

Rocks and shards: geoarchaeology and palaeoenvironments of the Al-Rustaq Manaqi Archaeological Complex in north-central Oman

Jiri Chlachula^{1,2*}, Mohamed Hesein^{3*}, Guillaume Gernez⁴, Khaled Douglas³, Jacek Michniewicz⁵, Nasser Al-Jahwari³

¹ Institute of Geocology and Geoinformation, Adam Mickiewicz University, Krygowskiego 10, 61-680 Poznań, Poland

² Environmental Research Centre, Stare Mesto, Czech Republic;  <https://orcid.org/0000-0002-7887-2496>

³ Department of Archaeology, Sultan Qaboos University, Muscat, Oman;

MH  <https://orcid.org/0000-0002-7407-9087>, KD  <https://orcid.org/0009-0005-2678-192X>,
NA-J  <https://orcid.org/0000-0002-4737-7724>

⁴ Department of Art History and Archaeology, University Paris 1 Panthéon-Sorbonne, France;
 <https://orcid.org/0009-0003-5101-2159>

⁵ Institute of Geology, Adam Mickiewicz University, Krygowskiego 12, 61-680 Poznań, Poland;
 <https://orcid.org/0000-0002-1110-1494>

* corresponding authors, e-mails: paleo@amu.edu.pl, mohamedhesein@squ.edu.om

Abstract

The present study discusses the results of geological and geoarchaeological research at Manaqi in Al-Rustaq, the new Iron Age (1300–300 BC) complex in north-central Oman. The regional relief attests to pronounced geo-environmental dynamics, largely linked to orogeny of the central Jabal Akhdar Range, as well as climate change. The investigated pre-historic site provides evidence of multiple phases of occupation, the earliest being represented by numerous stone tools, documenting a sequenced presence of Palaeolithic people in the vicinity of an ancient fluvial channel. The principal Iron Age site with residential buildings, tombs and other architectural elements (defensive, irrigation, stone-mining) bear witness to a well-organised settlement with distinct areas, suggesting specific functions. The size and layout of households and funerary structures built from local bedrock and alluvial boulders point to social complexity of a semi-sedentary society. The spatial organisation and internal arrangement of the Manaqi Site suggest that its economic significance was likely linked to an ancient trade route along the present Wadi Al-Fara, connecting the Al-Hajar Mountains with the coast of the Sea of Oman. The synthesized field and analytical data provide a geo-contextual background for the regional pre-Islamic settlements within the South Batinah Governorate. The Manaqi locality also represents a most interesting geo-site, illustrating a multi-faceted geological and palaeoenvironmental history of the present rocky desert subjected to active geomorphic modelling with an ancient anthropogenic imprint. Climate was a key factor in controlling the rise of pre-Islamic civilisation in the Oman Sultanate.

Keywords: Hajar Mountains, Quaternary, climate change, desert, wadi, geoarchaeology, prehistory, occupation

1. Introduction

For decades, Oman, located in the south-east Arabian Peninsula, remained one of the least-stud-

ied areas in the Middle East. Geoarchaeology and environmental archaeology, with application of novel field reconnaissance and analytical techniques, are gaining now importance by addressing

geomorphic settings and the palaeoecology of past settlements exposed to specific site-formation processes within arid lands (e.g., Cremaschi et al., 2015; Hilbert et al., 2015; Beuzen-Waller et al., 2019; Parton & Bretzke, 2020; Al Kindi et al., 2021).

The Sultanate has experienced a long and complex cultural history that is from far known. Following scattered Late Neolithic settlements and more advanced regional Bronze Age groups, consolidation of local chieftain powers occurred within the broader study area during the early first millennium BC (Cleuziou & Tosi, 2021). The preceding Wadi Suq Period (2000–1300 BC) is one of the most interesting stages in the country's prehistory (Velde, 2003). Preserved architectural remains (houses, tombs), especially those dating from the Early Bronze Age Umm an-Nar Period (2600–2000 BC), attest to a high social complexity (Yule et al., 1994). The localised Middle and Late Bronze Age milieu (Döpfer, 2021) passed into more complex and autonomous socio-economic entities of the Iron Age (1300–300 BC) at the geographical limits of ancient Near-Eastern civilisations. Monuments studied testify to major cultural progress based on copper metallurgy and a vital, long-distance trade network evidenced by imported items, such as fine pottery and objects of daily use.

The trigger behind the emergence of the Early Iron Age socio-economic entities in the southern Arabian Peninsula has been the subject of debate (Yule, 2020). Both deteriorating climatic conditions and progressive civilisation impulses from ancient Mesopotamia, Iran and the Near East were the key factors that affected human occupation (Parker et al., 2006a). New technologies, such as whirl-ring pottery production and copper smelting (Yule & Kervran, 1993; Barker, 2002; Thornton & Ghazal, 2007) played significant roles. The introduction of run-off farming economy (Purdue et al., 2019, 2021) coped with progressing territorial dryness. A secure food-procurement strategy enabled permanent, urbanised settlements (e.g., Jabal Al Salūt with impressive stone towers; Phillips, 2015), as well as effective management of arid lands.

The culture-historical importance of north-central Oman during the Iron Age period (1300–300 BC) was highlighted by initial studies in the South Batinah Governorate (Al-Jahwari & Kennet, 2015; Kennet et al., 2016; Engel et al., 2024). On the banks of the Wadi Al-Fara, part of the Wadi Al-Ghashab system which provides the main seasonal water supply to the study area, several large archaeological sites – settlements with cemeteries – were documented during initial Rustaq-Batinah surveys in 2010–2015 (Kennet et al., 2016). Following this pilot

archaeological reconnaissance, the Al Rustaq-Manaqi Site is now regarded as one of the key and most representative Early Iron Age monuments within the area (Fig. 1). Other principal prehistoric places include Old Wabil – an extensive fortified Iron Age town partially damaged by modern building works (Douglas et al., 2023) – and Al-Tikha, an Early Bronze Age (3rd millennium BC) settlement along the northern flanks of the Al-Hajar Mountains, with distinct residential areas, monumental towers and tombs (Economou et al., 2022).

The present study discusses the geographical and geomorphic background, and the geo-contexts of the Manaqi Site. The geoarchaeological research approach, integrated into complex investigations, is outlined. The geological history of the locality and the chronology of its sequenced occupation are discussed, along with the past environments preceding and postdating the main Iron Age settlement. The documented stratigraphies of the excavated residential and funerary structures, as well as the spatial arrangement of other architectural elements provide additional information on late prehistoric community lifestyles and beliefs. The mapped site-formation processes allow for reconstructions of Iron Age occupation history and wasteland management, including exploitation of nearby natural resources. General aspects of regional prehistoric sites, such as visibility and preservation, are discussed in conjunction with single archaeological loci within the area.

2. Study area

2.1. Geography, geology and relief

The study area (Wilāyat Al-Rustaq) is located in north-east Oman, ~80 km west of Muscat in the Al Hajar Mountain foothills (Figs 1A–B). Geologically, the sector studied lies between the northern margin of the Jabal Akhdar Range and the southern part of the Semail Ophiolite Formation (Umino, 1995). The Semail Ophiolite consists of an oceanic lithosphere plate (Levell et al., 2021). At Al-Rustaq, the ophiolite is the mantle component of the local geological base, mostly harzburgite, in part serpentinised (Gealey, 1977). Rocks forming the foundation of the present wadis, draining the northern foothills, belong to the Hawasina Formation (mostly shale, schist, chert), representing part of a former deep-sea basin at the Arabian Plate margin during the Cretaceous and early Cenozoic (Csontos et al., 2010). These mostly low-metamorphic sedimentary rocks (cover page)

erode easily and are subject to intensive weathering. The Jabal Akhdar Dome, which constitutes the major regional orographic body and the highest Omani mountain range (maximum elevation 3,018 m a.s.l.) became exposed during the Late Eocene to Oligocene (Scharf et al., 2022). It is formed by deep-sea Upper Palaeozoic and Lower Mesozoic carbonates of the Arabian Platform (Scharf et al., 2021a, b). Stratigraphically, the youngest lithified units forming most of the lower relief belong to the mid-Cretaceous Natih Formation which, in places, is covered by Quaternary alluvial and aeolian beds.

The Oman Mountains experience uplift today as result of the present isostasy of the southern part of

the peninsula. This process is generated by a large-scale erosion of the soft ophiolites, causing a rise of regional lithosphere crust (Cowan et al., 2014; Searle, 2019). The Quaternary uplift may be, in some places, rather pronounced, as seen in massive conglomerate deposits and the progressing incision of the present wadies. Al-Rustaq is not linked to the northern seismic areas of Sur-Quriyat and Musandam. Modern tectonic stress and plate deformation within the region are relatively minor. Some Quaternary neotectonics and thrusting north-west of the Jabal Akhdar Dome have been recorded (Moraetis et al., 2020). The Pleistocene relief in central and east Oman is represented by uplifted river terraces and

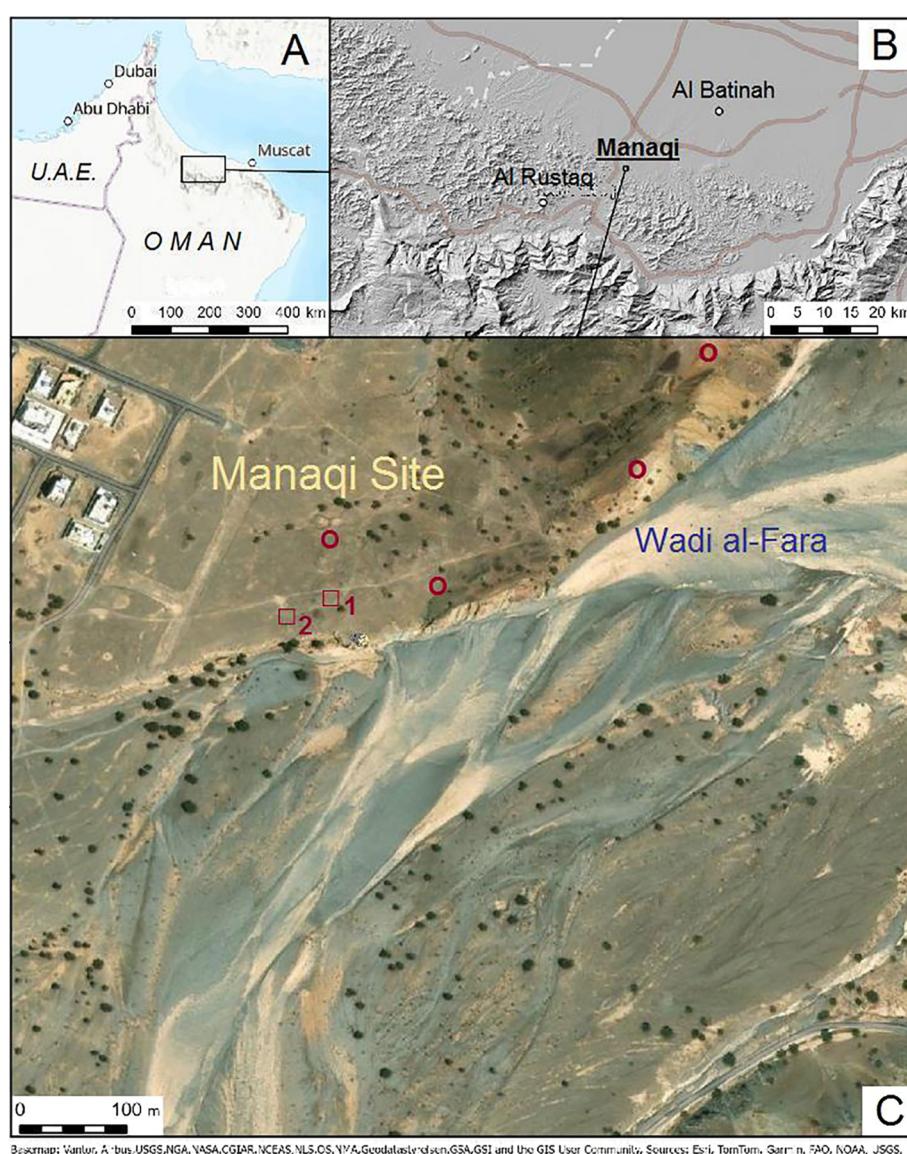


Fig. 1. A - Geographical location of the study area (South Batinah Governorate, north-central Oman); B - A 3D-topographic projection of the central Al-Hajar Mountains and adjoining desert plains of the coast of the Gulf of Oman; the Manaqi archaeological locality positioned at the Jabal Akhdar foothills; C - Satellite view of the Wadi Al-Fara valley and the Manaqi Site with the excavated Iron Age structures (1, 2) and the burial tombs (o).

marine terraces found along the northern coast. Neotectonic movements relate, most likely, to seismicity (Hoffmann et al., 2013). Massive alluvial fans and raised Pliocene-Pleistocene palaeo-channel systems found along the western foothills (Maizels, 1987) testify to major past accumulation and erosional processes. These geo-forms are quite extensive to the north of the Al-Hajar Mountains. There, series of marine terrace elevations (5–400 m a.s.l.) point to continuous uplift of the Oman Mountains with rates between 0.9 and 6.7 mm *per annum* (Moraetis et al., 2018). Largely arid conditions with shorter humid episodes of the eastern monsoons prevailed during the Quaternary in Oman.

2.2. Cultural history

Recent geoarchaeological investigations at the Manaqi locality have provided evidence of a very early occupation in the form of a series of Middle and Late Palaeolithic industries using local bedrock lithologies found on present-day desert surfaces (Chlachula, 2025). Early and mid-Holocene settlements in the area are represented by several Neolithic open-air sites (Parton & Bretzke, 2020; N. Mazzucco et al., unpublished data). A chronologically more recent and well-defined cultural monument, the Al-Tikha Site in the Wilāyat Al-Rustaq area near the confluence of Wadi Al-Ghashab with Wadi Al-Sahtan, has revealed a sophisticated Early Bronze Age settlement with impressive buildings, towers and tombs, dated >4,500 years before present (Economou et al., 2022; K. Douglas et al., unpublished data). The regional archaeological record became more manifest during the following centuries and millennia. The political, economic and cultural consolidation dates to the early mediaeval period when the early Islamic town Rustaq, the former capital city of the Oman Sultanate, was established, following annexation by the Sasanian Empire in the 5th century AD.

The archaeological site of Manaqi represents a large Iron Age (1300–300 BC) village with a nearby necropolis. These two central places are part of the so-called Manaqi Complex (Kennet et al., 2016), which incorporates two other prehistoric settlements along with a hill-top sacral place at Al-‘Uqayriyyaha (Kennet, 2016). Manaqi has produced rich archaeological material. Pottery shards and ritual terracotta figurines are particularly common; they reflect the importance and a specific social-economic meaning of the place. The site was likely divided into several sectors, each fulfilling specific functions, with remains of stone dwellings and tombs visible at the surface. While the villages of the Man-

aqi Complex took advantage of the local wadis to practice the aflāj-irrigated agriculture, an agricultural water-management system inaugurated in this period (Del Cerro, 2015), the principal role of Manaqi was probably military/administrative related to copper trade and control of a strategic road linking the southern mountains to the northern coast. The site was reused as a large necropolis during the Late Iron Age (300 BC–300 AD) with a funerary complex devoted to infant burials. A few Islamic tombs are scattered in the north-western part of the present Manaqi village residential area.

The Iron Age Manaqi Site is characterised by a topographically prominent setting above the present Wadi Al-Fara (Fig. 1C). The prehistoric monument integrates residential, as well as sacral, architectural remains, represented by rectangular dwelling structures and burial mounds/tombs, respectively. The archaeologically significant area focused on in field research occupies ~20,000 m² (100x200 m space). Geoarchaeological investigations were carried out in December 2023, January 2025 and February 2026. Excavations of two central Iron Age households and other structural elements were carried out in January 2024 and 2025.

3. Material and methods

Geo-science investigations at the locality were aimed at geomorphology, contextual geology, geoarchaeology and palaeoenvironmental proxies retrieved from the stratigraphical and superficial background of this multi-sequenced prehistoric site, complementing the archaeological records alone. The fieldwork included a spatial (cartographic) and remote sensing mapping of the uncovered cultural features and characteristics of their structural geology, sedimentology, petrography, pedology and geoarchaeology. The complex analytical studies were aimed at documenting the locality’s geological history and at reconstructing past occupation habitats. The time-diagnostic cultural inventories, primarily ceramics and lithic artifacts, provided a chronological framework for the prehistoric settlements. Palynomorphs and charcoal represent the only palaeoenvironmental proxies retrieved from the stratigraphical units of burial mounds and residential structures (mortar), and water-management ponds. Preservation of pollen spectra analysed (Institute of Earth Sciences, Sankt Petersburg State University) is poor overall as a result of adverse geo-contextual conditions.

Geoarchaeology of the locality followed standard approaches and techniques of recording, sam-

pling and analysing archaeologically relevant stratigraphical units, features and their geological contexts. The principal sections of coarse alluvia exposed by present wadi erosion, cutting the eastern site margin (Fig. 2C), were subjected to a close examination (sedimentary clastic and stratigraphical facies analyses, grain-size, mineralogy, lithology and geochemistry of sealing matrix) at the Institutes of Geoecology and Geology, Adam Mickiewicz University, Poznań. Sedimentology was assessed by the Malvern Mastersizer 2000. Studies of buried and exposed soils evaluated the nature of pedogenic processes, diagnostic of environmental conditions at the time of prehistoric site occupancy (The Canadian System of Soil Classification, 1987). Radiocarbon dating of organic materials from the uncovered burials (2025) is in progress.

The petrographic study of ten Iron Age ceramic samples was conducted at the Department of Geology, Adam Mickiewicz University, Poznań. The analyses were carried out using an Olympus AX70-Provis polarising microscope and a Hitachi SN3700 scanning electron microscope (SEM), coupled with a NoranSix energy-dispersive spectrometer (EDS).

This study aimed to identify vessel-forming techniques and to characterise the mineralogical and chemical composition of pottery in order to distinguish between local and non-local raw materials, with reference to comparative data from early Omani pottery (Baker, 2002; Bernardini et al., 2020).

Geodetic relief analysis documented the topography and spatial extent of the Manaqi settlement, its internal organisation and the arrangement of single architectural elements. Remote sensing images delivered close aerial views of the locality and the adjoining Wadi Al-Fara. High-resolution Google Earth satellite photographs, and the Spot 5 and Ikonos multi-spectral data (2.5 m resolution) were used, while published works provided a reference to other key Iron Age localities in north-central Oman.

4. Manaqi site

4.1. Geography and geomorphology

The Manaqi site (23°29'45.1"N; 57°28'28.9"E) is located at the north-eastern margin of the village of Manaqi, ~12 km north-east of the city of Al-Rustaq and ~50 km south of the Oman Gulf coast (Fig. 1B). Situated on the west (left) bank of the Wadi Al-Fara, at an altitude of 240–245 m a.s.l., the prehistoric locality is geomorphologically defined by a partly gullied erosional platform (200 × 500 m) (Fig. 1C).

The present inner wadi, 150–200 m wide, bordering the site, transgresses into a broader, 500–800 m wadi, opening towards the north into a seasonally flooded plain (Fig. 2B). The Wadi Al-Fara valley is delimited on both sides by the northern flanks of the Al-Hajar Mountains (maximum elevation within the closer area is 2,900 m a.s.l.) (Fig. 2A).

The relief setting of the central prehistoric settlement is shaped by an alluvial terrace 10–15 m above the perennial river channel. The site is positioned on a prominent rocky rampart – the Palaeozoic (Permian) to Mesozoic (Triassic) Hawasina sedimentary sequence, forming a geological base to the overlying Pleistocene alluvia and the ancient wadi floor (Figs 2B–C). The present multi-channel wadi accommodates a high volume of seasonal waters. Apart from the household sector, a sacral complex created by a group of large burial mounds (Figs 1C, 4A) is found on the flat top of a nearby hill (260 m a.s.l.), ~20 m above the main Iron Age habitation area. Barren, rocky hills (300–500 m high) of the northern foothills of the Jabal Akhdar Range, formed by extrusive geological bodies, border the present wadi (Fig. 2A). Sparse xerophytic vegetation characterises the present-day surroundings of Manaqi.

4.2. Geology

The barren rocky desert within the Manaqi Site environs is structured principally by lithified sedimentary bodies – chert, schist and shale (Figs 3A–B), which are blanketed by cemented coarse gravelly alluvia and coarse sands (Figs 3C–D). In the eastern part of the site Hawasina chert units are succeeded by finely laminated, turbiditic sandstones (Matabat Formation) formed in a Mesozoic (Lower Jurassic) deep-sea basin (Csontos et al., 2010). The bedrock surface is covered by a 0.2–0.5-m-thick and archaeologically significant pavement of coarse clastic deposits of a former river/alluvial fan setting (Fig. 3E) that drained the exposed, channelised palaeo-surface laterally, well beyond the limits of the present Wadi Al-Fara. Relics of ancient alluvial accumulations reach the highest terrace-like elevations up to 150 m above the modern river beds, suggesting an Early Pleistocene or pre-Quaternary (Pliocene?) age (Map Sheet 1:100000, Al-Rustaq, 2020).

Sub-angular to well-rounded pebble- to cobble-sized clastics are distributed over the main occupation space and form the raised platform (the main settlement surface) (Figs 2C, 3E), suggesting various geological sources and transport mechanisms. A series of channel rills creates shallow elongated depressions cutting the site and wadi margin.

Sedimentologically mature fluvial gravels of diverse origin and lithologies were eroded from the upper reaches of the valley, progressing from the igneous and metamorphic sole of the Al Hajar Mountains. Oolitic limestone boulders (Jurassic Guwayza Formation) are found close to the river side, pointing to past high-energy flows. Quartz varieties are the best-represented component of the deposits, along with quartzite and hard sandstone, mixed with fragments of gneiss and schist. Soft rocks such as limestone and shale occasionally occur.

The principal geological face of the Manaqi Site consists of thrust Hawasina rocks inclined 45–60°

to the present wadi base (Fig. 2B). The multicolored, stratified plastic deformations of the alternately bedded (1–10 cm thick layers) chert and shale facies of the folded, low-metamorphosed geological body, exhumed by fluvial erosion, are impressive (Fig. 3B). A lithified bed of laminated sand (medium-grained sandstone) forms the base of the partly cemented Pleistocene alluvium, overlying the Hawasina bedrock (Fig. 3D).

A suite of Quaternary stratigraphical units were mapped in the lateral wadi cutting (Fig. 2C). The basal part is structured by massive channelised alluvia, including up to 0.5-m large stones, inter-



Fig. 2. A - View of the Manaqi locality and Wadi Al-Fara, seasonally draining waters from the Jabal Akhdar Range; B - Upper Palaeozoic (Permian) – Mesozoic (Triassic) bedrock exposure (Hawasina chert) along the margin of Wadi Al-Fara; C - Erosional cutting along the wadi with exposure of the Pliocene-Quaternary alluvia (field photographs by J. Chlachula).

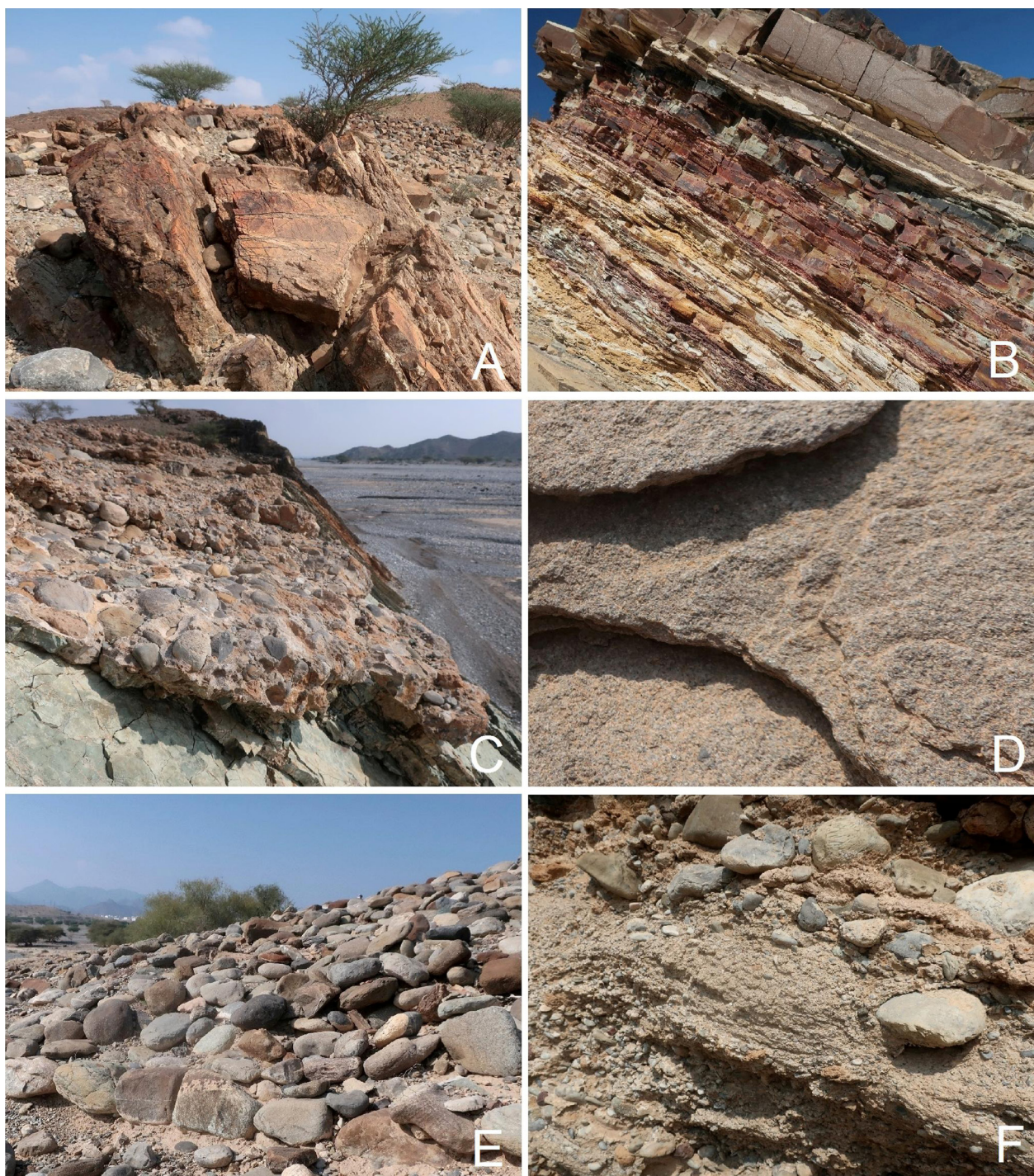


Fig. 3. **A** - Loose blocks of near-vertically exposed, folded low-metamorphic bodies, forming the geological base of the site; **B** - Hawasina chert used as raw material for the prehistoric (Palaeolithic to Neolithic) tool making; **C** - Cemented gravel pavement overlying bedrock; **D** - Coarse-grain sandstone at the base of the Quaternary sedimentary formation defining a major stratigraphical and time disconformity (~200 Ma) in the geological record at Manaqi; **E** - Unconsolidated imbricated cobble-boulder gravels of a former channel, positioned 10 m above the present wadi; the stones were used for Iron Age constructions (buildings, tombs). Anthropogenic placement of the linearly arranged boulders seen at the base provided a fixing ground support; **F** - Late Quaternary fluvial/alluvial fan gravity flow facies forming the top surface of the site.

bedded by smaller-sized, imbricated pebble-cobble beds cemented within a calcareous sandy matrix. The upward-fining, sedimentary sequence relates to a former, laterally shifting, riverine (wadi) stream of high capacity, with bulk accumulations along its main channels. The middle part of the section comprises laminated, undulating mudflow strata (0.8–1.2 m thick) covered by coarse to massive, boulder-size deposits (0.7–1.0 m thick). The infilling pockets of finer gravels point to periodic hydro-dynamics and changing sedimentary conditions along the former channel (now 227–230 m a.s.l.). The upper part of the section includes lithologically uniform, 5–10° inclined, small pebble-sized gravels (0.3–0.5 m thick), interstratified with coarse sands following the natural relief gradient (Fig. 3F). This fine clastic deposit of a fluvial (wadi) origin (a subsidiary alluvial facies) constitutes the top part of the geologically youngest, presumably upper Quaternary, units. Deformed massive sedimentary structures with chaotically arranged cobbles seen in the main stratigraphical exposure along the wadi margin indicate high-energy mudflows or cataclysmic floods. Relics of a brownish fossil soil with a ferric silty sand pedogenic horizon, sealing the stratigraphical section, point to stabilisation in the past of a dried-up surface exposed to weathering.

Geochemistry of the culturally significant units and associated geoarchaeological strata significantly varies depending on the lithology and grain-size of the deposit fill of the constructions and burials, and the ground's sedimentary matrix. Both fossil and present-day locality surface is rather calcareous (7–48%), with a diverse organic matter context (3–10%).

4.3. Geoarchaeology

Geoarchaeology of the Manaqi locality provides evidence of a periodic active use of the local broken topographic setting and its geological base by prehistoric people (Chlachula, 2024; Hesein et al., 2026). The repeated occupation of the site took advantage of its strategic position, the availability of lithic raw materials and proximity of water channels. The flat platform – a remnant of the former (pre-Holocene) alluvial terrace exposed above the present wadi – constituted the principal ground for the Manaqi settlement across the ages. The documented multi-sequenced occupation spans the Middle Pleistocene to historical times.

Initial fieldwork at the Iron Age Manaqi locality focused on mapping the principal archaeological features visible on the surface and those shallowly buried within the rocky desert ground. A total

of ~750 m² of the surface area of the rocky desert, bearing the prehistoric cultural records, was investigated during the 2023–2025 fieldwork. Large clastic rocks and pre-shaped quadratic bedrock pieces were used for construction of buildings as well as circular tombs (about 30 in total, not counting collective graves) situated on the Pleistocene terrace above the main wadi channel (Fig. 4C). The Iron Age dwelling structures (two excavated) are found exposed directly on the surface without a discrete stratigraphical base (Fig. 4A). Deeper structural foundations relate to the principal residential monuments placed on big alluvial boulders.

Past anthropogenic activities and a cultural landscaping are also evidenced by accumulations of large clastics without any particular spatial and architectural design, and some architectural elements integrated into the chert bedrock. The geological bodies of the landforms along the Wadi Al-Fara provided an abundance of construction materials for the habitation structures and tomb cairns, which are the most expressive archaeological features on the Early Iron Age landscape (Fig. 5A). Some stone cairns, aligned directly along the natural folds of the exposed Hawasina bedrock (Fig. 2A), illustrate use of local relief for the prehistoric burial practices. Large cobbles and boulders were collected from the massive gravelly deposits exposed by fluvial flows and gravity slope erosion acting on the occupation surface overlooking the wadi. The non-weathered stones were brought directly from the wadi about 10 m below the elevated occupation grounds. The uncovered residential buildings (the burial mounds less so), were preferentially constructed from the naturally pre-shaped (semi-rectangular) bedrock blocks (Figs 5B–C).

Except for the Iron Age archaeological material, primarily fragmentary ceramics, ergonomically fashioned lithic instruments with apparent signs of use display hard cutting and manipulation (Fig. 6C). Their Pleistocene age is inferred from the stone-flaking attributes and the resulting tool forms characteristic of the Early, Middle as well as Late Palaeolithic (Chlachula, 2025; Chlachula & Hesein, 2025). Iron mineral-patination and an intense aeolian polish (desert varnish) corroborate the assumed antiquity of these earliest cultural collections. Some of the larger Palaeolithic items were re-used in the construction of the Iron Age buildings and tombs. Discarded archaeological finds (pottery shards, lithic artifacts) are found all over the site (Figs 6E–F).

The unique relief configuration and geoarchaeology at Manaqi allow a closer look into past geo-ecology processes as well as the lifestyles of the Iron Age community.

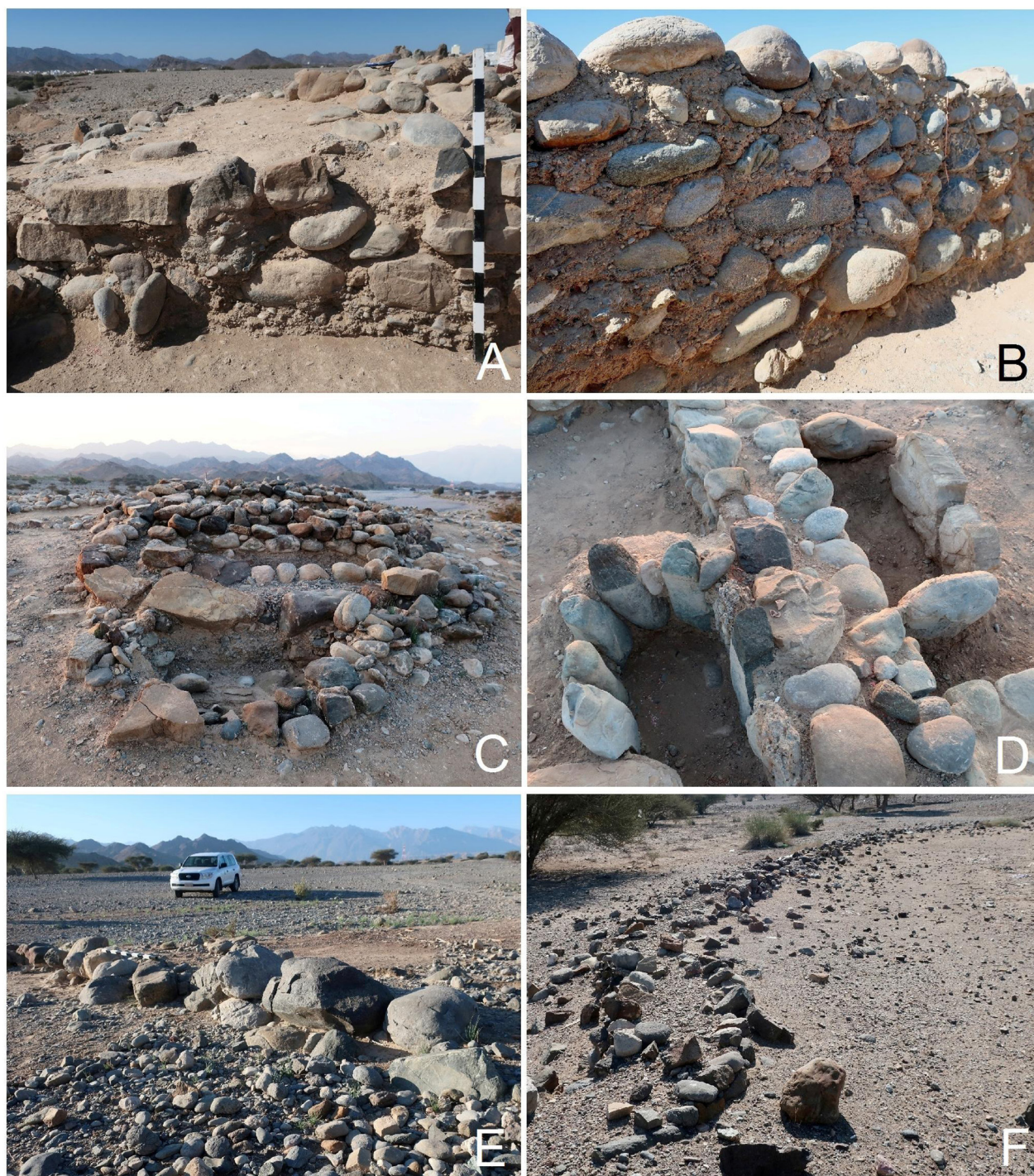


Fig. 4. Manaqi; Iron Age constructions. **A** – Stratigraphical section (building S2), showing horizontal and vertical layouts of construction blocks. Some stones were re-used for cairns; **B** – South wall of building, built from alluvial limestone boulders placed on a mud mortar; the non-weathered stones were brought from the wadi below the site; **C** – Shallow, circular burial mounds of mixed construction materials adjoining building S1; **D** – Small Iron Age cairns with vertically placed boulders and metamorphic slabs aligned along a former household wall (S1); **E** – Arrangement of alluvial boulders forming a bank-attached dam(?) or a pathway to the former Wadi Al-Fara during high-water season; **F** – Water-dam construction in a subsidiary valley near the site within a relief depression (January 2025).

4.4. The Iron Age archaeology

At the Manaqi Site, the Iron Age material predominates; by comparison, rather minor cultural records date from the pre-Islamic period. Except for the documented architectonic features, the late pre-historic site chronology follows diagnostic archaeological inventories, principally pottery, terracotta figurines and funerary practices in relation to other Iron Age monuments excavated in Oman (Yule & Kazenwadel, 1993; Kroll & Yule, 2013; Gernez et al., 2017; Jean et al., 2018; Degli Esposti et al., 2019).

Some of the most distinctive structural elements were investigated in order to determine their age and function (Hesein et al., 2025). Two stone-made

buildings (S1, S2), preserved in ruins a height of 1–1.5 m above ground, were excavated (2024–2025). Their presumed religious meaning is inferred from abundant fragments of small votive statues found within a closed space. Building S1 is the larger of the two (over 300 m²). Only the original surface layout was excavated making it possible to delineate several rectangular rooms (Fig. 5B). The original construction was aligned by more recent tombs dating from the late pre-Islamic period (Late Iron Age / Samad Period, 300 BC–400 AD), most of which had been looted. Silver and agate ornaments discovered in one of the burials illustrate the rich offerings originally placed into the tombs. The pottery style



Fig. 5. Manaqi; Iron Age archaeological monuments. **A** – Looted tumuli tombs on the northern site hill-top (Fig. 1C); **B** – Partly exposed building structure (S1) on the alluvial platform; **C** – Central building structure (S2) with secondary tombs (2025 excavation).



Fig. 6. Manaqi; Iron Age constructions. **A** – Staircase made from regularly worked/cut step blocks and partly naturally pre-shaped bedrock stones; **B** – Large quadratic sandstone blocks removed and transported from nearby (50 m up-slope) vertically exposed bedrock strata in the northern, rocky hill sector; **C** – Vertically split, hard limestone cobble with an anthropogenically used distal end; **D** – Grave placed into a small cairn of building S2 with a votive jar. Poor preservation of skeletal remains due to carbonate-rich deposit fill; **E, F** – Fragments of wheel-made Iron Age pottery of a diverse artisanal quality, and technological processing and performance discarded on present rocky desert surface (January 2025).

suggests ancient Iranian or Mesopotamian forms and iconographic themes, likely as local imitations.

Building S2 covers an area of ~100 m². Its structure is unprecedented in Oman. It has a distinctive geometric plan, separated into four main areas: a square room and two sectors, each divided into two rectangular spaces along a corridor (Fig. 5C). All spaces of the building were intentionally filled with pebbles. The structure was built in two phases. In the central place (Room 1), a large tomb was dug into the gravel layers and lined with large stone blocks. This plundered tomb contained remains of several adults and a grave inventory dated as Late Iron Age. Around fifty graves of children and neonates were located alongside the walls, inside and outside and stratigraphically over the building's layout (Figs 4D, 6D). The structure either was originally used as a funerary or residential (?) monument built in the Early Iron Age or belonged exclusively to the Late Iron Age. Some of the burials could be contemporary with the original building, while others were established shortly after its collapse. In any case, it continued to be used as a funerary monument after partial destruction, since some of the stratigraphically most recent tombs are cut through its walls.

The excavated construction (S2), enclosing principally the children's graves, is unique in Oman. It differs from the common funerary customs of Early or Late Iron Age. The size and meticulous layout of some of the tombs hints at the high status of the buried people. Complete ceramic jars discovered in some of the graves (Fig. 6D) suggest an Iranian/Parthian provenance, which raises questions about the ethnic identity of the dead. Stone tomb constructions and mortuary ritual practices in Oman go back to the Early Bronze Age (Bortolini & Munoz, 2015; Williams, 2024). In sum, the buildings, together with the tombs, attest to their special standing, and a certain functional (religious/spiritual?) meaning.

Some of the stone-made constructions at Manaqi, relics of which are preserved on the surface, may have been used as households in light of the high number of pottery fragments, unless this had a symbolic/religious connotation. Shards of wheel-made pottery constituted a part of the graves' fill as well as mortar-inclusions. There are some similarities to the Early Bronze Age dwelling structures from the Umm an-Nar settlement in terms of size and layout (Al Jahwari et al., 2020; Al-Jahwari & Douglas, 2021; Douglas et al., 2024). No diagnostic and time-equivalent ceramic elements were found that would allow for a closer determination of the erection of these habitation structures. The fragmented pottery constitutes just a terminus *post-quem* for the chronological assessment of the buildings alone. Silty clays

with a varying sandy admixture comprise the paste or body of ceramics.

The stratigraphy of the building S2 documents a rectangular foundation placement of a massive boulder-size layout (Fig. 4A). A dried-up, hardened silty / loamy silt mud mixed with sand (10–15%) was used as mortar for the stone walls masonry (Fig. 4B). Some structural units display a more pronounced cementation due to calcium (CaCO₃) inclusions. A terrace-like alignment is seen along the very margin of the main occupation space (Fig. 3E). Other documented construction elements of the Manaqi Site are found in the form of regularly shaped pieces of sandstone and limestone integrated into the metamorphic bedrock to form a staircase or a paved walk descending to the wadi (Fig. 6A). The shape and lithology of the material used indicate extraction and transport from natural outcrops within a short distance. Intentional removal of large sandstone blocks from the surface-exposed rocky folds on the opposite side of a rocky hill (Fig. 6B) seems likely. The presence of a readily available construction material was evidently a key factor in the establishment of this prehistoric village.

The recorded architectural features include an enclosure with an opening (a gate?) in the northern sector of the site, and obvious irrigation constructions (Figs 4E–F). Their presence suggests a strategic/protective role for the Iron Age village. Foundations identified on a hill on the opposite (right) side of the Wadi Al-Fara could have fulfilled a similar defensive or observational (control-point) function. An analogue may be found at some other Iron Age sites in Oman (Magee, 2003). Massive fortifications at Lizq underscore the power-oriented status of the Omani Early Iron Age society (Kroll & Yule, 2013). The hill-top constructions and the burial tumuli (Fig. 5A) may indicate a place of a high symbolic or social importance, such as a meeting place for ritual practices as interpreted at the site of Salūt (Phillips, 2015). The large size of some funeral constructions and their prominent geomorphic location on top of the Manaqi terraced hill (Fig. 2A) suggest an elite status of the buried individuals and presumes a certain hierarchy within the Iron Age community.

4.5. Ceramics production

Pottery is the most frequently encountered archaeological remain, discarded on the present surface and occasionally used as fill in the households and funerary structures. Except for rare, well-preserved jars and amphoras from the tombs (Fig. 6D), the pottery is found in fragments of a diverse formal

appearance, a various clay-mass composition and mineralogy, artisanal dexterity, degree of firing and an overall quality of the individual ceramic pieces. A set of 30 visually different shards of Iron Age

ware was subjected to analyses (discussed in detail elsewhere). The ceramic samples of superior quality presented here are of a meticulously made type, light red in colour (10R 6/8), with cream (5YR 8/3)

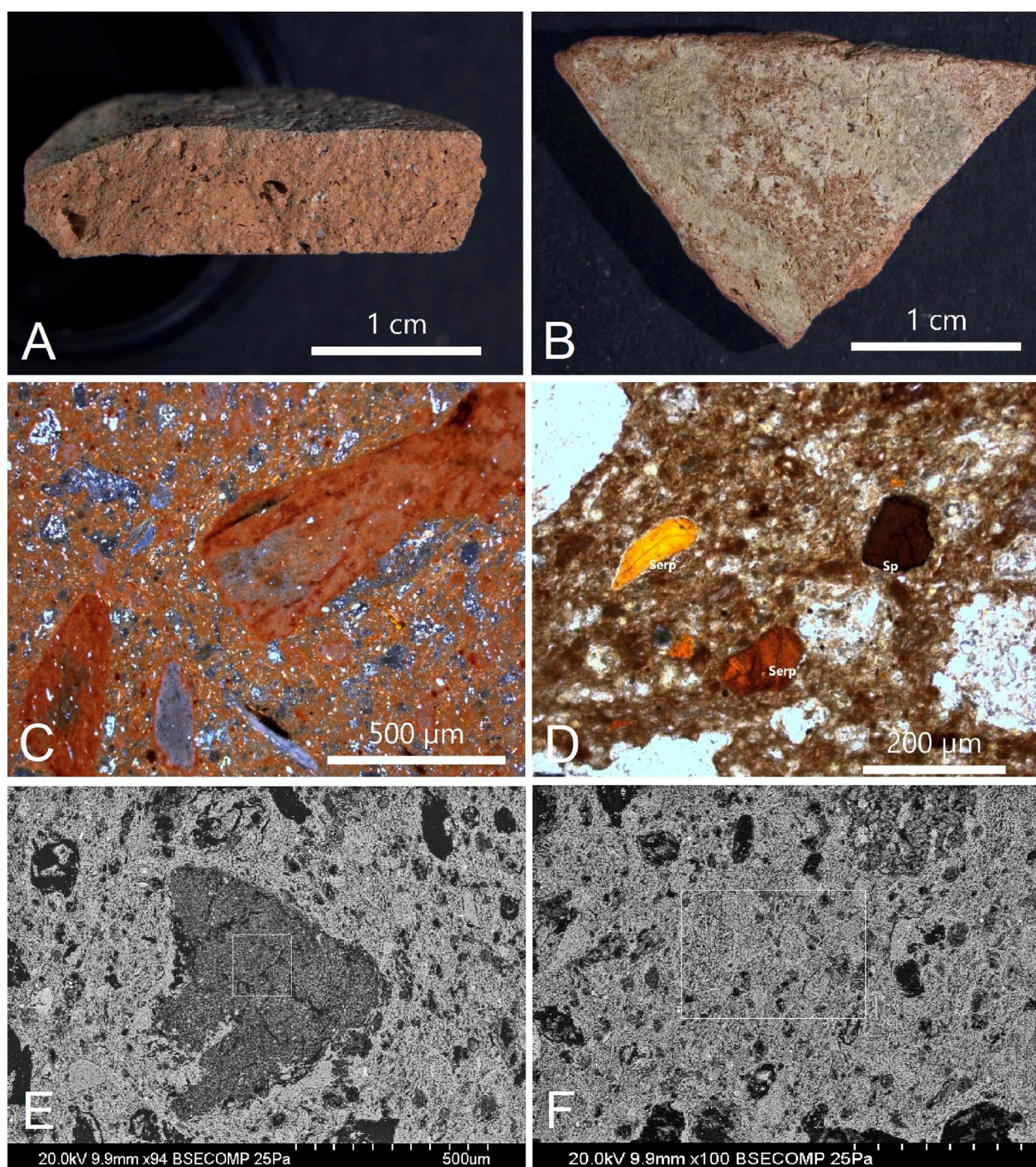


Fig. 7. **A** – Cross section of Iron Age pottery sample analysed; **B** – Sample surface area displaying a partly removed fine clayey finish; **C** – Petrographic image of shale fragments dispersed within ceramic groundmass (CPL) pointing to local provenance of clayey matrix; **D** – Petrographic view (PPL); red and yellow serpentinite (Serp) fragments and dark red spinel (Sp); **E** – SEM image in backscattered electron mode (SEM-BSE) with EDS spectrum; a coarse white fragment (arrow) replaced by chlorite; **F** – Micro-photograph SEM-BSE, spectrum EDS of pottery shard micro-mass within marked area (Table 1) with presence of magnesiochromite.

Table 1. Semi-quantitative chemical composition of pottery sherd micro-mass (see Fig. 6F).

Element	Weight [%]	Atomic [%]	Oxide Formula	Oxide [%]
O	47.69 S	63.32		–
Mg	2.68	2.34	MgO	4.44
Al	8.61	6.78	Al ₂ O ₃	16.26
Si	30.54	23.10	SiO ₂	65.34
K	2.44	1.33	K ₂ O	2.94
Ca	2.45	1.30	CaO	3.43
Fe	4.30	1.64	Fe ₂ O ₃	6.15
Ba	1.29	0.20	BaO	1.44
Total	100.00	100.00		100.00

S – calculated by stoichiometry.

patina on the outer surface. Numerous fine grains on the cut surface are visible, mainly white; less frequently grey. The presence of the serpentine-group minerals and spinels indicates the relationship of the pottery-made material mass to the area of the rocks belonging to the Semail Ophiolite (Searle, 2019; Miki et al., 2024). Likewise, the presence of particular chert minerals is diagnostic of the overall local pottery provenance.

The micro-mass of fragments is predominantly reddish brown (PPL), slightly active in cross-polarised light (CPL), nearly devoid of silt-size quartz (Figs 7A–B), with a few laths of muscovite, moderately porous (10–15%). The pores usually irregular in shape are infilled by creamy particles of phyllosilicates of a chlorite composition and a calcium-carbonate micrite. The presence of numerous cherry-red shale fragments with varying amounts of quartz silt, often highly sintered (inactive) characterises the vessel fabric (Fig. 7C).

Sand-sized inclusions encompass ~10–15% of the thin-section area analysed. Most of the macroscopically observed white grits are strongly decomposed; irregular voids remain, and have been partly replaced by creamy phyllosilicate particles, mainly of chlorite (Fig. 7E) and calcium-carbonate. SEM-EDS analysis confirmed the presence of serpentine-group minerals, the chlorite within a clayey matrix (Fig. 7D) and single magnesiochromite (Fig. 7F). The chemical composition of the ceramics micro-mass is listed in Table 1. Silica (65%) and aluminium (16%), ferric (6%) and manganese oxides (4%) are the principal geochemical constituents.

The most distinctive provenance feature of the ceramics analysed is the presence of dispersed oval and elongate yellow and red-fired fragments of serpentine minerals. There are also a few monocrystalline subrounded quartz grains, polycrystalline mosaic cherts (Fig. 7E), single plagioclase, amphiboles

and very few dark red isotropic spinels (Fig. 7D); quartz silt, often highly sintered (inactive) characterises the vessel fabric (Fig. 7C).

Altogether, these preliminary results indicate largely a local source of the material used for production of the Iron Age pottery / ordinary vessels (Michniewicz & Chlachula, 2025). A high-temperature clay burning was performed. Ophiolite-rich fine-grain sediments characterise the source areas within the upper reaches of the Wadi Al-Fara (the upstream deposits). These provenance-specific ultramafic lava rocks (snakestones) were detected as detrital fragments in pre-Quaternary sedimentary layers ~2 km upstream from the central Manaqi Site occupation area. The availability of suitable geological resources/clay outcrops for quality pottery-making added to an overall economy base of the Iron Age site.

5. Natural context of early desert settlements, South Batinah

5.1. Regional geo-environments

The field mapping revealed a rather complex geological history at the Manaqi locality and in the environs of Wadi Al-Fara. The wider region experienced intense orogenic uplift, generating large-scale extrusive lithologies (Loosveld et al., 1996). A Cenozoic age of deformations of the low-metamorphosed Mesozoic bodies, constituting the bedrock base of the locality, is presumed. The Pliocene and Pleistocene orogeny is documented in the eastern Al Hajar Mountains, north-central Oman (Moraetis et al., 2018, 2020). Neogene and Quaternary tectonics became more pronounced in southern Oman (the Jebel Al Qara Range), resulting in formation of

deep structural escarpments (Zerboni et al., 2020). Marked atmospheric shifts, bringing regional variations in temperature and precipitation, are well evident in the contextual geological, geomorphic and archaeological proxies.

The structural geology and climate evolution of the study area, with multiple phases of geomorphic restructuring, with a periodically activated fluvial discharge in the wadis and accumulations of thick alluvial, gravity slope and aeolian deposits, predetermine the geoarchaeological contexts of prehistoric sites. Large-scale past natural processes and events are preserved as relict landscapes mainly in the foothills that form the transitional topographic belt between the Al-Hajar Mountains and the northern coastal plains (Fig. 1B). These palaeo-relief features constitute the geo-environmental background of the early human settlements and predisposed the traditional nomadic lifestyles, some persisting to the present day.

The Manaqi Site stratigraphies provide testimony of the changing past hydrological conditions as well as pre-Holocene relief configuration. Tectonics and climate-driven surface erosion were the controlling factors. The riverine and proluvial systems assigned to the Pliocene-Lower Pleistocene are coupled with humid phases. The younger, terraced deposits and channelling are associated with semi-arid periods of the Middle to Late Pleistocene low sea levels (Maizels, 1987). Extensive alluvial fans along the western edge of the Sharqiya (Wahiba) Sands on the opposite side of the Jabal Akhdar Range display complex palaeo-channel topography, forming a series of superimposed gravel ridges. Fossil dune fields occur in South Batinah.

These natural cycles triggered shifts in the local palaeo-hydrological conditions and prompted increased (up to cataclysmic) fluvial discharge in the valleys as seen at the mapped Manaqi sections. There were evidently several stages of deposition of coarse gravelly deposits forming the top (habitation) surface at the archaeological site studied. The alluvia overlying the main Iron Age occupation space likely correlate with younger (Late Quaternary) alluvial fan deposits and terrace veneers with weakly cemented ophiolitic gravels. This is indicated by microscopic ophiolite minerals present in the archaeological geo-contexts (Fig. 10I). Such geologically young superficial deposits are found along the Al Hajar foothills (Woor, 2023). The most recent Pleistocene river channel conglomerates situated within a close distance to wadi settings are dated as 35,000–7,000 BP (Beydoun, 1980). Subsequent aeolian deflation at Manaqi removed the fine sandy particles leaving behind rocky desert. The exhumed, formerly buried, dried-up palaeo-channels became the occupation surface for the Iron Age (as well as former and later) desert inhabitants.

Desert varnish and mineral staining on the low-metamorphosed sedimentary rocks confirm a high age and a mixed provenance of the surface deposits. The long-term changing temperature generated thermal fractionation of softer lithics and corrosion of compact alluvial limestone cobbles. The same features apply for the oldest (Early/Middle) Palaeolithic artefacts.

The fine desert sediment is dominated by fragments of carbonate rocks representing an eolianite facies, mainly of pelloidal-oolitic packstones to grainstones lithified by micrite and sparite cement. Carbonate components constitute more than 60%

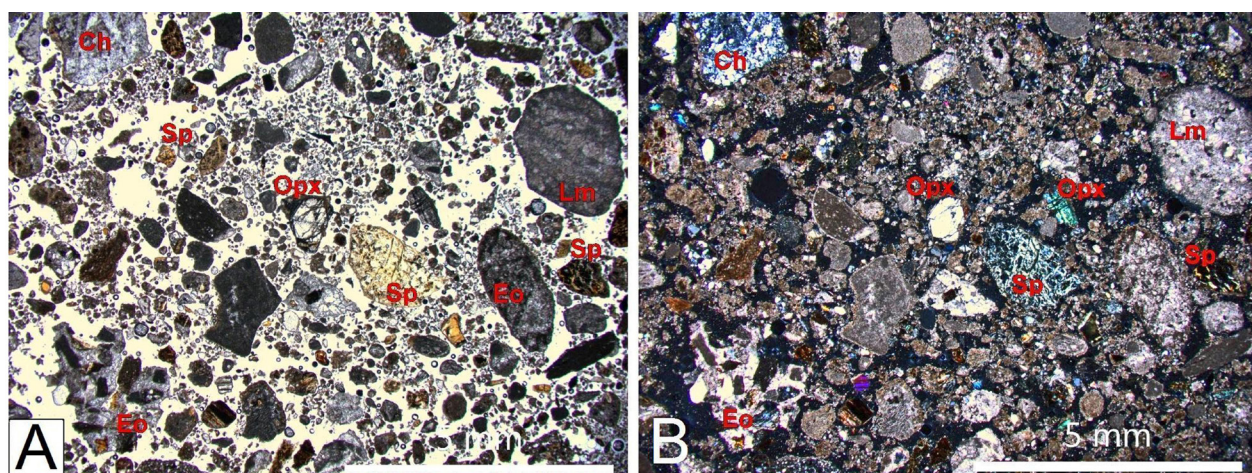


Fig. 8. Manaqi Site. A – Petrographic image of a representative sample of the desert sediment (MH7) from the S2 stratigraphic section at –30 cm obtained in plane-polarized light (PPL); B – The same view field in cross-polarized light (CPL). Abbreviations: Ch – chert; Opx – orthopyroxene; Sp – serpentine; Lm – limestone; Eo – aeolianite.

of the sediment volume. Approximately 30% of the grains consist of olivine-pyroxene material of peridotitic affinity, largely serpentinized, with olivine partially replaced by iddingsite. Colorless, non-pleochroic pyroxenes occur less frequently. Other subordinate components (~10%) include single grains of chert, quartzitic sandstone, chlorite schist, some monocrystalline quartz grains, and chromian spinels. Most of these grains preserve relics of carbonate cementation in the form of thin carbonate rims surrounding the clasts. In some cases, grains derived from ophiolitic rocks form integral components incorporated into the eolianites (Figs 8A–B). It is noteworthy that the non-carbonate grains display a clear similarity to the temper identified in the studied ceramics, confirming it's largely a local production.

The Holocene surface stabilisation allowed for pedogenic alteration of the loose geological substrate with deflation of the small-grained sediment matrix on the South Batinah plains along the Al Hajar Mountains. Most of the resistant wind-sorted fines are likely trapped within the stabilized fossil sand dune fields, and the active Khabat al-Qadan (White Sands) found ~50 km east of Manaqi (Fig. 9C) characterized by quartz-dominated aeolian deposit lithologies. The mineralogical and geochemical composition of the transported desert sediments mirrors a geo-environmental dynamics of the source loci. The wind-blown sands point to easterly directed atmospheric flows across the foothill plains and deposition of the drifted, fine aeolian material along the coast. The incorporated igneous detritus from the ophiolite belts found in the sand dunes fields suggests a deflation of the Plio-Pleistocene fans along the mountain foothills (Garzanti et al., 2003). These large-scale erosional/accumulation processes shaped the palaeo-landscapes of Manaqi over the past millennia.

The Holocene-Neolithic and later prehistoric (Bronze and Iron Age) settlements were located within relatively stable natural settings; the archaeological records are largely sealed in low geo-contexts or are exposed directly on the present rocky desert surface, occasionally subjected to rain/fluviol discharge erosion, and a drifting aeolian sand transfer.

5.2. Prehistoric occupation habitats

Arid to hyper-arid conditions, with short humid intervals, characterised past climates in Oman (Parker et al., 2006b; Al Kindi et al., 2021). Most of the prehistoric archaeological sites within the Al Rustaq

area are found on the barren rocky desert surface or are shallowly buried. The broken foothills and the inner valley settings of the topographically prominent Jabal Al Akhdar Range provided most suitable geo-environmental situations for a sequenced prehistoric occupation since the Pleistocene. Geological backgrounds of the archaeological monuments along with cultural records alone mirror past climate change and natural transformations in the arid foothills and desert plains. The earliest cultural evidence found at Manaqi (and the entire South Batinah Governorate), represented by Middle and Late Palaeolithic complexes, confirm the presence of early hominids, some of the most ancient in south-east Arabia (Chlachula, 2025; Chlachula & Hesein, 2025). Within the study area, more recent Neolithic hunter-gatherer settlements left behind short-term camps and isolated rock-art sites (Bretzke et al., 2018; Parton & Bretzke, 2020). More permanent, semi-sedentary lifestyles of early nomads in productive, rainfall-fed desert settings are known since the mid-Holocene.

Since antiquity, the perennially flooded wadis acted as natural migration routes for ethnic movements and cultural interactions; and as corridors of goods exchange in later prehistoric and historical times. Recurrent peopling of north-central Oman is explicitly evident from the rich archaeological landscape. The environmentally favourable river valleys north of the Al-Hajar Mountains, accentuated by the geomorphological configuration of the surrounding hills, served as the principal passages for settlements in the interior parts of the peninsula, and gateways for the coastal-continental Bronze and Iron Age trade (Fig. 9A).

The changing natural conditions and adaptive patterns of nomadic communities to the local desert habitats are evidenced through the prehistory until the recent historical times. The general trait of the early (Holocene-age) occupation is the practice of pastoral economy.

In the Oman Peninsula, this desert livelihood adaptation is securely documented since the late Neolithic (Preston et al., 2012; Uerpmann & Uerpmann, 2020) – in relation to raised atmospheric humidity over southern Arabia, persisting until ~6,500/3,500 BP (Lüning & Vahrenholt, 2019). The increased fluvial discharge and environmental amelioration at ~2,800 cal. BP in the piedmont area of the Al-Hajar Mountains provides evidence of shifting regional hydro-climatic conditions (Beuzen-Waller et al., 2022). Subsequent stages of climate deterioration and regional aridification are evidenced by the expansion of sand dunes in the Gulf of Oman area (Miller et al., 2016; Purdue et al., 2019), and a

shift to an oasis-style herding system responding to progressing landscape dryness (Méry, 2013).

Environmental factors related to climate change and promoting the rise of civilisation in south-east Arabia, including north-central Oman, indicate precipitation increase within the period of 5,000–4,200 cal. BP. The humid climate variations favoured adaptations to the desert landscapes in the Al Rustaq area, as well as within the inter-montane depressions of South Batinah watered by seasonal wadies. This change is believed to have contributed to consolidation of the regional Bronze Age cultures (Parker et al., 2006b). An introduction of the aflaj-irrigated agriculture during the Omani Early Iron Age (Fig. 9B) responded to the progressing countryside aridity and desert-land expansion at the expense of the former monsoon-fed grasslands. Inhabitation of the foothill places during the Late Holocene in reaction to continuing regional aridity

is testified by inauguration of sophisticated, irrigation-based land use practices centred at the major cultural loci with large necropolises and building constructions (Lézine et al., 2002). The Iron-Age water management at Manaqi is exemplified by dam-retention structures in the tributary valley, adjoining the locality and as linear constructions connecting the main wadi. Large stony slabs from the local outcrops were used for construction of these water-storage facilities (Fig. 4E–F).

Subfossil pollen records retrieved from stratified contexts of the Manaqi building structure (S2) and the natural contexts of the nearby wadi point to arid to semi-arid settings during the Iron Age occupation (Fig. 10). Poor palynomorph preservation is due to overall unfavourable conditions and geoarchaeological/depositional geological situation. The highest diversity and concentration of pollen and spores was recorded in basal clays below the main



Fig. 9. A – Present-day rocky desert with patchy *Acacia* woods at the archaeological site Manaqi above the dried-up Wadi Al-Fara; B – The aflaj irrigation system following prehistoric irrigation-channel practices; gardens of the Al Hazm Islamic fort (18th century AD) near Al-Rustaq; C – Khabat al-Qadan (White Sands) dunes with an active sand drifting, with the Al-Hajar Mountains in the background.

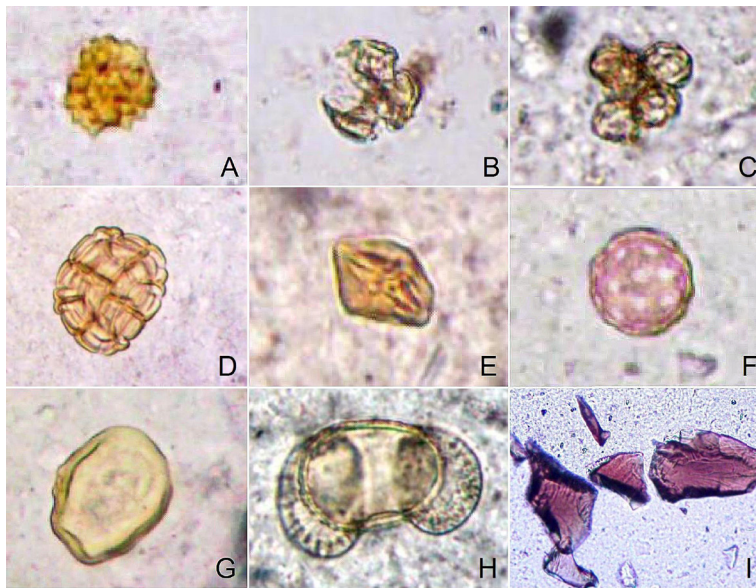


Fig. 10. Manaqi Site subfossil pollen from culturally significant archaeological strata. **A** – Asteraceae; **B** – Rosaceae; **C** – indeterminate; **D** – *Acacia* sp.; **E** – indeterminate; **F** – Chenopodiaceae; **G** – Poaceae; **H** – Pinaceae; **I** – Microscopic fragments from Semail Ophiolite (analysis by L. Savelieva).

occupation grounds (M6 section); much less so in a mortar of building S2 at –25 cm above the foundation base (Fig. 4B) and within the associated grave fill (Fig. 6D). Most fungal spores were detected at the base of the wadi dam (Fig. 4E).

Acacia wood, wild rose shrubs along with sparse flowering plants (Asteraceae, Chenopodiaceae), grasses (Poaceae) and sedges (Gramineae, Cyperaceae) document xerophytic wasteland vegetation comparable to that of the present-day rocky desert. Cichoriaceae may also indicate secondary pasturelands. The pollen composition points to incomplete vegetation cover owing to increased regional aridity (Parker et al., 2004) and possibly also linked to anthropogenic interferences. Isolated pine pollen grains (*Pinus* sp.) suggest the existence of a patchy forest cover in the cooler upstream foothills of the Jabal Akhbar Mountains. At large, the pollen spectrum reflects climates analogous to the present ones (Bellini et al., 2015). The presence of coniferous pollen in the Manaqi palaeoenvironmental contexts may indicate long-distance transport from the foothills due to decreased monsoon activity in the northern part of Central Oman recorded during the early 1st millennium AD (Unkelbach et al., 2025). Trees covers are documented in Dhofar, South Oman, at ~3,100 cal BP. An increase of xeric taxa after ~2,900 cal BP within interior deserts was due to decreasing rainfall and possible impacts of intensified human activity contributing to environmental aridity (Horisk et al., 2023). A similar scenario is envisaged for the Iron Age landscapes of north-central Oman. The sporadic occurrence of Brassicaceae (cabbage family) and Cerealia pollen may suggest anthropogenically cultivated plants and early agricultural practices, presuming irrigation. The latter

may also be an indicator of the presence of wild cereal species in this part of Arabia, except for their domesticated derivatives. Finally, the retrieved spores of fungi (*Sordaria*, *Cercophora*, *Trichocladium*) commonly found in faeces of herbivore animals may be linked to a rural pastoral economy during the Iron Age settlement.

In sum, the palynological evidence points to the existence of an arid vegetation cover within the late prehistoric occupation space, and provides some picture, although still fragmentary, of an early cultural landscape at Manaqi during the 1st millennium BC.

6. Environmental change and rise of civilisation in Oman

The sequenced human history in north-central Oman, in relation to specific natural backgrounds, provides testimony of interactions between ancient peoples and past landscapes. Timing and forms of prehistoric settlements in the south of the Arabian Peninsula were regulated by climate-driven environmental shifts, as well as by new cultural impulses across millennia (Magee, 2014; Cleuziou & Tosi, 2021; Beuzen-Waller et al., 2022). The past fluvial systems, controlled by West Indian monsoons, provided the most suitable conditions for desert inhabitation throughout the Holocene. In contrast, some wasteland places with distribution of earlier (Stone Age) cultural records became (and still are) vacant.

Middle and Late Holocene climate change ultimately predetermined the present landscape configuration, distribution of mosaic geo-ecosystems as

well as modes of (pre-) historic cultural adjustment to desert habitats. Palaeoclimate and geoarchaeological evidence from south-east Arabia shows a direct relationship between phases of increased atmospheric humidity and those of expanding settlements both inland and along the coast (e.g., Lézine et al., 2002, 2010; Uerpmann et al., 2010; Cremaschi et al., 2015; Neugebauer et al., 2022; Teillet et al., 2024). On the other hand, the coastal sites were subjected to destruction by tsunami events attesting to the vulnerability of maritime settings (Hoffmann et al., 2015; Beuzen-Waller et al., 2019; Andreou et al., 2022). A winter-rain pattern similar to the present-day one became dominant after ~5,000 year ago. Increased dryness became established after ~4,500 BP, approaching contemporary climate conditions (Lézine et al., 2002). Long-term precipitation minima at ~5,000 and 4,200 cal BP recorded in inter-dune lake sediments of southern Arabia, linked to a weakening of the West Indian monsoonal system (Parker et al., 2006a), coincide chronologically with the sequenced inauguration of the regional Early and Middle Bronze cultural entities. Apart of this, an inland extension of the North African summer monsoons across the Red Sea into the southern Arabian Peninsula during the mid-Holocene is believed to have generated rainfall changes, mainly at higher topographic elevations in the mountainous ranges (Enzel et al., 2015).

Temporarily humid conditions at ~3,250–2,380 cal BP were followed by progressed territorial aridity ~2,380–1,870 cal BP (Purdue et al., 2019), corresponding in time with the emergence of the Iron Age civilisation phenomenon across Oman. The weakening winter-rainfall regime triggered shifts to drier conditions, and extension of xerophytic grasslands and shrubs along with mobilisation of sand dune fields. Seasonal run-off from the highlands became the only natural freshwater source (Lézine et al., 2010). In spite of the increased aridity, culminating at ~1000 BC (Parker et al., 2006a), the ancient south-east Arabia experienced a significant rise in number of settlements, in particular during the Early Iron Age (1100–600 BC). Since then, the environmental conditions in south-east Arabia remained relatively stable, similar to those of the present day (Fleitmann et al., 2007).

The mid- and late Holocene landscape aridification in the north-central part of the country fostered inauguration of regulated water management (supplies and storage) at Bronze Age sites (e.g., Charbonier, 2015; Desruelles et al., 2016; Economou et al., 2022). Wastelands and rocky deserts north of the Al Hajar Mountains remained the main occupation habitats of local late prehistoric semi-sedentary

pastoral settlements. A regular water supply for more permanent stone-made, village-style communities established in the vicinity of the seasonally water-filled wadis was essential (Harrower et al., 2022). Runoff farming became a key hydro-agricultural strategy at least three thousand years ago (Purdue et al., 2019, 2021) as an alternative to oasis-style settlements (Häser, 2010). The novel aflāj channel system provided regular mountain water supplies in addition to water-retention strategies along with ground-water wells practiced in seasonally flooded channels (Wilkinson, 2022). Its beginning in the Al-Rustaq area lies in local Bronze Age traditions (e.g., Al Tihka Site; K. Douglas et al., unpublished data). The irrigation agriculture, enabling intensified cultivation of crops (Bellini et al., 2011; Cremaschi et al., 2018), was the fundamental factor behind the rise of the Early Iron Age civilisation in Oman (13–9th C. BC). This form of rural economy continued through the Early Pre-Islamic Period (350–200 BC) and throughout the Late Islamic Period (8–18th C. AD) (Purdue et al., 2021), up to modern times (Fig. 9B).

Another principal factor of the early rise in Omani civilisation was the introduction of large-scale copper mining and metallurgy, linked to rich local metallic resources (Lehner et al., 2023), contributing to long-distance trade and goods exchange (Frenéz, 2019; Degli Esposti & Pavan, 2020). Within the close study area, prosperous copper mineralisation deposits associate with the Semail Ophiolite bedrock, forming the foothill bodies north of the Hajar Mountains (Cooper, 1988; Mahfoud & Beck, 1997; Csontos et al., 2010).

Apart of past climates, the diversity of the broken relief of north-central Oman with desert, foothill and perennial riverine settings predetermined the occupation habitats of the prehistoric and early historical settlements. The main Iron Age establishment at Manaqi reflects favourable geomorphic and environmental (primarily hydrological) predispositions of this desert place. The adjoining wadi allowed for the run-off agricultural practices, likely on a regular basis, and facilitated a certain socio-economic stability of the local community. The uncovered remains of ancient architectural monuments contribute to our understanding the life and organisation of the Omani Iron Age society. The site geoarchaeological contexts, along with palaeoenvironmental data, help reveal the presumed (and real) functions of this unique cultural place. The late prehistoric geo-ecology records add to comprehension of the adaptive strategies of the ancient communities – both livelihood-based and religious.

The present Manaqi locality mirrors a dynamic geo-setting between the mountains and the coastal

plain. Torrential rains, generating unprecedented floods over past years, represent a major geo-environmental threat to the archaeological sites positioned closer to the perennial channels. The erosional margin of central part of the site is being progressively undercut by high waters of the Wadi Al-Fara (Fig. 2C). This fact calls for an operational rescue excavation of the archaeological monuments positioned close to active watercourses.

7. Conclusions

The South Batinah area played a pivotal role in the development of civilisation in east Arabia during the 2nd and 1st millennium BC. Geoarchaeological and geo-ecological investigations at the Al Rustaq-Manaqi multi-sequenced occupation locality complement cultural-historical studies in northern Oman. The contexts of mapped spatial, geomorphic, geological and geoarchaeological at this site provide new insights into past landscape formation processes and environments in the course of prehistoric peopling of the peninsula. With respect to size and configuration of the ancient village with the stone-built architectural monuments – residential buildings, impressive tombs and water-supply constructions, the Manaqi complex becomes one of the most important Iron Age cultural entities in the country. The past natural events stored in the geo-contextual and palaeo-ecological proxy records contribute to our comprehension of adaptive patterns of ancient communities – the economic, livelihood-based, as well as the religious. The availability of the local rocky material resources used for construction, copper smelting and pottery making, along with the strategic topographic position of the sites within a narrowed river valley, were the key factors for the repeated prehistoric settlements at this place. The reconstructed Iron Age geo-settings add to present knowledge on the natural and cultural history of the Oman Sultanate.

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Contributions

All authors contributed to this study. M.H., G.G., K.D. and N.J. carried out the Manaqi pilot archaeological excavations. J.C. conducted the geoarchaeological investigations at the locality (2023, 2025, 2026) and wrote the manuscript of this paper commented by all the co-authors. J.M. made the pottery analysis (2025).

Competing interests

The authors declare no competing interests.

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