the location of settlement networks and the economic strategies of the first Arabian Neolithic populations along the eastern Arabian coast (Berger et al., 2013). Mangrove ecosystems represent a natural resource base for silviculture and a large range of economic products, and also provide habitats for rare fauna (fish, shellfish, birds and crustacean species). Geomorphological and environmental studies have shown that during the middle of the fifth millennium yr BC, a maximal marine transgression caused a major phase of


(a)
fresh water supply by wadis
Core 1
Khor
Midholocene marine inputs
Bedrock
Ruways village (old island ?)
fresh water supply by wadis
Bedrock
Khor
Oman Sea
Core 2
Core 4
Core 3
RWY-1
Midholocene marine inputs when the khors were open
N
Bedrock
1km
Google
Clay
Sand
0
100
200
300
400
480
Potamides conicus : 5655 +/- 35 BP (4240-3937 BC)
(c)
Nassarius persicus: 5500 +/- 30 BP (4041-3724 BC)
Cerithium scabridum : 5485 +/- 30 BP (4024-3715 BC)
Marcia sp: 6290 +/- 35 BP (4940- 4591 BC)
Marcia marmorata : 6295 +/- 30 BP (5012- 4664 BC)
Ostreidae : 6345 +/- 40 BP (5012- 4664 BC)
Cerithium scabridum : 5910 +/- 35 BP (4498- 4218 BC)
Bivalve : 6575 +/- 35 BP (5275- 4943 BC)
Bivalve : 6705 +/- 35 BP (5409- 5077 BC)
Veneridae : 6680 +/- 30 BP (5366- 5050 BC)

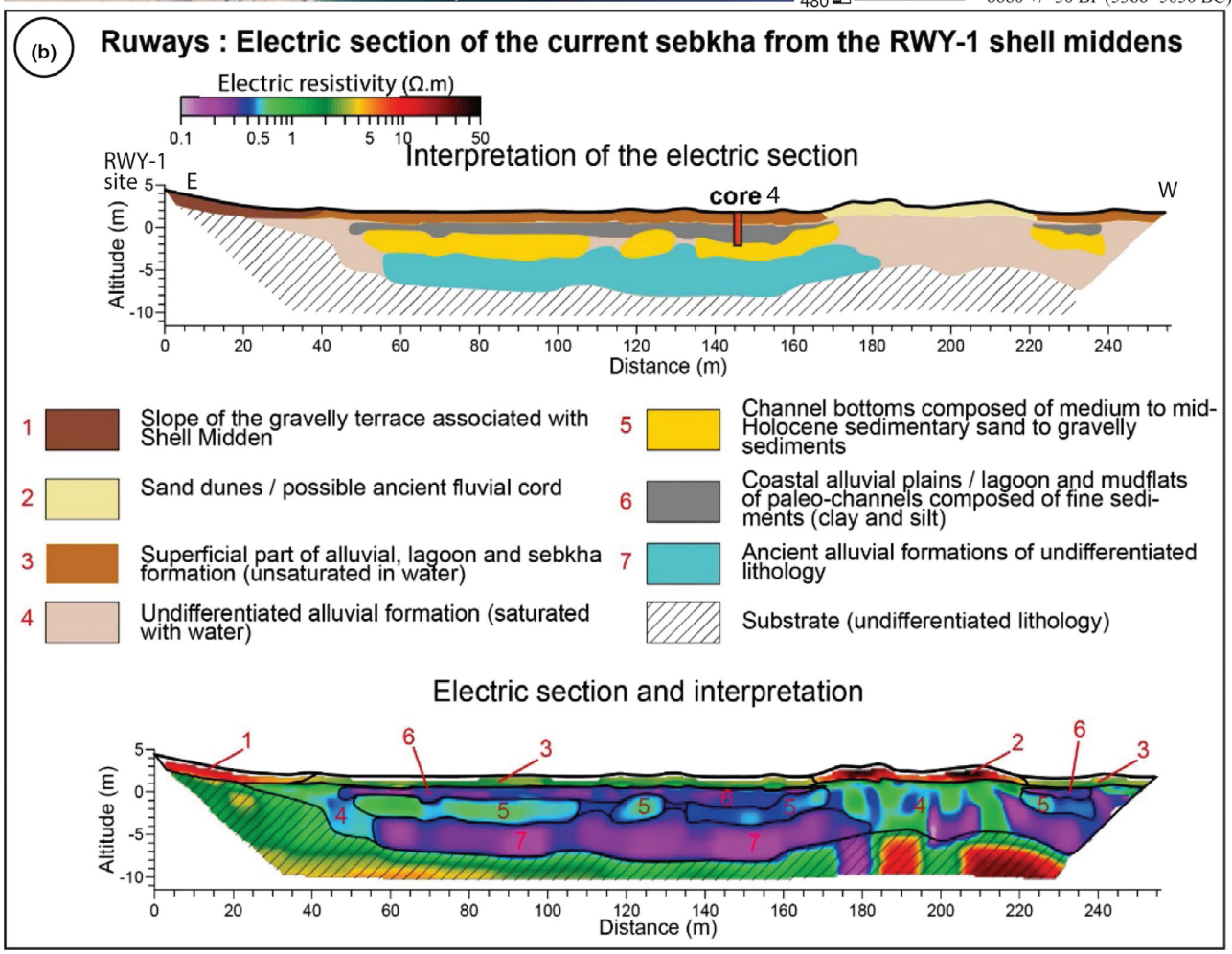

(b)
Ruways : Electric section of the current sebkha from the RWY-1 shell middens
Electric resistivity (Ω.m)
0.1 0.5 1 5 10 50
Interpretation of the electric section
RWY-1 site
E
core 4
W
Altitude (m)
5 0 -5 -10
0 20 40 60 80 100 120 140 160 180 200 220 240
Distance (m)
1 Slope of the gravelly terrace associated with Shell Midden
2 Sand dunes / possible ancient fluvial cord
3 Superficial part of alluvial, lagoon and sebkha formation (unsaturated in water)
4 Undifferentiated alluvial formation (saturated with water)
5 Channel bottoms composed of medium to mid-Holocene sedimentary sand to gravelly sediments
6 Coastal alluvial plains / lagoon and mudflats of paleo-channels composed of fine sediments (clay and silt)
7 Ancient alluvial formations of undifferentiated lithology
Substrate (undifferentiated lithology)
Electric section and interpretation
Altitude (m)
5 0 -5 -10
0 20 40 60 80 100 120 140 160 180 200 220 240
Distance (m)

FIGURE 8 (a) Map of the Ruways micro-region with the proposed Neolithic extension of a wide open lagoon with mangrove ecosystems (in purple) and the two khors situated on each side of the current village of Ruways, with the position of the four geological cores (yellow stars) and the RWY-1 site (orange area). (b) Electrical resistivity tomography section of the current sabkha located in the western part of the RWY-1 site, with the main superficial sedimentary formations and the location of core 4. (c) Lithological sequence of core 4 with the radiocarbon dating series on shells in BP and in cal. yr BC age [Colour figure can be viewed at wileyonlinelibrary.com]

lagoon expansion and the optimum conditions for mangrove forests, which are occupied today mainly by sabkhas (Berger et al., 2013; Glover, 1998; Sanlaville & Dalongeville, 2005). To correlate the evolution of the occupation strategies of the RWY-1 site with the local palaeogeographic, eustatic and climato-environmental records resulting from the sedimentary lagoon, the mangrove and sabkha archives, and the regional data resulting from the archives of the Indian Ocean (marine cores), a systematic off-site geoarchaeological and geophysical survey was made in 2017 and 2018 across the large current sabkha located in the western part of the site (Fig. 8a). This sabkha of more than 10 km^2 shows two closed and infilled khors, located on either side of the current village of Ruways, towards which converge the non-perennial and meandriform beds of the two main wadis (Fig. 8a). They were most probably widely open to the Arabian Sea during the middle Holocene, and connected with large lagoons and wadis. We performed electrical resistivity tomography (ERT) across the sabkhas to determine the sedimentary structures and locate the best area for coring operations (Fig. 8b), obtained topographical transects by dGPS to position the ERT profile, the cores, and the current structure of the local landscape, and finally obtained four thermic mechanical corings from depths of 3–5 m (with a Cobra corer) to obtain a series of the geological archives from the current sabkhas (Fig. 8a). The ERT of the current sabkha has successfully reproduced the geometry of its river-lagoon formations (Fig. 8b). It has distinguished the four main sedimentary units in the upper 10 m filling. A deep, probably late Quaternary, alluvial formation (from −8 to −3 m) is shown in blue, the coarse sandy to gravelly alluvial pre-mid-Holocene formations organised in a succession of paleochannels (around −4 to −1 m) are shown in yellow, the fine fluvial-lagoon silty-sand formations associated with the maximum marine transgression (around − 3 to +1 m) are shown in dark grey, and finally the superficial part of the current sabkha, consisting of red silts and gypsum interbedded with aeolian sands and sometimes dune forming (+1 to +3 m), is shown in brown. The locations of the cores in the deeper part of the fine fluvial-lagoon formation have confirmed the superficial sedimentary structure of the hinterland sabkha and its absolute chronology by radiocarbon dating of shells. One lithological sequence of the C3 core is presented in Fig. 8c. This confirms the contemporaneous development of an open lagoon associated with a mangrove forest between the second half of the sixth and the end of the fifth millennium yr BC (the subject of ongoing sediment and pollen studies).

12 | CONCLUSIONS

The current appearance of the shell midden is the result of a long interaction between natural and anthropogenic processes of aggradation and phases of truncation by wind. Only the destruction of half (8 ha) of the RWY-1 shell midden by quarrying activities and the provision of long continuous sedimentary sequences have allowed us to understand and render this long history.

RWY-1 is a site with a long sequence of occupation (6380–3400 yr BC), with probable occupation at the beginning of the middle Neolithic, which is still unprecedented in Ja'alan in a stratified context (6380–6000 yr BC), but which must be possible to relate to the Neolithic horizons of the wadi Wuttaya dated 6170–5980 yr BC (Uerpmann, 1992), which has close technological similarities with the Pre-Pottery Neolithic B (PPNB) B. They can also be associated with the last Fasad-point industries at sites near Ra's al Jins-37 and Al-Haddah-BJD1 in Ja'alan, which do not have ^{14}C dates (Charpentier, 2008). RWY-1 is also associated with very old Neolithic burials (5300–5200 yr BC) that represent particular funeral rituals under analysis, and presents a great potential to reconstruct the economic strategies of Neolithic coastal populations, which were strongly oriented with the exploitation of lagoons and mangrove ecosystems (A. Marrast, PhD thesis, and a collective study of the MNHN-Paris team). The lithic industry is based on predominant expedients in the 15 upper units, which contrast with the little elaborate expertise (arrowheads). The combined radiocarbon dates of the shellfish and charcoal, currently being finalised, will make it possible to propose a reference for the micro-regional marine reservoir effect between the end of the seventh and fourth millennia yr BC. Finally, a systematic chrono- and lithostratigraphic study allows us to better determine the evolution of the shell middens, from their building to their partial erosion (site formation processes). The multidisciplinary analysis of this site and the neighbouring geological cores will, in the coming months, allow the first socio-environmental model for the Ja'alan Neolithic to be proposed, with this model covering three millennia.

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