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RESEARCH ARTICLE

Applied Methodology of Field Survey and Selective Excavation to Understand the Late Islamic Landscape of Suhaila (Hatta, Dubai)

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Abstract

The archaeological site of Suhaila (Hatta, Dubai) constitutes one of the most representative late Islamic rural landscapes in the south-east of the Arabian Peninsula. This paper presents the results of a multi-scale investigation carried out between 2025 and 2026, integrating geospatial analysis using remote sensing and Geographic Information Systems (GIS), terrestrial laser scanning (TLS), systematic field survey and archaeological excavation. Spatial analysis of 16 sites and the documentation of over 190 structures reveal a clear relationship between settlement distribution and fluvial landforms: 60% of the structures are located on terraces and 68% in areas of temporary water accumulation, despite their limited coverage of the territory. These results suggest that site selection was closely linked to water availability in an arid environment. Excavations at Suhaila 6, 9, 10, 11 and 12 provide complementary information that allows the occupation to be dated mainly to the second half of the 19th century.

Keywords: South-Eastern Arabia, GIS, TLS, Gulf Archaeology, Hatta, Suhaila, Late Islamic Period, Mountainous Landscapes, Islamic Heritage.

1. Introduction

The Suhaila archaeological complex (Hatta, Dubai) constitutes one of the most representative late Islamic rural landscapes in the south-east of the Arabian Peninsula, comprising multiple sites distributed across a mountainous environment and dating from the 16th to the 20th centuries.

Research conducted in arid environments has repeatedly highlighted the decisive role of water resources in settlement organization and subsistence strategies (Butzer, 1982; Wilkinson, 2003). In regions such as south-eastern Arabia, where water availability is limited and highly variable, human communities have developed forms of adaptation closely linked to the exploitation of favorable microenvironments, both on the surface and in underground systems (Edgell, 2006; Glennie, 2005). In this regard, *wadis*, together with hydraulic technologies developed by human communities, such as *falaj* systems, have played a fundamental role in shaping the inhabited landscape (Costa, 1985; Wilkinson, 1977).

In the Hatta area and its immediate surroundings, these dynamics take on particular significance due to the geomorphological conditions of the Al-Hajar mountain range, characterized by greater relative water availability compared to the surrounding plains. Recent studies have highlighted how these mountainous environments generate micro-spaces with greater potential for the development of agro-pastoral activities and permanent settlements (Magee, 2014; Al-Hashimi, 2022).

In this context, the Suhaila site represents a prime case study for exploring the relationship between environmental conditions and settlement organization. Recent research, funded by *the Dubai Culture and Arts Authority* and carried out by *the Sanisera Archaeology*

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Institute, has significantly expanded our understanding of the site through a multi-scale approach integrating systematic survey, terrestrial laser scanning (TLS), geospatial analysis using Geographic Information Systems (GIS) and stratigraphic excavation.

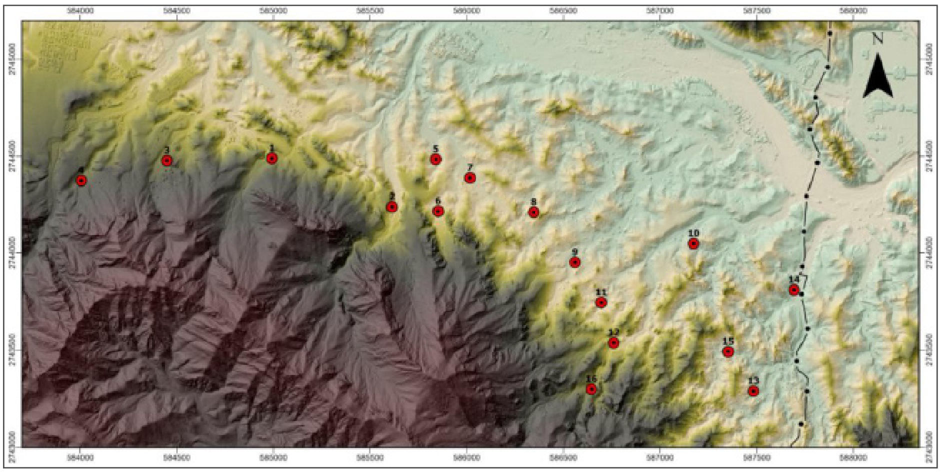

Figure 1. *Spatial distribution of Suhaila sites overlaid on a 3D digital terrain model. © Adrián Fernández-Sánchez and Esther Fernández*

The Suhaila archaeological complex is located in the Hatta area, in the Emirate of Dubai, within the Al-Hajar mountain range (Figure 2). The site's coordinates are X:24.80030928, Y:56.18500416769029.

The Suhaila archaeological site represents a strategic enclave in the foothills of the Jabal Qallat Sabba Mountain range (Feulner, 2023). This mountainous and arid environment (Boer, 1997) has significantly shaped human settlement, both in terms of its spatial distribution and its temporal patterns. It comprises nearly a thousand structures dating from the 16th to the 20th centuries, grouped into more than 16 sites on the northern slopes of Jabal Qallat Sabba (250–450 m).

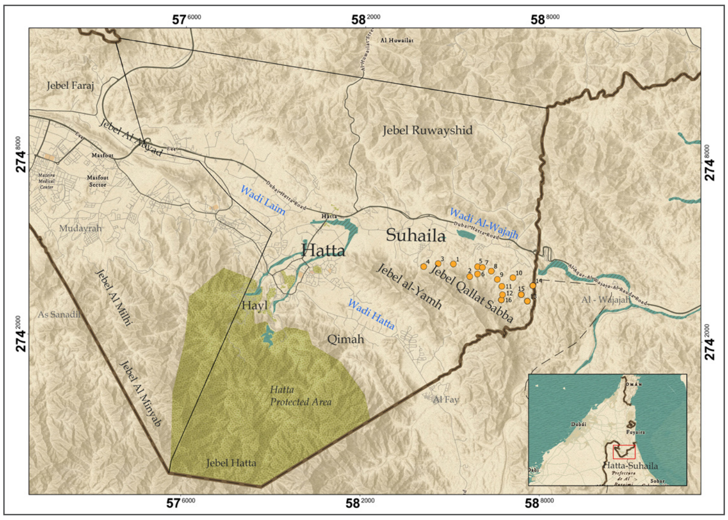

Figure 2. *Location of Hatta within the United Arab Emirates (UAE), showing its position near the Oman border. © Esther Fernández and Adrián Fernández*

The lithology of the study area combines ophiolitic geological materials with sedimentary and metamorphic formations (UAE Ministry of Energy, 2006); tectonic fracturing and faults generate a rugged topography and a dense network of *wadis* (Pain & Abdelfattah, 2015) which determines how the settlement is situated in Suhaila.

The climate is characterized as arid mountainous, with scarce rainfall concentrated in winter and summer monsoon episodes (UAE Ministry of Energy, 2006). In contrast to the desert plains, these areas feature cooler and more humid microenvironments favorable to settlement.

The Al-Hajar Mountains stretch 600 km parallel to the Omani coast (Burt, 2024); they have served as both a physical barrier and an 'oasis' with the highest rainfall within the surrounding desert environment of the south-east Arabian Peninsula. Furthermore, Suhaila lies on the northern slope of Jebel Al-Yamh, near Wadi Al-Wajajah and Wadi Hatta, which collect water from all the neighboring mountains.

Archaeological research carried out at the Suhaila site in recent years has contributed to our understanding of the historical and archaeological heritage preserved in the Hatta region. The work carried out by *Chronicle Heritage Arabia* focused on the Suhaila 1, 3 and 4 sites, where excavations of domestic structures and associated agricultural features were conducted, combined with topographic surveys, geoarchaeological sampling, photogrammetry and laser scanning. These interventions generated high-resolution stratigraphic, architectural and environmental datasets, enabling significant progress in reconstructing the development of agricultural terraces, sedimentary dynamics and long-term landscape use in the mountainous environment of Hatta (Chronicle Heritage Arabia, 2025).

At Suhaila 2, the work carried out by *ARCHITravs* combined archaeological excavation with partial restoration of the site, alongside high-resolution laser scanning and the creation of a geospatial database aimed at architectural documentation and conservation planning (ARCHITravs & DCAA, 2024).

In parallel, the survey programs led by *the Dubai Culture and Arts Authority* expanded archaeological documentation to new areas of the site, particularly at Suhaila 10, 13, 14, 15 and 16. Through systematic foot surveys, total station survey and rapid architectural documentation, this work enabled the identification of over a hundred previously undocumented structures, contributing to a better understanding of settlement distribution patterns in the eastern sectors of the landscape (Dubai Culture and Arts Authority, 2025).

2. Methodology

The project integrated remote sensing, geological, geomorphological and hydrological analysis, TLS scanning, field survey and excavation. It was carried out in six phases between June 2025 and February 2026 (Figure 3). These phases comprised: geospatial data acquisition, GIS analysis, systematic field survey and TLS scanning carried out in parallel during the fieldwork.

Subsequently, integrated interpretation (Nov 2025–Feb 2026) and excavation (Jan–Feb 2026) provided the final stratigraphic and chronological data.

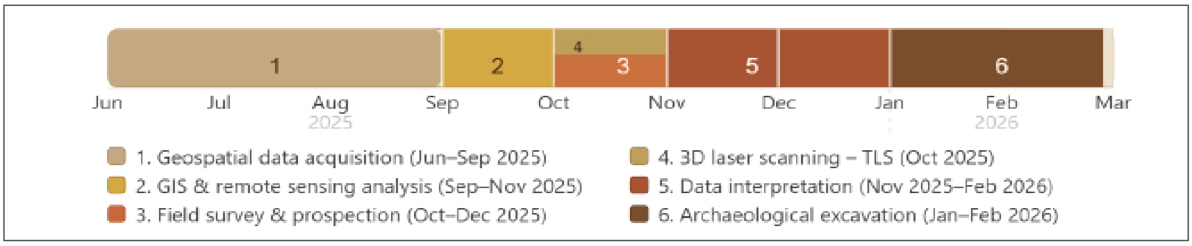

Figure 3. *Timeline of the research carried out at Suhaila by the Sanisera Archaeology Institute.*

2.1 Acquisition and Processing of Spatial Data

Cartographic and remote sensing sources (both public and high-resolution commercial) were compiled to establish the spatial framework of the project (Table 1).

Table 1. *Data sources used in the project.*

Product	Resolution	Source	Format	Transformation applied
Satellite image	15 cm	Skyfi	.tif/jpg	Radiometric correction
Satellite image	50 cm	Airbus/Living Atlas ESRI	.tif	-
Satellite image 1998	50 cm	Airbus	.tif	-
Aerial photograph 1965	2 m	CORONA Program	.tif	Georeferencing
Topography (contour lines)	10 m	Nextmap	Shapefile	-
DEM	30 m	ASTER/NASA DEM	Raster/DEM	Conversion to contour lines
DTM	1 m	Pleiades/photogrammetric restitution	Raster/DEM	3D visualization and geomorphological analysis
LiDAR surveying (3D scanning)	2 mm	Amelia Hub	.las/.laz	Georeferencing and point clouds
Regional geological mapping	-	BGS/Styles et al., 2006/ Lacinska et al., 2015	Vector/ publications	Georeferencing and digitization in ArcGIS Pro
Location of deposits	-	Dubai Culture and Arts Authority	.kml	-

The main reference was a 15 cm Skyfi satellite image, radiometrically corrected in ArcGIS Pro (Figure 4), supplemented by a 50 cm Airbus image from Living Atlas to provide a broader context.

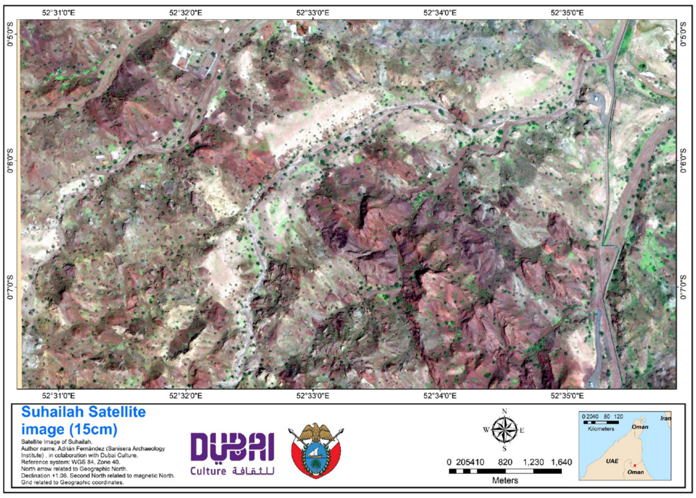

Figure 4. *Ultra-high-resolution satellite image (15 cm pixel size). © Adrián Fernández-Sánchez*

For topography, Nextmap contour lines (10 m), a derived DEM and the 30 m ASTER DEM (NASA, 2019) were used. Pleiades stereo pairs (20 cm) were acquired, forming the basis for the high-resolution DTMs. All data were integrated into ArcGIS Pro to generate base maps (contour lines at 2 and 20 m intervals, shaded relief and settlements from DCAA KML) (Figure 5).

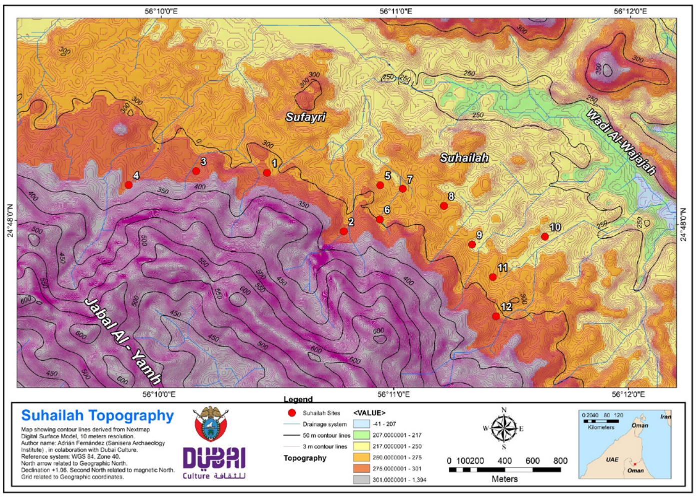

Figure 5. *Contour map (5 m interval) showing the drainage system and Suhaila sites. Topographic map with shaded relief and elevation values derived from Nextmap (10 m resolution). © Adrián Fernández-Sánchez*

2.2 Generation of High-Resolution Digital Elevation Models

The Sanisera Archaeology Institute and the company *AlturaGeo* generated a high-precision DEM using photogrammetric processing of Pleiades Neo imagery, an alternative to drones (which are not authorized in Suhaila as it is located in a border zone). The 30 cm resolution and stereoscopic capture enabled the creation of a high-precision DEM (Figure 6).

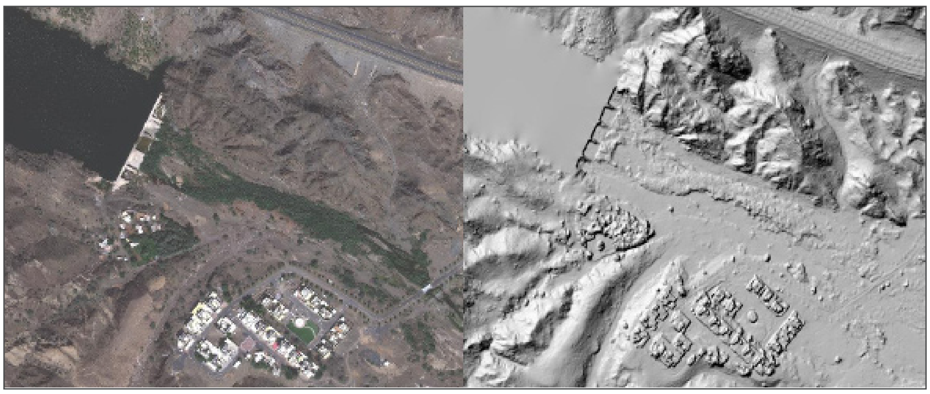

Figure 6. *Example of satellite image conversion to a Digital Elevation Model.*

Table 2. *General properties of the data used.*

Sensor	Date	Solar Elevation	Off – nadir	GSD
Pleiades NEO	25/10/2024	50.00°	16.72°	30 cm
	25/10/2024	49.94°	13.00°	30 cm
Reference image	12/04/2024	52.00°	ND	0.15 m

Pleiades NEO stereo pairs and a reference Sentinel DEM (CE90 <5 m; 15 cm ground resolution) were used, generating DEMs at 0.5 and 1 m resolution in Ortho Engine (PCI Geomatics) using the panchromatic band. The Ortho Engine software estimated the initial position using RPC methodology, Manual GCPs (RMS <5 m) were then added, together with automatic control points derived from NCC correlation and the SUSAN corner detector; both are essential for 3D reconstruction. Following RPC correction, epipolar resampling and DEM extraction via semi-global correlation (SGM) were applied, smoothed with average filters at 0.3 and 1 m. The adjustment achieved a planimetric RMS of 1.02 m and an altimetric RMS of 3.58 m (43 active GCPs), with 150 link points at sub-pixel RMS (<0.1 m), confirming the consistency of the stereo model.

2.3 Environmental Characterization: Geology, Geomorphology, Climatology, Hydrology and Land Cover Classification

A range of environmental analyses were carried out, including geomorphological, geological, climatic and hydrological analyses, as well as analyses of water-collecting surfaces and areas. To this end, aerial photointerpretation techniques—both current and historical—were employed, alongside classifications based on *machine learning* and the analysis of climate time series.

To characterize the geological framework, regional maps were consulted (Lacinska et al., 2015; Styles et al., 2006; BGS), which were subsequently georeferenced and digitized in ArcGIS Pro in order to correlate the lithology with the distribution of the deposits. The analysis focused on identifying the types of materials and rocks (lithology), as well as geological formations, taking into account the evolution and chronology of the deposits.

Geomorphological mapping was carried out by combining photointerpretation of high-resolution imagery (15 cm), historical CORONA imagery from 1965 and a 1-metre resolution digital elevation model (DEM) from Pleiades (SNCZI, 2015; Elorza, 2013). This approach allows for the modelling of past landscapes (Tucker & Hancock, 2010) and the analysis of the relationship between the sites and the physical environment (Forti et al., 2023; Sofia, 2020; Xiong et al., 2022).

Fluvial, volcanic, structural, eolian and gravitational landforms, as well as areas of surface water accumulation, were mapped as vector layers in ArcGIS Pro. Among the fluvial landforms, modern, ancient and very ancient terraces, valley floors, *wadi* sediments, point bars, meanders, scroll bars and alluvial fans were identified; the distinction between ‘modern’ and ‘ancient’ is based on criteria of relative position, rather than absolute dating. Each landform was linked to possible anthropogenic interpretations, such as the use of modern terraces in agricultural contexts.

Using the 15 cm Skyfi image, areas of surface water accumulation with higher seasonal moisture were identified, which favour vegetation and potential livestock use. An automatic classification using Machine Learning in ArcGIS Pro was applied to the RGB spectral signatures.

The Classification Wizard tool performed this supervised classification on a pixel-by-pixel basis using training areas and models such as Random Trees or Support Vector Machines. The entire territory was classified (scrubland, acacia trees, sediments, fissuring, water accumulation, etc.) and compared with settlements.

To characterize daily precipitation in Suhaila, the ERA-5 reanalysis (1979–1990) was used, comparing it with arid inland areas of Dubai and some other parts of the UAE. For the 18th–20th centuries, paleoclimatic proxies (speleothems from Hajar; Fleitmann et al., 2004, 2007) and studies on precipitation in the UAE (Ouarda et al., 2014) were used. Aquifer and *wadi* recharge was interpreted using the arid hydrogeology literature (Alsharhan & Rizk, 2020; Burt, 2024), integrating precipitation with geomorphological and hydraulic field evidence.

The hydrographic network was generated using the Spatial Analyst tool in ArcGIS Pro and manual digitization via photointerpretation. The automated phase was based on the 10-metre resolution NextMap digital elevation model (DEM), from which flow direction and accumulation were derived.

The result was a coherent and reproducible drainage network, subsequently refined through manual photointerpretation of high-resolution (15 cm) Skyfi imagery across the entire Suhaila area (1–16), in order to improve its fit for hydrological and archaeological analysis.

2.4 Anthropic Context: Ancient Transport Routes, Hydraulic Structures and Cultivated Areas

The archaeological interpretation of the areas modified by human activity in the Suhaila territory was manually represented on the ArcGIS platform, differentiating it into three themes: communication routes between sites, water management structures, and the designation of areas suitable for cultivation and irrigation.

The historical routes were obtained by combining automated calculations in ArcGIS Pro with manual digitization of images from 1965 and 1998. The 'Optimal Path as a Line' tool defined the lowest-cost corridors based on the 1-metre DTM, prioritizing the gentlest gradient and greatest accessibility.

The routes were cross-checked against visible paths in the CORONA (1965) and Airbus (1998) imagery; the 1965 routes, predating modern tourism, were assumed to be the closest to the ancient ones. They were digitized for Suhaila 1–16.

Using the 15 cm image and the 30 cm DEM from Pleiades NEO, dams, *falaj-type* canals and man-made flood defenses were identified. These same man-made structures were subsequently confirmed in the field through geological survey analysis.

Former and still-active agricultural areas were digitized using images from 1965, 1986 and 1998. These areas coincided with artificial or natural terraces (Figure 7).

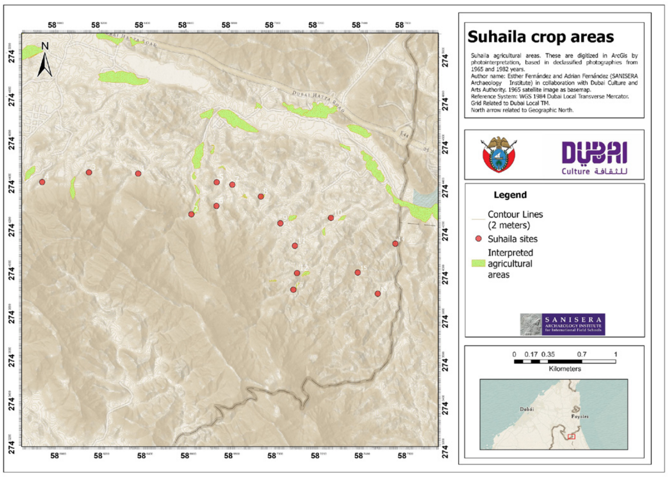

Figure 7. *Identification of ancient cultivation areas through photointerpretation. © Esther Fernández and Adrián Fernández*

Geomorphological mapping was integrated with information on human land use in order to identify areas with different potential for historical use. To this end, a correlation was established between the various geomorphological units and possible land uses, based on criteria of water availability, moisture retention and sediment accumulation.

Based on this analysis, categories of potential use (high, medium and low) were defined for each type of landform. Modern river terraces and alluvial fans were considered areas with a high probability of having supported agricultural activities, whilst ancient and very ancient terraces were classified as having a medium probability. Areas of surface water accumulation were interpreted as areas with a high probability of pastoral or agricultural use.

Meanwhile, valley floors, *wadi* sediments and internal river bars were classified as areas with a low probability of agricultural use, but with high potential for the presence of hydraulic infrastructure, such as irrigation systems or wells. Finally, point bars were considered areas with a high probability of both agricultural use and hydraulic exploitation.

2.5 Field Archaeological Survey and Previously Unrecorded Structures

Initially, two surveys were carried out: one using remote sensing techniques on 15 cm resolution imagery to detect structures and geological areas of interest, and another involving direct archaeological reconnaissance.

In the field (October–December 2025), the surveys at Suhaila 8–12 guided *Amelia Hub* in the work to be carried out using a laser scanner for each site.

2.6 Site Documentation Using TLS/3D Scanning

This type of documentation was carried out at the Suhaila 8–12 sites using terrestrial laser scanning (TLS), due to restrictions on the use of drones in areas near the border with Oman. The area covered was 48.3 ha, with a total of 222 structures documented around two wadis of Wadi Al-Wajajah. Data acquisition was carried out by the company Amelia Hub using a Leica RTC360 scanner (accuracy ±1.9 mm at 10 m, range of 130 m and capacity of 2 million points per second).

Positioning was carried out using GPS bases established via reference coordinates provided by the DCAA, defining control points at each site (S9-2, S11-1, S12-1 and S10-1). Georeferencing was completed by placing Leica HDS retro-reflective targets on the structures, enabling the transformation from the UTM system to DLTM with errors of less than ±5 mm.

The scanning of the structures was carried out in 2–3-minute sessions, generating high-density point clouds and associated orthophotos. Multiple positions were taken to ensure complete coverage of the area. Of particular note is the documentation of the Suhaila 9-22 well (7–9 m deep), recorded using a 15 m extendable tripod in an inverted position, whose point cloud enabled the identification of dry-stone construction features attributable to the 19th century.

Data processing was carried out in parallel with the fieldwork using Leica Cyclone REGISTER 360 software, and the data was subsequently exported in .LAZ and .LAS formats with full RGB information. The data was integrated into GIS environments (ArcGIS Pro and QGIS), as well as into specific CAD formats (.E57 and .LSG).

The vector digitization of the structures in CAD, carried out by *Amelia Hub*, was subsequently supervised in the field by *the Sanisera Archaeology Institute* to ensure the interpretation was as accurate as possible, distinguishing between elements such as internal and external walls, structural frameworks and areas of collapse. This process enabled the generation of a high-precision cartographic base integrated into the spatial analysis of the site.

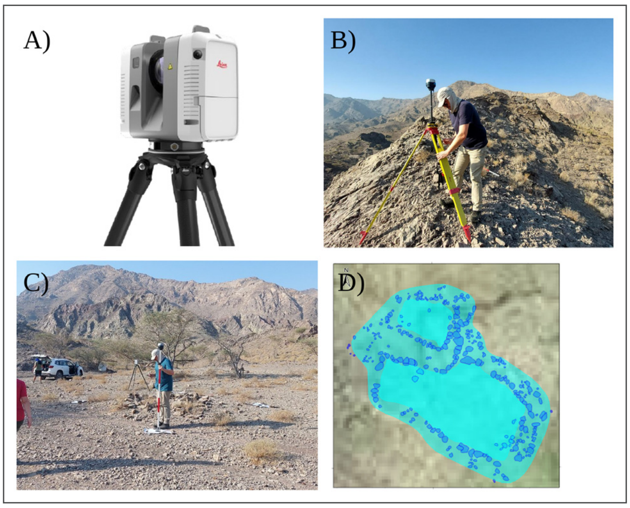

Figure 8. *A) Leica RTC360 phase-based laser scanner used for data acquisition. B) Amelia Hub technician positioning the GNSS rover on high ground for georeferencing control points. C) Scanning session in the Suhaila 8 area. D) Stone-by-stone digitisation. © Amelia Hub / Sanisera Archaeology Institute / DCAA.*

2.7 Archaeological Excavation

Regarding the archaeological excavation, several structures were selected from various sites within the Suhaila complex. At Suhaila 6, structures 5, 6, 7 and 23 were excavated; at Suhaila 9, structure 18; at Suhaila 10, structure 31; at Suhaila 11, structure 4; and at Suhaila 12, structure 11. This work enabled us to expand the available information on different areas of the archaeological complex.

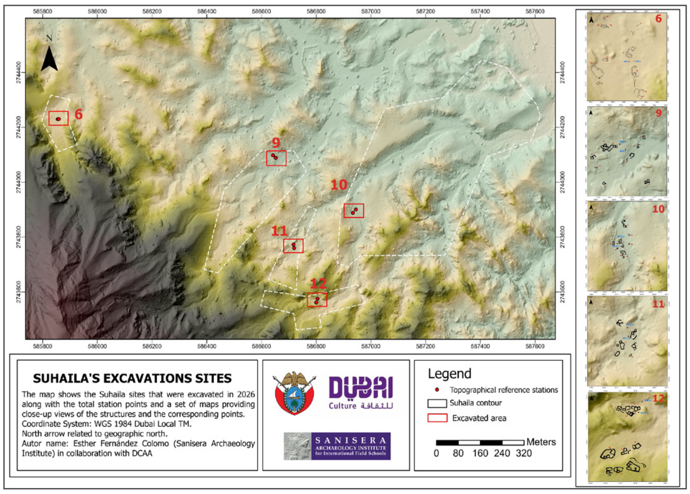

Figure 9. *Suhaila excavation sites (6, 9, 10, 11, 12) showing excavated areas and reference points used for the total station. © Esther Fernández*

The excavation was carried out following single-context stratigraphic methodology based on the Harris matrix. Sediments were sieved, individual finds were recorded using a total station, and systematic sampling of charcoal and ash was carried out for radiocarbon (^{14}C) dating (Figure 10).

Figure 10. *A) Sieving of excavated sediment using a 5 mm mesh during fieldwork at Suhaila. B) Recording of archaeological finds using a total station. C) Sampling of charcoal from a combustion feature for radiocarbon (^{14}C) D) Photographic setup for the documentation of archaeological materials.*

3. Results

3.1. Acquisition and generation of geospatial data

High-resolution topographic mapping was generated: 1 m for Suhaila 1–16 and 30 cm for Suhaila 8–12. Figure 11a shows the 1 m topography between Suhaila 1 and 16, with contours every 25 m from the Pleiades DEM. Figure 11b shows the 30 cm topography for Suhaila 8–12.

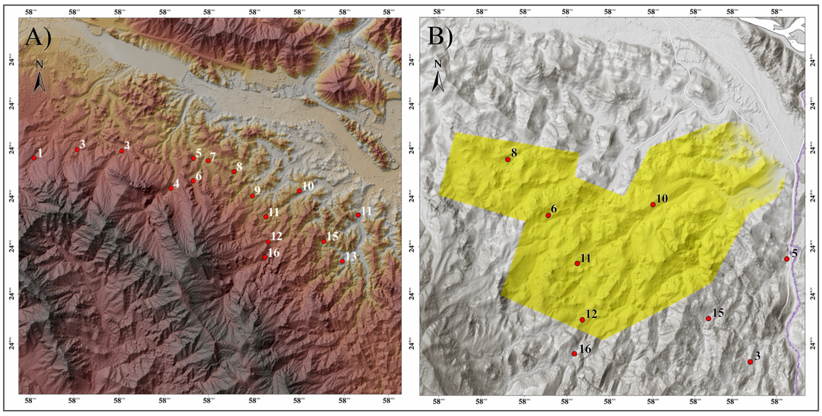

Figure 11. *A) General topography of the Suhaila site between sites 1 and 16 at 1-metre resolution B) Topography at 30-centimetre resolution for Suhaila 8–12.*

The 30 cm map is key for hydrological, geological, geomorphological and hydraulic structure analysis. The external orientation has a planimetric accuracy of ~1 m and an altimetric accuracy of ~4 m; the RMS in Z is ~3.6 m. The expected vertical accuracy is 3–5 m on non-steep surfaces, consistent with metric RPC/GCP products.

3.2 Environmental Characterization: Geology, Geomorphology, Climatology, Hydrology and Land Cover Classifications

Suhaila lies on the northern slope of Jebel Al-Yamh, with volcanic rocks, mafic dikes and wadi sediments, shaped by folds, faults and eroded dikes; to the south, colluvial foothills predominate. Lithologically, volcanic rocks of the Hawasina Series dominate (Styles et al., 2006; Figure 17): Mesozoic *nappes* (265–86 Ma), remnants of the Tethys margin thrust onto the Arabian Plate in the Upper Cretaceous, comprising the Hamrat Duru and Wahrah formations and a complex tectonic folding pattern. Possibly Palaeozoic conglomerates outcrop in the upper part, while Quaternary sediments dominate the foothills and Wadi Al-Wajajah. The sequence ranges from the Mesozoic (Hawasina) to the exposure of ancient conglomerates following erosion.

Archaeologically significant exceptions: Suhaila 2 on quartzite; Suhaila 7 and 8 on the mafic volcanic dyke; Suhaila 10 at the dyke/Hawasina transition. Hawasina rocks were the main building material; the fissility of the mafic dikes favours the drilling of wells (Suhaila 8, 15 and 16).

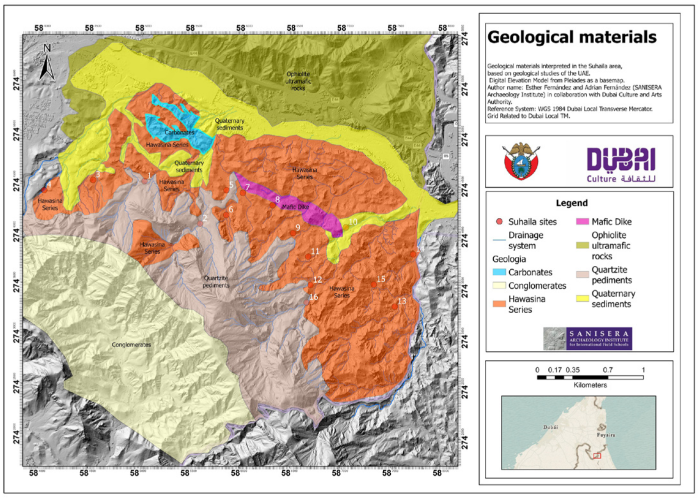

Figure 12. *Map of geological materials in Suhaila. © Adrián Fernández-Sánchez*

The dominant landform in the area is modern terraces (337 areas, 0.46 km² = 4.28% of the total 10.8 km²), with a high probability of human use (crops or livestock). The 28 ancient or very ancient terraces cover 1.23 km² (10%); they have a low probability of cultivation but are suitable for deep wells or irrigation channels (Burt, 2024). The two identified alluvial fans cover 1.2% and retain a high probability of cultivation, and are still active today.

In total, more than 5.6% of the Suhaila area is highly likely to be cultivable (modern terraces + alluvial fans). Table 3 shows the geomorphological classification beneath each Islamic dwelling.

Table 3. *Percentage of Islamic structures located on each of the landforms.*

Geomorphology	*Percentage of structures in each geomorphology*
Alluvial Fan	0%
Anticline	0%
Fluvial Bar	0%
Landslide	0%
Wadi sediments	4%
Old terraces	26%
Modern terraces	38%
Geological dike	0%
Fissured dike	30%
Colluvial	4%
Total	**100%**

34% of the structures are situated on modern terraces and 26% on ancient ones: the total of 60% on terraces highlights the link with areas suitable for cultivation and water extraction. The second most common landform is fissured volcanic rock (30%), found in Suhaila 8, 15, 16 and part of 10; although difficult to build on, it is favorable for wells. The remainder is situated on valley floor sediments and colluvial deposits.

Machine learning detected numerous areas of surface water accumulation due to herbaceous vegetation, useful as livestock pasture and for extracting water via wells. Supervised classification identified 12 areas (Table 4); the accumulation zones accounted for 9.1% (1.1 km²) of the total.

Table 4. *Percentage of Islamic structures at Suhaila located in each of the classified areas.*

Classified	*Percentage of structures in each surface classification*
Volcanic rock	4%
Terraces	4%
Sediments	0%
Fissured rock	3%
Colluvial	14%
Water	0%

Dwellings	0%
Developed	1%
Uninhabited	6%
Acacia area	0%
Palm areas	0%
Pastures	68%
Total	**100%**

The second group consists of colluvial areas (14% of the structures); the remainder is distributed among terraces, fissured terrain and volcanic areas. Figure 18 shows that, despite being in the minority, water accumulation zones contain the majority of the structures.

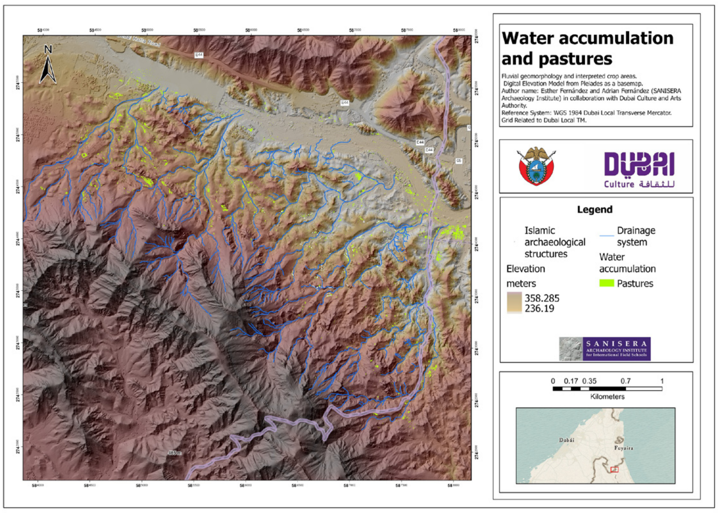

Figure 13. *Results of the automatic detection of areas of temporary water accumulation or pasture.*

Information on precipitation in Suhaila is limited due to the absence of local weather stations; the available data come mainly from reanalyzes and specific studies from the late 20th century. Current average annual precipitation in the Hajar Mountains is around 180 mm, higher than in the surrounding deserts, although characterized by high interannual variability (Purdey and Crépy, 2025; Ouarda et al., 2014).

In the adjacent arid areas, daily precipitation maxima do not exceed 3–5 mm, indicating greater relative water availability in Suhaila. However, rainfall is infrequent, as only around 3% of days in the year record values of 1 mm or more. This rainfall regime is therefore defined both by a relatively higher amount of precipitation and by a strong concentration of intense, sporadic rainfall events. The combination of this irregularity, sparse vegetation cover and rugged topography favours the development of highly ephemeral *wadis*, with a very limited capacity for water retention.

Data from the 20th century, whilst useful as a reference, fall chronologically outside the main period of occupation documented at Suhaila, and for the 16th–20th centuries there are hardly any direct records of precipitation. Between the 17th and 20th centuries, an alternation of wet and dry phases is documented, with a general trend towards drier conditions during the 20th century, intensifying from the end of that century onwards (Ouarda et al., 2014), in line with patterns observed at a regional scale in the United Arab Emirates.

In this context, the Hatta and Suhaila *wadis* act as natural collectors that transport sediments and promote aquifer recharge during short-lived rainfall events, in the absence of permanent watercourses (Alsharhan and Rizk, 2020). This hydrological framework suggests that settlement dynamics may have been influenced by water availability, including possible movements towards the *Hajar* Mountains from more arid areas in search of greater water stability.

The hydrographic networks of Suhaila (1–16) were calculated in ArcGIS Pro and manually refined through photointerpretation. The hydrographic network is hierarchical but young, with elongated and short channels that flow into Wadi Al Wajajah in close proximity to one another.

The longest *wadi* measures 3,262 m and crosses Suhaila 2, without crossing other sites downstream, possibly due to recent human activity. The second (2,693 m) crosses the border with Oman via Suhaila 14 and 16. There are five other *wadis* >1 km (light blue on the map).

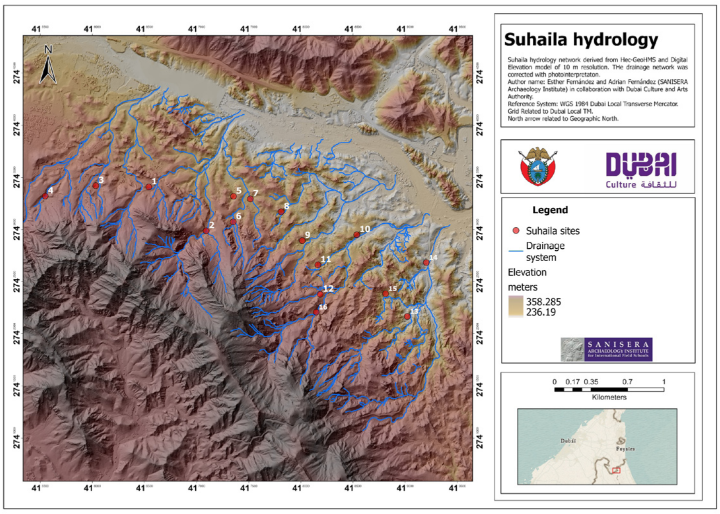

Figure 14. *Suhaila river basins, together with the river network and their numbering. © Esther Fernández and Adrián Fernández.*

Most sites are associated with long rivers, except for Suhaila 5, 6 and 7. Features of structural control (possible faults) are observed, particularly in meanders with abrupt changes in direction.

Five main sub-basins were identified, indicative of each river's catchment area. Basins 1 (border with Oman) and 7 are the largest (2.05 km² each), with the highest catchment area and potential flow. Nevertheless, the sites are concentrated in basins 2 and 5 (the 2nd and 3rd largest), including the densest ones: Suhaila 10, 12 and 2.

Table 5. *River basin number, area in km² and sites associated with each basin.*

Watershed Number	Area (Km^2)	Sites
1	2.05	13, 14, 15
2	1.59	10, 11, 12, 13
3	1.21	9 and 8
4	0.34	None
5	1.77	2, 5, 6, 7
6	0.34	None
7	2.05	9 and 8

Suhaila 10, 11, 12 and 16 account for 45% of the dwellings and share the wadi of basin 2. Rounded sediments >1 m and the terraces indicate that this wadi carried the greatest volume of water; in Suhaila 10, the dwellings are situated high above the terraces, a sign of a flow that was at times violent. The concentration in basin 2 suggests a possibly higher flow rate. Basins 1 and 7, despite being larger, have permeable substrates (sands, fissured shales/quartzites) that reduce the effective flow rate.

3.3 Anthropic Context: Hydraulic Structures, Ancient Transport Routes and Cultivated Areas

Fieldwork revealed dams, canals, wells and cisterns that demonstrate the use of water resources, which are scarce but present. The dams are small in scale, indicative of the highly seasonal nature of the *wadis*, capable of capturing a few hundred liters, but essential for retaining the flow.

Figure 15. *Two dams found near Suhaila 9-7. Channels distributing water*

Figure 16. *Suhaila 10, showing falaj structures (blue arrow), dams (yellow line), and artificial terraces (red line).*

At Suhaila 10, man-made terraces, defenses along the riverbed and a falaj leading from a small dam have been identified (Figure 16). Some of the stones may have been repositioned with modern machinery, although the overall structure is morphologically consistent with an early construction and shows clear signs of collapse.

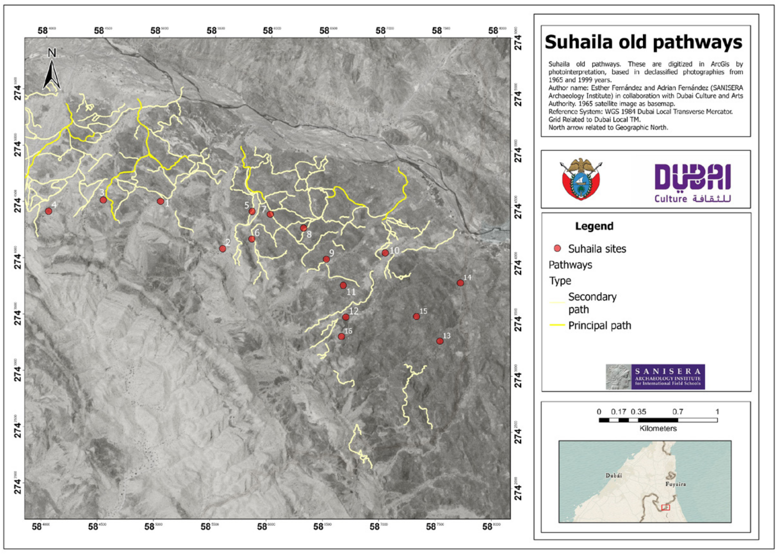

Figure 17. *Ancient routes photo-interpreted in Suhaila. © Esther Fernández and Adrián Fernández.*

The ancient routes were calculated in ArcGIS Pro and refined manually using images from 1965 and 1998. All the main settlements were interconnected, with an uninterrupted route running west to east from Suhaila 4 to Suhaila 12 or 16. Suhaila 13, 14 and 15 appear disconnected, with no identifiable ancient routes.

It is likely that these routes existed, although the eroded rock prevents them from being clearly observed. Figure 17 shows the main and secondary routes interpreted according to the methodology. Suhaila 2 appears disconnected from the routes, but is accessible via the wadi, indicating that the *wadis* themselves were used as an additional route.

The cultivated areas were digitized from images dating from 1965 and 1998, prior to the complete transformation of Suhaila; some degraded ancient crops may date from the early 20th century. The cultivated areas and *falaj* were digitized in ArcGIS Pro from these images.

Figure 18 shows crops concentrated near Wadi Al-Wajajah, on the flat, fertile natural river terraces. Near Suhaila 3 there are minor crops, and at Suhaila 1 and 4 there are artificial terraces for irrigation. Most of the crops are in the western area.

Many crops are established on agricultural plots measuring between 150 and 200 m, with a roughly rectangular layout, adapted to the topography by means of artificial terraces. Agricultural production was specialized according to the sediments: date palms, oases and species adapted to the arid environment. Figure 18 shows date palm crops that were active in 1986, as confirmed by the historical satellite image.

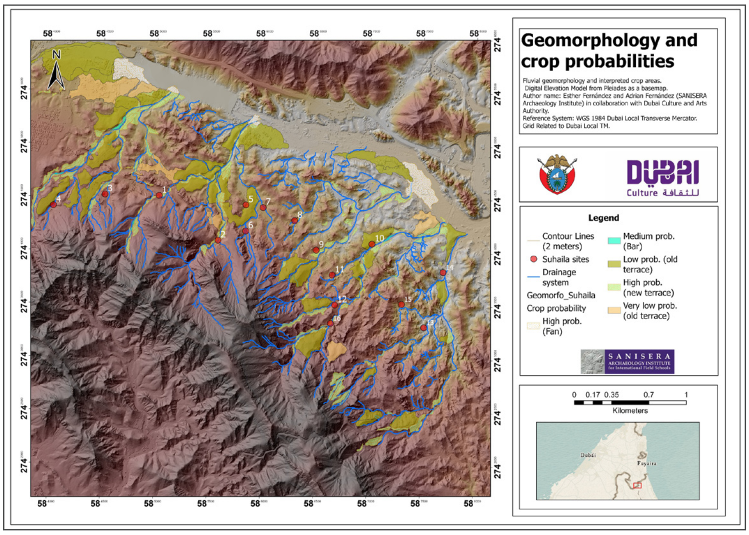

Figure 18. *Geomorphological mapping of areas under human use in the Suhaila region, using the Pleiades DEM as a base map. © Esther Fernández and Adrián Fernández.*

3.4 TLS Scanning of Islamic Structures

The TLS documented 194 structures across 65 hectares at four sites (Table 6): Suhaila 9 (82), Suhaila 12 (50), Suhaila 11 (26) and Suhaila 8 (23). Suhaila 10 was only partially documented due to its large extent. At Suhaila 9 and 11, dwellings of 4–5 m and livestock structures of up to 8 m predominate; at Suhaila 10 and 12, structures of up to 6 m in diameter.

Table 6. *Number of scanned structures, newly identified structures and other evidence.*

Site	Area	Structures scanned	New structures	Other evidence	Scanning method
Suhaila 8	7.77 ha	23	1	1 possible tomb	RGB Colour
Suhaila 9	12.22 ha	82	1	2 hydraulic dams	RGB colour
Suhaila 10	28.15 ha	13	1	1 hydraulic dam	Grayscale
Suhaila 11	4.88 ha	26	2	1 undetermined	RGB colour
Suhaila 12	2.87 ha	50	0	2 indeterminate	Grayscale
TOTAL	56 ha	194	5	7 pieces of evidence	

The digitization of the structures at each site generated four cartographic outputs in ArcGIS Pro: outline, stone-by-stone, combination without fill, and a functional map colour-coded according to domestic, livestock or funerary use.

The kernel density analysis (Figure 19) shows that the southern groups, corresponding to Suhaila 12 and the center of Suhaila 10, have the highest concentration of structures, suggesting that the Suhaila 10 *wadi* valley may have been a settlement of some size on which the population center of Suhaila 12 was entirely dependent.

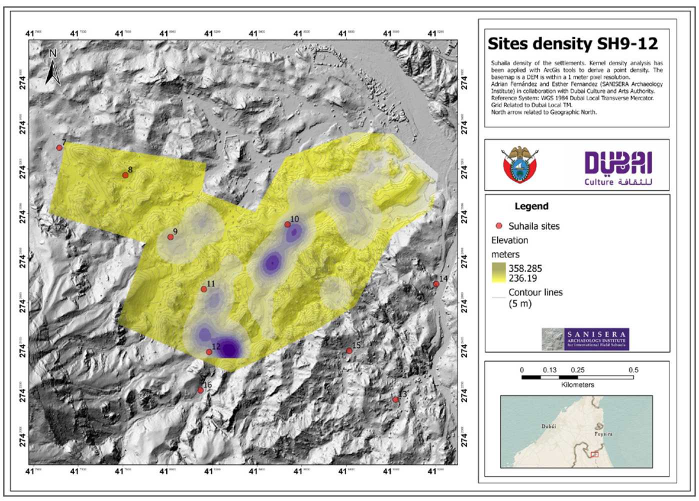

Figure 19. *Map of structural density at the Suhaila 9 to 12 sites, created in ArcGIS Pro.*

3.5. Archaeological Excavation: Architectural Characterization, Materials and Chronology

Excavations at the Suhaila 6, 9, 10, 11 and 12 sites have documented a series of architectural units distributed close to the *wadis*. From a stratigraphic point of view, the structures display a simple sequence, characterized by a level of abandonment associated with the collapse of the walls, with thicknesses of between 10 and 20 cm, which directly covers a single occupation level. No evidence of structural alterations or modifications to the walls has been identified, suggesting a single phase of use in the excavated structures.

At Suhaila 6 (Figure 20a), several rectangular domestic structures (5, 7 and 23) were identified, featuring enclosed floor plans and defined entrances, alongside a semi-open space bounded by a wall (structure 6) adjacent to structure 7. At Suhaila 9 (Figure 20b), Structure 18 has a tripartite layout comprising two domestic rooms (18a–b) and a larger adjacent area to the west (18c). At Suhaila 10 (Figure 20c-21), Structure 31 comprises a domestic unit (31a) and a courtyard with an internal subdivision, accessed by a stepped descent from ground level; this leads first to an upper space and then to a lower one to the north, where four hearths were documented (31b). Two separate spaces, potentially used as livestock shelters, were also identified (31c-d). At Suhaila 11 (Figure 20d), Structure 4 comprises a domestic room (4a) and an adjacent courtyard to the south, containing four hearths (4b). Finally, at Suhaila 12 (Figure 20e), Structure 11 comprises a complex of multiple rooms organized around a central space (11a–d), with a domestic unit situated at a higher elevation in the southern part (11a).

Figure 20. *Aerial views of the excavated sites at Suhaila: A) Suhaila 6, structures 5, 6, 7 and 23; B) Suhaila 9, structure 18; C) Suhaila 10, structure 31; D) Suhaila 11, structure 4; E) Suhaila 12, structure 11.*

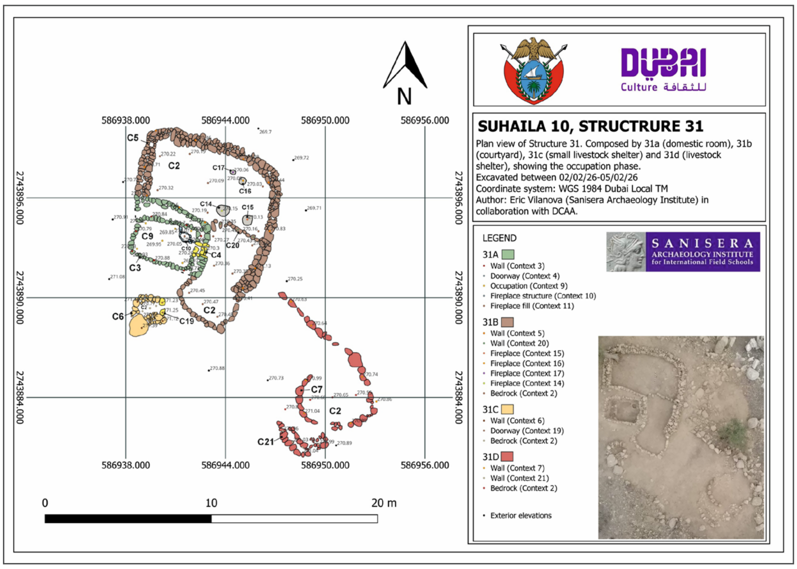

Figure 21. *Plan view of Suhaila 10, structure 31. © Eric Vilanova.*

Within the excavated units, the rooms identified as domestic spaces are characterised by the presence of formalised entrances, the existence of fireplaces within them and relatively uniform dimensions, ranging from approx. 3.10–3.70 m in length and 1.80–2.30 m in width (Figure 22a). The fireplaces, of quadrangular or semi-quadrangular plan, are dug into the subsoil and delimited by rows of slabs, with approximate dimensions of 0.48–0.55 m x 0.58–0.65 m. These are situated near the entrances and are associated with small features adjacent to the walls, raised 10–20 cm above ground level, formed of compacted earth and delimited by stones, interpreted as possible support bases (Figure 22b).

At the five excavated sites, the domestic spaces are constructed below the level of the surrounding ground, by direct excavation into the bedrock or compacted sediments. This configuration promotes thermal insulation and mitigates heat conditions. Alongside these spaces, other distinct areas are documented, with varying shapes and dimensions, potentially used as courtyards, livestock shelters or storage areas. The walls are built using local stone laid in irregular courses (Figure 22c), generally in dry stone and stabilised by small wedges, although the use of earthen bonding material is occasionally observed. When built against the natural ground, they have a single exposed face; conversely, when raised above ground level, they adopt double-walled configurations, sometimes with internal fillings of earth and gravel. The structures frequently adapt to the natural slopes of the terrain, combining excavated and built areas (Figure 22d).

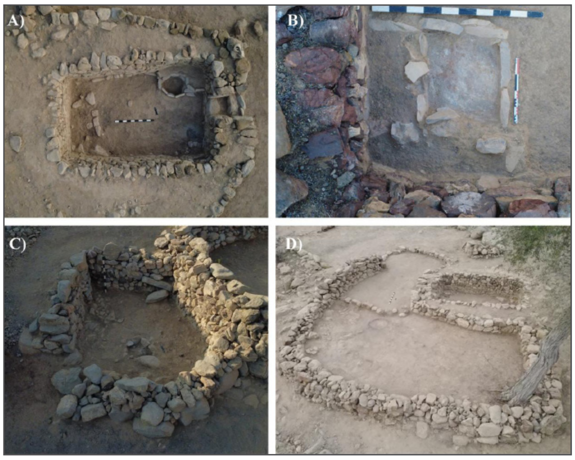

Figure 22. *Architectural features documented at the Suhaila sites: A) feature 31a, a domestic unit excavated into the subsoil, with a defined entrance and the presence of a hearth; B) fireplace in the domestic unit 4a, with the ash layer exposed; C) space 11d, partially excavated into the natural substrate, with walls built from blocks of varying sizes forming irregular courses of drystone; D) space 31b, courtyard with two distinct levels and walls preserved in between three and five irregular courses of drystone.*

Among the recovered materials, some items are particularly significant due to their association with both domestic activities and personal practices (Figure 23).

Among the functional objects, an iron sickle was identified (Figure 23a), intended for cutting the fronds and branches of date palms, and several rounded stones, found inside structures, possibly used for grinding food (Figure 23b). Personal adornments were also recovered, such as a silver ring with incised geometric decorations (Figure 23c) and a necklace composed of small beads (Figure 23d).

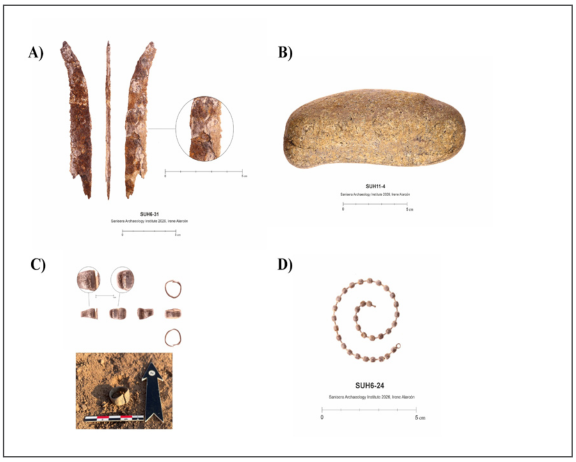

Figure 23. *Selected artefacts from the Suhaila excavations: A) iron sickle used for cutting palm fronds and branches (exterior of Structure 7); B) grinding stone (4a); C) silver ring with geometric motifs (18c); D) necklace composed of 32 beads.*

The ceramic assemblage recovered at Suhaila 6, 9, 10, 11 and 12 consists of 337 fragments (Table 7), most of which are heavily fragmented, with no complete vessels. From a typological perspective, the assemblage is dominated by unglazed pottery, notably White Incised (26.4%), Julfar Ware (25.8%) and White Ware (25.5%), which together account for more than three-quarters of the total. Other unglazed types, such as Choc (3.0%) and White Fine (0.6%), are present in smaller quantities.

Glazed ceramics are less well represented, with Manganese being the most common type (9.5%), followed by Green Glazed (2.1%) and Bahla Ware (0.3%). Porcelain constitutes a minority component of the collection, comprising the Coffee type (6.2%) and Chinese Blue and White (0.6%).

In terms of provenance, the ceramic collection is dominated by productions from Oman and Ras al-Khaimah, which together account for 78.6% of the total, mainly White Incised, White Ware and Julfar Ware. Productions from Al Ain (Choc, Manganese and Green Glazed) account for significantly lower percentages (14.6%), whilst East Asian porcelain constitutes a small proportion of the collection (6.8%).

The distribution of ceramic material varies considerably between sites, with Suhaila 9 having the largest collection (N=160), followed by Suhaila 10 (N=83) and Suhaila 12 (N=65), whilst Suhaila 6 (N=14) and Suhaila 11 (N=9) yielded significantly fewer fragments. At all sites, ceramic material was recovered from the interior and the immediate surrounding areas, with no specific deposition pattern or significant concentrations at particular points observed.

Table 7. *Distribution of ceramic classes across Suhaila 6, 9, 10, 11 and 12, based on fragment counts (N = 337), including totals and relative percentages.*

Ceramic Class	Technological Group	Origin	Suhaila 6 (N)	Suhaila 9 (N)	Suhaila 10 (N)	Suhaila 11 (N)	Suhaila 12 (N)	Total (N)	% of Assemblage
White Incised	Unglazed Ware	Oman (local/regional production)	6	54	16	0	13	89	26.4%
White Ware	Unglazed Ware	Oman (local/regional production)	5	50	8	2	21	86	25.5%
Julfar Ware	Unglazed Ware	Ras al-Khaimah (regional production)	3	31	29	2	22	87	25.8%
White Fine	Unglazed Ware	Oman (local/regional production)	0	2	0	0	0	2	0.6%
Choc	Unglazed Ware	Al Ain (regional production)	0	10	0	0	0	10	3.0%
Manganese	Glazed Ware	Al Ain (regional production)	0	3	20	4	5	32	9.5%
Green Glazed	Glazed Ware	Al Ain (regional production)	0	6	1	0	0	7	2.1%
Bahla Ware	Glazed Ware	Oman (local/regional production)	0	0	0	0	1	1	0.3%
Coffee	Porcelain	East Asia (imported)	0	11	7	0	3	21	6.2%
Chinese Blue & White	Porcelain	East Asia (imported)	0	0	1	1	0	2	0.6%
TOTAL	—	—	**14**	**160**	**83**	**9**	**65**	**337**	**100%**

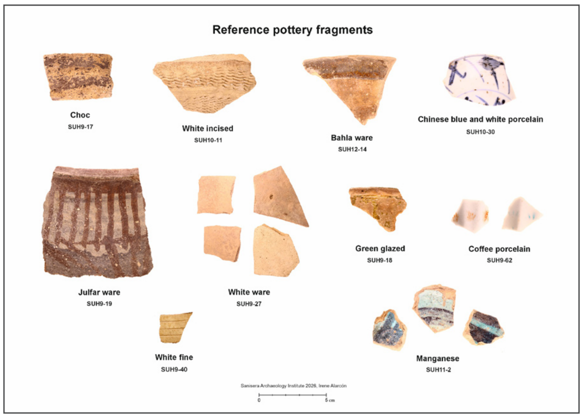

Figure 24. *Ceramic types documented in the excavations at Suhaila 6, 9, 10, 11 and 12. © Irene Alarcón.*

Among the recovered materials, a small collection of seven cartridge cases from Suhaila 6 and 9 was documented. At Suhaila 6, a cartridge case was identified with the mark 'KYNOCH' stamped on the base, corresponding to British-made ammunition (Figure 25a). At Suhaila 9, six cartridge cases were recovered, one of which bore the alphanumeric inscription '71–86', also located on the base (Figure 25b).

The set exhibits some typological variation, comprising medium-sized rimmed cartridge cases and larger specimens associated with rifle ammunition. Although several fragments do not allow for precise caliber identification due to deformation, their morphological and technological characteristics are consistent with industrially produced metal cartridges, widely documented between the late 19th and early 20th centuries. The identification of the KYNOCH mark is particularly significant, as it corresponds to one of the leading ammunition manufacturers based in Birmingham (Bourne, 2014, 160–161).

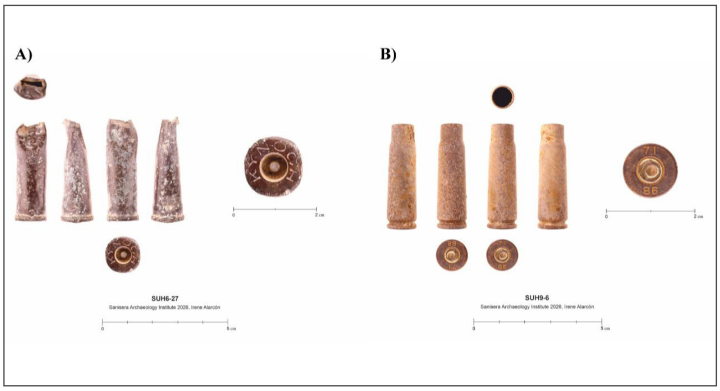

Figure 25. *A) SUH6-27. Cartridge case marked KYNOCH, found at Suhaila 6. B) SUH9-6. Cartridge case marked '71/86', found at Suhaila 9. © Irene Alarcón.*

Another significant category is the numismatic collection recovered from Suhaila 9, 10 and 12. Four coins were found, three of them in the occupation phase of domestic units. The exception is a ¼ anna coin from Suhaila 9, minted in 1898 AD under the rule of Faysal bin Turki, recovered outside in front of the entrance to domestic unit 18b (Figure 26a). In Suhaila 10, two ¼ anna coins minted in British India, dated 1833 and 1858 (Figure 26b-c), were identified, and in Suhaila 12 another from 1835 (Figure 26d).

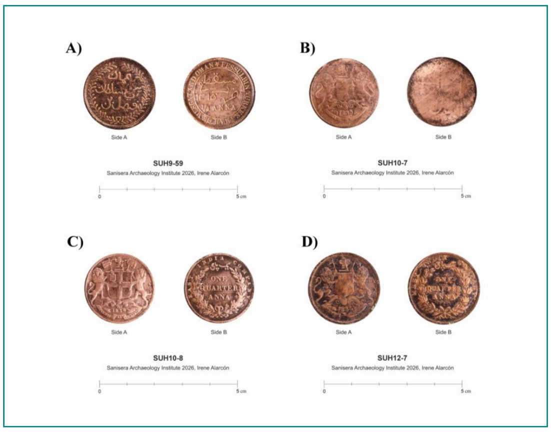

Figure 26. *Numismatic record. A) SUH9-59. ¼ Anna coin, AD 1898, Suhaila 9. B) SUH10-7, 1833. C) SUH10-8, 1858. D) SUH12-7, 1835. © Irene Alarcón.*

Samples of charcoal and sediment from hearths were selected for AMS radiocarbon dating (FTMC laboratory) in order to refine the chronological framework (Table 8). The results obtained range from 81 ± 29 BP to 186 ± 28 BP.

Table 8. *Radiocarbon results from charcoal samples recovered from fireplace combustion deposits at Suhaila. Ages are reported as conventional radiocarbon ages in BP and as calibrated date ranges in cal AD at 95.4% probability (2σ).*

Sample	Laboratory Code	Site and Context	Sample Type	Radiocarbon Age (BP)	Calibrated Age (cal AD, 95.4%)	pMC (%)
SUH6-23	FTMC-ST24-4	Suhaila 6 (Structure 23, fireplace fill, Context 8)	Charcoal	186 ± 28	1653–1695; 1724–1813; 1838–1878; 1916–1950	97.72 ± 0.34
SUH9-36	FTMC-ST24-6	Suhaila 9 (Structure 18b, fireplace fill, Context 4)	Charcoal (humic acid fraction analysed)	156 ± 29	1664–1785; 1793–1895; 1902–1950	98.08 ± 0.22
SUH10-5	FTMC-ST24-5	Suhaila 10 (Structure 31a, fireplace fill, Context 11)	Charcoal (humic acid fraction analysed)	81 ± 29	1683–1736; 1802–1936	99.00 ± 0.22
SUH11-12	FTMC-ST24-3	Suhaila 11 (Structure 4a, fireplace fill, Context 3)	Charcoal	116 ± 27	1682–1738; 1754–1762; 1801–1938	98.57 ± 0.34
SUH12-40	FTMC-ST24-1	Suhaila 12 (Structure 11d, fireplace fill, Context 26)	Charcoal (humic acid fraction analyzed)	167 ± 29	1658–1825; 1837–1895; 1904–1950	97.94 ± 0.21

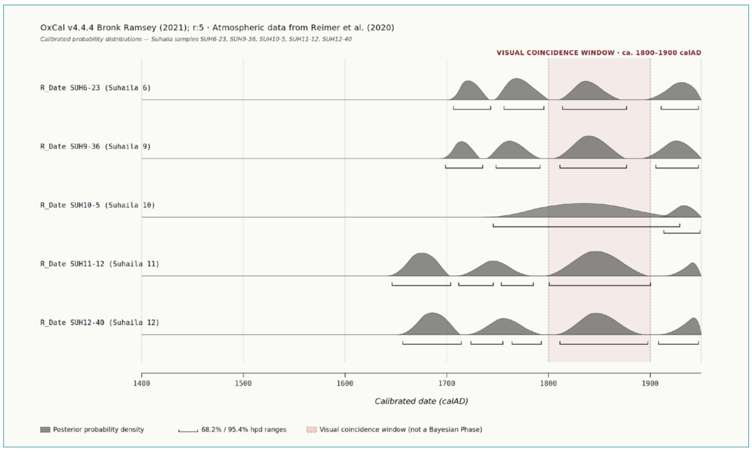

Figure 27. *Calibrated radiocarbon dates from the Suhaila sites (Suhaila 6, 9, 10, 11 and 12), plotted using OxCal v4.4.4 and the IntCal20 calibration curve.*

The overlap between the five calibrated distributions was examined by intersecting their 95.4% (2σ) highest-probability-density ranges, as listed in Table 8. Several common intervals emerge, among which cal AD 1838–1878 constitutes the widest continuous range and therefore represents the most likely shared interval across the dated contexts. This intersection-based estimate should be regarded as provisional, and a Bayesian Phase model in OxCal is planned in future work to refine it.

A secondary, more restricted overlap is also observed at cal AD 1916–1936. Given its limited duration, this interval is considered less reliable as an indicator of a common phase.

Taking into account the coins dated between 1833 and 1898, together with the presence of industrially produced ammunition from the late 19th–early 20th centuries, the documented occupation can be more precisely situated in the second half of the 19th century, with a possible extension into the early decades of the 20th century.z

4. Conclusion

The results obtained indicate that the spatial distribution of Islamic structures in Suhaila concentrates habitable areas on the Quaternary fluvial stratigraphy. In terms of water resources, Suhaila functioned as a refuge, an 'oasis' in the Al-Hajar mountain range, with microclimates and pockets of moisture that allowed for habitation in cooler conditions and with higher relative precipitation compared to the UAE national average. These conditions enabled irrigation systems and water retention structures in the form of dams and wells, which were conducive to cultivation and the existence of small, more or less permanent settlements of certain family groups or clans during the second half of the 19th century, with a possible extension into the early decades of the 20th century.

Proximity to *wadis* is the most common pattern: the 222 dwellings at Suhaila 9–12 surround two wadis of the Wadi Al-Wajajah, and Suhaila 10, 11, 12 and 16 (45% of the total) are aligned in basin 2. Furthermore, the dams, cisterns and wells documented at Suhaila 9-5, 9-7 and 11-12B confirm systems comparable to the *falaj* of UNESCO (2025).

The network of ancient routes reveals a well-organised connectivity system that integrates almost all the settlements. The west-east route through the sites, and most clearly between Suhaila 4 and 12, is very evident and is still preserved today.

As for the settlement pattern, dwellings with one or two rooms predominate at the Suhaila 9 to 12 sites, alongside other spaces dedicated to sheltering livestock in the form of stables. In some exceptional cases, a dwelling may comprise between 6 and 10 rooms.

In terms of urban layout, Suhaila 9 is divided into two somewhat scattered settlements. Suhaila 10 presents an exceptional pattern, with two dense structural centers delimited by the main channel of a *wadi*. Suhaila 11, meanwhile, has a fragmented and highly dispersed layout, and finally, Suhaila 12 constitutes a main settlement occupying a modest area of land, with a high concentration of structures and dwellings that must have been dependent on Suhaila 10.

The results of the archaeological investigation carried out on the structures selected by DCAA at Suhaila 6, 9, 10, 11 and 12 provide a deeper understanding of the settlement of Suhaila in the 19th century, particularly in its second half. They reveal an architectural pattern common to all the building types observed in the Suhaila area, which to date comprises 16 sites.

The excavated domestic structures can be clearly identified in structures 5, 7 and 23 (Suhaila 6); spaces 18a and 18b (Suhaila 9); space 31a (Suhaila 10); and space 11a (Suhaila 12). Their function as domestic spaces is further supported by the discovery of three coins, dated between 1833 and 1898, found within the occupation levels of these structures (31a and 11a), and one at their entrance (18b).

Alongside these domestic structures, the presence of other open or semi-open areas, courtyards and enclosures potentially intended for storage (11c) or livestock housing (11a, 31c and 31d) has been documented. It is worth noting the absence of any waste disposal areas (rubbish dumps) and the notable scarcity of faunal remains. Furthermore, no structures serving as drainage channels for domestic or waste water management have been identified.

As for the ceramic repertoire, there is a clear predominance of locally and regionally produced wares (93.2%) compared to a small proportion of porcelain from East Asia (6.8%), associated mainly with domestic activities. A predominance of unglazed ceramics is observed. This pattern, characterized by a strong presence of Julfar Ware, has also been documented in a recent study of Suhaila 2 (Priestman et al., 2026). The predominance of local and regional ceramics suggests a strong integration into local production and distribution networks, particularly in relation to the neighboring areas of Oman and Ras al-Khaimah, from where East Asian porcelain tableware would also have been traded.

In this regard, another significant find is the collection of seashells, which confirms Suhaila's direct link with the Indian Ocean coast, specifically the Kalba–Fujairah coastline, from which the Hatta region would have been regularly supplied.

This connection with supra-regional trade networks is not limited to the ceramic record. The identification of British-made ammunition, based on the KYNOCH mark, associated with one of the main manufacturers based in Birmingham (Bourne, 2014, 160–161), constitutes significant evidence. This type of material not only provides chronological information but also reflects the region's integration into trade networks within the maritime circuits of the Gulf and the Indian Ocean. In this context, the recovered cartridge cases should not be interpreted as evidence of a direct military presence, but rather as material indicators of circulation, exchange and access to imported manufactured goods, whether through trade, private acquisition or indirect distribution networks (Clarizia, 2022, 46–47).

Finally, it is worth mentioning the evidence of farming and date production activities documented in the vicinity of the Suhaila settlements. A notable example is the recovery of an iron sickle used for date harvesting, as well as several rounded stones used for grinding grain, which points to agricultural use or domestic consumption of flour.

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