SRYAHWA PUBLICATIONS

Annals of Archaeology
ISSN: 2639-3662 | Volume 8, Issue 2, 2026
https://doi.org/10.22259/2639-3662.0802001

RESEARCH ARTICLE

The Agricultural Terraces and Hydraulic Management Systems of Suhaila 3 Archaeological Site in Hatta, Dubai (UAE), During Late Islamic Period

Hassan Zien[1], Mansour Boraik[1], Julian Jansen van Rensburg[2], Matthew Jameson[2]

[1]Dubai Culture and Arts Authority, Dubai, UAE.
[2]Chronicle Heritage Arabia (CH Arabia).

Received: 09 May 2026 Accepted: 25 May 2026 Published: 29 May 2026

Corresponding Author: Mansour Boraik, Dubai Culture and Arts Authority, Dubai, UAE.

Abstract

The Hatta archaeological landscape is an exceptional example of human adaptability in mountainous regions, exemplified through the introduction of a falaj hydraulic management system during the Late Islamic period. The presence of terraces in mountainous areas suggests the need for landscape management and water control in response to fluctuating environmental conditions. Suhaila archaeological site comprises 16 Lat Islamic settlements. These settlements were built in the valleys on the slope of Al-hajar mountain. More than 449 structures were documented in these sites, including complex houses, single bedroom, mosques, watching towers, and boundary walls. But the most important structures were surveyed are agriculture terraces which are in two of the settlements, one at Suhaila 2 archaeological site and the second group of these terraces is at Suhaila 3 site. At Suhaila 3 archaeological site, agricultural terraces and water management features with intact stratigraphy exposed by wadi downcutting were documented as part of a geoarchaeological survey by Dubai Culture & Arts Authority (DCAA) and Chronicle Heritage Arabia (CH Arabia). The sedimentary sequences from seven sections identified in that survey reveal dynamic interactions among colluvial, fluvial, and soil formation processes shaped by episodic high-energy fluvial events, periods of landscape stabilization, and human activity. The strategic placement of agricultural terraces and water management systems within and adjacent to the wadi utilized locally available seasonal water, the local topography, and fertile soils. These factors likely enhanced the agricultural potential of the area, enabling more permanent occupation within the mountainous village environment, and offers a unique opportunity to understand past, sustainable agricultural practices.

Keywords: Agriculture Terraces, Late Islamic Period, the Stratigraphy, Hydrology, Al-Hajar Mountain.

1. Introduction

The Hatta archaeological landscape is renowned for its unique cultural and natural heritage and is currently enlisted on the United Arab Emirates Tentative List to qualify its inclusion in the UNESCO World Heritage List. The Suhaila 1, 3, and 4 heritage sites are situated within the Hatta Archaeological Landscape, which is classed as an exceptional example of human adaptability to mountainous regions, with extensive terraces located on gentle mountain slopes, that are considered to have potential Outstanding Universal Value (OUV). The natural landscape contains fertile valleys and unique ecosystems in the Hajar Mountains forming the Hatta Mountain Reserve, which forms part of a wider zone of conservation areas within the region. The cultural significance of Hatta is considerable, forming an area that was extensively utilized and likely permanently occupied from the

Citation: Hassan Zien, Mansour Boraik, Julian Jansen van Rensburg, *et al.* The Agricultural Terraces and Hydraulic Management Systems of Suhaila 3 Archaeological Site in Hatta, Dubai (UAE), During Late Islamic Period. Annals of Archaeology. 2026;8(2): 01-18.

Bronze Age through to the Islamic Period. Previous investigations in the area involved comprehensive documentation of numerous Hafit burial tombs, and Umm an-Nar, Wadi Suq, and Iron Age period tombs (Valante *et al*. 2022: 413–431). Therefore, suggesting that terraced slopes were ideal locations for early human settlement and agricultural activities, providing a unique archive for human-environment interactions in mountainous terrain over the long durée (Wei *et Al*. 2016: 388–403).

One unique feature of the Hatta archaeological landscape is the presence of a substantial and sophisticated agricultural terraced landscape. Within the broader context, agricultural terraces were built for various reasons, and vary in both typology and chronology, and are widespread in mountainous areas in Arabia (Wilknson.1999: 183–191; Pietsch & Mabit. 2012:48–60; Charbonnier et al. 2017: 13–28; Purdue *et Al*. 2021: 105406). Agricultural terraces also form important ecosystem services (Brown et al. 2021: 107579), and are unique examples of sustainable land management and adaptability to mountainous environments(Luedeling *et Al*. 2005: 273–285). The benefits of constructing agricultural terraces is that they can reduce natural hazards and erosion and help regulate water, climate and ecosystems(Wei *et Al*. 2016: 388–403). Reduced runoff and erosion, floods, sedimentation, and damage to infrastructure such as fields downslope are significantly reduced when terraces are established (Ferro-Vázquez *et al*. 2017: 500–513). Water is also regulated by increasing soil moisture, decreased runoff, reduced evaporation, water retention, and recharge of shallow groundwater aquifers. Terraces also enable the regulation of local climate by the sequestration and stabilization of carbon in soils, referred to as soil organic carbon (SOM) (Djuma *et al*. 2020: 104741). Characterization and analysis of SOM is important, as soils are considered the second largest pool of carbon after oceans (Stockmann *et al*. 2013: 80–99), which can be used to mitigate and reduce CO_2 emissions entering the atmosphere (Rumpel & Kögel-Knabner 2011: 143–158). Terraces also help stabilize landscapes enabling the ecosystem to flourish where plants begin to diversify (Moratis *et Al*. 2020: 114152), and increased grassland cover provides an abundance of fodder for grazing animals in mountainous areas (Azaiez *et al*. 2020: 159). Agricultural terraces are important for sustainable landscape management, and through conservation efforts and raising awareness amongst local communities (Stanchi *et al*. 2012: 90–100; Dhawi & Aleidan 2024). Therefore, these agricultural systems have significant potential for enhancing the cultural value and significance of the landscape.

This study conducted a geoarchaeological survey of natural exposures to enhance the understand the physical setting and geomorphological context for the site (Suhaila 3). Additionally, the survey included detailed recordings of sediment stratigraphy associated with landscape management features to document the deposits, determine the site-formation processes, and assess the site's geoarchaeological potential.

1.1 Physical Setting

As part of this study, terraces and water management features located between 300-360 m asl on the northern slopes of Jabal Qallat Sabba were investigated. Numerous wadi tributaries running down slope orientated south to north have deposited extensive units of colluvium and alluvium across the area. Along one of these tributaries are the remnants of agricultural terraces and water management systems, such as dams, which have been partially destroyed by more recent flash floods. To the west of the site lies a gravel alluvial fan that has accumulated between denudated hills composed of various rocks of the Hamrat Duru Group (Glennie *et al*. 1974). (Figure 1)

Figure 1. *The agriculture terraces in Suhaila3*

To understand the physical setting of the terraced landscape, this study also involved an assessment of geological and hydrological baseline data, maps and literature, to provide a broader context and understanding of the physical landscape. The main geological units exposed in the area have significantly shaped the valley's topography (Figure 2). The elevation from the southwest to the northeast starts with Semail Ophiolite rocks, forming the harzburgite where tributaries of Wadi Jeema (Qimah) have dissected Late Cretaceous fluvial conglomerates (Glennie *et al*. 1974).

At lower elevations, denudated hills have formed from various Haybi units consisting of chert and volcaniclastic sequences. Areas of extensive colluvium and alluvium have accumulated on either side of Jabal Qallat Sabba (658 m asl). This peak is a folded anticline that has exposed various limestones and volcanics of the Sumeini Group. Continuing to the northeast, the elevation drops significantly where the lower duplexes of the Hamra Duru Group are found (Glennie *et al*. 1974).

At the lowest elevation are deposits of alluvium formed by the meandering Wadi Hatta. Between the duplexes and the Semail Ophiolite is a transform fault that displaces this unit(Glennie *et al*. 1974). Towards the northeast, the elevation increases again significantly. The valley is overlooked by a linear northwest-southeast mountain range, including the peak of Jabal Ruwayshid (438 m asl), which consists of the same Semail Ophiolite found in Wadi Jeema (Glennie *et al*. 1974). The Hatta valley landscape demonstrates the role of climate change in shaping the landscape throughout the Quaternary period, forming unique landforms such as valleys, alluvial fans, and isolated hills that provided unique environmentditions for agriculture to flourish.

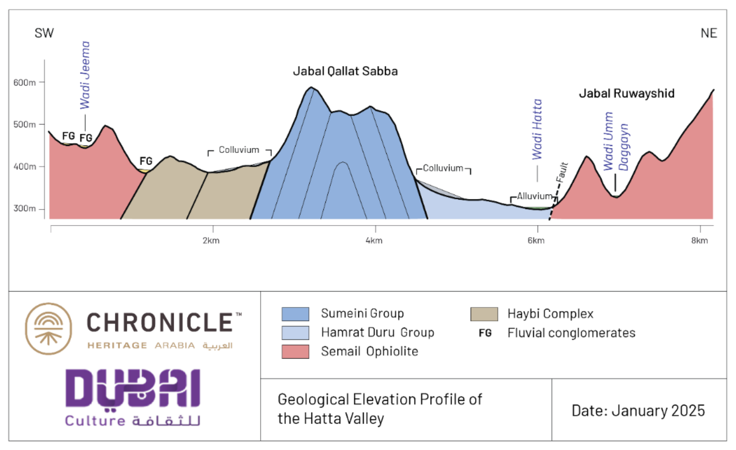

Figure 2. *Geological elevation profile of the Hatta Valley*

1.2 Climatic Setting

The current climate of Hatta is characterized by a hot desert climate and is classified as BWh according to the Köppen-Geiger classification(Kotte *et al*. 2006: 259–263; Beck et al. 2018: 180–214). The average summer temperature can reach 42°C and above, and as low as 10°C in the winter. Hatta receives 95 mm of precipitation annually, with most rainfall occurring in February and March. Paleoclimatic records reflect changes in Indian summer monsoon precipitation and positioning of the Inter Tropical Convergence Zone (ITCZ) during the Holocene (Burns. 2001; Fleitsmann *et al*. 2003: 223–232; 2007: 170–188). These records show that the periodic northwards displacement and intensification of the IOSM resulted in periods of higher rainfall in south-east Arabia (Blechmidt *et al*. 2009: 128–139; Atkinson *et al*. 2013: 292–301; Preston et al. 2015: 277–292; Muller *et al*. 2023: 111–127.

During the early Holocene, sedimentation increased significantly, reaching its peak in 9-8 ka, followed by decreased sedimentation after 8 ka as arid conditions prevailed (Fuchs & Burkert. 2008: 546–55) The hydrological network reflects the changing climate throughout the Holocene, which had a direct impact of the environmental conditions within the Hatta Valley, resulting in increased sedimentation within narrow valleys and at the foothills forming alluvial fans (Fuchs & Burkert. 2008: 546–558; Woor *et al*. 2023: 104316). In addition to the Ophiolite Aquifer, which provides the main source of water in the region, the Quaternary sediments provided additional shallow groundwater reserves within the Hatta Valley.

1.3 Hydrological Setting

To the northwest of the Suhaila sites, Wadi Hadf originates within the mountain valleys south of Hatta valley, passing through the town of Sinadil and its eight wells before emerging to form an alluvial fan at Sayh Mudayrah near the village of Tawi Mudarah. This fan is bounded by Jabal Mudayrah and Jabal al Bayd to the northeast. Wadi Hadf forms a braided channel, flowing southeast parallel to Wadi Laim, which lies on the northern side of Jabal al Bayd and passes through the town of Shariyah, where a fort and tower are located. Wadi Hadf then merges with Wadi Lishan from the southwest and reaches Masfut, a town with a fort, a tower, and at least 17 wells. From here the wadi flows to the next town, Sufayri, where there are two wells and a tower, located near a small hill before the landscape transitions into a gravel plain. Within this piedmont area, residual hills, denudational hills, and structural hills are present. Further southeast is the town of Hajarain, with at least six wells and a tower, where Wadi Hatta emerges from the south and flows northward. Wadi Hatta is joined by Wadi Qimah (Wadi Jeema), which originates from the town of Qimah and the village of Tawi Waragah further southeast. The southeastern valley extends to Wadi al-Fay, which originates from valleys in the south and southwest, and the northern Oman mountains. As Wadi Hatta continues to flow east passing the town of Suhaila, it merges with Wadi Umm Daqqayn from the north near Jabal Ruwayshid. As the wadi continues further east, it merges with Wadi al-Fay, before reaching al-Wajajah. From here, Wadi Hatta forms an expansive alluvial fan on the Batinah coastal plain, contributing to the cultivated areas of ‘Aqr and Wasiyat, where other alluvial fans emerge along the coastline.

1.4 Research Context

In addition to the presence of numerous ephemeral wadies and artificial wells, cultivation was and continues to be dependent on higher rainfall from the mountains that is transported via irrigation networks forming the traditional falaj (pl. aflaj) system. This is a system is widespread across the Arabian Peninsula, which likely dates to prehistory(al-Tikriti. 2002: 117–138). The system allows access to water from perennial flow in surface gravels from wadies sourced from the mountains and from sub-surface sources via tunnels or from natural springs found at the slopes of mountains (Wilkinson. 1977). This system is based on gravity flow and channels that lead water downhill to settlements and adjacent cultivated areas. Typically, within the gardens, a main channel splits into several branches to feed different terraces and adjoining fields. These systems are managed according to water allocation rights which rotate accordingly at certain times during the day (Wilkenson. 1977). When falaj flow is highly variable, additional water was collected from cisterns and local wells. More recently, the government established municipal wells to overcome periodic water shortages in the region. The direction and flow of wadis in the Hatta valley influenced the construction, direction, and flow of falaj systems and the positioning of agricultural terraces within the landscape. Therefore, it is important to consider the broader Hatta Valley’s hydrological system to understand the placement of the water-management systems that enabled agriculture to thrive in the area during periods of pronounced climatic variability.

Despite a lack of fertile soil, the region has nevertheless been important historically for agricultural production due to its shallow aquifer, which is recharged through rainfall in the Hajar Mountains. Soil types in the Hatta region are influenced by its arid climate, characterized by low rainfall (generally less than 100 mm per year), extreme temperature variations, and predominantly coarse sandy textured soils. These soils are generally low in soil fertility, with limited groundwater and degraded natural vegetation. (Harahsheh *et al*. 2013: 133–146)

The main soil types are Torriorthents and Fluventic Haplocambids. In the valley oases the soils are susceptible to salinization, whilst in upland areas where terraces soils are located, they are disconnected from the groundwater table and are not affected by this (Luedeling *et al*. 2005: 273–285). In the mountainous areas, especially on steep slopes, the soil is often shallow, gravely, and stony, making them unsuitable for agriculture. Instead, they are mainly used as seasonal pasture for sheep and goats (Brinkmann *et al*. 2009: 1035–1045; Dickhoefer *et al*. 2010: 962–972). In addition to the threat from overgrazing (below), natural erosion can be severe along mountain wadis during intense rainfall. Evidence for anthropogenic improvement and enhancement of soil quality is achieved by constructing agricultural terraces and water-management systems, providing conditions for abundant vegetation growth (Nagieb *et al*. 2004: 81–106).

Agricultural terraces are common in these mountainous valleys, usually established on more stable gravel terraces within narrow valleys. The construction of soil terraces to create arable land in rugged areas is a very labor-intensive form of agriculture in arid regions (Moraetis *et al*. 2020: 114152). The Jabal al-Akhdar (“Green Mountains”) are famous for their extensive, historical terrace systems, also known as “hanging gardens,” fed by falaj irrigation within terrace basins (called *jalba*) (Buerkert *et al*. 2021: 7709). In Yemen, similar soil terraces are thought to be of an early origin (Wilkinson. 1999: 183–191; Pietsch & Mabit. 2012: 48–60). In the small-scale oasis agriculture, goats are essential for providing a source of income and food for the rural community (Zaiber *et al*. 2004: 131–140), as well as manure for fertilizing agricultural terraces (Luedeling *et Al*. 2005: 273–285). Animal fodder was widely grown, which included the cultivation of green feeds such as maize, sorghum, oat, barley, and alfalfa. Animals also consumed concentrate feeds such as dates, dried sardines, and old bread (Schlecht *et al*. 2009: 355–363; 2011: 1136–1146). Most of the animals' daily feed comes from vegetation grown on steep slopes and plateaus of mountains that surround nearby settlements. However, intensive grazing often contributes to landscape degradation and erosion (Schlecht *et al*. 2009: 355–363).

Alternatively, in the Hatta Valley, the abandonment of these agricultural terraces has appeared to cause soil desertification and erosion that has ultimately led to terrace wall collapse (Figure 3)(Luedeling *et Al*. 2005: 273–285). These developments are potentially linked to water shortages caused by a shift away from traditional crops towards rose and fruit cultivation which require more intensive irrigation (Moraetis *et al*. 2020: 114152). Research has shown that in other areas of the Hajar Mountains, sediments/regoliths were integrated into soil terraces from nearby wadis after heavy flooding (Nagieb *et al*. 2004: 81–106)

Recent studies have confirmed this, where terrace soils containing sediments of lacustrine origin (as indicated by ostracod microfossils) were anthropogenically transported and deposited into these features (Moraetis *et al.* 2020: 114152) .

This evidence suggests that such terrace systems require a substantial labor force to excavate and transport upslope the large volumes of required sediment from nearby wadis.

Figure 3. *Eroded agricultural terraces and collapsed terrace walls at Suhaila 3*

The vegetation of the area is dictated by the physical conditions of the landscape. The mountainous areas, including wadis and gravel terraces at elevations between 100 and 600 m asl are dominated by natural vegetation that includes *Acacia tortilis* (Fabaceae) and *Euphorbia larica*, both well adapted to arid and rocky conditions (Brown and Feulner. 2023; Feulner. 2024) Other plants found in this rugged landscape include *Leucas inflata* (Lamiaceae) commonly found on slopes; *Tephrosia apollinea* (Fabaceae); *Aizoon canariense* (Aizoaceae); *Fagonia bruguieri* (Zygophyllaceae); *Tribulus terrestris* (Zygophyllaceae); *Ficus salicifolia* (Moraceae); *Rumex vesicarius* (Polygonaceae); *Ochradenus aucheri* (Resedaceae); and the Sidr tree *Ziziphus spina-christi* (Rhamnace Such plants are important for stabilizing slopes and reducing soil erosion. Overgrazing, particularly of herbs and shrubs has nevertheless significantly impacted the mountainous areas. Such overgrazing results in increased sediment deposition along wadis such as Wadi Hatta and Wadi Jeema, which forms alluvial plains at lower elevations. Commercial crops are also found in the landscape, including the date palm (*Phoenix dactylifera L.*). An important perennial crop grown at lower elevations, this crop plant is replaced by others such as pomegranate (*Punica granatum L.*) in oases of higher altitudes (Buerkert *et Al*. 2021: 7709).

Extensive archaeobotanical research has been undertaken on high-altitude agricultural oases, which are typically between 1,640 and 1,950 m asl in the region(Buerkert *et al*. 2017: 75–86; 2021: 7709; Gebauer *et al*.. 2007: 465–481; Luedeling et *et al*. 2009: 219–237). Published studies show that these oases were planted with Mediterranean and temperate-climate perennial species introduced through trade and exchange throughout the region (Hammer *et al*. 2009: 547–560). Crops planted at such high elevations include pomegranate (*Punica granatum* L.), peach (*Prunus persica* L.), rose (*Rosa damascena* L.), and walnut (*Junglans regia* L.). Crops found in smaller numbers include apricot (*Prunus armeniaca* L.), grape (*Vitis vinifera* L), pear (*Pyrus communis* L.), plum (*Prunus domestica* L.), apple (*Malus domestica* Borkh.), papaya (*Carica papaya* L.), guava (*Psidium guajava* L.), and fig (*Ficus carica* L.). In addition, fodder crops such as alfalfa (*Medicago sativa* L.), maize (*Zea mays* L.), wheat (*Triticum* spp.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), and the cash crop garlic (*Allium sativum* L.) were also planted (Schlecht *et al*. 2009: 355–363). Also cultivated are sweet potato (*Ipomoea batatas* L.), potato (*Solanum tuberosum* L.), Guinea grass (*Panicum maximum* Jacq.), eggplant (*Solanum melongena* L.), tomato (*Solanum lycopersicum* L.), chili (*Capsicum frutescens* L.), radish (*Raphanus sativus* L.), pumpkin (*Cucurbita pepo* L.), lablab (*Lablab purpureus* L.), faba bean (*Vicia faba* L.), cabbage (*Brassica oleracea* L.), salad (*Lactuca sativa* L.), parsley (*Petroselinum crispum* (Mill.) Nym.), and carrot (*Daucus carota* L.) (Hammer et al. 2009: 547–560). A recent increasingly widespread introduction, sponsored by Oman's Ministry of Agriculture, is the drip-irrigated cultivation of olive (*Olea europaea* L) (Gebauer *et al*. 2007: 465–481).

Depending on annual rainfall, these oases have seen the increasing necessity for falaj irrigation and the application of manure to enhance nitrogen and carbon from the grazing of sheep and goats (Burekert *et al.* 2017: 75–86; Dickhoefer *et al*. 2012: 131–141). Recent land-use studies in Oman have revealed diverse uses of agricultural terraces which depend on the local environmental conditions, water availability, and socio-economic factors (Buerkert *et al*. 2021: 7709). Terraces in the region are often utilized for various agricultural purposes, including the cultivation of woody plants such as fruit trees, a mix of woody plants and seasonal crops, crop cultivation only, or, in some situations are left to fallow or are abandoned. Furthermore, these studies note the predominance of rose (*Rosa damascene*) and pomegranate (*Punica granatum*), due to their high economic value and adaptability to arid, high-altitude environments. This shift in crop preferences is due to climate change, which has altered traditional agricultural practices and influenced water resource management in the region. In addition to these crops, olive (*Olea europaea*) cultivation has increased in the region, supported by initiatives from Oman's Ministry of Agriculture (Gebauer *et al*. 2007: 465–481). The introduction of modern techniques, such as drip irrigation, has enabled (Gebauer *et al*. 2007: 465–481) (olive production in the arid and semi-arid conditions of the area. As a result, olives have become the fourth most-common crop cultivated preceded by date palms, pomegranate, and rose (Buerkert *et al*. 2021: 7709).

2. Methodology

The survey identified seven sections with naturally exposed stratigraphy and conducted one archaeological excavation of a well-preserved agricultural terrace (Figure 4). A geoarchaeological approach was taken, integrating earth-science methods to address archaeological questions related to landscape dynamics and site-formation processes (Buizer. 1982; Goldberg *et al*. 1993; Schiffer. 1987). These methods were employed to describe the sediments accumulated in various landscape features, with the aim of identifying natural and anthropogenic influences in sediment accumulation which influenced human-environment interactions at neighboring archaeological sites. Landscapes are formed by complex interrelated natural and cultural processes and contain valuable information for understanding long-term interactions between humans and their environments (Butzer. 1982; Wilknson. 2003). Multiple methods and sources were used to inform the Geoarchaeological Survey as part of the macro-scale desk-based assessment of the Project Area. Reference was made to published soil and geological maps of the UAE at 1:1,000,000 and 1:500,000 scales by Glennie and others (1974). Unfortunately, no geotechnical data was commercially available that covered the Project Area. The geomorphological map published as part of the wider Hatta Archaeological Landscape Project was also reviewed (Valente *et al*. 2022: 413–431). In addition, Google Earth Engine (GEE) was used along with the timeline and elevation functions to enable rapid assessment of the landscape character and the preservation potential of exposed stratigraphy in the Project Area prior to fieldwork.

2.1 Stratigraphic Recording

The stratigraphy of the seven natural exposure sections identified were first cleaned using an archaeological trowel to ensure clear visibility of the sedimentary layers. Each stratigraphic section was assigned a unique section code: Suhaila 3 (SH3) 1-7. Both the natural section exposures and the archaeological units uncovered in the test trench were systematically recorded following Jones and others (1999).

To identify vertical variations within each stratigraphic section, sedimentological characteristics such as Munsell soil color (2023), texture(Thien. 1979: 54–55), sorting (Powell. 1998: 1–32) level of compaction, particle roundness (Powers. 1953: 117–119), grain-size, (Wentworth.1922: 377–392), and recording of depth, thickness and the presence of sedimentary structures (Reineck & Songh. 2012). In addition, iron mottling, carbonate nodules, and evidence for bioturbation (frequency and size of roots) were recorded if present(Courtly. 2001: 205–239; Goldberg *et al*. 1993, 2022).

2.2 Sampling Methodology

After photographing and recording the sections, a selective sampling strategy was employed following Historic England Geoarchaeological guidance (Historic England 2015). Sediment sub-samples were collected from each depositional unit of the stratigraphic sections for further geoarchaeological analysis if necessary. Each sub-sample (~25 grams [g] of sediment) was excavated from the section using an archaeological trowel and put into labeled self-seal plastic sample bags. The depth of each sub-sample taken was also recorded on the bag and in ArcGIS Survey123 digital forms.

In addition, optically stimulated luminescence (OSL) test samples were taken from selected units following *English Heritage Luminescence Dating Guidelines* (Duller.2008). OSL samples were collected by inserting a black PVC tube horizontally into the cleaned section avoiding any boundaries and areas of disturbance. A photograph of the tube in the section was taken prior to removal. OSL samples were carefully removed from the stratigraphic section, wrapped and labeled with the unit number, section number, and depth in m bgl. The latter was recorded with field notes to determine the contribution of cosmic radiation as part of the dating analysis. OSL samples were wrapped and stored in light-tight conditions to avoid exposure to daylight.

Environmental background gamma spectrometry samples were taken within a 30 cm radius of the OSL tube sample for water content and radio nuclide concentration (Uranium, Thorium and Potassium isotopes) (Duller.2008).

Figure 4. *Sampling location map, Suhaila 3.*

2.3 Deposit Modeling

A deposit model is a visual representation of the vertical and lateral distribution of sedimentary units below modern ground level and is used to reconstruct past landscapes at various scales (Carey *et al*. 2018; Historic England 2020). The stratigraphic descriptions were used to draw the logs to illustrate the variations in texture with depth. The thickness of deposits was also used to illustrate the lateral and vertical extent of various units along a transect of natural exposures down the wadi channel. This enabled a visual interpretation of the deposits, which were then grouped into broad depositional; units (topsoil, subsoil, and colluvium), to form a preliminary deposit model. Stratigraphic logs were drawn using Inkscape vector graphics editor (version 1.0).

3. Results

3.1 Section 1 (SH3-1)

Section 1, located at 297 m asl, represents a 0.62 m colluvial sequence associated with an agricultural terrace (Figure 5).

The basal deposit consists of 0.37 m of colluvium, composed of fine to medium sand intermixed with poorly sorted medium and coarse gravels. This deposit was likely formed by high-energy fluvial activity, indicating periods of intense water flow possibly linked to episodic flooding or seasonal inundation.

Figure 5. *Section 1 stratigraphic sequence and OSL sample location*

Overlying the basal layer is a 0.20 m thick deposit of coarse sand containing fine to medium gravels and frequent roots. This layer forms the primary fill of the terrace, suggesting it was anthropogenically modified or accumulated naturally during the construction or maintenance of the terrace. This fill was sampled for scientific dating (GEO-Sample 11) which may help to provide a chronology of terrace use.

The uppermost layer was a thin 0.05 m unit of colluvial slope wash composed of silty fine sand. Its composition suggests low-energy processes, such as gradual sedimentation from the runoff slope. This may signify a period of reduced agricultural activity due to a shift in environmental conditions enabling natural sediment accumulation across the terrace surface.

3.2 Section 2 (SH3-2)

Section 2 is a 0.93 m sequence of fluvial gravels overlain by colluvium, situated at 300 m asl (Figure 6). The basal deposit is a cobble layer cemented within a clay matrix, interpreted as part of natural fluvial gravel fan deposits, reflecting high-energy depositional processes.

Figure 6. *Section 2 stratigraphic sequence and OSL sample location*

Overlying this was another 0.09 m thick unit of coarse gravels in a silty clay matrix, most likely deposited by continuing high-energy fluvial activity. This is followed by 0.05 m of silty clay colluvium containing frequent coarse sand, gravels, and carbonate nodules, indicating slope way and possible weathering processes.

A 0.12 m layer of coarse gravels and cobbles consisting with subangular to flat clasts was deposited above, with the horizontal orientation of the clasts suggesting deposition by slope wash processes. This is overlain by 0.08 m of sandy silty clay, which was sampled for scientific dating (GEO-Sample 15).

The next unit is a 0.03 m layer of silty clay with frequent coarse sands, fine gravels, and carbonate nodule inclusions. Above this, 0.29 m of silty clay marks a more stable period of fine sediment deposition. Overlying this was the top layer consisting of 0.09 m of silty sand containing frequent fine to medium gravels, roots, and occasional mollusks. The presence of mollusks, most likely freshwater *Melanoides tuberculata*, offers potential for reconstructing the environmental conditions.

3.3 Section 3 (SH3-3)

Section 3 consists of a 1.10 m sequence of colluvium and deposits interpreted as the fill of a possible dam, located at 301 m asl (Figure 7). The basal deposit is a 0.19 m thick layer of silt and fine sand containing occasional mollusks. This unit was sampled for scientific dating (GEO-Sample 20), which could provide insights into the timing of sedimentation and the potential construction or use of the dam.

Figure 7. *Section 3 stratigraphic sequence and OSL sample location*

Above this is a 0.36 m unit of medium to coarse sand with occasional medium gravels and frequent mollusks, suggesting continued fluvial deposition by moderate energy conditions. Overlying this is a thin (0.05 m) unit of medium sand, followed by a 0.12 m unit of finer silty sand containing frequent mollusks, possibly indicating low-energy deposition or periods of standing water.

This is followed by 0.10 m of laminated silts and fine sand. Above this, a 0.23 m layer of medium to fine gravels with occasional boulders and fine sand lenses was deposited. The presence of boulders and poorly sorted gravels suggests episodes of higher-energy flow, potentially associated with dam breach events or significant slope runoff.

The topsoil of this sequence was a 0.05-m-thick unit of coarse sand, poorly sorted with occasional cobbles, likely to reflect recent surface activity such as natural erosion by recent flooding.

3.4 Section 4 (SH3-4)

Section 4 consists of 0.88 m thick colluvial and terrace soil deposits, located at 304 m asl (Figure 8). The basal deposit, 0.13 m thick, consists of silty sand containing frequent fine to medium angular gravels. This layer was interpreted as an agricultural terrace subsoil with some slope wash.

Figure 8. *Section 4 stratigraphic sequence*

Above this is a 0.53-m-thick unit of coarse sand with frequent fine to medium gravels and occasional large roots. This layer represents the main soil horizon formed behind the terrace wall, providing stability and supporting agricultural activities. GEO-Sample 25 was taken from this fill for scientific dating, which may help establish the chronology of terrace construction and use.

The topsoil layer was 0.22 m thick, composed of silty sand with medium and coarse sand and occasional cobbles. This unit suggests stabilization processes and more recent soil accumulation and bioturbation by vegetation.

3.5 Section 5 (SH3-5)

Section 5 consists of a 0.94 m thick colluvium accumulation behind a terrace or possible dam, located at 306 m asl (Figure 9). The basal unit, 0.30 m thick, consisted of a medium to coarse sand frequent coarse gravels, likely deposited by high-energy fluvial slope wash. Above this is a compact 0.14 m layer of medium to coarse sand unit with occasional carbonate nodules, indicative of sediment stabilization and soil formation processes.

Overlying this unit was another carbonate-rich layer consisting of silty clay with occasional medium gravels, forming a 0.10 m compact layer. This layer may have formed during a period of exposure and weathering, marking a phase of landscape stability.

Above this is a 0.14 m unit of fine, medium and coarse gravels with discontinuous lenses of coarse sands, deposited by high-energy fluvial processes. This is followed by another layer of medium and coarse gravels, 0.11 cm thick, found containing frequent roots, mollusks, and occasional carbonate nodules, suggesting periods of vegetation growth and stagnant freshwater.

Deposited above this was a thin 0.06 m layer of fine gravels, with frequent roots and occasional mollusks. Overlying this was a 0.04 m silty sand layer with fine to medium gravel inclusions and frequent carbonate nodules, suggesting a mixture of colluvial deposition and soil development.

The topsoil was 0.05 m thick and consisted of silt with occasional medium gravels and frequent carbonate nodules, reflecting more recent surface modification by surface slope wash.

Figure 9. *Section 5 stratigraphic sequence*

3.6 Section 6 (SH3-6)

Section 6 consists of a 1.15 m thick colluvial sequence located at 306 m asl (Figure 10). The basal deposit consists of poorly sorted gravel containing cobbles and boulders, interpreted as part of a larger alluvial fan reflecting high-energy fluvial deposition.

Overlying this is a 0.25 m thick unit of poorly sorted gravels in a medium to coarse sand and silt matrix, suggesting continued high-energy deposition with some finer sediments incorporated.

Above this is a 0.36 m unit of silt with coarse sands and frequent fine to medium gravels, indicating a shift to lower-energy conditions. The next layer is a 0.12 m unit of carbonate-rich silty clay containing frequent fine to medium gravels and occasional roots. This deposit suggests a phase of reduced sedimentation, enabling soil formation or exposure and evidence of bioturbation. A 0.16 m layer of reworked colluvium was deposited above this unit, consisting of silty sediments mixed with medium to coarse sand and frequent fine gravels, indicative of slope wash or localized reworking of sediments.

The top unit, 0.26 m thick, is composed of silt with coarse sand and fine to medium gravel. Frequent roots, occasional carbonate nodules, and mollusk inclusions indicate bioturbation and reworking by vegetation growth and stagnant freshwater.

Figure 10. *Section 6 stratigraphic sequence*

3.7 Section 7 (SH3-7)

Section 7 consists of a 0.50 m thick colluvial sequence overlying weathered natural bedrock, located at 307 m asl (Figure 11).

The basal deposit, 0.17 m thick, consists of silty fine sand with frequent fine to medium gravels. This layer is highly compacted and stiff with evidence of oxidization by the presence of iron mottles. This suggests exposure and weathering of the natural bedrock before subsequent burial.

Above this is a 0.28 m-thick unit of compacted medium to coarse gravels embedded in a silty matrix. This layer suggests an older phase of colluvial deposition, deposited by moderate-energy slope processes and fluvial activity.

The top unit was a 0.17 m-thick layer of silty sand with frequent coarse sands and fine to medium gravels. Occasional carbonate nodules and mollusks are present, suggesting the deposit formed part of a large alluvial gravel fan. Subsequent exposure at the top of the wadi has led to weathering and erosion, likely due to downcutting by recent wadi floods, which have altered this layer.

Figure 11. *Section 7 stratigraphic sequence*

3.7.1 Trench 1

The 5 × 3 m trench was excavated on the third terrace, part of a larger system of agricultural terraces on the northern foot slopes of a substantial hill within an area of extensive colluvial deposition.

The trench was located on the third terrace, part of a larger group of agricultural terraces. The terraces, which were recorded during the geoarchaeological survey, were placed on the northern foot slopes of a substantial hill within an area of extensive colluvial deposition. At the base of the terrace wall (SH3.056) a surface irrigation channel was identified during the initial survey (SH3.057) (Figure 12). A 5 × 3 m trench was established here to understand the relationship of this channel and the terrace wall and associated fills.

Figure 12. *Trench 1 at the end of excavation, with the channel running through its center*

Four contexts were recorded in this trench. Context SH3.055, a compacted reddish brown silt loam with occasional small pebbles and shells, was the first context uncovered. Underlying this was context SH3.058, a thin (5 cm) silt loam context with occasional pebble inclusions. This deposit was likely deposited by fluvial runoff from the terrace forming part of the stone lined irrigation channel (SH3.057). *Anadara* and *Circe* marine mollusks were found within SH3.058. Underlying this was another silt loam context (SH3.059), interpreted as a compacted natural deposit forming the main terrace fill.

Contexts SH3.055, SH3.058 and SH3.059 were bulk sampled for archaeobotanical analysis. Due to the compacted nature and thickness of the contexts, no OSL samples could be obtained. Alternatively, any suitable organics recovered from the bulk samples may be considered for further ^{14}C dating.

3.8 Interpretation

The sedimentary sequences from Sections 1-7 located in the Hatta archaeological landscape reveal dynamic interactions between colluvial, fluvial, and soil formation processes, shaped by episodic high-energy fluvial events, periods of landscape stabilization, and human activity. Basal layers primarily consist of coarse gravels and sands, indicative of wadi fluvial deposition, which may have formed part of a larger alluvial fan. The units overlying these show evidence for soil formation within terraces, along with exposure and weathering during surface modification, marked by the presence of compacted silts and carbonate nodules. The presence of freshwater mollusks, such as *Melanoides tuberculata*, suggests the presence of stagnant water facilitated by water management infrastructure such as dams. The topsoil shows evidence for reworking, colluviation, and bioturbation due to vegetation growth, particularly within thick soils behind terrace walls such as those found in Section 4. The geoarchaeological survey illustrated the complex geomorphology of the mountain foot slopes and its influence on wadi drainage systems. The strategic placement of agricultural terraces and water management systems adjacent and within the wadi utilized locally available seasonal water, topography, and the presence of fertile soil. These factors have likely enhanced the agricultural potential of the area, enabling more permanent occupation within the mountainous oasis environment.

4. Deposit Modeling

The stratigraphic relationship between the topsoil, subsoil, colluvium, and fluvial gravels is presented in Figure 12. Sections 1, 2, and 4 consisted of a terrace topsoil with a thick unit of subsoil overlaying colluvium and basal gravels. The thickest sequence of colluvium was recorded in Section 6 followed by Section 3, likely associated with a substantial agricultural terrace wall or dam structure. The shallowest sequence was recorded in Section 7, which consisted of colluvium over an older silty clay deposit derived from the weathering of local bedrock.

The sequence demonstrates the variability in depositional environments, forming a succession of sedimentary deposits created by the weathering and erosion of soft sedimentary bedrock along the mountain hillside.

Deposits range from high-energy fluvial gravels to low-energy accumulations of fine sand, silts, and clays within slope wash colluvium and agricultural soils. The presence of gravels (fine, medium and coarse) suggests high-fluvial energies formed during single or multiple short-lived wet events, most likely from between the Late Pleistocene (MIS 2) to the Holocene Humid Period, as suggested by similar dated fluvial archives from the region (BeuzenE-Waller *et al*. 2022: 223–239; Preston *et al*. 2015: 277–292).

After this was an aggradation phase, characterized by colluvial deposits formed through fluvial slope wash during intermittent wet events during increasingly arid conditions from the mid-late Holocene(Feltman & Matter. 2009: 633–642).

These deposits provided stable surfaces utilized for agriculture, aided by the construction of terrace walls and water management infrastructure, enabling soils to form. The presence of terraces in mountainous areas suggests the need for landscape management and water control in response to fluctuating environmental conditions.

The sequence of deposits was subsequently exposed by more recent wadi downcutting during flashfloods. This suggests stable areas previously used for agriculture were most likely abandoned due to fluctuating local environmental conditions. This is suggested by sediments containing carbonate nodules, which formed during exposure and subsequent drying.

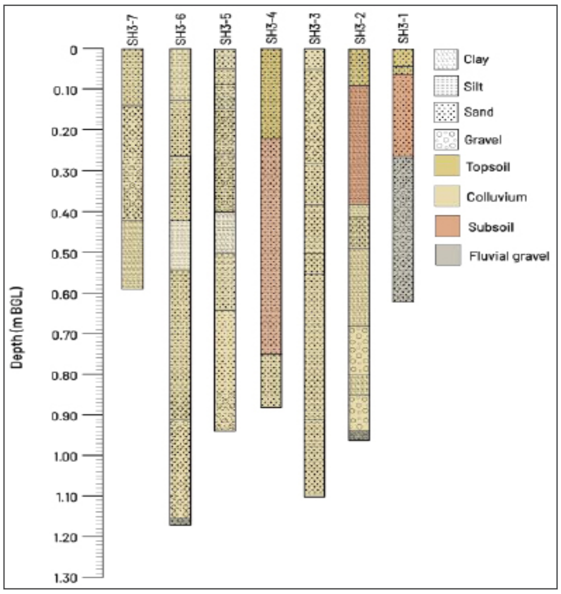

Figure 13. *Stratigraphic logs of Sections 1-7. Depositional Environment*

The geoarchaeological survey was conducted to characterize sediments and soils, which were subsequently used to interpret broad site-formation processes that influenced the deposition and preservation of depositional contexts. The main depositional processes that can occur across the Arabian landscape include sediments deposited by fluvial, colluvial, aeolian, and anthropogenic processes (Brown. 1997; Goldberg *et al*. 2022; Muhs. 2013: 149–183; Scherer *et Al*. 2021: 105040).

Within the Project Area, two main natural depositional environments were identified, these were broadly characterized as colluvial and fluvial sedimentary deposits. Fluvial deposition occurs through the natural movement of sediments by flowing water, such as wadis, which deposit layers of clay, silts, sands, and gravels. Colluvial sediments result from the downslope movement of material by natural gravitational slope processes, and slope wash during wet periods. These sediments and associated soils may become modified by anthropogenic landscape processes. In the context of high-altitude mountainous oases, human activities such as soil amendment, tree removal, plowing, planting crops, and cultivating palm trees, contribute to the reworking and redistribution of sediments. These practices, combined with the alteration of nearby wadi channels such as the construction of channels, check dams, and banks, can change the sedimentary structures in fluvial and colluvial depositional contexts. To confirm this a series of sediment sub-samples were taken for further sedimentological analysis and characterization (Table 1) and were obtained from Sections 1-4 and 6. Section 6, which consisted of a more compact sequence of sediments, was challenging to sample for dating, and so only sub-samples were obtained. These samples will help gain a broader understanding of stratigraphy and sedimentological context.

5. Chronology

As part of the Geoarchaeological Survey, four samples were obtained for OSL dating, a chronometric technique that is used to directly date sediments and now widely applied to terraces and associated features to understand the chronology and evolution of agrarian landscapes (Table 1). Sections 1, 2, 3 and 4 were samples to better understand the chronology and development of these terraces and water management systems. These samples were chosen to obtain different depositional contexts and phases of terrace evolution through the wadi. Section 1 (GEO_Sample 11) was taken from the main fill of an agricultural terrace, which is important for understanding the terrace chronology and how it evolved over time. This terrace is likely to be associated with the same phase of terracing documented as part of the Archaeological Survey. Section 2 (GEO_Sample 15) was taken from an intermediary fluvial deposit linked to a possible dam structure, which may provide further insight into fluvial events and their role in terrace and water management construction. Section 3 (GEO_Sample 20) was taken from a basal colluvial deposit, potentially representing an early phase of fluvial deposition, which may provide a chronology for the initial stages of terrace formation. Section 4 (GEO_Sample 25) was sampled from the main soil horizon behind a terrace wall.

These samples were taken from different depositional phases within proximity, with the aim of covering multiple stages of terrace construction and modification. Given the source geology and geomorphological setting, the initial focus is to test the samples to determine if there are datable minerals, such as quartz and feldspar, present within the sediments and if a suitable signal can be obtained. To date, there are no published OSL dates from similar contexts in the region, and so these samples are treated as test samples to assess their potential of OSL dating in this landscape. The tests will inform whether this technique can be expanded to other terraces and archaeological features in future research, if possible.

Table 1. *Summary Table of Samples Obtained as Part of the Geoarchaeological Survey at Suhaila 3*

Section No.	Sediment Sub-Samples	Scientific Dating
Section 1	• GEO_Sample 12 • GEO_Sample 13 • GEO_Sample 14	GEO_Sample 11
Section 2	• GEO_Sample 16 • GEO_Sample 17 • GEO_Sample 18 • GEO_Sample 19	GEO_Sample 15
Section 3	• GEO_Sample 21 • GEO_Sample 22 • GEO_Sample 23 • GEO_Sample 24	GEO_Sample 20
Section 4	• GEO_Sample 26 • GEO_Sample 27 • GEO_Sample 28	GEO_Sample 25
Section 6	• GEO_Sample 29 • GEO_Sample 30 • GEO_Sample 31 • GEO_Sample 32 • GEO_Sample 33	-
Total	**19**	**4**

6. Results and Conclusion

The strategic placement of terraces and water management systems at Suhaila 3 is a clear example of how communities in Suhaila adapted to the geomorphology and hydrological challenges in the region. With limited fertile land and the risk of flooding from nearby wadies, this area was exploited to provide land for agriculture. Previous research demonstrated the importance of falaj systems and terracing to enhance the agricultural potential of mountainous regions dominated by arid environmental conditions (Moraitis *et al*. 2020: 114152). The excavation and survey results support this, which revealed that the terraced fields and water infrastructure were constructed to harness seasonal wadi flow and reduce soil erosion of the mountain slopes.

The intact stratigraphy recorded in the terraces at Suhaila 3 provides insights into environmental and climatic variability. Carbonate-rich layers and nodules identified within the deposits are indicative of semi-arid to arid conditions, where annual rainfall rarely exceeds 500 mm (Achyuthan *et al*. 2012: 155–169).

These suggest wider geomorphic surface stability and offer potential for reconstructing paleo drainage conditions (Alonso-Zarza. 2003: 261–298), which is particularly useful for detecting periods of localized aridity (Urban & Buerkert. 2009: 296–305), soil formation, and groundwater processes(Achyuthan *et al*. 2012: 155–169). However, geochemical analysis is necessary to understand the chemical composition of these sediments to better understand their paleoenvironmental significance.

The sedimentary sequences recorded in Sections 1-7 and Trench 1 at Suhaila 3 revealed the influence of colluvial slope processes in the formation of terraces. This evidence provides further insight into the site-formation processes on a local scale that can be used to complement the broader geomorphological complexity of the area described by Valente and others (Valante *et Al*. 2022: 413–431), where the topography and proximity to wadies were important factors in determining the soil fertility and agricultural potential of the area. Differences in site-formation processes were recorded, such as high-energy fluvial deposition linked to periods of enhanced rainfall and active wadis in the early to mid-Holocene. These findings are also reported in regional paleoenvironmental records (Enzel *et al*. 2015: 69–91; Fleitmann et al. 2011: 783–787; Fleitmann & Matter. 2009: 633–642).

The presence of alluvial gravel fans nearby and gravel basal layers within the stratigraphy suggests more intensive fluvial deposition of sediments during wetter periods. Overlying these are fine-grained sediments associated with water management infrastructure, which likely enabled freshwater to accumulate behind large walls or dams to be channeled to nearby terraces along the mountain slope. The presence of these deposits demonstrates the role of the agricultural terraces and associated water management features in stabilizing the land surface and enhancement of the fertility and agricultural potential. This reflects similar findings from other sites in the Hajar Mountains, where terrace construction has been well documented (Gebauer *et al*. 2007: 465–481; Luedeeling *et Al*. 2005: 273–285; Nagieb *et al*. 2004: 81–106).

The eventual abandonment of terraces may have been caused by a combination of increased aridity and shifting land-use practices during the mid to late-Holocene. Paleoenvironmental records from the region suggest extreme arid events in northern Oman during this period (Fleitmann *et al*. 2022: 1317–1321; Fleitmann & Matter. 2009: 633–642). The construction of terraces and water management features may have been a response to this enhanced aridity and climate variability(Harrower *et al*. 2012: 131–138). This is further supported by a dated paleoenvironmental record from similar depositional environments containing a continuous sequence of alluvial, colluvial, and aeolian sediments located near agricultural terraces(Urban & Buerkert. 2009: 296–305).

The vegetation surrounding the terraces at Suhaila 3 further supports environmental change and adaptation to mountainous regions. In similar contexts, the presence of drought-resistant species such as *Ephedra ciliata(*Urban & Buerkert. 2009: 296–305) , and open juniper woodlands typically found at altitudes of 2,000 m (Ghaxanfa.1992; 1998: 241–264), suggests increasing aridity over the last six millennia. The introduction of irrigation techniques, such as the falaj system (Costa. 1983: 273–295), supported agriculture during periods of limited rainfall and environmental degradation. Despite this, human activities such as overland trade, fuelwood harvesting, and intensified agricultural practices put pressure on the landscape and likely contributed to long-term landscape changes (Darbrowski *et al*. 2021: 104512).

6.1 Recommendations

To refine thcontextualizingpositional model at SH3, additional topographic data, scientific dating, and stratigraphic and paleoenvironmental analysis is recommended to contextualize the data collected during this geoarchaeological survey within the broader archaeological landscape and environmental setting. A chronology of the deposits is essential for understanding the establishment, use, and abandonment of terraces and water management systems in the Hatta archaeological landscape.

Scientific dating of sedimentary sequences associated with agricultural and water management activities would establish a direct link to the cultural record of Hatta. Therefore, it is recommended that sediment samples be tested to determine their suitability for optically stimulated luminescence (OSL) dating.

Furthermore, a comprehensive geoarchaeological survey and sediment characterization, combined with routine paleoenvironmental analysis is recommended. This may include the analysis of mollusks, pollen, and other environmental proxies from Quaternary stratigraphic sequences, to reconstruct the environmental and landscape history of the Suhaila archaeological sites preserved in Hatta. This approach would further our understanding of anthropogenic and natural landscape processes, providing further insights into human-environment interactions in the past.

7. References

1. ACHYUTHAN. H. et Al, 2012: “Geochemistry of calcretes (calcic palaeosols and hardpan), Coimbatore, Southern India: formation and paleoenvironment’’. Quaternary International 265: 155–169.
2. ALONSO-ZARZA A.M. et Al, 2003: ’Paleoenvironmental significance of palustrine carbonates and calcretes in the geological record’. Earth-Science Reviews 60/3: 261–298.
3. Al-TOKRITI, W.Y, 2002: ‘’The south-east Arabian origin of the falaj system’’, Proceedings of the Seminar for Arabian Studies 32, 117–138.
4. ATKINSON, O.A.C et Al, 2013: ‘’Late Quaternary humidity and aridity dynamics in the northeast Rub’ al-Khali, United Arab Emirates: Implications for early human dispersal and occupation of eastern Arabia’’. Quaternary International 300, 292–301.
5. AZAIEZ, N et Al, 2020: ‘’Assessment of Soil Loss in the Mirabah Basin: An Overview of the Potential of Agricultural Terraces as Ancestral Practices (Saudi Arabia)’’. Open Journal of Soil Science 10/05, 159.
6. BECK, H. E et Al, 2018: ‘’Present and future Köppen-Geiger climate classification maps at 1-km resolution’’. Scientific Data 5/1, 180–214.
7. BEUZEN-WALLER, T. et Al, 2022: ‘’Late Pleistocene-Holocene fluvial records of the Wadi Dishshah: Hydro-climatic and archaeological implications (Southern piedmont of the Hajar Mountains, Oman)’’. Géomorphologie: relief, processus, environment 28/4, 223–239.
8. BLECHSCMIDF. I et Al, 2009, ‘’Monsoon triggered formation of Quaternary alluvial megafans in the interior of Oman’’. Geomorphology 110/3, 128–139.
9. BRINKMANN K et Al, 2009: ‘’Vegetation patterns and diversity along an altitudinal and a grazing gradient in the Jabal al Akhdar mountain range of northern Oman’’. Journal of Arid Environments 73/11, 1035–1045.
10. BROWN, A.G, 1997: ‘’Alluvial geoarchaeology: floodplain archaeology and environmental change’’, Cambridge, UK,Cambridge University Press.
11. BROWN, A.G et Al, 2021: ‘’Ending the Cinderella status of terraces and lynchets in Europe: The geomorphology of agricultural terraces and implications for ecosystem services and climate adaptation’’, Geomorphology 379 , 107579.
12. BROWN, A.G. & Feulner G.R, 2023,: The vegetation of the United Arab Emirates and ecosystem management issues. Pages 121–159 in Burt (ed.) A Natural History of the Emirates. Cham, Switzerland, Springer Nature.
13. BROWN, A.G. & Feulner G.R, 2023: The vascular flora of the United Arab Emirates. Pages 387–425 in J. Burt (ed.) A Natural History of the Emirates. Cham, Switzerland,Springer Nature.
14. BUERKERT, A. et Al, 2021: ‘’Agro-ecological land use transformation in oasis systems of Al Jabal Al Akhdar’’, northern Oman, Scientific Reports 11/1, 7709.
15. BUERKERT, A. et Al, 2017: ‘’Carbon and nutrient balances in three mountain oases in Northern Oman’’, Journal of Agricultural and Marine Sciences [JAMS] 22, 75–86.
16. BURNS, S.J, 2001: ‘’Speleothem evidence from Oman for continental pluvial events during interglacial periods’’, Geology 29/, 623-626.
17. BUTZER, K.W, 1982: Archaeology as human ecology: method and theory for a contextual approach. Cambridge, UK, Cambridge University Press.
18. CAREY, C., et Al, 2018: Deposit modelling and archaeology, Exeter, Short Run Press Ltd.
19. CHARBONNIER, J et Al, 2017: ‘’Taming surface water in pre-Islamic southeast Arabia: archaeological, geoarchaeological, and chronological evidence of runoff water channeling in Masāfī (UAE)’’, Journal of Field Archaeology 42/1, 13–28.
20. COSTA, P.M, 1983: ‘’Notes on traditional hydraulics and agriculture in Oman’’, World Archaeology 14/3, 273–295.
21. COURTY, M.A, 2001: Microfacies analysis assisting archaeological stratigraphy. (Revised edition). Pages 205–239 in P. Goldberg, V.T. Holliday, & C.R. Ferring (eds.) Earth Sciences and Archaeology. Boston, MA, Springer US.
22. DAWBROWSKI, V et Al, 2021: ’’Archaeobotanical analysis of food and fuel procurement from Fulayj fort (Oman, 5th-8th c. CE) including the earliest secure evidence for sorghum in Eastern Arabia’’ Journal of Arid Environments 190, 104512.
23. DHAWI F. & ALEIDAN, M.M, 2024,: ‘’Oasis agriculture revitalization and carbon sequestration for climate-resilient communities’’, Frontiers in Agronomy 6, 1–24.
24. DICKHOEFER, U et Al, 2010,: The role of pasture management for sustainable livestock production in semi-arid subtropical mountain regions. Journal of Arid Environments 74/8, 962–972.
25. Djuma H. et Al, 2020: ‘’The effect of agricultural abandonment and mountain terrace degradation on soil organic carbon in a Mediterranean landscape’’, CATENA 195, 104741.

26. DULLER, G.A.T, 2008: Luminescence dating: guidelines on using luminescence dating in archaeology. Bristol, English Heritage.
27. ENZEL, Y. et Al.: 2015. The middle Holocene climatic records from Arabia: Reassessing lacustrine environments, shift of ITCZ in Arabian Sea, and impacts of the southwest Indian and African monsoons. Global and Planetary Change 129: 69–91.
28. FERRO-Vázquez C. et Al, 2017: ’’When is a terrace not a terrace? The importance of understanding landscape evolution in studies of terraced agriculture’’, Journal of Environmental Management 202, 500–513.
29. FLEITMANN, D. et Al, 2007: ’’ Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra)’’. Quaternary Science Reviews 26/1–2, 170–188.
30. FLEITMANN, D. et Al, 2003: ‘’Changing moisture sources over the last 330,000 years in Northern Oman from fluid-inclusion evidence in speleothems’’, Quaternary Research 60/2, 223–232.
31. FLEITMANN, D. et Al, 2011: ‘’Holocene and Pleistocene pluvial periods in Yemen, southern Arabia’’. Quaternary Science Reviews 30/7, 783–787.
32. FLEITMANN, D. & MATTER, A, 2009,: ’The speleothem record of climate variability in Southern Arabia’. Comptes Rendus. Géoscience 341/8–9, 633–642.
33. FUCHS, M. & BUERKERT, A, 2008: ‘’A 20-ka sediment record from the Hajar Mountain range in N-Oman, and its implication for detecting arid–humid periods on the southeastern Arabian Peninsula’’. Earth and Planetary Science Letters 265/3–4, 546–558.
34. GEBAUER, J. et Al, 2007: ’’Mountain oases in northern Oman: an environment for evolution and in situ conservation of plant genetic resources’’, Genetic Resources and Crop Evolution 54/3, 465–481.
35. GHZANFAR, S, A.D, 1992: ‘’An annotated catalogue of the vascular plants of Oman and their vernacular names’’. Meise, National Botanic Garden of Belgium.
36. GHZANFAR, S.A.D, 1998 :Plants of economic importance. Pages 241–264 in S. A. Ghazanfar & M. Fisher (eds.) Vegetation of the Arabian Peninsula, Dordrecht: Springer Netherlands.
37. GLENNIE, K.W. et Al, 1974: Geology of the Oman Mountains. In Koninklijk Nederlands Geologisch Mijnbouwkundig Genootschap (ed.) Verhandelingen Koninklijk Nederlands Geologisch Mijnbouwkundidg. Amsterdam, Genootschap.
38. GOLDBERG P. et Al, 1993: Formation processes in archaeological context. Madison, Wisconsin, Prehistory Press.
39. HAMMER, K. et Al, 2009:’’Oman at the cross-roads of inter-regional exchange of cultivated plants’’, Genetic Resources and Crop Evolution 56/4, 547–560.
40. HARAHSHEH H et Al: Soil thematic map and land capability classification of Dubai Emirate. Pages 133–146 in S. A. Shahid, F. K. Taha, & M. A. Abdelfattah (eds.) Developments in soil classification, land use planning and policy implications: innovative thinking of soil inventory for land use planning and management of land resources. Dordrecht, Springer Netherlands.
41. HARROWER, M.J. et Al, 2012: ‘’Hydro-geospatial analysis of ancient pastoral/agro-pastoral landscapes along Wadi Sana (Yemen)’’, Journal of Arid Environments 86, 131–138.
42. KOTTEK, M. et Al, 2006: ‘’World Map of the Köppen-Geiger climate classification updated’’. Meteorologische Zeitschrift, 259–263.
43. LUEDELING, E. et Al, 2005: Drainage, salt leaching and physico-chemical properties of irrigated man-made terrace soils in a mountain oasis of northern Oman. Geoderma 125/3, 273–285.
44. LUEDELING, E. et Al, 2009: ‘’Climate change effects on winter chill for tree crops with chilling requirements on the Arabian Peninsula’’ Climatic Change 96/1, 219–237.
45. MORAETIS, D. et A, 2020: ’Terrace agriculture in a mountainous arid environment. A study of soil quality and regolith provenance: Jabal Akhdar (Oman)’’, Geoderma 363, 114152.
46. MUELLER D. et Al, 2023: ‘’Luminescence chronology of fluvial and aeolian deposits from the Emirate of Sharjah, UAE’’ Quaternary Research 112, 111–127.
47. MUHS, D, 2013: ‘’Loess and its geomorphic, stratigraphic, and paleoclimatic significance in the Quaternary’’, Treatise on Geomorphology 11, 149–183.
48. MUNSELL A.H, 2023: A color notation: a measured color system based on the three qualities, hue, values and chroma with illustrative models, charts and a course of study arranged for teachers. Delhi, Lector House.
49. NAGIEB, M. et Al, 2004 : ‘’ Settlement history of a mountain oasis in Northern Oman-evidence from land-use and archaeological studies’’ Die Erde; Zeitschrift der Gesellschaft für Erdkunde zu Berlin 135, 81–106.
50. PIETSCH D. & MABIT L, 2012: ‘’Terrace soils in the Yemen Highlands: Using physical, chemical and radiometric data to assess their suitability for agriculture and their vulnerability to degradation’’, Geoderma 185–186, 48–60.

51. POWELL D.M, 1998: ‘’Patterns and processes of sediment sorting in gravel-bed rivers’’, Progress in physical geography 22/1, 1–32.
52. POWERS M.C, 1953: ‘’A new roundness scale for sedimentary particles’’, Journal of Sedimentary Research 23/2, 117–119.
53. PRESTON, G.W. et Al, 2015: A multi-proxy analysis of the Holocene humid phase from the United Arab Emirates and its implications for southeast Arabia’s Neolithic populations. Quaternary International 382, 277–292.
54. PURDUE, L. et Al, 2021: Ancient agriculture in Southeast Arabia: A three-thousand-year record of runoff farming from central Oman (Rustaq). Catena 204, 105406.
55. REINECK.H.E. & Singh I.B, 2012: Depositional sedimentary environments: with reference to terrigenous clastics. (Second edition). New York, Springer Science & Business Media.
56. RUMPEL, C. & Kögel-Knabner I, 2011: ‘’Deep soil organic matter—a key but poorly understood component of terrestrial C cycle’’, Plant and Soil 338/1, 143–158.
57. SCHERER, S. et Al, 2021: What’s in a colluvial deposit? Perspectives from archaeopedology. CATENA 198, 105040.
58. SCHIFFER, M.B, 1987: ‘’Formation processes of the archaeological record’’. Salt Lake City, Utah, University of Utah Press.
59. SCHLECHT, E. et Al, 2009: ‘’Grazing itineraries and forage selection of goats in the Al Jabal al Akhdar mountain range of northern Oman’’, Journal of Arid Environments 73/3, 355–363.
60. SCHLECHT, E. et Al, 2011: ‘’The importance of semi-arid natural mountain pastures for feed intake and recycling of nutrients by traditionally managed goats on the Arabian Peninsula’’ Journal of Arid Environments 75/11, 1136–1146.
61. STANCHI, S et Al, 2012: Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps): A review. Quaternary International 265, 90–100.
62. STOCKMANN, U. et Al, 2013: ‘’The knowns, known unknowns and unknowns of sequestration of soil organic carbon’’, Agriculture, Ecosystems & Environment 164, 80–99.
63. THIEN, S.J, 1997: ‘’A flow diagram for teaching texture-by-feel analysis’’, Journal of Agronomic Education 8/1, 54–55.
64. Urban, B & Buerkert, A, 2009: ‘’Palaeoecological analysis of a Late Quaternary sediment profile in northern Oman’’, Journal of Arid Environments 73/3, 296–305.
65. Valente, T., et Al, 2022: ‘’The Jabal al Yamh tombs (Hatta, Dubai, UAE): The architecture, spatial distribution, and reuse of prehistoric tombs in south-east Arabia’’, Proceedings of the Seminar for Arabian Studies 51, 413–431.
66. Wei, W. et Al, 2016: ‘’Global synthesis of the classifications, distributions, benefits and issues of terracing’’, Earth-Science Reviews 159, 388–403.
67. Wentworth, C.K.: A scale of grade and class terms for clastic sediments. The Journal of Geology 30/5,1922, 377–392.
68. Wilkinson J.C, 1977: Water and tribal settlement in South-East Arabia- a study of the Aflaj of Oman, Oxford.Oxford University Press.
69. Wilkinson T.J, 2003: Archaeological landscapes of the Near East. Tucson, University of Arizona Press.
70. Wilkinson, T, 1999: Settlement, soil erosion and terraced agriculture in highland Yemen: a preliminary statement. Proceedings of the Seminar for Arabian Studies 29, 183–191.
71. Woor, S. et Al, 2023 :Morphology and controls of the mountain-front fan systems of the Hajar Mountains, south-east Arabia. Earth-Science Reviews 237. 104316.
72. Zaibet, L. et Al, 2004: Social changes, economic performance and development: the case of goat production in Oman. Small Ruminant Research 54/1, 131–140.