Archaeomalacology of the Iron Age Site of Muweilah: Taphonomy and Sustenance Assessment

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Inés de la Fortuna Müller García

Publications included in this Dissertation

1.
Müller García, I.D.L.F., Nebelsick, J.H. (2024): Morphology and taphonomy of the gastropod *Terebralia palustris* from an iron age site in the Arabian Peninsula. Facies, 70(4): 13. https://doi.org/10.1007/s10347-024-00688-9

2.
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Author contributions

Nr.	Accepted manuscript (peer-reviewed) yes/no	№ of authors	Position of candidate in list of authors	Scientific ideas by the candidate (%)	Data generation or/and programming by the candidate (if applicable) (%)	Analysis/ interpretation/ technical work by the candidate (if applicable) (%)	Paper writing done by the candidate (%)
1	Yes	2	1	70	100	80	100
2	Yes	2	1	80	100	90	100
3	In prep*	2	1	90	100	95	100

*The final manuscript is currently in preparation (not yet published).

Use of AI-assisted tools

AI-assisted tools (ChatGPT, Open AI), were used in a limited capacity to improve the language and grammar of parts of this dissertation. The scientific concepts, data collection, analyses, interpretations, and conclusions presented in this work are entirely the responsibility of the author.

Abstract

Archaeomalacology, the study of mollusk remains from archaeological contexts, provides key insights into past human-environment interactions, including resource use, technology, and cultural practices. The present study examines over 40,000 mollusk remains from the Iron Age II site of Muweilah (northern United Arab Emirates), offering a rare perspective on marine resource use in an inland desert settlement. The assemblage was analyzed with respect to taxonomy, morphometry, and taphonomy to reconstruct patterns of collection, processing, and use, as well as environmental constraints. Intra-site variation was assessed using quantitative and diversity measures across excavation contexts and compared with other Southeast Arabian sites.

Results show selective exploitation of a limited range of food species, with processing and cooking practices strongly influencing preservation alongside shell morphology. Non-dietary use was limited: most bivalves were likely collected post-mortem, while larger gastropods were occasionally used for ornamentation or as containers. Smaller species may have arrived incidentally. Spatial analyses reveal clear intra-site differentiation corresponding to architectural divisions. Notably, the columned hall (Building II) is marked by high oyster frequencies and low species diversity, whereas other areas show greater diversity dominated by *Marcia cordata*, indicating functionally distinct spaces. Regional comparisons highlight strong similarity with nearby coastal sites. In contrast, assemblages from Oman and the eastern Gulf reflect greater variability, reflecting environmental and cultural influences.

Taken together, the findings demonstrate how inland communities integrated coastal resources to mitigate subsistence risk while participating in wider networks of mobility and exchange. At the same time, intra-site variation points to structured spatial organization and potentially socially differentiated activity areas. The study underscores the value of archaeomalacological evidence for understanding adaptation, subsistence, and regional connectivity in Southeast Arabia.

Zusammenfassung

Die Archäomalakologie, also die Untersuchung von Mollusken aus archäologischen Kontexten, liefert wichtige Erkenntnisse über vergangene Wechselwirkungen zwischen Mensch und Umwelt, darunter die Nutzung von Ressourcen, Technologie und kulturelle Praktiken. Diese Studie untersucht über 40.000 Weichtierreste aus der Fundstätte Muweilah (nördliche Vereinigte Arabische Emirate) aus der Eisenzeit II und bietet einen seltenen Einblick in die Nutzung mariner Ressourcen in einer Siedlung im Wüsteninneren. Die Funde wurden hinsichtlich Taxonomie, Morphometrie und Taphonomie analysiert, um Muster der Sammlung, Verarbeitung und Nutzung sowie ökologische Einschränkungen zu rekonstruieren.

Nicht-ernährungsbezogene Nutzung war begrenzt: die meisten Muscheln wurden wahrscheinlich post-mortem gesammelt, während größere Schnecken gelegentlich zu Schmuckzwecken oder als Behälter verwendet wurden. Kleinere Arten sind möglicherweise zufällig an den Fundort gelangt. Räumliche Analysen zeigen eine deutliche Differenzierung innerhalb der Fundstelle, die den architektonischen Unterteilungen entspricht. Bemerkenswert ist, dass die Säulenhalle (Gebäude II) durch eine hohe Häufigkeit von Austern und eine geringe Artenvielfalt gekennzeichnet ist, während andere Bereiche eine größere Vielfalt aufweisen, die von *Marcia cordata* dominiert wird, was auf funktional unterschiedliche Räume hindeutet. Regionale Vergleiche zeigen eine starke Ähnlichkeit mit nahegelegenen Küstenfundstellen. Im Gegensatz dazu weisen die Fundkomplexe aus Oman und dem östlichen Golf eine größere Variabilität auf, was auf ökologische und kulturelle Einflüsse zurückzuführen ist.

Insgesamt zeigen die Ergebnisse, wie Binnenlandgemeinschaften Küstenressourcen integrierten, um Risiken für ihre Lebensgrundlagen zu mindern, während sie gleichzeitig an umfassenderen Mobilitäts- und Austauschnetzwerken teilnahmen. Gleichzeitig deuten die Variationen innerhalb der Fundstelle auf eine strukturierte räumliche Organisation und potenziell sozial differenzierte Aktivitätsbereiche hin. Die Studie unterstreicht den Wert archäomalakologischer Belege für das Verständnis von Anpassung, Lebensgrundlagen und regionaler Vernetzung im Südosten Arabiens.

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List of supplementary material

1. Introduction

Archaeomalacology, the study of mollusk remains from archaeological contexts, provides a valuable tool for reconstructing past human-environment interactions and cultural practices, from shell-embroidered temple decorations at Teotihuacan to mollusk consumption in prehistoric New Zealand (e.g., Bar-Yosef Mayer 2002; Çakirlar 2011; Gutiérrez-Zugasti et al. 2011; Szabó et al. 2014). More broadly, mollusks have been exploited for a variety of purposes, including subsistence, ornamentation, ritual practices, tool manufacture, pigment production (e.g., purple dye from *Muricidae*), and were even incorporated into constructions (Kuhn et al. 2001; Mannino & Thomas 2002; Trubitt 2003; Hammond 2014; Romagnoli et al. 2017). Analyzes of bivalves and gastropods therefore highlight patterns of resource exploitation, technological practices, and cultural behaviors (e.g. trade networks), while also yielding paleoenvironmental information, such as past climatic conditions and the availability of coastal resources (Gensheimer 1984; Bar-Yosef Mayer 2002; Andrus 2011; Szabó et al. 2014).

Despite extensive shell assemblages in Southeast Arabia, the area remains comparatively underexplored. Studies are often limited to qualitative taxonomic listings, frequently omitting minor species and neglecting factors influencing shell preservation and distribution, such as environmental provenance, human handling, or microstructural alterations. This gap is particularly evident in the Iron Age, a period marked by settlement expansion and subsistence strategies characterized by the exploitation of mollusks for food and cultural purposes (Magee 1998, 2004; Van Neer & Gautier 1993; Boivin & Fuller 2009).

The present study examines the Iron Age II site of Muweilah in the northern United Arab Emirates, where the assemblage comprises over 40,000 shell remains. Given the well-established archaeological and environmental context of the site (Magee 1996 [a], 2004; Blau et al. 2000; Magee et al. 2018; Karacic et al. 2018), Muweilah offers a unique opportunity to investigate mollusk use in an inland desert settlement and to assess relationships between environmental availability, human exploitation, and cultural practices. Addressing the absence of a comprehensive archaeomalacological study, this research integrates analyses of taxonomy, taphonomy, morphology, environmental affinities, handling techniques, intra-site

variation, and regional comparisons to refine our understanding of human–mollusk interactions in Southeast Arabia.

1.1 Southeast Arabia: Geographic and Environmental Setting

The Arabian Gulf forms a shallow, semi-enclosed marine basin that is linked to the Gulf of Oman via the Strait of Hormuz. It is characterized by generally low water depths (on average ~35 m) and broad shallow coastal shelf areas (Glennie & Singhvi 2002; Alsharhan & Kendall 2003). The physiography of the United Arab Emirates reflects the contrast between the coast, featuring coastal sabkhas along the Arabian Gulf as well as aeolian dune systems extending inland from the Rub' al Khali, and the Al Hajar Mountains acting as a barrier in the east. Southeastern Arabia is predominantly arid, receiving less than 50 mm of annual precipitation, with sparse vegetation and limited mangrove remnants (Glennie & Singhvi 2002; Brook et al. 2006; Forti et al. 2024).

During the Late Pleistocene, lowered global sea levels exposed the Arabian Gulf, which remained dry until the early Holocene (Lambeck 1996; Parker et al. 2006 [a]; Boivin & Fuller 2009). This transgression (ca. 10,500 BC) coincided with a strengthened Indian Ocean Monsoon, supporting the expansion of mangrove stands, which provided favorable habitats for mollusk taxa archaeologically attested in Southeastern Arabia (Parker et al. 2006 [a], [b]; Boivin & Fuller 2009; Berger et al. 2013). From around 4000 BC, weakening monsoon influence and the rise of Mediterranean winter rainfall promoted progressive aridification, leading to a decline of mangroves, expansion of sabkha environments, and renewed aeolian activity (Lambeck 1996; Staubwasser et al. 2002; Parker et al. 2006 [b]; Berger et al. 2013; Damien et al. 2020). By the beginning of Iron Age II (ca. 1100 BC), present day climatic and environmental conditions were established, while sea levels had largely stabilized (Lambeck 1996; Parker et al. 2006 [a]; Boivin & Fuller 2009; Damien et al. 2020).

The marine ecology of the Arabian Gulf is characterized by the shallow bathymetry and extreme environmental conditions, including high summer sea-surface temperatures (up to ~33 °C), elevated salinity, and intense evaporation, which restrict water circulation and limit marine biodiversity. Consequently, species

richness is markedly lower than in the Gulf of Oman or the wider Indo-Pacific (Sale et al. 2011; El-Sorogy et al. 2015; Albano et al. 2016; García-Ramos et al. 2016; Bejarano et al. 2023).

Coastal ecosystems along the southern Arabian Gulf are dominated by soft-substrate environments, with limited hard-substrate habitats such as coral reefs. Prominent habitat types include seagrass beds, sandy and rocky shores, mudflats, and occasional mangroves (Price et al. 1993; Carpenter 1997; Sale et al. 2011; El-Sorogy et al. 2015, 2019). Seagrass beds, primarily composed of *Halodule uninervis* and *Halophila* spp., provide important habitats for economically significant mollusks, including pearl oysters (*Pinctada* sp.) (Price et al. 1993; Carpenter 1997; Sale et al. 2011).

Sandy and muddy intertidal zones support diverse assemblages of burrowing bivalves and gastropods (e.g., *Glycymeris*, *Mactra*, *Marcia*, *Anadara*, *Potamides*, *Cerithium*), whereas rocky shores host stress-tolerant taxa (e.g. *Pteriidae*, *Ostreoidea, Muricidae*, *Conidae, Cypraeidae* (Price et al. 1993; Carpenter 1997; Sale et al. 2011; El-Sorogy et al. 2015; Bejarano et al. 2023). The occasional mangrove ecosystems are dominated by *Avicennia marina*, with *Rhizophora* largely restricted to cultivated stands. Although present-day mangrove coverage is restricted, particularly along the southern Gulf coast, these environments are highly productive and support characteristic mollusks such as *Ostreoidea* and the gastropod *Terebralia palustris*, which is now largely absent from the United Arab Emirates (Price et al. 1993; El Gendy et al. 2015; García-Ramos et al. 2016; Bejarano et al. 2023).

1.2 Cultural Developments and Mollusk Use in the Iron Age II (ca. 1000–600BC)

The Iron Age in Southeast Arabia is conventionally dated to ca. 1300–300 BC and subdivided into several phases based on ceramic typology and architectural developments. During Iron Age II (ca. 1000 – 600 BC), settlements in the United Arab Emirates expanded from the coastal sabkhas at the Arabian Gulf to the Hajar mountains in the East (Figure 1.1 A) (Magee 1996 [b], 1998, 2003; Potts 2001). Settlement intensification was driven by camel domestication and advances in seafaring. The introduction of the falaj irrigation system (Figure 1.1 B) supported intensified agriculture and the formation of ceramic production centers in the piedmont and mountain zones, which contributed to social differentiation as well as the emergence of politically organized entities (Magee 1998, 2004, 2014; Blau et al. 2000; Magee et al. 2002; Potts 2001; Al Abed et al. 2006; Boivin & Fuller 2009; Charbonnier 2015; Moussa 2019).

In the coastal and desert zones, by contrast, intensive farming was not feasible; and subsistence strategies combined various resources, including marine exploitation, animal husbandry, hunting, and limited cultivation such as cereals and date palms (Magee 1998; Potts 2001; Al Abed et al. 2006). Archaeological evidence indicates a differentiated political economy with uneven access to elite goods such as painted ceramics (Magee 2004, 2014; Stepanov et al. 2020). Desert sites functioned as strategic nodes linking coast, oases, and mountains (Magee 2004, 2014; Magee et al. 2009, 2018).

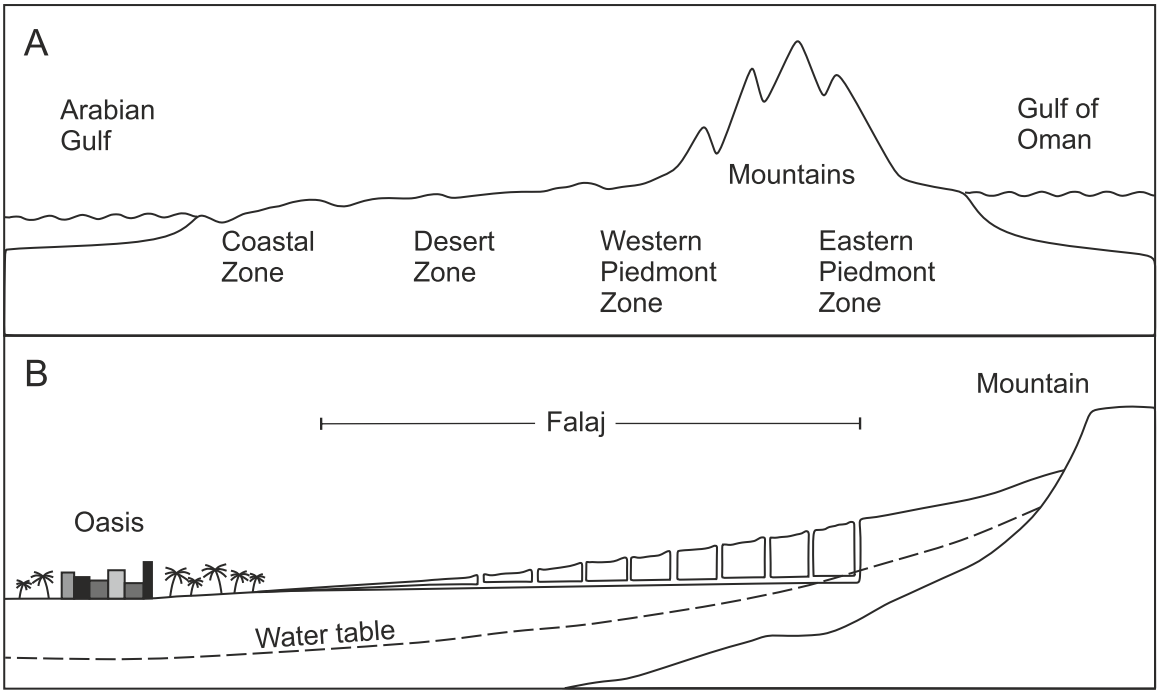

Figure 1.1 A) Geomorphological zoning of the United Arab Emirates from the Arabian Gulf to the Gulf of Oman. B) Falaj irrigation system. Illustrations based on Magee (1998) and Cremaschi et al. (2018).

Marine resources were used in diverse contexts in Southeast Arabia, with intensity and function varying by region and period. The most common use was subsistence, reflected by frequently found large shell assemblages at coastal sites (Van Neer & Gautier 1993; Parker & Goudie 2007; Boivin & Fuller 2009; Magee et al. 2009; Händel 2013; Hausmann et al. 2019; Lidour et al. 2020). The significance of mollusks for the regular diet remains debated and likely varied according to coastal proximity and environmental availability (Szabó et al. 2014; Rick et al. 2015; Rick 2024; Hausmann et al. 2019; Callapaz & Dinis 2020). At inland sites, mollusks played a more limited dietary role and were often employed for non-subsistence purposes, such as for ornamentation (Potts et al. 1996; Al-Jahwari 2011; Uerpmann et al. 2013; Del Cerro 2013; Roberts et al. 2019).

Beyond food, mollusks were widely used for craft and symbolic purposes. Shells were modified into beads, discs, and occasionally engraved ornaments, recovered from both settlement and funerary contexts (Potts et al. 1996; Charpentier & Méry 2008; Al-Jahwari 2011; Uerpmann et al. 2012; Roberts et al. 2019). They also served as tools, including scrapers, containers, and cutting implements

(Charpentier & Méry 2008; Del Cerro 2013; Tumung et al. 2015; Szabó & Koppel 2015; Lidour et al. 2024; Lidour & Cuenca Solana 2024). Additionally, certain forms of shell use common elsewhere are absent or rare in Southeast Arabia. Although *Muricidae* were exploited for purple dye in the Mediterranean, in this region they were likely exploited solely for consumption (Bar-Yosef Mayer 2002; Koren 2001; Çakirlar 2011; Guckelsberger 2013; Oliver 2015; Sukenik et al. 2015, 2021). Similarly, shells as construction materials are seldom documented; isolated finds, such as small mollusks in floor deposits at Saar, may have arrived unintentionally (Glover 1995; Trubitt 2003).

1.3 The Archaeological Site of Muweilah

Muweilah, an Iron Age II settlement in the northern United Arab Emirates, was occupied in the 10th century BC until its destruction by fire between the late 8th and 6th centuries BC (Magee 1996 [a], 2004; Magee et al. 2018). Following a French survey in 1988, Muweilah has been the subject of systematic excavation since the mid-1990s under the direction of Peter Magee, resulting in extensive documentation of its architecture and material culture (Magee 1996 [a], 2004; Blau et al. 2000; Karacic et al. 2018).

Situated ~15 km inland from the modern coast within an aeolian sand belt near Sharjah (Figure 1.2), the site lies between the Arabian Gulf and the Al-Hajar Mountains (Potts 2001; Magee & Thompson 2001; Magee 2004, 2014; Benoist 2008; Boivin & Fuller 2009; Uerpmann et al. 2013). The establishment of a permanent settlement in this arid environment was facilitated by broader Iron Age II technological and economic developments, including camel domestication, improved herd management, and irrigation-based agriculture. Within this framework, Muweilah functioned as a strategic node in regional production and exchange networks, linking coastal, desert, and mountain zones (Magee 2004, 2014; Potts 2001; Boivin & Fuller 2009; Moussa 2019).

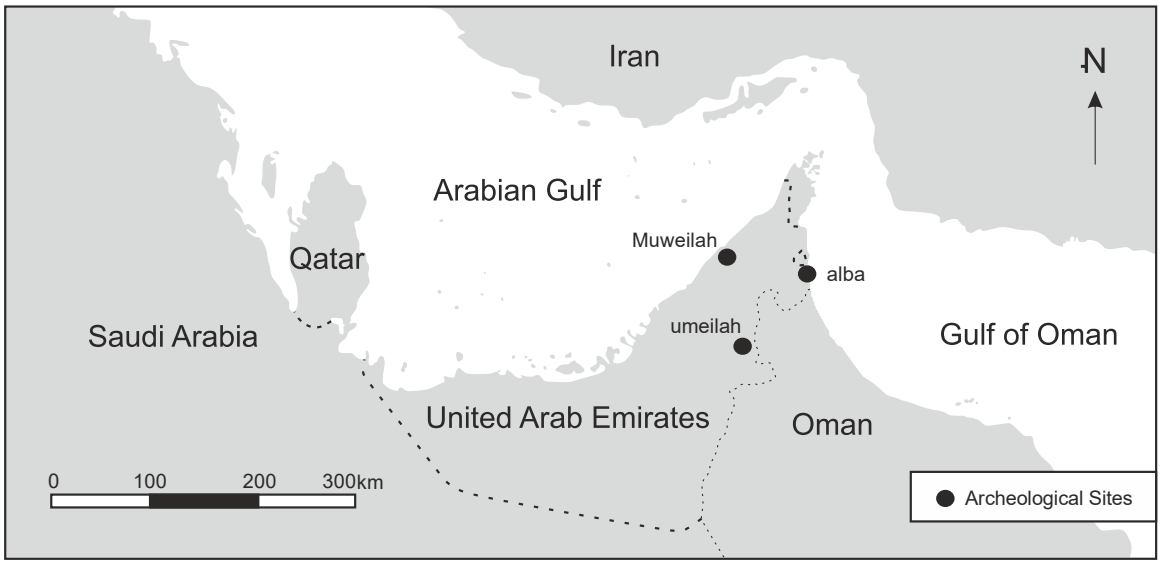

Figure 1.2 Map of Southeast Arabia with location of Muweilah. Illustration based on Müller García and Nebelsick 2026).

The site is divided into a Western and a Central Area (Figure 1.3), separated by an inner wall and collectively enclosed by an outer fortification, reflecting social differentiation (Magee 1996 [a], 2004; Karacic et al. 2018). The Western Area is dominated by a large columned hall (Building II) interpreted as an elite space for the regulation and redistribution of valuable goods (Magee 2004, 2014; Magee et al. 2002; Stepanov et al. 2020). Comparable forms at sites such as Rumeilah indicate that this building belongs to a broader Iron Age tradition of administrative architecture (Boucharlat & Lombard 2001; Magee et al. 2002). In contrast, the Central Area contains standardized domestic buildings organized around main rooms with subsidiary spaces (Karacic et al. 2018; Magee et al. 2018). The absence of this pattern in the Western Area underscores the functional distinction between the two zones. Controlled access to the Western Area further suggests social stratification, although the specific identities of those permitted entry remain unknown (Magee et al. 2002; Karacic et al. 2018).

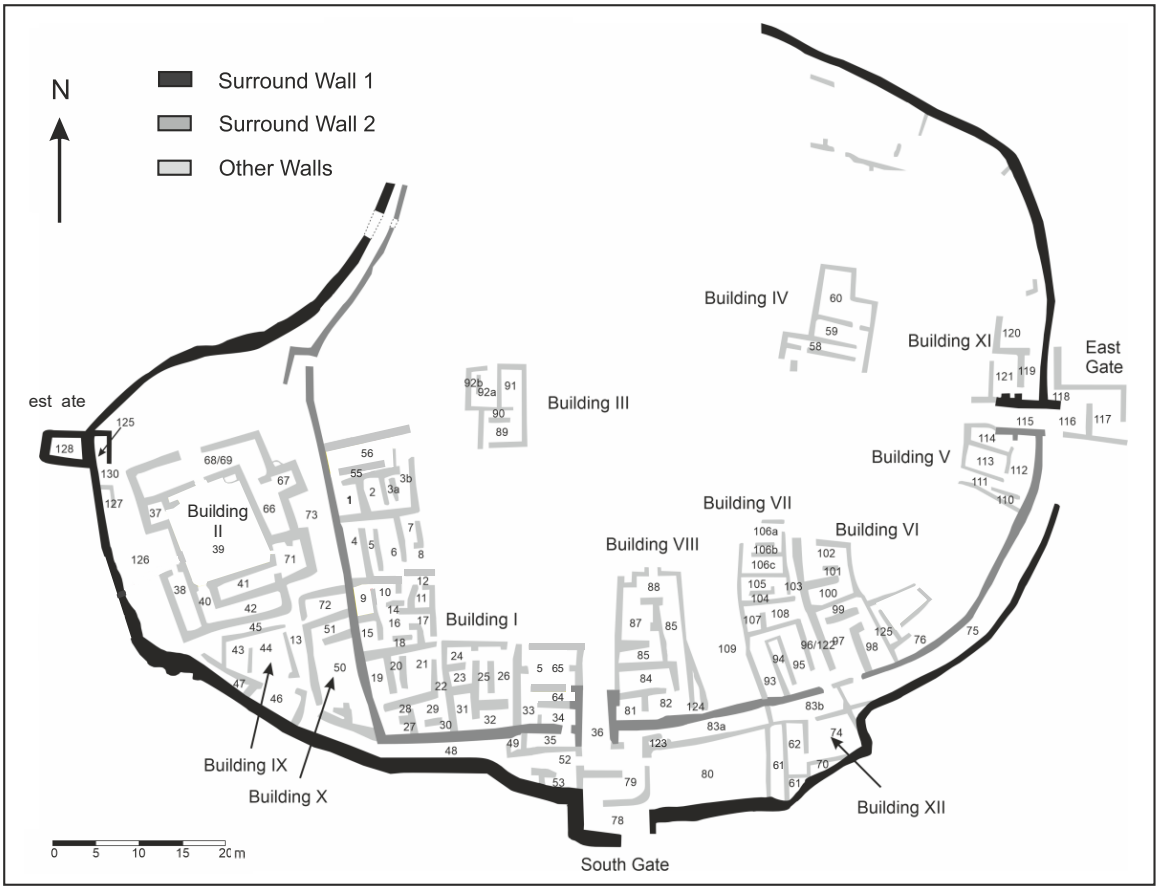

Figure 1.3 Map of the archaeological site of Muweilah. Illustration based on Karacic et al. 2018 and Müller García and Nebelsick 2026.

The botanical and faunal evidence in Muweilah provides insight into the environmental setting and subsistence strategies. Charcoal and plant remains indicate the exploitation of oasis-related species, particularly date palm, alongside other woody taxa, such as acacia, used for fuel and construction. The absence of cereals may reflect preservation biases rather than their exclusion from the local economy, whereas coastal mangrove species were naturally not part of the assemblage (Magee 1996 [a]; Magee & Thompson 2001; Tengberg 2009). The faunal remains include domestic animals such as dromedaries, sheep, goats, and cattle, as well as hunted species, including gazelle, oryx, carnivores, and marine birds. Together, the botanical and faunal data point to a diversified subsistence strategy consistent with Iron Age II adaptations to arid inland environments (Magee 1996 [a], 2014).

Pottery represents the most abundant category of material culture at the site and includes both utilitarian wares and finely painted vessels. The latter occur with particular frequency in Building II and derive from multiple production centers, including the Al-Hajar Mountains, Bahrain, and Mesopotamia, highlighting Muweilahs integration into regional and interregional exchange networks (Magee 1996 [a], 2004, 2014; Magee & Thompson 2001). Evidence for bronze and iron working, dromedary figurines, and the earliest South Arabian inscription on a locally produced vessel further underscore the administrative and symbolic significance of Building II within the settlement (Müller 1999; Magee 1998, 2014; Stepanov et al. 2020).

1.4 Mollusk Assemblage: Contextual Overview

The Muweilah mollusk assemblage comprises 40,668 specimens representing 54 taxa: 24 gastropods, 30 bivalves, and a single scaphopod (Figure 1.4). The assemblage is strongly dominated by a few species, notably *Terebralia palustris* among gastropods and *Marcia cordata* among bivalves, which together account for the majority of individuals. Among the remaining taxa, *Hexaplex kuesterianus* is the most common gastropod and *Ostreoidea* sp. the most frequent bivalve. Minor species contribute only a small fraction of the assemblage. Despite the larger number of bivalve taxa, gastropod individuals slightly outnumber bivalves overall.

Preservation of the assemblage varies from complete shells to heavily fragmented specimens. Bivalves are consistently disarticulated, and most shells display surface abrasion and color alteration. Rare features, such as punctures, superficial cracks, or encrustations, occur sporadically. These taphonomic characteristics were systematically documented and inform interpretations of species representation, depositional context, and post-depositional processes. This overview provides the baseline for subsequent functional and environmental analyses.

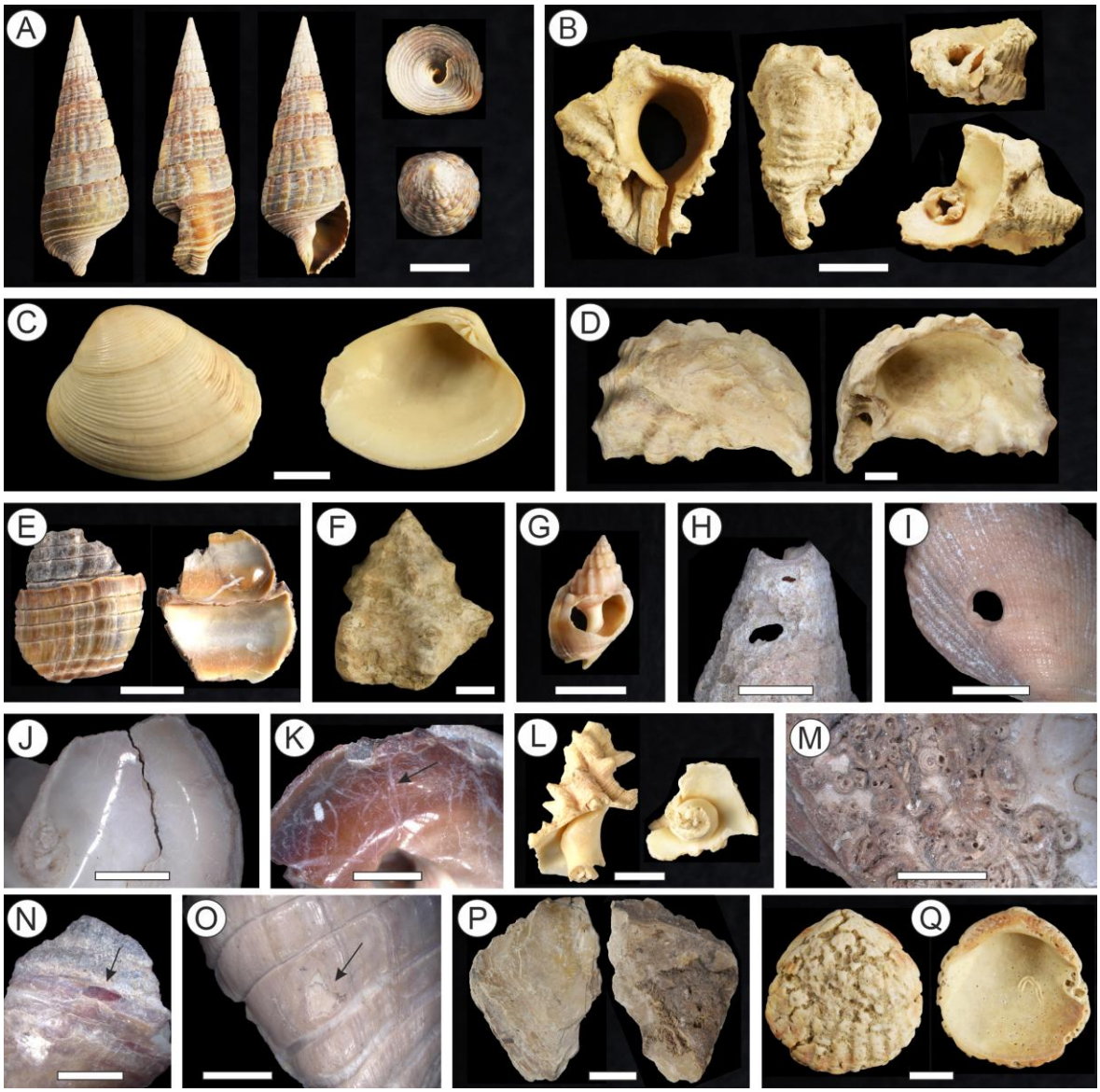

Figure 1.4 Selection of gastropods, bivalves and mollusk taphonomy from the archaeological context of Muweilah. Illustrations based on Müller García and Nebelsick 2026. A *Terebralia palustris* (Locus 85042), B *Hexaplex kuesterianus* (Locus 92174), C *Marcia cordata* (Locus 85138), D *Ostreoidea* sp. left valve (Locus 85100), E *Terebralia palustris* in a good state of preservation regarding color alteration, shininess and ablation (Locus 85124), F *Hexaplex kuesterianus* with strong ablation (Locus 92135), G–I *Nassarius fissilabris*, *Terebralia palustris* and *Barbatia obliquata* with holes (Locus 99029, 85138, 50055), J–K *Terebralia palustris* with cracking (Locus 85138), L *Hexaplex kuesterianus* with color alteration (Locus 92135), M *Pinctada margaritifera* with incrustation in form of serpulid worms (Locus 13029), N–O *Terebralia palustris* with surface abrasion (Locus 85138), P–Q *Pinctada* sp. and *Glycymeris arabica* with bad states of preservation (Locus 94058 and 92005). (Scale: B) 40 mm; A), D), P) 20 mm; C), E–G), Q) 10 mm; H–O) 5 mm)

1.5 Aims and Objectives

Although many Southeast Arabian sites contain abundant mollusk remains, detailed archaeomalacological studies remain scarce despite their ecological, subsistence, and cultural significance. Such analyses can refine our understanding of resource use, trade networks, and human–environment interactions. Muweilah is particularly suited for this research due to its strategic position linking coastal and mountain networks as well as its large assemblage. This study investigates the collection, processing, and use of marine mollusks at Muweilah, examining how taxonomic composition and preservation reflect human activities while also assessing intra-site variation and situating the assemblage within a regional framework. It addresses four objectives:

1. Species-specific handling and taphonomy: Analysis of the dominant gastropod *Terebralia palustris* using shell morphology and microstructure (thin sections, SEM) to evaluate handling, preservation biases, and to distinguish cultural from natural accumulations.

2. Taxonomic and environmental analysis: Identification of the assemblage and systematic assessment of preservation states, combined with environmental affinities to reconstruct collection areas and procurement strategies.

3. Human use and impact**:** Investigation of mollusk exploitation for subsistence, tools, and ornamentation through fragmentation, surface modification, ablation, color alteration and perforation.

4. Intra-site variation: Comparison of assemblages across settlement contexts using taxonomic composition, abundance, species richness, habitat distribution, and diversity indices (e.g., Shannon, equitability) to identify spatial patterning.

Results are compared with other Southeast Arabian sites to situate Muweilah within a broader regional framework of mollusk exploitation. By integrating microstructural, taxonomic, taphonomic, and spatial analyses, the study advances understanding of shell use, cultural practices, and human–environment interactions in the region.

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2. Morphology and Taphonomy of the Gastropod *Terebralia palustris* from an Iron Age Site in the Arabian Peninsula

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2.1 Context and Scope

This manuscript contributes to the overall objective of this dissertation by investigating *Terebralia palustris*, the dominant gastropod species recovered from the archaeological site of Muweilah (United Arab Emirates). As a key component of mangrove ecosystems with a wide geographic distribution and frequent occurrence in archaeological contexts, this species provides an excellent basis for comparing natural and archaeological accumulations.

The research focuses on the relationship between shell architecture, morphology, and fragmentation patterns, with particular attention to processes of preservation and taphonomic alteration. A central objective is to differentiate between natural and anthropogenic modification processes. To address these questions, an integrated methodological approach is applied, combining morphometric analyses, thin sectioning, and scanning electron microscopy (SEM) of recent specimens with a semi-quantitative taphonomic assessment of archaeological material. The results contribute to a better understanding of shell processing, including flesh extraction, cooking practices, and waste disposal.

This manuscript provides the analytical foundation for Manuscript 2, in which a broader assemblage of mollusk remains from the site is examined. By focusing on *Terebralia palustris* as both the dominant species and a taphonomically distinct case, it establishes a framework for interpreting the more extensive dataset. Due to its numerical dominance, this species plays a key role in the overall understanding of the molluscan assemblage from Muweilah. In addition, its close association with mangrove environments informs the environmental interpretations developed in Manuscript 3.

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ORIGINAL ARTICLE

Morphology and taphonomy of the gastropod *Terebralia palustris* from an iron age site in the Arabian Peninsula

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Abstract
The Indo-Pacific gastropod *Terebralia palustris* is particularly suitable for comparing natural and anthropogenic induced taphonomic pathways due to its wide geographic distribution and common presence within archeological context. The present study aims to (1) correlate shell architecture and morphology with fragmentation pattern and preservation, (2) quantify taphonomic changes to differentiate between natural vs. anthropogenic preservation features, (3) provide a guideline for analyzing fragmented shell remains in archeological material. Shells and taphonomic features were studied from both recent mangrove environments from the Emirate of Sharjah, United Arab Emirates as well as archeological material within the Iron age II site (1000–600 BC) of Muweilah near the City of Sharjah. Techniques utilized include morphometry, thin sectioning, scanning electron microscopy (SEM) of recent specimens and a semi—quantitative taphonomic analysis of anthropogenic material. Thin sectioning shows a complex internal shell morphology with a tripartite subdivision of shell layers. The recent material shows better preserved features on both the exterior and internal shell surfaces than the highly fragmented material recovered from the archeological context, which shows a distinct size distribution as well as showing higher levels of surface abrasion, surface cracks and color alterations. These features are correlated to extraction techniques, cooking methods and waste disposal handling.

Keywords Taphonomy · Morphometry · Shell middens · *Terebralia palustris* · Archeomalacology · Arabian Peninsula

Introduction

Archeomalacological studies have increasingly emphasized the interactions between mollusks and human activity, especially regarding the utilization of marine resources for both dietary and non–dietary purposes (e.g., Kuhn et al. 2001; Bar–Yosef Mayer 2002; Gutiérrez–Zugasti et al. 2011; Andrus 2011; Çakirlar 2011; Li et al. 2013; Szabó et al. 2014; Szabó and Koppel 2015; Oliver 2015; Sukenik et al. 2021). Due to the nutrient–richness and easy collectability of intertidal and shallow water species (such as *Terebralia palustris* of the present study), mollusks have played an important role in sustentation, especially in desert coastal regions (Marean et al. 2007; Mannino and Thomas 2002).

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Ecological distribution and natural environment of *Terebralia palustris*

Terebralia palustris (Linnaeus 1767), also known as the mudwhelk, is commonly found in Indo–Pacific mangrove forests where it consumes leaf litter reaching a maximum height of 190 mm (Fratini et al. 2000, 2001, 2004; Carlén and Ólafsson 2002; Pape et al. 2008; Mujiono 2009; Lindauer et al. 2017). The age specific distribution may vary strongly depending on various environmental factors (Houbrick 1991; Slim et al. 1997; Fratini et al. 2004; Pape et al. 2008; Penha–Lopes et al. 2009; Lindauer et al. 2017). Populations have been studied with respect to movement, dietary niche sizes, genetic properties, isotopic analysis, resilience against desiccation and starvation (e.g., Soemodihardjo and Kastoro 1977; Rambabu et al. 1987; Slim et al. 1997; Fratini et al. 2000, 2004, 2008; Carlén and Ólafsson 2002; Pape et al. 2008; Vannini et al. 2008; Cannicci et al. 2009; Penha–Lopes et al. 2009; Raw et al. 2017; Ratsimbazafy and Kochzius 2018).

Table 1 Archeological sites of the Indo–Pacific and Arabic Peninsula with occurrences of *Terebralia palustris*

Locality	Age	Author
Mandu Mandu Creek (Australia)	~21 k.y.a	Veth et al. (2017)
Jansz (Australia)	13–4 k.y.a	Veth et al. (2017; Przywolnik 2005)
Bubog caves (Ilin Island, Philippines)	Early–middle Holocene	Pawlik et al. (2014, 2015)
Al–Hamriyah (UAE)	Neolithic–Iron Age	Magee et al. (2009)
Tell Abraq (UAE)	Bronze age– Iron Age	Magee et al. (2017)
Saruq al–Hadid (UAE)	Wadi Suq– Iron Age II	Roberts et al. (2019)
Husn Awhala (Awhala, UAE)	Wadi Suq– Iron Age II	Potts et al. (1996)
Lothal (Gujarat, India)	Harappan period (5–4 k.y.a)	Deshpande–Mukherjee (2015); UNESCO World Heritage Centre (2014)
Kilu (Melanesia)	7 k.y.a	Allen (1996)
Asfet and Gelalo Northwest (Eritrea)	9–6 k.y.a	Bar–Yosef Mayer and Beyin (2009) Beyin (2011)
Barrow Island (Australia)	9–8 k.y.a	Veth et al. (2017)
Wadjuru Rockpool (Australia)	9–7 k.y.a	Przywolnik (2005)
Clarke's Cave (Australia)	8 k.y.a	Przywolnik (2005)
Kot–Bala (Pakistan)	7–6 k.y.a	Biagi et al. (2013)
Ramlah 3 (UAE)	7–6 k.y.a	Uerpmann and Uerpmann (1996)
RH6 Ra's al Hamra (Oman)	7–6 k.y.a	Biagi and Nisbet (1992)
Anadara Mound (Australia)	7 k.y.a	Przywolnik (2005)
Nickol River Mound (Australia)	7 k.y.a	Przywolnik (2005)
Beri, Lower Sindh (Pakistan)	6 k.y.a	Biagi (2010)
Mulanda Bluff (Australia)	6 k.y.a	Kendrick and Morse (1990)
El Gouna (Red Sea, Egypt)	6 k.y.a	Vermeersch et al. (2005)
Al–Daith (United Arab Emirates)	6–5 k.y.a	Parker and Goudie (2007
RH5 Ra's al Hamra (Oman)	6–5 k.y.a	Biagi and Nisbet (1992)
Akab (Jazirat al–Beidah, UAE)	5–4 k.y.a	Prieur and Guérin ((1991); Charpentier and Méry (2008): Méry et al. (2009); Lidour et al. (2020)
Dholavira (India)	6–4 k.y.a	Sengupta et al. (2020)
Volandriake (Madagaskar)	4–1 k.y.a	Douglass (2017)
Alor (Indonesia)	3–2 k.y.a	Louys et al. (2017)
Shimal (United Arab Emirates)	2 k.y.a	Grupe and Schutkowski (1989); Potts (1996)
Juani primary school site (Tanzania)	1–2 k.y.a	Crowther et al. (2016)
Al–Madar (UAE)	1 k.y.a	Uerpmann and Uerpmann (1996)
Sudi Bay (Tanzania)	15th– eighteenth century	Ichumbaki (2014)

The mangrove forest represents a low energy, protected environment often affected by tidal movement. Many taphonomic features associated with higher energy environments such as fragmentation, surface abrasion and other features (e.g. Zuschin & Stanton 2001; Chojnacki and Leighton 2014; El Gendy et al. 2015; El-Sorogy 2015) are not expected to occur. The shells of *T. palustris* are used postmortem by hermit crabs (Burggren and McMahon 1988; Epa and De Silva 2011), which can lead to shell degradation as well as to discrepancies with respect to size frequencies, facies distributions and preservation features (Frey 1987; Walker 1989; Paul 1991). Specific preservation features that can be assigned to hermit crab use include a polished whorl section attributed to dragging the shell across the sediment surface and increased incidences of abrasion, bioerosion and encrustation due to extended exposure. Additionally, some land hermit crabs remove the columella or cause further mechanical damage relative to the occupied shells (Frey 1987; Walker 1989).

The morphological characters of *T. palustris* have been described in detail in numerous historical as well as more recent monographs and descriptions (e.g., by Houbrick 1991; Bosh et al. 1995; Sälgeback and Savazzi 2006). There are fewer studies concerning their shell microstructures (e.g., Tojo and Ohno 1999; Milano et al. 2018; Lindauer 2019). Mollusk shells in general consist of various layers of calcium

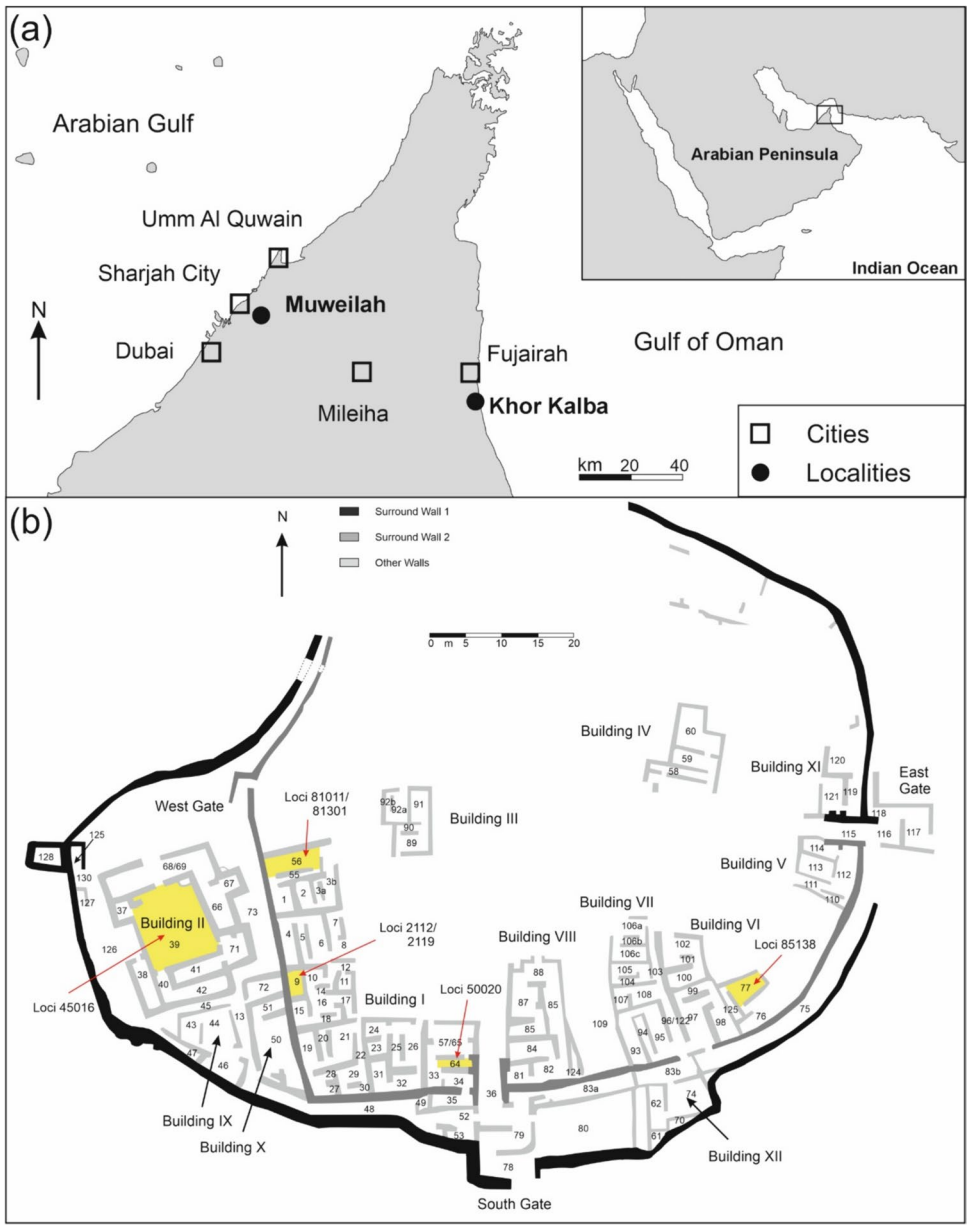


Fig. 1 **a** Overview map of study area on the Arabian Peninsula including the locality of Muweilah. **b** Map of the archeological site Muweilah: Molluscan remains have been recovered from most of these loci and are available for study. Figures adapted from Figs. 1 and 2 in Karacic et al. (2018)

carbonate infused by large quantities of organic matrix and a thin organic exterior periostracum (see Carter 1990; Naka 2010; Müller 2011; Aparicio and Ginebra 2015).

Terebralia palustris in archeological sites of the Indo–Pacific and the study site

Terebralia palustris occurs frequently at archeological sites around the Indo–Pacific (Table 1), with the earliest archeological occurrences dating back to the Pleistocene (Veth et al. 2017). Its study has been largely restricted to species identification, dating and quantification (e.g., Grupe and Schutkowski 1989; Biagi and Nisbet 1992; Uerpmann and Uerpmann 1996; Parker and Goudie 2007; Crowther et al. 2016; Roberts et al. 2019). *T. palustris* is used as an indicator species for mangrove habitats (e.g., Pawlik et al. 2015; Douglass et al. 2017). Further studies concern taphonomic relevant processes including fragmentation and consumption (e.g., Vermeersch et al. 2005; Ichumbaki 2014; Douglass 2017; Veth et al. 2017; Sengupta et al. 2020). Studies have also analyzed possible cooking techniques and the heating effects on shell microstructures (Milano et al. 2016, 2018; Lindauer et al. 2018; Aldeias et al. 2019).

Terebralia palustris is now extirpated along the northern Arabian Peninsula (e.g., Al–Ansi and Al–Khayat 1999; Apel and Türkay 1999; Houbrick 1991; Coles and McCain 1990; Feulner 2006; Hellyer and Aspinall 2006; Al–Khayat et al. 2021; Fleitman et al. 2022) although

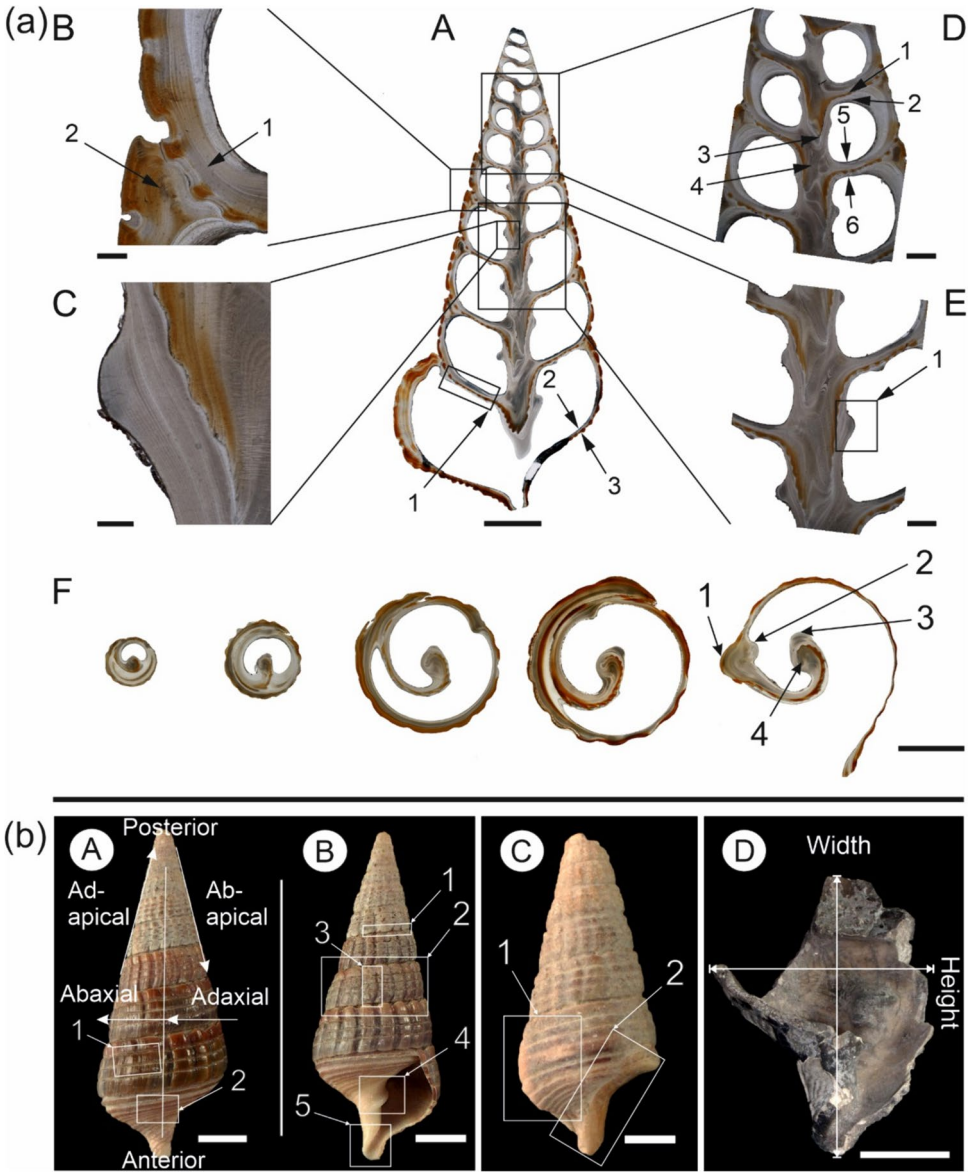


Fig. 2 **a** Longitudinal and transversal thin section of *Terebralia palustris* (Linnaeus 1767). **A** Complete longitudinal thin section. 1 = transversal wall, 2 = inner surface of the exterior wall and 3 = outer surface of the exterior wall (Scale: 10 mm) **B** Suture. 1 = external wall of an older and 2 = external wall of a younger developmental stage. (Scale: 0.5 mm) **C** Columellar fold. (Scale: 0.1 mm) **D** Columella and transversal walls. 1 = anterior whorl base of an older developmental stage, 2 = colorless layer of a younger developmental stage added on top of the older, colored layer, 3 = anterior point of the external wall of an older developmental stage, 4 = colorless layer of a younger developmental stage added on top of the older, colored layer, 5 = adapical surface of the transversal wall and 6 = whorl base. (Scale: 0.5 mm) **E** Columella. 1 = columellar fold (Scale: 0.5 mm) **F**) Serial section from the apex region to the aperture. 1 = enlarged varix, 2 = parietal teeth, 3 = columellar fold, 4 = anterior end of a younger developmental stage. (Scale: 0.5 mm) **b** General morphology of *T. palustris*. **A** Complete specimen with descriptions of the positions compared to the apex and the columella. 1 = spiral grooves and 2 = weak striae. **B** 1 = suture, 2 = whorl, 3 = axial rib, 4 = columella with columellar folds and 5 = siphonal canal. **C** 1 = prominent varix and 2 = inner lip. **D** Burned specimen with height and width parameters. Scale: 10 mm

it is still present along the Iranian coast (e.g., Ghasemi et al. 2011; Vahidi et al. 2020). A sharp decline of *T. palustris* occurred with the beginning of the Iron Age (Händel 2013; Magee et al. 2017) which is correlated to

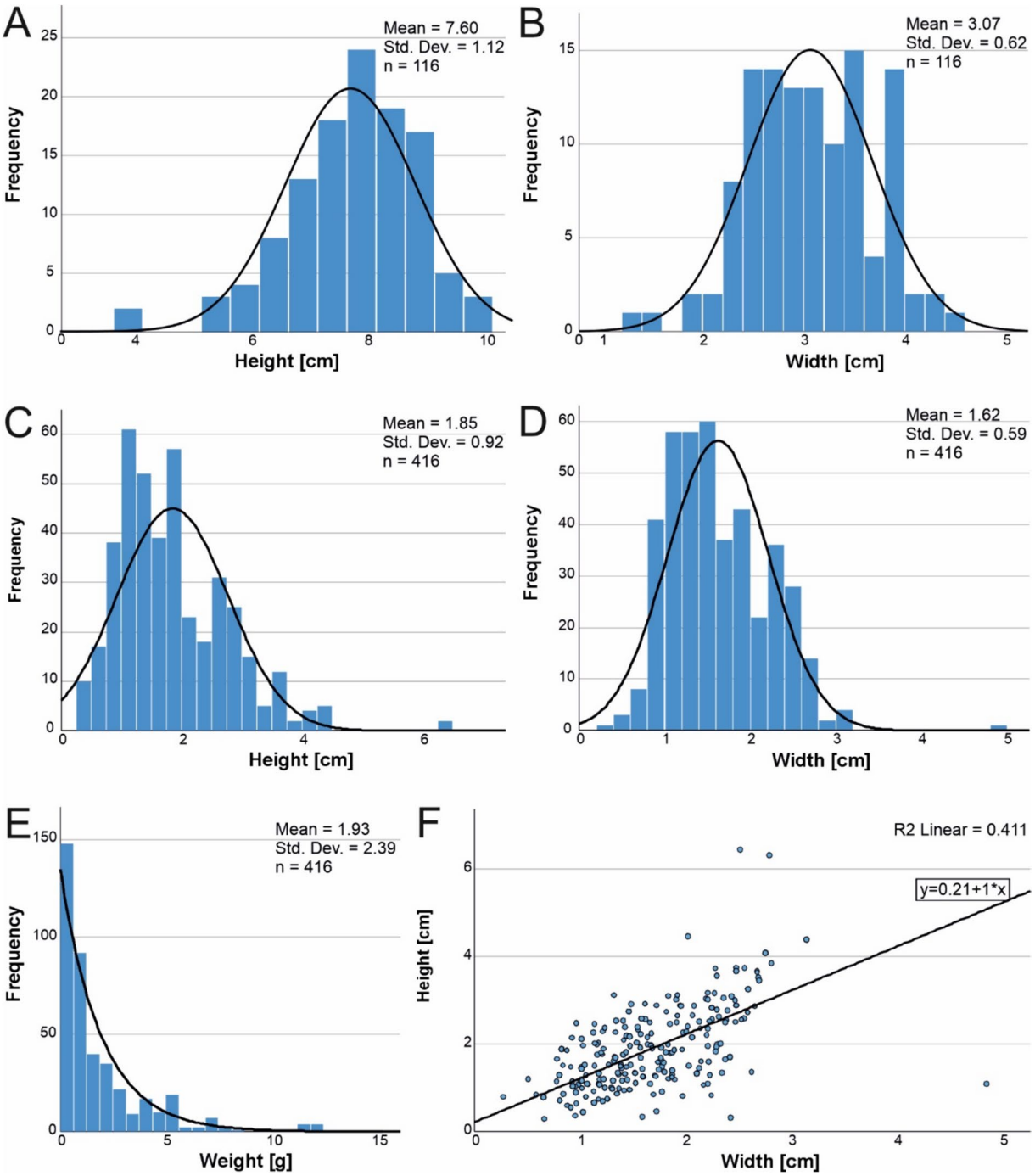
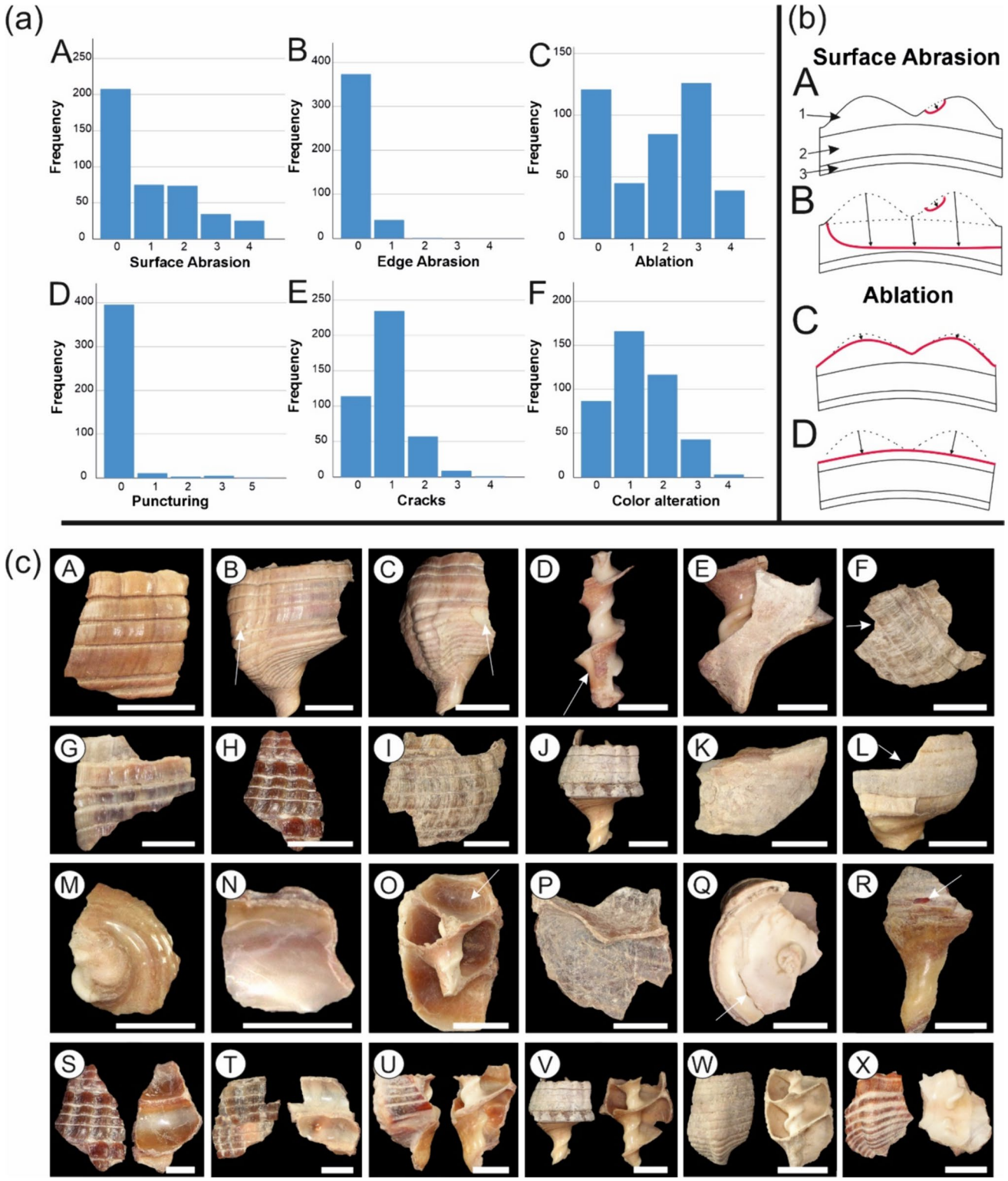


Fig. 3 Histograms of recently deceased *Terebralia palustris* from Kalba Khor (N = 116): **A** height and **B** width, and from the archeological context of Muweilah (N = 416): **C** height, **D** width, **E** weight, and **F** width/height

the over–exploitation and disappearance of the mangrove habitat at around ~ 4000 years ago (Feulner 2006; Händel 2013). Further possible explanations such as extreme water temperature and salinity, reduced freshwater input due to increasing aridity and negative impacts of varying ocean



currents are also suggested (Feulner 2006; Fleitman et al. 2022).

Terebralia palustris in Arabia (Table 1) is usually deposited in shell middens along with other mollusks (Parker and

◂**Fig. 4** **a** Levels of intensities (0—4) of taphonomic features on fragments of *Terebralia palustris* (Linnaeus 1767) from Muweilah. **A** surface abrasion, **B** edge abrasion, **C** ablation, **D** puncturing, **E** cracks and **F** color alteration. **b** Difference of surface abrasion and ablation. **A**–**B** Surface abrasion and **C**–**D** Ablation, with **A**, **C**) low intensity and **B**, **D** high intensity. 1 and 3 = interior and exterior surface layer. 2 = Cross–lamellar layer. Dotted line: old surface bevor surface abrasion/ablation. Red line: new surface after surface abrasion/ablation. **c** Taphonomic features of fragmented *T. palustris*. **A–E** Fragments with **A** no surface abrasion to **E** strong surface abrasion (**A**: Locus 2112, **B**–**E**: Locus 85,138). **F** An by edge abrasion unaffected specimen (Locus 50,020). **G**–**K** Fragments with **G** no ablation to **K** strong ablation (**G**: Locus 81,011, **H**: Locus 85,138, **I**—**L**: Locus 50,020). **L** A specimen with a low intensity edge abrasion (Locus 50,020). **M**—**Q** Fragments with **M** no cracks to **P** high frequency of superficial cracks (intensity 3) to **Q** a deep crack going through all shell wall layers (intensity 4) (**M**: Locus 81,011, **N** 45,016, **O**, **P**: Locus 50,020, **Q**: Locus 85,138). **R** Surface abrasion revealing a deeper, better preserved shell layer regarding coloration (Locus 85,138). **S**–**W** Fragments with **S** no color alteration to **W** complete color erosion (**S**, **T**: Locus 85,138, **U**: Locus 81,011, **V**, **W**: Locus 50,020). **X** Picture of the varix and parietal teeth (Locus 50,020). Scale: 10 mm

Goudie 2007; Händel 2013; Magee et al. 2017, 2018) where it dominates along with *Murex kuesterianus*, *Marcia* sp. and the oyster *Saccostrea cucculata*. A shift in domination from *T. palustris* to the mudflat inhabiting bivalve *Marcia* sp. occurred at the Neolithic to Iron Age transition, following mangrove habitat reduction (Händel 2013; Magee et al. 2017, 2018). Furthermore, preparation techniques changed from grilling to boiling resulting in a frequency decrease of burned specimens (Händel 2013; Magee et al. 2017). Although *T. palustris* has been found in conjunction with shell processing at burial and ritual sites, its utilization for sustenance clearly dominates. In addition, the greater importance of *T. palustris* at permanent sites has been recorded (e.g., Grupe and Schutkowski 1989; Potts 1996; Händel 2013; Magee et al. 2017, 2018; Roberts et al. 2019; Lidour et al. 2020).

Muweilah, an Iron Age II site near Sharjah (Emirate of Sharjah, United Arab Emirates), is located in an aeolian sand dune belt 15 km from the coast (Fig. 1a). The site was inhabited during the tenth century BC and was abandoned after a single fire event destroyed the city between 800 and 600 BC (Magee 1996, 2004, 2018; Karacic et al. 2018). Camel domestication and advanced herd management led to the reconfiguration of the trade systems and positions of settlement enabling the establishment of Muweilah. Advantages of the location were the possibility to control trade to and from coast and between coastal systems, as well as its position within reach of the coastal resource procurement zone though far enough away to be safe from coastal piracy attacks (Magee 2004; Uerpmann et al. 2013).

This paper concentrates on the taphonomy and morphology of *T. palustris* in archeological as well as natural settings and aims to: (1) analyze how shell structure affects taphonomic processes including fragmentation, (2) correlate handling and consumption techniques with preservation patterns in order to characterize material derived from archeological material, and (3) provide a guideline for analyzing fragmented shell remains in archeological material. The results can be used to compare different find localities within and among archeological sites in order to emphasize the importance of marine consumption among differing ecological as well as cultural backgrounds.

Methods

Living specimens of *Terebralia palustris* were observed in the mangrove of Khor Kalba (Sharjah, UAE), Gulf of Oman. Dead specimens from a mangrove section recently isolated and cut off from the sea were collected for thin sectioning and SEM analysis. Shells were sectioned using a DREMEL 300, cleaned in an ultrasonic bath, fixed to stubs using Plano Leit–C Plast and sputtered with Gold using a BALTEC CEA 035. Scanning electronic micrographs were taken using a Zeiss Crossbeam 550L Cryo–FIB–SEM at the Department of Geosciences, University of Tübingen and a Zeiss EVLO LS 15 at the State Museum of Natural History, Stuttgart, Germany. Further specimens of complete *T. palustris* (116 in all) collected at Khor Kalba were washed and dried. Height and width were measured (Fig. 2a D) using a Digitronic Caliper (IP54 series) and the results displayed using a histogram.

Fragments of mollusks including *T. palustris* were collected by hand under the supervision of Peter Magee, Bryn Mawr College (USA) from 1994 to 2006 from various loci. They are stored in the collections of the Sharjah Archeology Museum, Sharjah U.A.E. and were lent to the University of Tübingen for detailed study. For initial comparison, fragments from loci 45,016, 2112/2119, 81,011/81301, and 50,020 (Fig. 1b) were analyzed. Large samples were reduced using a sediment splitter (5 cm slat distance). 416 fragments were analyzed including height, width and weight (using a Sartorius type 1419 scale) and displayed using a histogram and statistically compared using Excel (Version 1808) and SPSS (Version 29). Size parameter were subjected to a Pearson's correlation analysis and interpreted using Cohen guidelines for evaluation (1988): 0.1–0.3 (weak effect), 0.3–0.5 (medium effect) and > 0.5 (strong effect). For existing correlations, a Friedman test was applied following a test

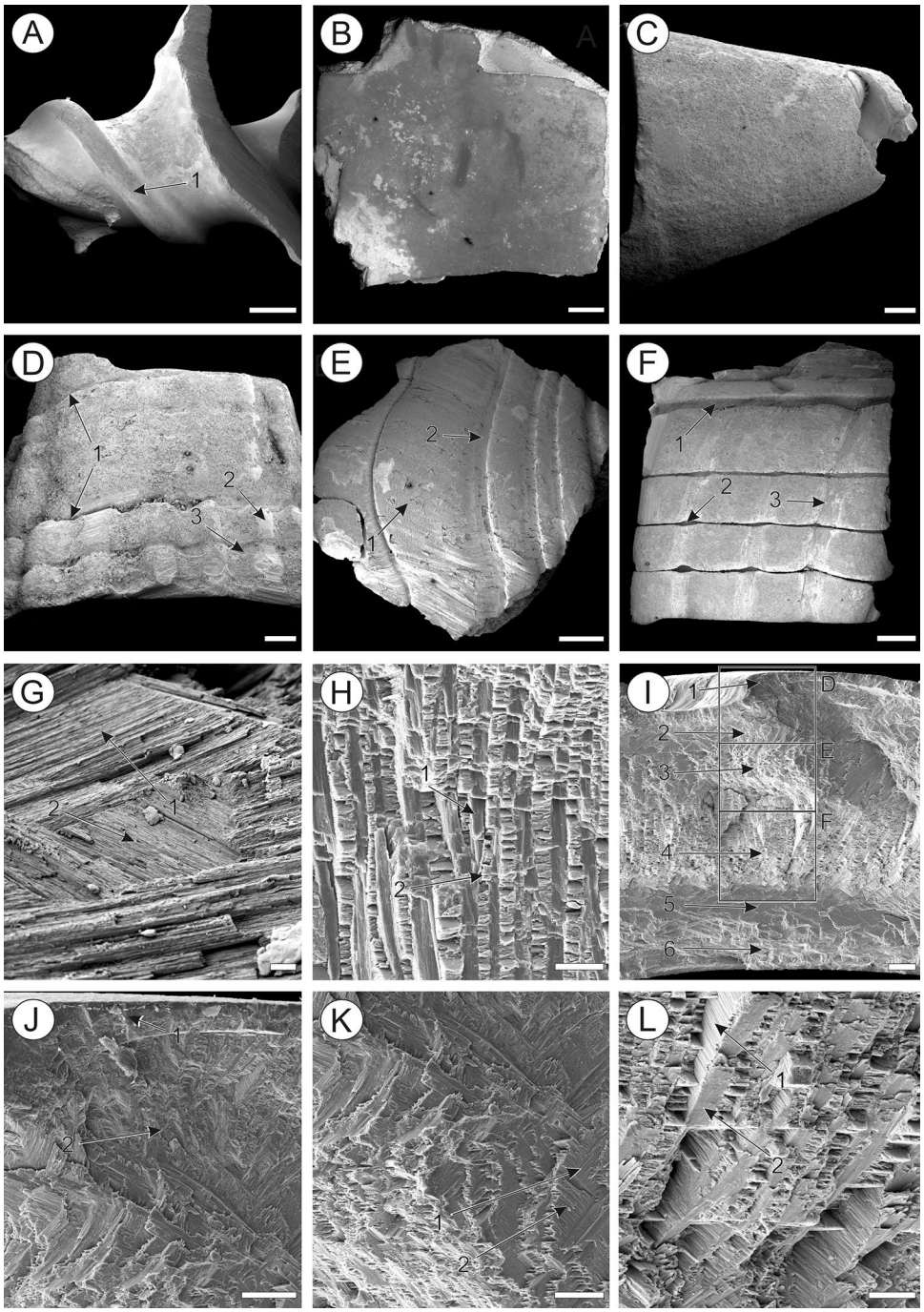


Fig. 5 SEM Micrographs of taphonomic features and shell constructions of *Terebralia palustris* (Linnaeus 1767). **A** Columella, with 1 = columellar fold. (Scale: 2 mm) **B** Internal surface of the external shell wall near the aperture. (Scale: 2 mm) **C** Apex. (Scale: 1 mm) **D** Fragment positioned slightly abapically from picture A, with 1 = suture, 2 = axial ornamentation, 3 = spiral ornamentation. (Scale: 1 mm) **E** External surface near the enlarged varix, with 1 = varix, 2 = spiral ornamentation. (Scale: 2 mm) **F** External surface near the aperture, with 1 = suture, 2 = spiral ornamentation, 3 = axial ornamentation. (Scale: 2 mm) **G–H** Cross lamellar layer with **G** block orientated in easy breaking direction (Scale: 0.1 mm) and **H** difficult breaking direction (Scale: 0.1 mm), 1 and 2 = lamellar layers. **I** Horizontal breaking edge, 1 and 6 = outer layer and 2–5 = differently orientated blocks. (Scale: 0.2 mm) **J** Close up of the outer layer and first block (easy breaking direction), 1 = outer layer, 2 = block. (Scale: 0.2 mm) **K–L** Close up of blocks in difficult breaking directions, 1 and 2 = lamellar layers. (Scale: K) 0.2 mm, **L** 0.05 mm)

for normal distribution (Kolmogorov–Smirnov and Shapiro Wilk tests). To compare height and width of the fragments from Muweilah with the complete specimens from Khor Kalba a Mann—Whitney U test was carried out. Results were subjected to a Pearson correlation analysis, again evaluated following Cohens guidelines (1988). Statistical evaluations were carried out using Excel (Version 1808) and SPSS (Version 29), Cohen (2013).

Shell fragment features were analyzed with respect to the preservation of (1) outer, and (2) inner surfaces of the exterior walls, (3) adapical surfaces of the transversal walls, (4) whorl base, (5) columella, (6) outer and (7) inner lip, and

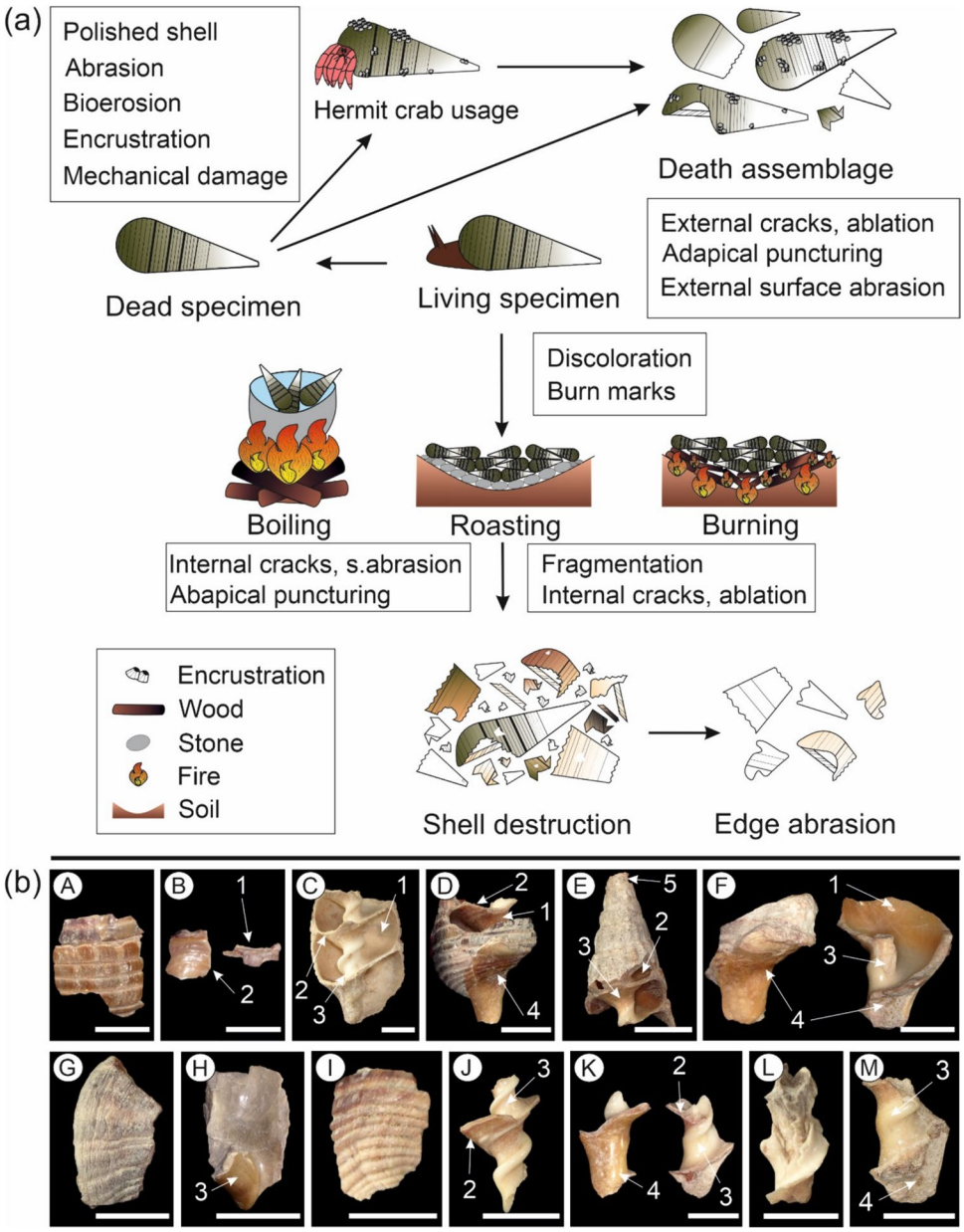


Fig. 6 **a** Taphonomic path of *Terebralia palustris* (Linnaeus 1767). The shell exterior of living specimens is exposed to adapical puncturing and external cracks, ablation and surface abrasion. Upper half: natural taphonomic path. After the death the empty shell may be used by hermit crabs, resulting in increased abrasion, bioerosion, encrustation, and mechanical damage or polished areas where the shell was dragged over the floor. Lower half: anthropogenic taphonomic path. Shown are three possible preparation methods: boiling and roasting dominate, while burning is considered an exception. Roasting includes lighting a fire on top of a stone covered surface and using the heated stones for preparation. Burning entails cooking *T. palustris* directly on an open fire (Meehan 1975). Depending on the preparation method and temperature, discoloration and burn marks appear. Shell destruction proceeds meat extraction, increasing fragmentation, abapical puncturing, internal cracks, surface abrasion and ablation. The open deposition inside the respective buildings causes slight edge abrasion. **b** Different fragment types of *T. palustris*. **A** Fragment of the external wall (Locus 2112). **B** Fragment with an external wall and a transversal wall (Locus 45,016). **C** Fragment with an external wall, a transversal wall, and a columella (Locus 50,020). **D** Fragment with an external wall, a transversal wall, a columella, and an inner lip (Locus 50,020). **E** Fragment with an external wall, a transversal wall, a columella, and an apex (Locus 81,011). **F** Fragment with an external wall, a columella and an inner lip (Locus 81,301). **G** Fragment of the outer lip (Locus 81,301). **H** Fragment with an external wall and inner lip (Locus 81,011). **I** Fragment of a transversal wall (Locus 81,011). **J** Fragment with a transversal wall and a columella (Locus 85,138). **K** Fragment of a transversal wall, a columella and an inner lip (Locus 81,011). **L** Fragment of the columella (Locus 81,011). **M** Fragment with a columella and an inner lip (Locus 81,011). (Scale: J) 5 mm, **A**–**I** and **K**–**M**) 10 mm)

(8) the apex (Fig. 2). Specific taphonomic features include: fragmentation patterns, surface and edge abrasion, surface ablation, puncturing, crack presence, color alterations and shininess. The intensity of surface abrasion, ablation, cracking, and color alteration were subdivided in to 5 categories, with 0 = not present, 1 = slight, 2 = moderate, 3 = high, and 4 = intense. Additionally, the quantity of burned fragments was determined. The minimum number of individuals (MNI) was calculated by counting the parietal teeth on the opposite site of the prominent varix. Photos were made using a Nikon D5100 and Keyence VHX Digital Microscope and merged using Helicon Fokus Software 8.2.2. Pictures were edited with respect to brightness and contrast using Photoshop version 16.0 × 64 and formatted using CorelDRAW (Version 24.3.0.571). Morphological terms follow Houbrick (1991), Bosh et al. (1995), Merle et al. (2011) and Phylum Mollusca 2023.

Results

Morphology of *Terebralia palustris*

Terebralia palustris has a solid, turriform shell with an acute apex and flat whorls (Fig. 2b A–C). The suture is deeply incised and abapically increasingly corrugated. Surface structure consists of axial ribs, three deep spiral grooves and occasional small varice. Axial ribs are crossed by weak striae at the base. The outer surface of the shell is covered by a greenish brown periostracum. A single thick varix is located opposite the outer lip of fully-grown specimens. Subordinate varice on earlier whorls are rare. The oval aperture is characterized by a fold at an acute angle at the posterior siphonal canal and a short, tubular anterior siphonal canal. Adaxically, the aperture is outlined by a large and smooth inner lip, a smooth parietal lip and a sharp outer lip. The shell color is a greenish dark brown, the varix can be lighter. The size distribution of complete specimens show normal distribution with a mean of 7.60 cm for height and 3.07 cm for width, and a maximum size of 9.60 cm (Fig. 3 A–B).

The interior is characterized by thick, fold bearing columella (Fig. 2a A, D–F) connected to the external wall by transversal walls ca. 1.7 mm thick. The whorl base is covered by a spiral pattern. Present on the internal surface opposing the varix are two parietal teeth, a larger, elongated one and a smaller, rounded one (Fig. 4c X). The inner abaxial surface shows a reddish–brown band concentrated on the middle of the whorl. This pattern is also present on the ad– and abapical surfaces of the transversal walls.

Consecutive growth of the shell leads to a complex internal morphology as layers are amalgamated into the shell. These layers show different colors ranging from translucent to more opaque brownish tones and are not restricted to distinct layers (Fig. 2a A–F). Abapically, internal sculpturing in the columella unite to form a continuous v–shaped line, while being separated from the surface by a few thin layers (Fig. 2a D–E). As the shell grows, the exterior walls of earlier whorls are successively covered by thin colorless layers (Fig. 2a D) as is the inner lip, which is incorporated into the columella. The columellar folds, which spiral along the columella, also increase in size. Finally, the apex of the shell is often infilled by shell material.

The internal shell construction of the aragonitic *T. palustris,* as revealed by SEM analysis of fragmented surfaces (Fig. 5G–L, Appendix Table 2), shows a thick central crossed lamellar layer (ca 0.6–2 mm thick) bounded by thin homogeneous layers on the inner (50–250 µm) and outer surfaces (40–260 µm thick). The crossed lamellar layer constitutes 70–89% of the shell thickness and is subdivided into distinct blocks, which are obliquely orientated to one another (Fig. 5I–L) with thicknesses which vary from 0.2 to 1 mm. These blocks consist of alternating sublayers of densely packed fibrous elements (up to 30 µm diameter) oriented obliquely to one another (Fig. 5G–H) (see Cuif et al. 2011).

Taphonomy of *Terebralia palustris*

Preservation of living and recently dead specimens

Recent *Terebralia palustris* shells are mostly complete and well preserved. Smaller specimens occasionally show broken basal walls or outer lips. The last few mm of the shell apex is always broken and more frequently affected by ablation of the periostracum. Ablation of the shell surface decreases in frequency and intensity towards the aperture along with color alterations resulting in a white to grey surface. Larger shells can also be polished near the aperture. Internal walls mostly show intense coloration and shininess with the exception of the inner lip and columella. The inner surfaces often show white spots or stripes of unknown origin near the aperture especially in larger shells. One highly fragmented specimen also shows serpulid encrustration as well as holes in the shell. Surface abrasion and cracking are not present in complete specimens.

Intensity and distribution of taphonomic features among fragments

The size parameters (Appendix Table 3) of fragments (Fig. 3C–F) show non–normal distributions (Appendix Table 4) with few outliers, whereby height and width display a linear correlation when plotted against each other. The distribution of height shows higher positive skewness (> 0) and kurtosis compared to weight. In Fig. 3, a normal distribution curve is inserted for the height and width, and an exponential curve for weight to illustrate the aberration from normal distribution. A two-tailed Pearson correlation test resulted in a strong positive correlation for all three parameter pairings, with a higher value for height–weight (Appendix Table 4). Correlation analysis show statistical independence of the three parameters. Weight distribution roughly follows an exponential distribution curve. Mann—Whitney U test indicates a strong significant difference for height and width between the fragments and the whole *T. palustris* shells. A calculated MNI of 81 individuals compared to the total number of fragments (416) results in an approximate five to one ratio.

Terebralia palustris shells from Muweilah are almost all very highly fragmented. The different fragment types and respective frequencies are illustrated in Fig. 6b A–M and included in Appendix Table 5. Common fragments are those consisting solely of exterior walls (34%), followed by various combinations of features, mostly also including exterior walls. The least common fragment types include the apex as well as isolated columella fragments.

Surface abrasion (Fig. 4c G–J) can lead to the complete removal of the outer surface layer and can even reach into the crossed lamellar layers (Fig. 4b) resulting in the reduction of shell thickness. Surface abrasion is widely distributed across the different shell areas (Fig. 4c G–K), yet noticeably locally confined and restricted to the outer shell layer. Following the high degree of fragmentation, specimens show numerous mostly sharp broken edges (Fig. 4c F, L and Appendix Table 6).

Very small oval to round holes are restricted to the exterior surface (Fig. 6b E), with one exception with up to five holes per specimen. These holes show smooth surfaces and appear in combination with strong ablation. Cracks are mostly restricted to the surface layer (Appendix Table 6) and often overlap leading to a reticulated pattern (Fig. 4c M–P). Larger holes and cracks (Fig. 4c Q) are rare.

Color, when preserved, is brown–greenish on the exterior walls (Fig. 4c S), light brown–reddish on the whorl base (Fig. 4c N), and brown in the remaining shell (Fig. 4c S—W). Fragments show a change in color compared to the complete specimens, reducing the intensity of the inner color banding and leading to more frequent color loss along the entire shell length, most severely at the outer lips, apex and columella (Fig. 4c V,W, Appendix Table 6). Surfaces affected by the complete loss of the original coloration change from white to light beige. Surface abrasion can reveal shell layers with a better color retention than the outer shell layer (Fig. 4c R). Shininess is most often restricted to the inner surfaces (Appendix Table 6) and shown by most of the shell areas with the exception of the apex, the outer surfaces of the exterior wall and outer lip. Evidence of burning (6% of specimens) as is indicated by grey to black colors can cover both limited areas as well as whole fragment surfaces (Fig. 2b D, Appendix Table 5).

Both surface and edge abrasion are dominated by intensity 0, with the former having a higher frequency of higher intensities 1–4 (Fig. 4a A–B). In contrast, ablation intensity distribution shows two peaks, firstly at intensity 0 and secondly at intensity 3 (Fig. 4a C). Puncturing is dominated by intensity 0 with very low frequencies of the remaining intensities (Fig. 4aD). Additionally, cracks and color alteration intensity (Fig. 4a D–E) distribution exhibit a peak at intensity 1, however, the latter has significantly higher values for the intensities 1–4. For the former, intensity 0 is more frequent than intensities 1–4.

Discussion

There is a clear difference in preservation of *Terebralia palustris* found in the mangrove settings and the remains recovered from the Iron Age site. The collected whole shells from the mangrove context show few signs of taphonomic processes other than apex perforations while archeological material is very highly fragmented and shows surface abrasion as well as strong ablation of the outer surfaces. Cooking practices lead to shell cracking, small perforations and color alterations.

Fragmentation

The very high rate of fragmentation resulting in a wide range of fragment types (Fig. 4.c, 6.b, Appendix Table 5) reflect consumption related processing methods, predominantly shell breakage to extract the flesh (Prieur and Guérin

1991; Prieur 2005; Charpentier and Méry 2008; Händel 2013; Lidour et al. 2020). Increased fragmentation rates, as shown by the Mann—Whitney U test are also reflected in the exponential weight distribution and the positive skewness compared to that of whole specimens (Fig. 3A–E). The unimodal distribution indicates a time averaged population of several harvests (Ford 1989). The cooking methods lead toward blocky shaped fragments (Fig. 3F) and reduced standard deviations and variances (Fig. 3, Appendix Table 3). Fragmentation patterns also suggest that the use of *T. palustris* shells other than sustenance is highly unlikely since the production of ornaments or tools would require a more selective fragmentation type and size distribution (Lidour et al. 2023). Despite the correlation between the size parameters, the Friedman test (Appendix Table 4) did not show any causality, which would require a clear cause – consequence relationship between the parameters. In this case, however, the parameters both influence each other: higher and wider specimen weigh predominantly more than smaller specimens, while heavier specimens are also predominantly larger. Likewise, higher specimens are predominantly wider and vice versa. This confirms that a specific fragment height or width was not targeted as such, but is rather a consequence of the meat extraction method.

The observed fragmentation patterns reflect the higher preservation potentials of thicker shell parts (e.g. Vermeij 1979; Zuschin and Stanton 2001; Zuschin et al. 2003; Dryer et al. 2018) (Fig. 2). Furthermore, these patterns are the result of the targeting of specific shell areas during the extraction process (Lidour et al. 2023). To extract the flesh, the body whorl is targeted (Prieur 2005; Händel 2013) leading to the separation of exterior walls along the entire width or in combination with internal walls (Fig. 6.2A–H). Transversal walls are preserved more frequently in combination with other shell areas (Fig. 6.2B–D, Appendix Table 6), i.e. either the columella or the outer shell. Only two fragments show larger sized holes which may be of anthropogenic origin. The fact that the apices are preserved significantly less frequently than the body whorl may be related to their smaller size, as well as to the type of consumption. The observation of Tryons (1887) who reported that the apex of *T. palustris* from the Eastern Archipelago was broken off during consumption in order to reach the flesh, however, seems unlikely in the present context as boiling and roasting are reconstructed as the main preparation techniques (see below). Fragmentation can also be influenced by the subsequent handling of shells as a waste product. It is not clear to what extent trampling can further affect preservation (e.g. Bally and Griffiths 1989; Ford 1989; Povey and Keough 1991; Rossi et al. 2007; Plicanti et al. 2016; Hausmann et al. 2019; Nicastro et al. 2019). It is also not known how subsequent exposure in a desert environment or subsurface conditions affected the shells.

Surface abrasion and ablation

The presence of surface abrasion in fragments as opposed to complete *T. palustris* (Fig. 4.c A–E, Appendix Table 5) suggests that this feature is a result of anthropogenic handling. Its more common presence on the outer surfaces can be explained by targeting the shell to reach the flesh, while the inner surfaces can only be affected after the destruction of the exterior wall. In addition, the frequency of surface abrasion decreases externally towards the apex which correlates with the targeting of the body whorl. Ablation occurs in complete specimens, where it increases in intensity towards the apex (Fig. 5), which represent older shell parts. In contrast, fragments (Fig. 4.c G–K, Appendix Table 6) show higher ablation near the aperture which, in turn, may reflect handling processes. In both cases ablation is less common on the inner surfaces (Fig. 5, Appendix Table 6).

Shell cracking and perforations

Shell cracking is interpreted to be the result of anthropogenic handling especially cooking (Milano et al. 2018; Aldeias et al. 2019) and it is absent on complete specimens from the mangrove environment. Cracks are predominantly located on interior surfaces of the exterior walls (Appendix Table 6) and are restricted to the inner and outer layers (Fig. 5). These discrepancies in shell cracking between the interior and outer surfaces (Fig. 4.c M—Q, Appendix Table 6) are thus most likely a result of subsequent surface abrasion and ablation of the shell during the cooking process. This assumption is supported by Meehan (1975), who reports that aborigines use pointed sticks or safety pins to separate the meat of *T. palustris* from its shell, if it did not detach immediately after fragmentation.

The lack of cracks in the central crossed-lamellar layer is certainly due to the prevention of crack propagation attributed to this layer (e.g. Carter. 1990). Small holes found near the apex are present in the complete mangrove specimens and are not of anthropogenic origin. Finally, the by shell material infilled apex as seen in living *T. palustris* (Fig. 6.b E, Appendix Table 6) is a common feature for gastropods (e.g. Kohn et al. 1979; Bourdeau 2010; Charifson 2019).

Color alterations and shininess

Color alterations corresponding to anthropogenic handling are due to cooking processes. Studies have shown that cooking causes temperature dependent microstructural alterations as well as δ13 and δ18O aberrations, which lead to color alteration at 200 °C or 300 °C (Milano et al. 2016 and 2018; Müller et al. 2017; Lindauer et al. 2018; Aldeias et al. 2019). At higher temperatures, the shell initially turns grey

(400–500 °C) and is unlikely to preserve in the archeological setting above 700 °C (Milano et al. 2016 and 2018; Lindauer et al. 2018). The small quantity of burned specimens (Appendix Table 5) indicate a predominant cooking temperature below 400 °C (Lindauer et al. 2018; Aldeias et al. 2019). Practices not directly related to cooking, however, can also lead to burned shell deposits, namely fires lit on top of a shell–rich matrix, which are difficult to preserve in an archeological setting and to identify (Aldeias et al. 2019). The complete loss of surface color may be due to ablation, although it may also reflect the influence of cooking processes on shell color (see below). Finally, abrasion exposes inner shell layers that show more intense coloration.

High rates of shininess are prevalent on almost all fragments (Appendix Table 6), especially on the interior surfaces which are first exposed after fragmentation during cooking (Händel 2013). Surfaces more frequently lacking shininess correspond to those exposed during life and include the apex, outer surfaces of the exterior wall and the outer lip.

Taphonomic pathways of *Terebralia palustris*

The different possible taphonomic pathways of *Terebralia palustris* are shown in Fig. 6. There is no evidence for a collection of *T. palustris* shells after a natural death in the mangrove environment. The lack of (1) smoothed surfaces in contact with the sediment surface, (2) increased encrustation, and (3) abrasion in areas previously covered by the gastropod indicate against the shell use by hermit crabs (Frey 1987; Walker 1989). With interior surfaces only being exposed after death and the subsequent shell breakage, their good preservation, as shown by the low ablation, surface abrasion as well as color alteration and increased shininess, serve as an indicator for the relatively short exposure time after handling. The low frequencies and intensities of edge abrasion (Fig. 4.c F,L, Appendix Table 6) also correspond to relatively short exposure time after fragmentation.

The different cooking procedures are highlighted in Fig. 6. Options for preparation (Aldeias et al. 2019) are boiling (100 °C), roasting techniques (200–300 °C) or burning (500 °C, see above). The color alteration of the colorless shell parts and of the inner surfaces (Fig. 4.a F) as well as the exposure of shell layers with a better color retention caused by surface abrasion (Fig. 4.c R) allude to roasting techniques. It is known from studies on bivalves that roasting techniques induce color alteration caused by temperatures generated between 200 °C and 300 °C, but more studies are needed to better predict the cooking process (Milano et al. 2016 and 2018; Lindauer et al. 2018). Indications of boiling are the many specimens without any color alteration (Milano et al. 2016, 2018; Lindauer et al. 2018; Aldeias et al. 2019). Identifying the preferred cooking process is made more difficult by the fact that the temperature is influenced not only by the method (e.g. boiling and roasting), but also by the distance to the fire and the fuel (Wolf et al. 2013; Hanson and Cain 2007).

In general, the preparation methods of shellfish in the Arabic Peninsula are still mostly unknown, but cooking processes are better known from Australia. Aborigines either steam or grill *T. palustris* for a few minutes in an open fire (Meehan 1975; Houbrick 1991; Loch 1987). It must be noted, however, that not only the geographical area but also the time period differ compared to the present study.

Conclusions

The differences in preservation of archeological material and living shells can be attributed to cooking processes. Specific morphological features related to internal shell structure, shell thickness, as well as position along the internal and external surfaces have important effects on fragment preservation.

Preservation features of living specimens are restricted to some ablation of the periostracum towards the apex as well as the degradation and puncturing of the tip of the apex. Besides higher levels of ablation, the highly fragmented archeological material also show higher levels of surface abrasion, surface cracks and color alterations. Complex internal layering creates different color intensities affecting the color preservation potentials.

Breakage of the shells by blunt force preceded meat extraction resulting in various sized, blocky shell fragments. The columella is rather robust, along with distal outer shell surfaces and the by infillings stabilized apices, as opposed to the more highly fragmented remaining outer shells and the inner shells. Fragmentation exposes the inner shell surfaces leading to increased incidences of ablation, while still conserving more difficult to recognize conservation features than on the more ablated outer surfaces. Inner surfaces and edge abrasion serve as indicators for the exposure time after handling. It is not clear to what extent trampling leads to further fragmentation, whereby the rather large and robust nature of these gastropod fragments must be considered.

Shell alterations attributed to cooking techniques are shallow cracks on the inner surfaces, increased ablation and surface abrasion near the aperture, as well as the presence of burn marks. Based on the correlation between color alteration and cooking temperature, boiling (100 °C) and roasting (200–300 °C) are the main, and burning (500 °C) a secondary cooking method.

Appendix

See below Appendix Tables 2, 3, 4, 5 and 6.

Table 2 Length [µm] and percentage [%] of the complete shell for each shell layer (Layer 1 to Layer 6) for two horizontal and a vertical breaking edge (Fig. 5) of *Terebralia palustris*

	1 Horizontal		2 Horizontal		1 Vertical	
	Thickness [µm]	Percentage [%]	Thickness [µm]	Percentage [%]	Thickness [µm]	Percentage [%]
Total	1910–2180	100	860–1520	100	1650–2390	100
Outer Layer	70–190	3–9	40–260	4–17	70–200	5–8
Cross lamellar Block 1	200–450	10–20	–	–	200–770	12–32
Cross lamellar Block 2	270–530	15–25	–	–	700—930	40
Cross lamellar Block 3	500–700	26–32	600–1100	70%	–	–
Cross lamellar Block 4	560–680	30	–	–	390–780	25–30
Inner Layer	50–60	3	130–250	15	70–130	5

Table 3 Statistical properties of the parameters height and width of *Terebralia palustris* of recently dead specimens (Recent) from Khor Kalba (Sharjah, U.A.E) and weight, height and width from the archeological context of Muweilah (Archeo)

	Height		Width		Weight
	Recent	Archeo	Recent	Archeo	Archeo
N	116	416	116	416	416
Mean	7.60	1.85	3.07	1.62	1.93
Std. Error of Mean	0.10	0.05	0.057	0.03	0.12
Median	7.72	1.69	3.04	1.52	1
Mode	3.66	1.16	3.48	1.02[a]	0.4
Std. Deviation	1.12	0.92	0.62	0.59	2.39
Variance	1.25	0.85	0.38	0.35	5.71
Skewness	−0.77	1.13	−0.12	0.71	2.59
Std. Error of Skewness	0.23	0.12	0.23	0.12	0.12
Kurtosis	1.14	2.21	−0.25	1.24	8.47
Std. Error of Kurtosis	0.45	0.24	0.45	0.24	0.24
Range	5.93	6.15	3.15	4.58	16.88
Minimum	3.66	0.29	1.26	0.27	0.093
Maximum	9.59	6.45	4.41	4.85	16.97
Sum	881.64	767.6	355.63	675.84	802.31
Percentiles					
0.4	6.96	1.16	2.60	0.4	0.4
50	7.72	1.69	3.04	1.52	1
75	8.40	2.47	3.52	2.03	2.39

[a] Multiple modes exist. The smallest value is shown

Table 4 Results of the Kolmogorov–Smirnov and Shapiro–Wilk test, Pearson Correlation analysis of the parameters weight, height and width, Friedman test of the parameter pairings weight–width, weight–height and width–height of *Terebralia palustris* from the archeological context of Muweilah, as well as Mann–Whitney U test for the parameters height and width of complete shells from Khor Kalba and fragmented shells found at Muweilah

	Kolmogorov–Smirnov[a]			Shapiro–Wilk		
	Statistic	df	Sig	Statistic	df	Sig.
Weight	0.22	416	< 0.001	0.70	416	< 0.001
Height	0.10	416	< 0.001	0.93	416	< 0.001
Width	0.09	416	< 0.001	0.96	416	< 0.001
Pearson correlation						
		Weight	Width	Height		
Weight						
	Pearson correlation	1	0.68[a**]	0.86[**]		
	Sig. (2–tailed)		< 0.001	< 0.001		
	N	416	416	416		
Width						
	Pearson correlation	0.68[**]	1	0.64[**]		
	Sig. (2–tailed)	< 0.001		< 0.001		
	N	416	416	416		
Height						
	Pearson correlation	0.86[**]	0.64[**]	1		
	Sig. (2–tailed)	< 0.001	< 0.001			
	N	416	416	416		
Friedman Test						
Sample 1 – Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[b]	
Weight–Width	− 0.38	0.069	− 5.44	< 0.001	0	
Weight–Height	− 0.67	0.069	− 9.64	0	0	
Width–Height	0.29	0.069	4.20	< 0.001	0	
Mann–Whitney U Test: Rank						
	Khor Kalba/Muweilah	n	Mean Rank	Sum of Ranks		
Height	Khor Kalba	116	474	54,984		
	Muweilah	416	208.64	86,794		
	Total	532				
Width	Khor Kalba	116	454.42	52,713		
	Muweilah	416	214.10	89,065		
	Total	532				
Mann–Whitney U Test: Statistics						
	Height	Width				
Mann–Whitney U	58	2329				
Z	− 16.441	− 14.890				
Asymp. Sign. (2-tailed)	< 0.001	< 0.001				
Pearson Correlation	0.71	0.65				

Each row of the Friedman test checks the null hypothesis that the Sample 1 and Sample 2 distributions are the same. Asymptotic significances (2–sided tests) are displayed. The significance level is 0.05. [a]Liliefors Significance Correction, ** = Correlation is significant at the 0.01 level (2–tailed) and [b]Significance values have been adjusted by the Bonferroni correction for multiple tests

Table 5 Different fragment types with the respective occurring shell areas and their corresponding percentages (%) as well as quantity and percentage [%] of fragments with burn marks

Fragment Types	Total	Burned	
	Percentage [%]	Quantity	Percentage [%]
Total	100	27	6.49
Exterior walls	33.89	5	18.52
Exterior and transversal walls	7.21	–	–
Exterior and transversal walls, and columella	6.25	1	3.70
Exterior and transversal walls, columella and inner lip	13.46	–	–
Exterior and transversal walls, columella, inner lip and apex	0.24	–	–
Exterior and transversal walls, columella and apex	8.41	–	–
Exterior walls, columella and inner lip	4.33	–	–
Exterior walls and outer lip	3.37	–	–
Exterior walls and inner lip	2.16	4	14.82
Transversal walls	0.96	4	14.82
Transversal walls and columella	14.18	–	–
Transversal walls, columella and inner lip	0.96	–	–
Columella	4.33	13	48.82
Columella and inner lip	0.24	–	–

Terebralia palustris specimens total 416

Table 6 Quantity (Q) and percentage (%) of surface and edge ablation, puncturing, cracks, color and shininess regarding the different *Terebralia palustris* shell areas

	Surface Abrasion		Edge Abrasion		Surface Ablation		Puncturing		Cracks		Color		Shininess	
	[Q]	[%]	[Q]	[%]	[Q]	[%]	[Q]	[%]	[Q]	[%]	[Q]	[%]	[Q]	[%]
Total (n = 416)	208	50	43	10.34	336	80.77	20	4.81	302	72.60	329	79.09	411	98.80
Outer surface of the exterior wall	129	39.21	37	11.25	310	94.22	20	100	27	8.21	184	55.93	62	18.84
Inner surface of the exterior wall	38	11.55	37	11.25	39	11.85	20	100	233	70.82	199	60.49	284	86.32
adapical surface of the transversal wall	23	10.65	11	5.09	19	8.80	0	0	78	36.11	31	15.28	160	74.07
Whorl base	29	13.43	11	5.09	31	14.35	0	0	68	31.48	142	65.74	176	81.48
Columella	22	10.09	0	0	11	5.05	0	0	82	37.61	14	6.42	190	87.16
Outer lip	0	0	1	7.14	9	64.29	0	0	1	7.14	1	7.14	2	14.29
Inner lip	19	22.62	0	0	42	50	0	0	17	20.24	73	86.90	73	86.90
Apex	2	5.88	–	–	34	100	18	90	0	0	5	14.71	0	0

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3. Archaeomalacology of an Iron Age Site of Muweilah (United Arab Emirates): Environmental Provenance and Taphonomic Pathways of a Major Food Source

Inés De La Fortuna Müller García and James H. Nebelsick

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3.1 Context and Scope

This manuscript presents a comprehensive taxonomic and taphonomic analysis of the molluscan assemblage from the archaeological site of Muweilah (United Arab Emirates). In contrast to Manuscript 1, which focuses on a single dominant species, this study examines the full assemblage, comprising 40,668 individuals representing 54 taxa.

The aim of the study is to investigate patterns of resource use and processing across the assemblage, including species-specific exploitation, taphonomic alteration, and the ecological origins of the taxa. To achieve this, taxonomic identification is combined with a semi-quantitative taphonomic analysis of the assemblage. Particular attention is given to the identification of source habitats of the shell remains in order to reconstruct the environmental and economic context of shell exploitation, as well as to compare the results with other relevant sites in Southeast Arabia.

This manuscript builds directly on the results of Manuscript 1, in which *Terebralia palustris* was established as a taphonomic reference framework. The broader dataset analyzed here allows these species-specific observations to be contextualized within the full assemblage. By integrating taxonomic composition, taphonomic patterns, and habitat information, this study provides the basis for the synthesis, as well as the analysis of intra-site variations and environmental interpretations developed in Manuscript 3.

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Archaeomalacology of an Iron Age Site of Muweilah (United Arab Emirates): Environmental Provenance and Taphonomic Pathways of a Major Food Source

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ABSTRACT

Archaeomalacological evidence offers important insights into dietary habits, shell use, human-environment dynamics, climate variability, and broader aspects of cultural behaviour. In this study, an extensive collection of molluscan remains from Muweilah, an Iron Age II (1000-600BC) site in the United Arab Emirates, were examined with respect to their taxonomy, taphonomy, and environment of origin. The analysis includes a total of 40,668 individuals from 54 taxa, which are dominated by the gastropods *Terebralia palustris* and *Hexaplex kuesterianus* and the bivalves *Marcia cordata* and *Ostreoidea* sp. Most specimens originate from mangrove and littoral environments and show a high degree of taphonomic alterations including fragmentation, ablation, superficial cracks, surface abrasion and different states of preservation with respect to colouration and shininess. These taphonomic features are consistent with the dominant taxa being used for sustenance, possibly supplemented by bivalves such as *Anadara and Pinctada*. The variation in taphonomic patterns likely reflects differences in processing as well as a species-specific cooking methods. Further remains, including *Cypraea* sp., *Conus* sp., and *Strombidae* sp., were likely collected for use as ornaments or utensils. Some specimens appear to have served as flooring material, while others, gathered as by-catch or through beach collection, may have been repurposed as tools.

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Introduction

The analysis of archaeological mollusk remains has proven valuable for understanding both dietary and symbolic shell use, while also offering insights into human-environment interactions, subsistence strategies under arid conditions, environmental change, and broader cultural practices (e.g. Beech and Glover 2005; Biagi 1999; Çakırlar 2011; Gutiérrez-Zugasti et al. 2011; Kuhn et al. 2001; Bar-Yosef Mayer 2002; Oliver 2015; Sukenik et al. 2021; Szabó et al. 2014; Uerpmann 1992). The taphonomic study of these archeological shell remains often focused on use-wear analysis of shell tools or jewelry, including experimental set-ups (e.g. Allen, Holdaway, and Fullagar 1997; Cuenca-Solana, Gutiérrez-Zugasti, and González-Morales 2017; Lidour and Cuenca Solana 2024; Romagnoli et al. 2017), with an increasing number of studies concerning the thermal alteration of shells predominantly related to cooking processes (e.g. Aldeias et al. 2019; Lindauer et al. 2018; Milano, Prendergast, and Schöne 2016, 2018). In addition, archaeomalacological studies have also started to cover other topics such as the marine radiocarbon reservoir effect, spatial variability in shell midden formation, the reconstruction of past collecting strategies, distinguishing natural from archeological shell accumulations, shell fragmentation and purple dye production (e.g. Ambrose 1983; Andrus 2011; Attenbrow 1992; Campbell 2008; Hausmann et al. 2019; Müller García and Nebelsick 2024; Oliver 2015; Sukenik et al. 2021; Zazzo et al. 2012).

While the broader relevance of mollusks in within archaeological sites in Southeast Arabia has been acknowledged, detailed species identification and taphonomic assessments remain limited, especially for Iron Age contexts, despite the abundance of shell residues, and are often restricted to ^{14}C dating (e.g. Al-Jahwari 2011; Çakırlar 2011; Lidour et al. 2020; Prieur 1990). This paper addresses this gap by analysing mollusk remains from the Iron Age II site of Muweilah (Emirate of Sharjah, UAE), a well-studied inland settlement located 15 km from the coast at 25°17′59.294″ N, 55°29′49.955″ E. Through taxonomic identification and taphonomic study of both gastropod and bivalve remains, the present study aims to reconstruct environmental conditions and mollusk collection contexts. These data will form a basis for interpreting human behaviour related to mollusk use during a period marked by climatic transition and increasing social complexity (Boivin and Fuller 2009;

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Fleitmann et al. 2022; Karacic et al. 2018; Magee 2004, 2014; Moussa 2019; Potts 2001).

Study Site

The present study analyses gastropods and bivalves remains from the Iron Age II site of Muweilah located 15 km from the coast in an aeolian sand dune belt (Figure 1). Previous studies have established the chronological framework of the site based on radiocarbon dating of date seeds, wood, charcoal, beam fragments, as well as gastropod and bivalve shells, indicating continuous occupation of the site from the 10th century BC until its destruction by a single fire in the 8th/6th century BC (Karacic et al. 2018; Magee 1996, 2002, 2003, 2004; Magee et al. 2009, 2018). Climatic conditions similar to those of today appeared at the beginning of the Iron Age II (see below), however, permanent occupation and an increased population were achieved despite these arid conditions through the domestication of the camel, improvements in herd management as well as the introduction of the falaj irrigation system, which consist of large tunnels transporting water from higher-lying aquifers to the settlements (Benoist 2008; Boivin and Fuller 2009; Magee 1998; Magee 2004, 2014; Magee and Thompson 2001; Moussa 2019; Potts 2001; Uerpmann et al. 2013). In addition to improvements of navigational skills in seafaring, these factors led to a beneficial trading location near the coast while ensuring greater safety from coastal dangers such as piracy (Benoist 2008; Boivin and Fuller 2009; Blau et al. 2000; Magee 2004, 2014; Potts 2001; Uerpmann et al. 2013).

Environmental Background

During the late Pleistocene, the landscape of southeast Arabia was shaped by hyper-arid climatic conditions, the formation of extensive mega dunes, and the desiccation of the Arabian Gulf due to glacially induced sea-level lowering. This situation persisted until approximately 10,500 BC, when rising sea levels initiated the flooding of the Gulf Basin through the Strait of Hormuz (Al-Farraj 2005; Lambeck 1996; Lokier et al. 2015; Parker et al. 2006a; Shakun et al. 2007). In the early Holocene, increasing sea levels coincided with a transition to more humid climatic conditions, driven by a northward migration of the Intertropical Convergence Zone (ITCZ) and the intensification of the Indian Ocean Monsoon (IOM). These conditions favoured the development of extensive mangrove ecosystems, particularly during two major climatic optima between 4800–4400 BC and 3800–3500 BC (Al-Farraj 2005; Banerji, Arulbalaji, and Padmalal 2020; Berger et al. 2013; Burns et al. 2001; Fleitmann et al. 2004; 2007; Lézine et al. 2017; Parker et al. 2006a; Parker et al. 2020; Shakun et al. 2007; Staubwasser et al. 2002). This humid phase was intermittently disrupted by drier periods, caused by temporary southward shifts of the IOM (Berger et al. 2013; Boivin and Fuller 2009; Händel 2015; Parker et al. 2006b).

Around 4000 BC, the monsoonal influence over southeast Arabia waned, giving way to a precipitation regime dominated by Mediterranean winter rainfall associated with low-pressure systems. This transition marked the onset of increased regional aridity, evidenced by the widespread decline of mangrove habitats, the development of sabkhas and desert scrublands, and the reactivation and accretion of sand dunes (Al-Farraj 2005; Berger et al. 2013; Damien, Kosmas, and Éric 2020; Fleitmann et al. 2022; Glover 1998; Lambeck 1996; Parker et al. 2006a, 2006b; Staubwasser et al. 2002). Despite these long-term arid trends, localised variations in precipitation occasionally led to the formation of lakes. A persistent hyper-arid phase was finally established at the beginning of the Iron Age II (ca. 1000 BC) and continues to the present day (Berger et al. 2013; Damien, Kosmas, and Éric 2020; Händel 2015; Lambeck 1996; Parker et al. 2006a, 2006b). Around 4000 years BP, the modern sea level was reached, followed by a period during which it temporarily exceeded the present level by up to 2 metres. Thereafter, the sea level gradually declined, with fluctuations, to the present sea level (Bernier et al. 1995; Damien & Kosmas 2020; Händel 2015; Parker et al. 2006a, 2006b, 2020; Paul and Lokier 2017; Rutkowski and Kiersnowski 2025).

Stratigraphy

The stratigraphic sequence at Muweilah, documented in the northern sector of the site and intersecting the northern fortification line, is illustrated in Figure 2 (after Blau et al. 2000). The exposed stratigraphy attains a maximum depth of approximately 80 cm and is composed primarily of sandy deposits containing fragments of both cemented and partially cemented material. In the southern portion of the profile, two discrete stratigraphic units containing cultural material, including marine shell deposits, are present. These layers consist of ash and charcoal within a sandy matrix, interspersed with lenses of clean sand (foot mould) (Blau et al. 2000; Karacic et al. 2018). To the north of these cultural layers, the remains of a mudbrick and stone structure, interpreted as the first surround wall, are preserved (see Figure 1). At the northern end of the section, deposits of Farush stone (beach rock) are present (Blau et al. 2000; Karacic et al. 2018).

Research History and Bioarchaeological Evidence from Muweilah

Ongoing excavations started in December 1994 under the supervision of Peter Magee from Bryan Mawr College (USA) following French explorations in 1988

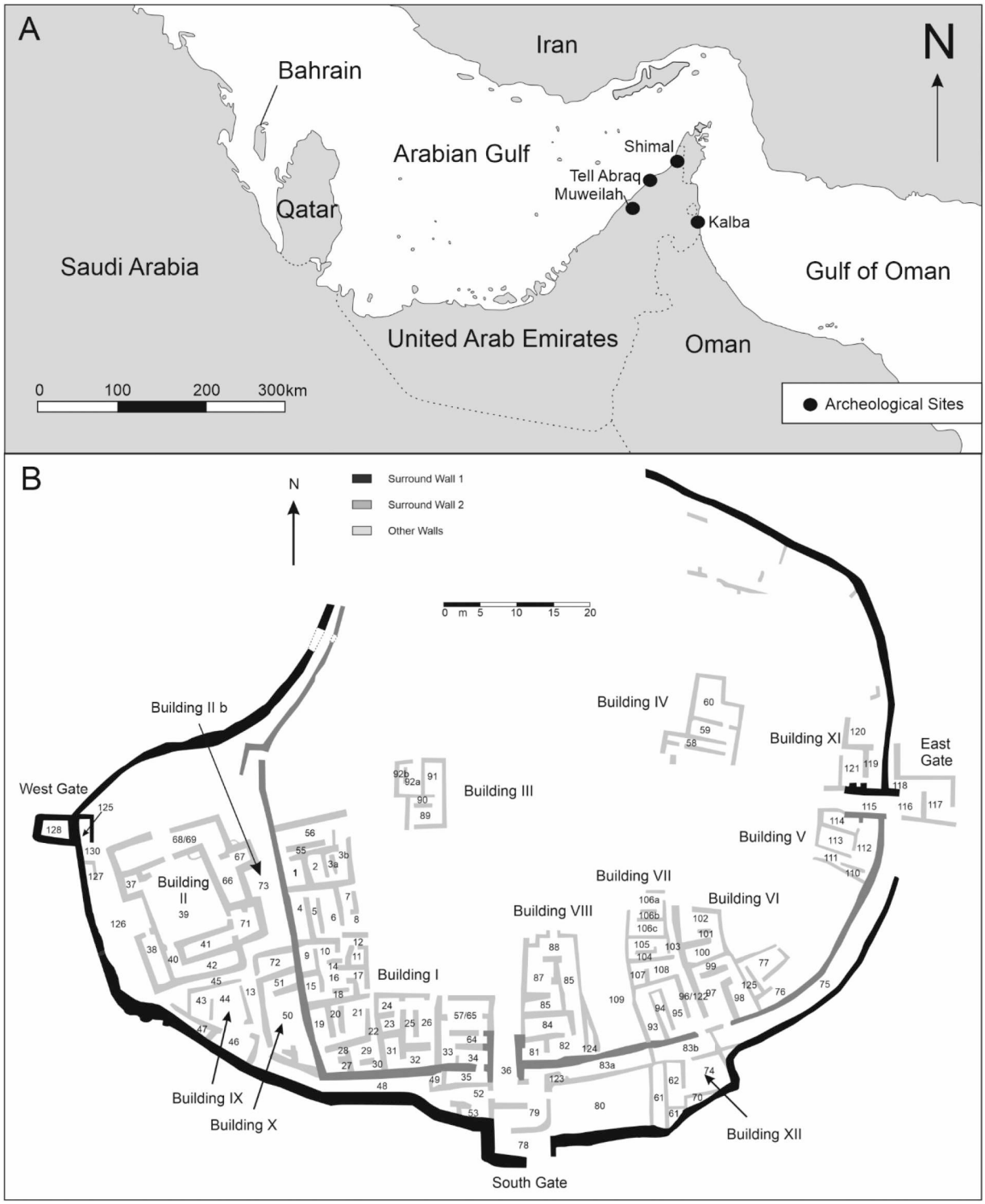

Figure 1. (A) Position of the archaeological site of Muweilah in the Arabian Peninsula with relevant archeological sites of the region and (B) Map of Muweilah (Figures adapted from Karacic et al. 2018; Lidour and Cuenca Solana 2024; Magee 2004 Müller García and Nebelsick 2024).

(Magee 1996). Numerous archaeological publications including a geophysical analysis followed revealing a large section of the settlement, leaving the north mostly unexplored (Blau et al. 2000; Karacic et al. 2018; Magee 1996, 2000, 2014). Botanical and vertebrate remains were examined by Uerpmann and Tengberg respectively (Magee 1996, 2014; Magee and Thompson 2001; Tengberg 2009), who recovered numerous date palm (*Phoenix dactylifera*) remains containing the rarely preserved dates in addition to the more common date seeds and wood. Dates represent an important part in sustenance in southeast Arabia, however, other areas of the plant, such as leaves and trunks, are also important for construction and wood supply (Magee 1996; Magee and Thompson 2001; Tengberg 2009). Charcoal fragments of tamarisk (*Tamarix* sp.), jujube (*Ziziphus*) and *Acacia* sp. were frequently found, but not the common *Avicienna*

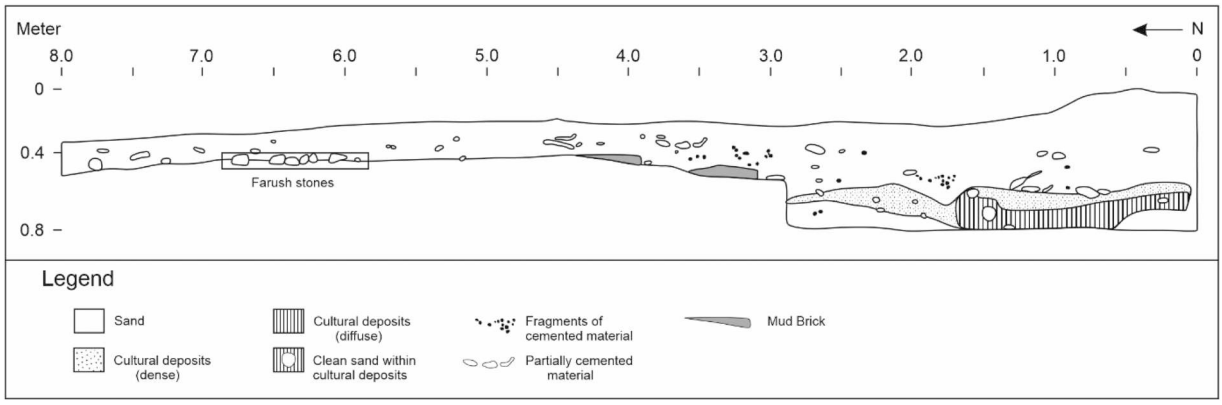

Figure 2. Stratigraphic sequence of Muweilah (Figure adapted from Blau et al. 2000 and Karacic et al. 2018).

marina and *Rhizophora/Bruguiera* nor cereals, which in the latter case may be correlated with selective preservation (Magee 1996; Magee and Thompson 2001).

Among vertebrate remains, fish and dromedaries were quite common as milk and meat resources alongside sheep and goats. Cattle, oryx and gazelles were the main hunted terrestrial animals alongside carnivores like foxes and wolves, as well as the Socotra cormorant (Magee 1996, 2014). Only few studies, however, have analysed the widespread shell accumulations (Magee and Thompson 2001), including a detailed taphonomic study of the gastropod *Terebralia palustris* (Müller García and Nebelsick 2024). This paper aims to contribute to a more extensive understanding of these mollusks remains.

Aims

Specifically, the present manuscript seeks to: (1) identify the mollusk species composition in Muweilah, (2) describe their taphonomy, and (3) their environmental backgrounds, as to draw conclusions about the potential locations of shell collection and to interpret their function, for instance for consumption, ornamentation, or other cultural practices.

By focusing on these shell remains, this study contributes not only to a more nuanced understanding of Muweilah itself but also adds to our understanding of the human – environmental relationship as well as to a broader archaeological knowledge of Southeast Arabia. Building on previous work (Müller García and Nebelsick 2024), this manuscript aims to enhance our understanding about the climatic context in which shell collection and use took place, while offering a methodological framework which can be applied to mollusk assemblages at other contemporaneous sites in the region.

Methods

A total of 40,668 shells originating from 541 Loci from Muweilah were identified on species level using Bosh et al. (1995) and verified using MolluscaBase (2025). Loci with a very high number of individuals were reduced to a processable quantity using a sediment splitter (5 cm slat distance). Material from floor samples consisting of micro-gastropods from Buildings VI and samples with unclear origin were excluded from the analysis.

The environmental distribution of taxa was recorded, distinguishing between mangrove, littoral, sublittoral, offshore and undetermined habitats, whereby both the number of individuals and the number of species was assessed. The habitat classification into the individual groups was primarily based on Bosh et al. (1995), alongside numerous other publications, which are listed in detail in Appendix 1. Statistical analyses were carried out using Excel (Version 1808) as well as R (Version 2024) and the diagrams assembled with the help of Coral Draw (Version 24.3.0.571).

The taphonomic state of preservation was described including (A) degree of fragmentation, (B) ablation, (C) puncturing, (D) crack presence, (E) colour alteration, (F) burning, (G) incrustation, and (H) shininess. Photographs were taken with a Nikon D5100 as well as a Keyence VHX Digital Microscope, edited concerning brightness and contrast using Photoshop (Version 16.0 × 64), and formatted with Coral Draw (Version 24.3.0.571). Images with different focal depths were merged into a single image using Helicon Fokus Software (Version 8.2.0).

Results

Taxonomic Analysis

The presence of mollusk remains is highly skewed with respect to abundance with both gastropods and bivalves being dominated by only a few taxa. A total of 54 taxa were identified at Muweilah, comprising 24 gastropod and 30 bivalve species as well as a single scaphopod belonging to the taxon *Dentalium octangulatum*(Figures 3–6; for taxonomic

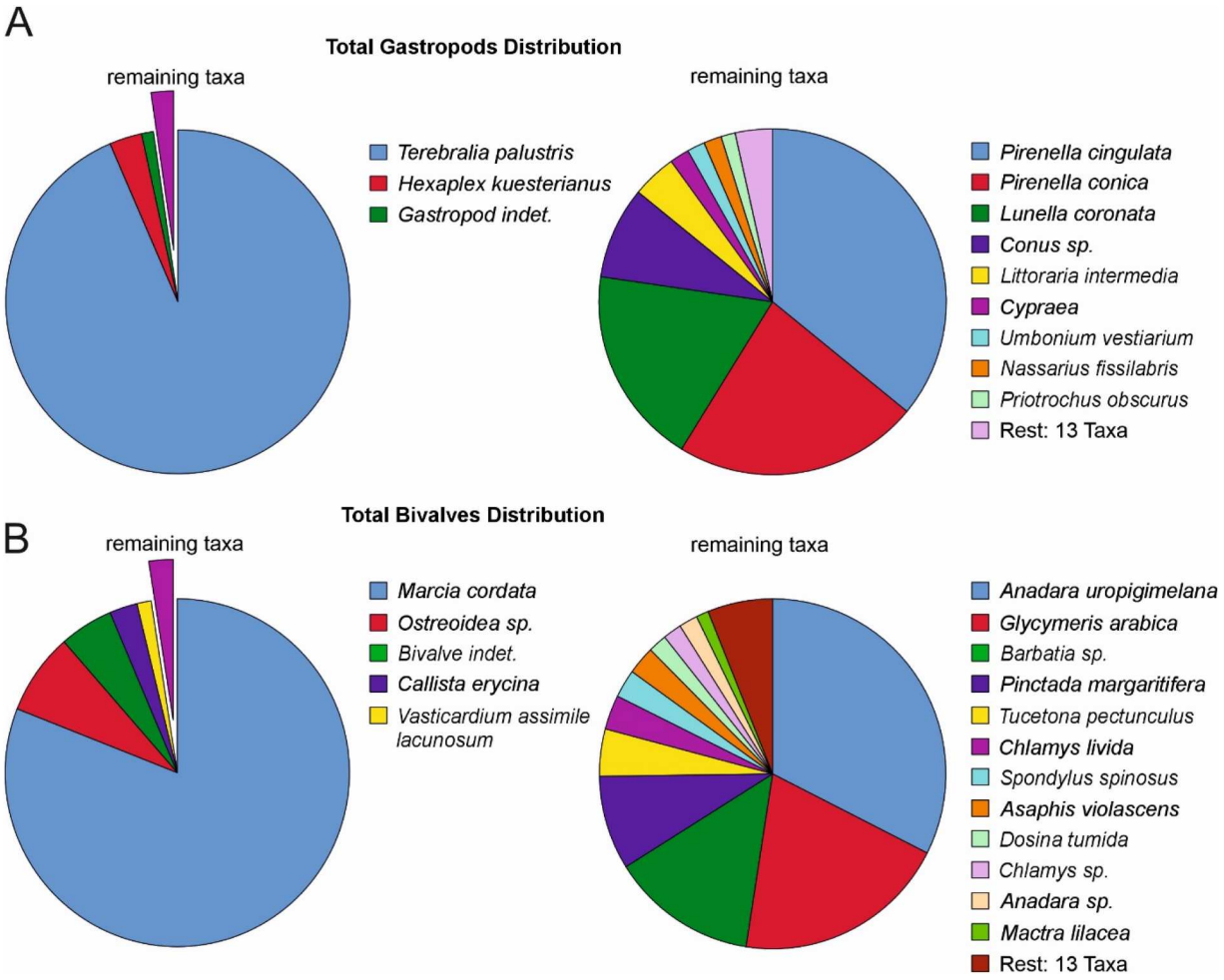

Figure 3. Gastropod/bivalve ratio from the archaeological context of Muweilah. (A) Distribution of the most common gastropods (left) and taxa with frequencies of less than 1% that sum up to 2.27% (right) in percentage of individuals. (B) Distribution of the most common bivalves (left) and taxa with frequencies of less than 1% that sum up to 2.44% (right) in percent of individuals. Taxa occurring in less than 1% summarised as Rest, for complete species list and authorship see Table 1.

authorship see Appendix 1). The assemblage shows a dominance of gastropods, which account for 65.17% of the material, compared to 34.83% bivalves.

Gastropods are overwhelmingly dominated by *Terebralia palustris*, which makes up 93.55% of all gastropod finds (Figure 3 A left side, Table 1). The second most common taxon is *Hexaplex kuesterianus* with 3.06%. The remaining 22 taxa account for 2.27% of specimens (Figure 3 A right side), with *Pirenella cingulata*, *Pirenella conica* and *Lunella coronata* occurring most frequently among them.

Among the bivalves, *Marcia cordata* is the dominant taxon, representing 80.98% of all bivalve finds (Figure 3 B, left side; Table 1). This is followed by *Ostreoidea* sp. with 7.58%, *Callista erycina* with 2.61%, and *Vasticardium assimile lacunosum* with 1.34%. The remaining 2.44% of bivalve finds (Figure 3 B, right side) consisting of 25 are dominated by *Anadara uropigimelana*, *Glycymeris arabica*, and *Barbatia* sp. Non-identifiable bivalves account for 5.05% of the bivalve finds.

Environmental Origin of Species

Species habitat distributions are presented in Figure 4 and Appendices 2 and 3. Most gastropod specimens originate from mangrove environments, whereas most bivalve individuals are derived from the littoral zones. Only a small number of shells are associated with sublittoral and offshore habitats. When considering the number of species rather than individual specimens, however, littoral habitats are the most species-rich, followed by offshore environments. Overall, bivalves exhibit greater diversity than gastropods with respect to separate environments, except for the mangrove habitat, where gastropods are more diverse.

Taphonomy

The dominant species *Terebralia palustris*, *Marcia cordata*, *Hexaplex kuesterianus* and *Ostreoidea* sp. (Figures 4–7), show a high degree of fragmentation. Although the valves of *M. cordata* and *Ostreoidea* sp. are more frequently preserved intact compared to

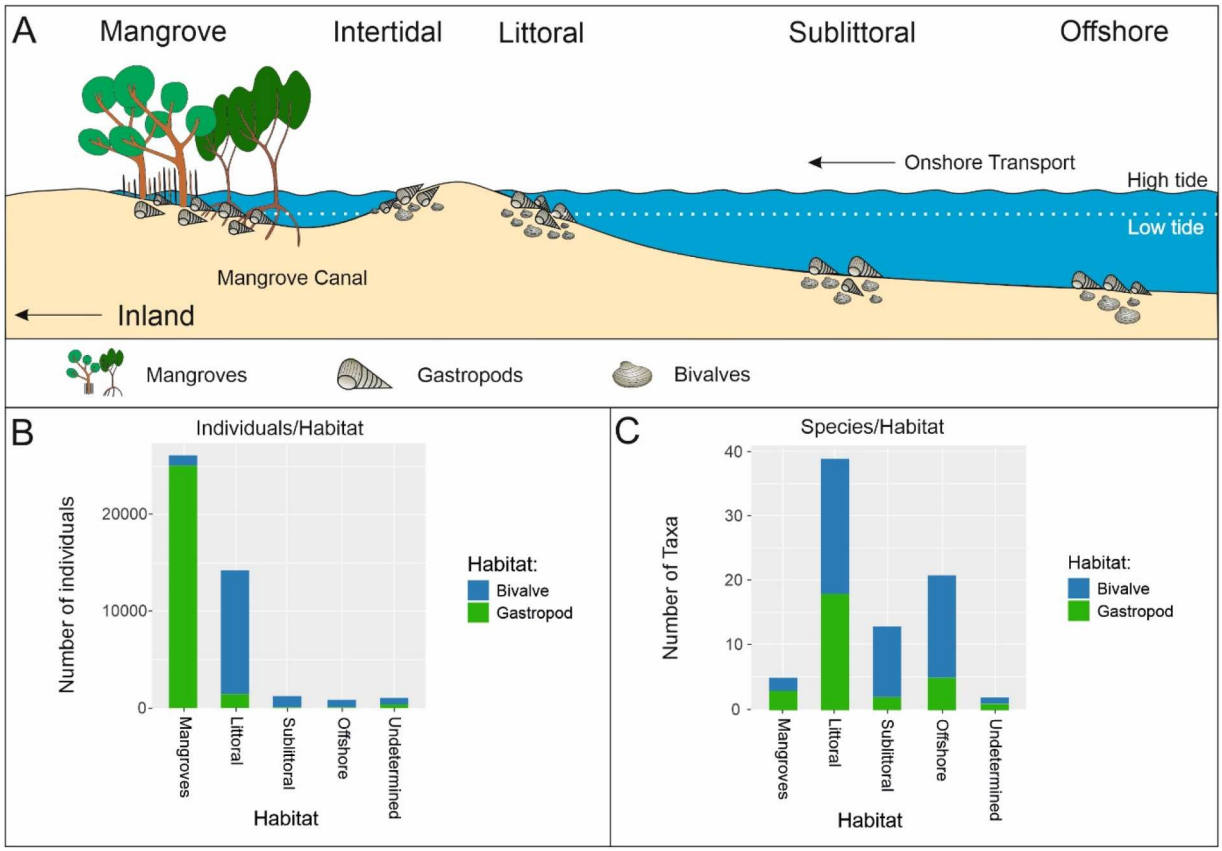

Figure 4. (A) Habitats from which the mollusks of Muweilah originated, including from left to right: mangrove, littoral, sublittoral, offshore and undetermined. Shells from deeper marine areas were washed ashore and collected there. Habitat of origin of (B) Individuals and (C) Species of the mollusks of Muweilah.

gastropods, a considerable number of broken fragments were nonetheless recovered. None of these four dominating species show signs of encrustation or bioerosion, which can occur in less frequently occurring species (see below).

Hexaplex kuesterianus does not exhibit original shell colouration in contrast to *Terebralia palustris*, which displays a high number of specimens retaining their natural pigmentation, alongside fragments with partially or completely faded colouration. In areas where the original colour has been lost, shells typically appear beige rather than white. Burned specimens are rare, and perforations are absent in both gastropods. Further differences between the two species include more frequent ablation of both internal and external surfaces in *H. kuesterianus*, whereas *T. palustris* more commonly displays small holes near the apex and superficial cracks on the inner surfaces. Surface abrasion, here defined as the loss of outer shell layers due to mechanical breakage rather than the gradual erosion of the outermost layer during ablation (see Müller García and Nebelsick 2024, Figure 4b), is also more prevalent in *T. palustris*. While *H. kuesterianus* fragments are generally poorly preserved in terms of ablation, colour alteration, and loss of surface shine, *T. palustris* specimens vary more widely and can be categorised into both well-preserved and poorly preserved examples.

Only two gastropod taxa exceeding 40 mm in total length were identified: *Conus* sp. and *Strombidae* (Figure 5). Both exhibit moderate to low levels of ablation and loss of shininess; however, the original pigmentation is largely absent. *Conus* sp., although broken at the outer lip, is overall better preserved than *Strombidae*. Punctures, encrustations, burn marks, and cracks are rare, and no surface abrasion was observed. The remaining, smaller gastropod taxa (< 40 mm; Figures 5–7) are mostly well preserved and typically complete, shiny, and showing minimal ablation. Cracks, encrustations, punctures, and burning are rare, and surface abrasion is generally absent, except in *Mitrella blanda* (ablated) and the fragmented *Rapana* sp. and *R. venosa*. Notably, *Cypraea* sp. features a large, smooth-edged, round hole on the dorsal side, covering nearly the entire back, with no associated cracking and an intact columella. In general, original shell colouration is preserved in only a few specimens.

Both *Ostreoidea* sp. and *Marcia cordata* occur as disarticulated valves and generally show poorer preservation regarding colouration compared to *H. kuesterianus* and *T. palustris*. A small number of *M. cordata* specimens, however, retain traces of their natural colouration. Neither surface abrasion nor perforations were observed in either bivalve species.

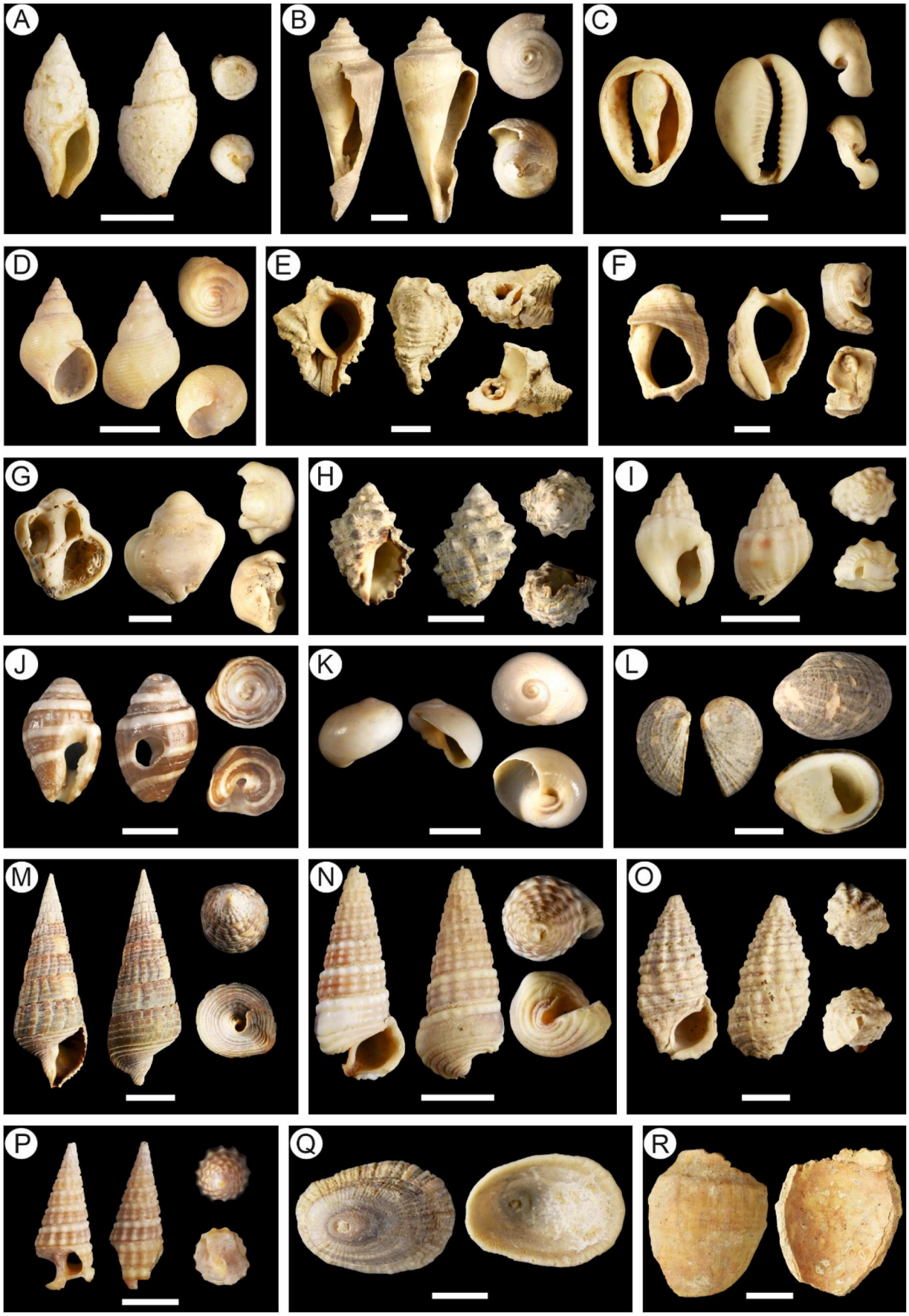

Figure 5. Gastropod species identified in the archaeological context Muweilah. (A) *Mitrella blanda* (Locus 80017), (B) *Conus* sp. (Locus 85137), (C) *Cypraea* sp. (Locus 85100), (D) *Littoraria intermedia* (Locus 92009), (E) *Hexaplex kuesterianus* (Locus 92174), (F) *Rapana* sp. (Locus 92135), (G) *Rapana venosa* (Locus 30003), (H) *Thylothais savagnyi* (Locus 30026), (I) *Nassarius fissilabris* (80017), (J) *Nassarius* sp. (Locus 94038), (K) *Neverita didyma* (Locus 92195), (L) *Nerita albicilla* (Locus 85126), (M) *Terebralia palustris* (Locus 85042), (N) *Pirenella cingulata* (Locus 85100), (O) *Pirenella conica* (Locus 85042), (P) *Pirenella sp.* (Locus 92147), (Q) *Siphonaria* sp. (Locus 81059), (R) *Strombidae* sp. (Locus 92172). (Scale: (A), (D), (J), (O) 5 mm, (P) 7.5 mm, (B-C), (F-G), (I), (K-L), (N), (Q) 10 mm, (R) 15 mm, (H), (M) 20 mm, (E) 40 mm).

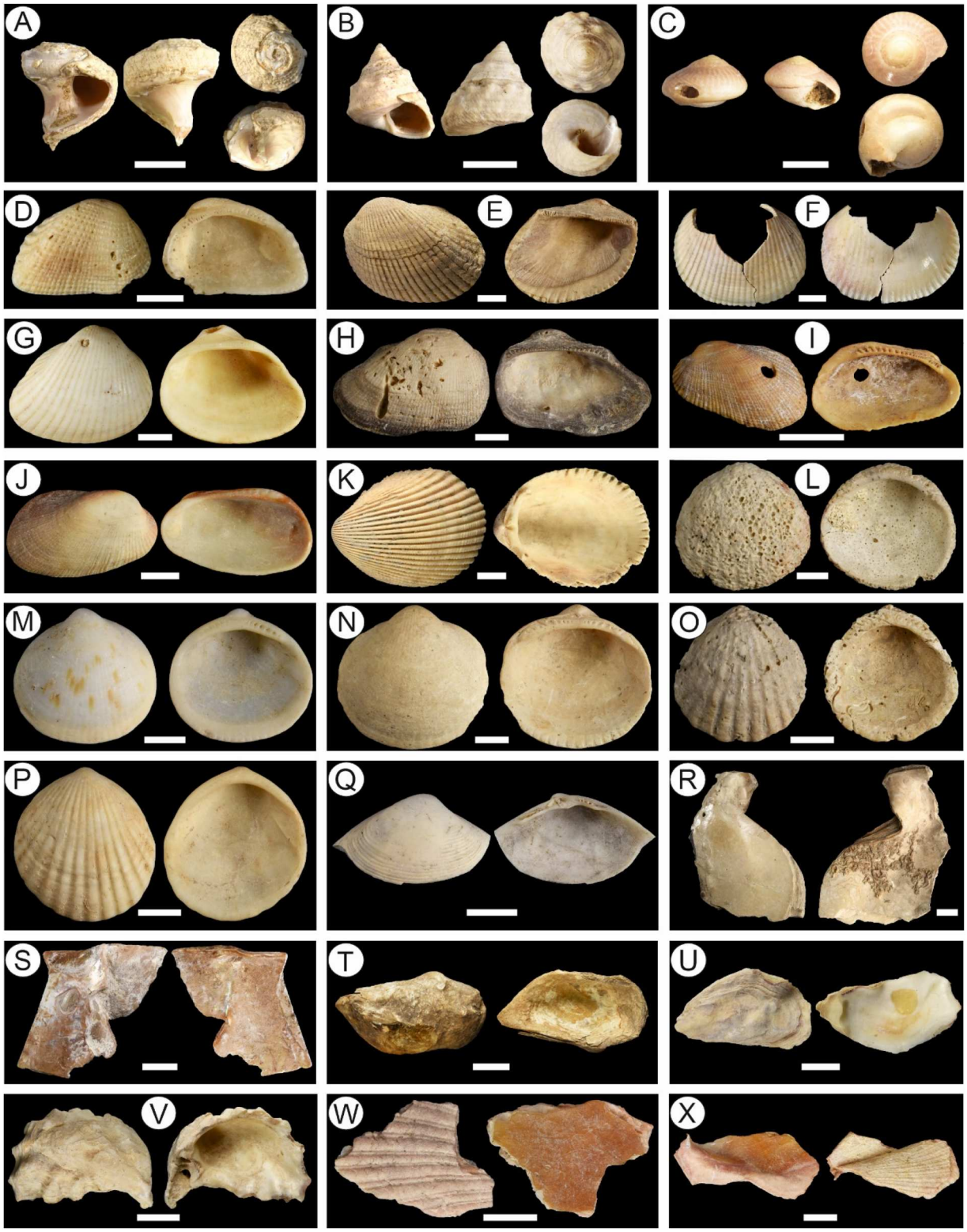

Figure 6. Gastropod and bivalve species identified in the archaeological context Muweilah (continued). (A) *Lunella coronata* (Locus 92005), (B) *Priotrochus obscururs* (Locus 81012), (C) *Umbonium vestiarium* (Locus 84033), (D) *Acar plicata* (Locus 50151), (E) *Anadara antiquata* (Locus 84033), (F) *Anadara* sp. (Locus 92004), (G) *Anadara uropigimelana* (Locus 92174), (H) *Barbatia foliata* (Locus 92132), (I) *Barbatia obliquata* (Locus 50055), (J) *Barbatia* sp. (Locus 85137), (K) *Vasticardium assimile lacunosum* (Locus 2905), (L) *Glycymerididae* (Locus 30003), (M) *Glycymeris arabica* (Locus 85126), (N) *Glycymeris livida* (Locus 50054), (O) *Glycymeris* sp. (Locus 81000), (P) *Tucetona pectunculus* (Locus 92174), (Q) *Mactra lilacea* (Locus 30008), (R) *Pinctada margaritifera* (13029), (S) *Pinctada* sp. (Locus 50109), (T) *Mytoloidea* sp. (Locus 50151), (U) *Ostreoidea* sp. right valve (Locus 85137). (V) *Ostreoidea* sp. left valve (Locus 85100), (W) *Chlamys* sp. (Locus 50007), (X) *Pectinidae* sp. (Locus 85144). (Scale: (C), (D), (M), (S) 5 mm, (B) 7.5 mm, (F), (H—L), (O—R), (W) 10 mm, (G), (N), (T), (X) 12.5 mm, (E) 15 mm, (A), (U-V) 20 mm).

Table 1. List of gastropod and bivalve species identified from the archaeological site of Muweilah, including taxonomic authorities and the number of specimens recorded for each taxon.

Family	Genus and species (author)	Total
Gastropods		
Columbellidae	*Mitrella blanda* (G. B. Sowerby I, 1844)	5
Conidae	*Conus* sp. (Linnaeus, 1758)	52
Cypraeidae	*Cypraea* sp. (Linnaeus, 1758)	11
Gastropod indet.	*Gastropod* indet.	296
Littorinidae	*Littoraria intermedia* (Philippi, 1846)	25
Muricidae	*Hexaplex kuesterianus* (Tapparone Canefri, 1875)	810
	Rapana sp. (Schumacher, 1817)	1
	Rapana venosa (Valenciennes, 1846)	2
	Tylothais savignyi (Deshayes, 1844)	1
Nassariidae	*Nassarius fissilabris* (A. Adams, 1852)	10
	Nassarius sp. (Duméril, 1805)	1
Naticidae	*Neverita didyma* (Röding, 1798)	3
Neritidae	*Nerita albicilla* (Linnaeus, 1758)	1
Potamididae	*Terebralia palustris* (Linnaeus, 1767)	24797
	Pirenella cingulata (Gmelin, 1791)	217
	Pirenella conica (Blainville, 1829)	138
	Pirenella sp. *(Gray, 1847)*	1
Siphonariidae	*Siphonaria* sp. (G. B. Sowerby I, 1823)	1
Strombidae	*Strombidae* sp. (Rafinesque, 1815)	1
Turbinidae	*Lunella coronata* (Gmelin, 1791)	112
Trochidae	*Priotrochus obscurus* (W. Wood, 1828)	9
	Umbonium vestiarium (Linnaeus, 1758)	10
Bivalves		
Arcidae	*Acar plicata* (Dillwyn, 1917)	1
	Anadara antiquata (Linnaeus, 1758)	1
	Anadara sp. (J. E. Gray, 1847)	6
	Anadara uropigimelana (Bory de Saint-Vincent, 1827)	112
	Barbatia foliata (Forssk ål, 1775)	2
	Barbatia obliquata (W. Wood, 1828)	2
	Barbatia sp. (Gray, 1842)	47
Bivalve indet.	*Bivalve* indet.	715
Cardiidae	*Vasticardium assimile lacunosum* (Reeve, 1845)	190
Glycymerididae	*Glycymerididae* sp. (Dall, 1908)	1
	Glycymeris arabica (H. Adams, 1871)	69
	Glycymeris livida (Reeve, 1843)	2
	Glycymeris sp. (da Costa, 1778)	2
	Tucetona pectunculus (Linnaeus, 1758)	15
Mactridae	*Mactra lilacea* (Lamarck, 1818)	4
Margaritidae	*Pinctada margaritifera* (Linnaeus, 1758)	30
	Pinctada sp. (Röding, 1798)	2
Mytiloidea	*Mytiloidea* sp. (Rafinesque, 1815)	1
Ostreoidea	*Ostreoidea* sp. (Rafinesque, 1815)	1074
Pectinidae	*Chlamys* sp. (Röding, 1798)	6
	Pectinidae sp. (Rafinesque, 1815)	1
	Scaeochlamys livida (Lamarck, 1819)	11
Psammobiidae	*Asaphis violascens* (Forsskål, 1775)	9
Spondylidae	*Spondylus gloriandus* (Melvill & Standen, 1907)	2
	Spondylus spinosus (Schreibers, 1793)	9
Veneridae	*Callista erycina* (Linnaeus, 1758)	370
	Callista florida (Lamarck, 1818)	3
	Dosinia tumida (Gray, 1838)	6
	Marcia cordata (Forsskål in Niebuhr, 1775)	11470
	Veneridae sp. (Rafinesque, 1815)	1
Scaphopoda		
Dentaliidae	*Dentalium octangulatum* (Donovan, 1804)	1

Overall, *M. cordata* is better preserved than *Ostreoidea* sp. in terms of shininess, ablation, and internal cracks.

Larger bivalve shells (> 6 cm in total length) can be divided into two groups based on their taphonomic characteristics: (1) Members of the families *Spondylidae* and *Margaritidae* (Figures 6 and 7) are typically fragmented and exhibit moderate to high levels of ablation. They generally lack shininess, except for some *Margaritidae* specimens, and show no evidence of surface abrasion. (2) Members of the genera *Anadara*, *Vasticardium assimile lacunosum*, *Callista erycina*, and *Asaphis violascens* (Figures 6 and 7) are less fragmented and display a better overall state of preservation compared to the first group. Cracks, burn marks, holes, and encrustations are generally rare, and surface abrasion is entirely absent. Both groups show signs of colour alteration, with the original pigmentation largely removed and colourless areas appearing beige. Only *Asaphis violascens* preserves faint traces of its original violet colouration.

Members of the family *Glycymerididae*, the genus *Barbatia*, and the superfamily *Mytiloidea* (Figures 6 and 7) are predominantly represented by complete valves, yet they are generally poorly preserved. This is reflected in strong ablation, loss of shininess, and colour alteration. In addition, serpulid worm encrustations are frequently present, while burning, cracking, and perforations are rare. Surface abrasion is absent. In contrast, *Callista florida*, *Mactra lilacea*, *Dosinia tumida*, *Acar plicata*, and members of *Veneridae* (Figures 6 and 7) are better preserved. These specimens show minimal ablation, lack incrustations, and typically retain their shininess. Most valves are complete, apart from fragmented examples of *C. florida* and *M. lilacea*. The single *Dentalium octangulatum* specimen from Building I (Figure 7) is fully preserved, beige, non-shining, and exhibits only slight ablation. It shows no signs of surface abrasion, punctures, cracks, burning, or encrustation.

Discussion

The distribution of molluscan taxa (54 in all) in the assemblage from the Muweilah site is highly skewed with only a few dominating taxa represented by the gastropods *Terebralia palustris* and *Hexaplex kuesterianus*, and the bivalves *Marcia cordata* and *Ostreoidea* sp. As discussed below, these taxa were specifically gathered and harvested from nearby coastal environments as an important food source. The remaining larger gastropod taxa *Conus* sp. and *Strombidae* were possibly collected for use for ornamentation or as bowls or containers, while smaller species such as *Pirenella cingulata* and *P. conica*, may reflect a mixture of beach-derived flooring material or unintentional bycatch. The subordinate remaining bivalves appear to have been collected post-mortem following onshore transport.

Taxonomy and Diversity of Mollusks with Respect to Environment of Origin

The majority of mollusk remains derive from mangrove (60.3%) and littoral (32.7%) habitats, reflecting the dominance of the mangrove species *Terebralia*

Figure 7. Bivalve and scaphopod species as well as mollusk taphonomy from the archaeological context Muweilah (continued). (A) *Scaeochlamys livida* (Locus 13029), (B) *Asaphis violascens* (Locus 92132), (C) *Spondylus gloriandus* (Locus 30008), (D) *Spondylus spinosus* (Locus 84033), (E) *Callista erycina* (Locus 2702), (F) *Callista florida* (Locus 92005), (G) *Dosinia tumida* (Locus 50055), (H) *Marcia cordata* (Locus 85138), (I) *Veneridae* sp. (Locus 60000). (J) *Conus* sp. burned (Locus 92174), (K) *Dentalium octangulatum* (Locus 85029), (L) *Terebralia palustris* in a good state of preservation regarding colour alteration, shininess and ablation (Locus 85124), (M) *Hexaplex kuesterianus* with ablation (Locus 92135), (N—P) *Nassarius fissilabris*, *Terebralia palustris* and *Barbatia obliquata* with holes (Locus 99029, 85138, 50055), (Q—R) *Terebralia palustris* with cracking (Locus 85138), (S) *Hexaplex kuesterianus* with colour alteration (Locus 92135), (T) *Pinctada margaritifera* with incrustation in form of serpulid worms (Locus 13029), (U—V) *Terebralia palustris* with surface abrasion (Locus 85138), (W—X) *Pinctada* sp. and *Glycymeris arabica* with bad states of preservation (Locus 94058 and 92005). (Scale: (K), (O—V) 5 mm, (G), (I) 7.5 mm, (F), (H), (J), (L—N), (X) 10 mm, (B—E), (W) 20 mm, (A) 40 mm).

palustris and the littoral taxa *Marcia cordata* and *Hexaplex kuesterianus*, as well as the frequent occurrence of *Ostreoidea* sp., which inhabits both environments (habitat classification following Bosh et al. 1995; see Appendix 1). While the abundance of shell remains is dominated by species from mangrove and littoral zones, patterns shift considerably when species richness is considered. Here, the majority of the identified

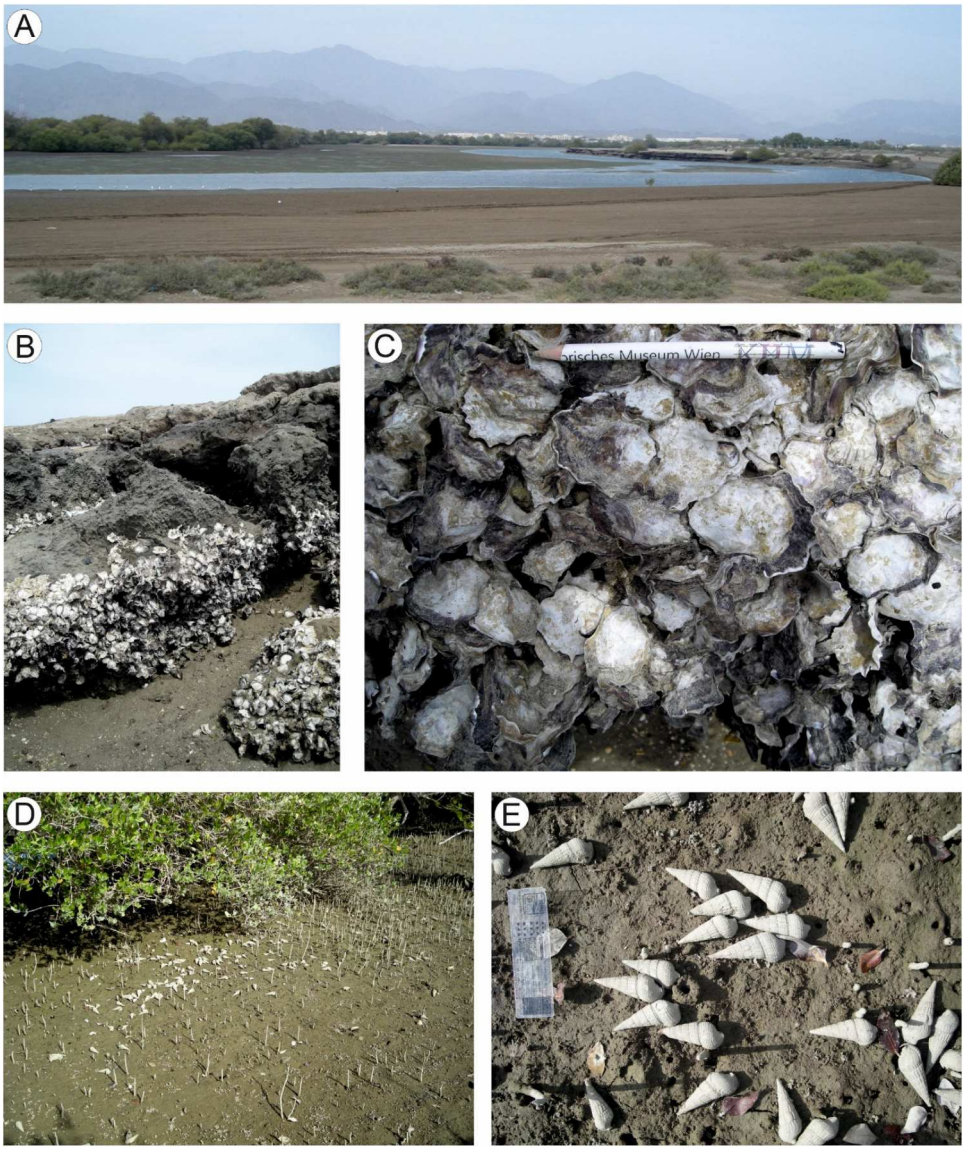

Figure 8. (A) Overview of mangrove channels at Khor Kalba (Gulf of Oman) with (B-C) oyster banks along channel slopes. (D-E) *Terebralia palustris* from mangrove remains of Khor Kalba (Gulf of Oman).

taxa originates from littoral (48.75%) and sublittoral (16.25%) habitats, whereas only 6.25% are associated with mangrove environments. This comparatively low diversity reflects the general paucity of mollusk taxa originating from mangroves; aside from *Terebralia palustris*, only *Pirenella cingulata*, *P. conica*, *Mytoloidea* sp., and *Ostreoidea* sp. occur in mangrove habitats (Al-Kandari et al. 2020; Bosh et al. 1995; El-Sorogy, Demircan, and Alharbi 2020; Lindauer et al. 2018; see Appendix 1).

The prevalence of shells from mangrove and littoral zones likely reflects their ease of collection; for instance, *T. palustris* can be readily gathered from the mangrove floor at low tide (Figure 8). This gastropod, which feeds primarily on mangrove leaf litter and attains sizes of up to 190 mm, historically represented an important food source in southeast Arabia (Aspinall et al. 2002; Bosh and Bosh 1989; Burt 2023; Carpenter et al. 1997; Fratini, Cannicci, and Vannini 2000; Mujiono 2009; Pape et al. 2008; Samsi et al. 2020). Populations typically occur in large aggregations beneath mangrove stands, though their age- and species-specific structure varies in response to local environmental conditions (Fratini, Cannicci, and Vannini 2001, 2004; Houbrick 1991; Pape et al. 2008; Penha-Lopes et al. 2009; Rao 1938; Slim et al. 1997; Soemodihardjo and Kastoro 1977). Once widespread across the region, *T. palustris* now persists only at Khor Kalba (United Arab Emirates), likely as a response to mangrove loss, increasing water temperature and salinity, overexploitation, reduced freshwater inflow, and shifting oceanographic conditions (Aspinall et al. 2002; Carlén and Ólafsson 2002; Carpenter et al. 1997; Feulner 2006; Fratini, Cannicci, and Vannini 2000, 2001, 2004; Hellyer and Aspinall 2006; Mujiono 2009; Pape et al. 2008).

Like *Terebralia palustris*, *Hexaplex kuesterianus* can also be easily collected, as it represents a relatively large, conspicuous epifaunal vagile snail inhabiting shallow rocky, muddy or sandy substrates (Burt

Table 2. Taphonomy of the mollusk from the archaeological site of Muweilah ordered by proposed use, with alternative uses, dominant taxa, total amount of mollusk belonging to each group, dominating taphonomic traits and suggested mode of collection.

Proposed use	Alternative use	Dominant Taxa	Total	Dominant Taphonomic traits	Suggested mode of collection
Food	—	*Terebralia palustris*, *Marcia cordata*, *Hexaplex kuesterianus*,			
Ostreoidea sp.	38.151	High fragmentation, superficial cracks, colour alterations, burn marks	Targeted collection of live animals		
Ambiguous (food, tool)	Pearl harvesting, fishhook production	*Anadara, Pinctada, Asaphis violascens*	160	Low fragmentation, generally good state of preservation, no incrustation, removal of original colouration	Targeted collection, live/dead status uncertain
Ambiguous (tool)	—	*Callista, Dosinia tumida*, *Vesticardium assimile lacunosum*, *Veneridae*	570	Low fragmentation, generally good state of preservation, no incrustation, removal of original colour	Collection after natural onshore transport (beach accumulation)
Ambiguous (tool)	—	*Barbatia*, *Glycymerididae*, *Mactra lilacea*, *Mytiloidea*, *Pectinidae*, *Spondylidae*	174	Serpulid worm encrustations on interior surfaces, predatory boreholes, strong ablation	Post-mortem collection (beach accumulation)
Ornament	—	*Conus* sp., *Cypraea*	63	Low ablation, perforations or natural opening	Targeted collection, live/dead status uncertain
Container	—	*Strombididae*	1	Moderate ablation, no shininess	Targeted collection, live/dead status uncertain
Inclusion in beach-derived flooring material	Intrusive background fauna without intentional human use	*Pirenella, Mitrella, Littoraria, Rapana, Tylothais, Nassarius, Neverita, Lunella, Priotrochus obscurus, Umbonium*	526	Low fragmentation,	Incidental transport with sediment, building material, or other collected taxa

2023; Güler and Lök 2018; Merle, Garrigues, and Pointier 2011; Morton, Peharda, and Harper 2007; Radwin, d'Attilio, and Mulliner 1976). As an opportunistic predator, it feeds on diverse bivalves, gastropods or barnacles using different techniques, but mostly either by drilling small circular holes or by chipping at the shell margin with its labral spine, with the method varying according to shell thickness. Historically, the species was widely exploited for food, purple dye, fish bait, and for incense production from its operculum (Doneddu and Trainito 2005; Güler and Lök 2018; Merle, Garrigues, and Pointier 2011; Morton, Peharda, and Harper 2007; Radwin, d'Attilio, and Mulliner 1976).

Additionally to both species mentioned above, *Ostreoidea* sp. also represented an easily accessible resource in the mangrove-associated habitats of Khor Kalba (Gulf of Oman). Individuals may be collected either from intertidal oyster banks along mangrove channel slopes or directly from aerial mangrove roots (Figure 8). These so-called 'true oysters' are suspension-feeding bivalves capable of withstanding extended desiccation through water storage, and they typically form large aggregates on a variety of substrates by cementing their left valve, including mangroves, rocks, reefs, and corals (Alf and Haszprunar 2015; Bosh and Bosh 1989; Burt 2023; Doneddu and Trainito 2005; Oliver, Thomas, and Meechan 1992; Zuschin and Oliver 2003).

Unlike the previously discussed taxa, *Marcia cordata* is the only common species that requires active searching, as it is a shallow burrower inhabiting intertidal sandy substrates and mudflats (Ahmed et al. 2023; Del Norte-Campos, Lapara, and Sanchez 2021; El-Sorogy et al. 2016; Hamli 2015; Jahangir et al. 2012; Oliver et al. 2023). According to Feulner and Hornby (2006), however, the bivalve can be observed on wet mud exposed to the sun during midsummer, which would lead to an easier collectability. Despite its wide Indo-Pacific distribution and recognised commercial value as a food species, *M. cordata* remains relatively understudied, with only limited research addressing its biology and ecology in detail (Ahmed et al. 2023; Hamli 2015).

Taphonomy and Shell Utilization

Collection as Live or Dead Animals

Key indicators for post-mortem collection include boreholes suggesting predation, primarily of bivalves, by naticid gastropods, as well as internal encrustations, such as serpulid worm tubes, which can only form after the animal's death and valve disarticulation (Dietl and Kelley 2006; Klompmaker and Dietl 2024). Additional evidence comes from signs of hermit crab occupation in empty gastropod shells, such as polished surfaces from dragging across sediment, as well as advanced abrasion and bioerosion (Frey 1987; Müller García and Nebelsick 2024; Walker 1989).

The state of preservation of exterior shell surfaces, which are subject to erosion throughout the animal's life, does not necessarily indicate whether the specimen was collected alive or after death. Significant ablation and erosion of the periostracum, for example, are

frequently observed near the apex, while pronounced ablation on interior surfaces more reliably reflect post-mortem exposure, whether in natural settings or archaeological contexts. The presence of disarticulated bivalve shells is likewise not a clear indicator of collection as dead animals, since shell separation may also occur on-site, for instance because of cooking or waste disposal handling (Dietl and Kelley 2006; Händel 2015; Klompmaker and Dietl 2024). For most species, there are no definitive signs that they were collected post-mortem, exceptions include *Barbatia*, members of the *Glycymerididae*, *Mactra lilacea*, *Mytiloidea*, *Pectinidae*, and *Spondylidae*. Additional context, however, such as the original habitat and possible uses of the shells can offer further insights.

Shell Utilization

Species selection (see Table 2) was largely shaped by their role for sustenance, with the dominant taxa *T. palustris*, *H. kuesterianus*, *Ostreoidea* sp., and *Marcia cordata* representing key food resources. Factors influencing the selection of these species are (1) edibility, (2) quantity, as well as difficulty of (3) collection and (4) preparation. The dominance of *T. palustris* can be attributed to its easy collectability at low tide, its abundance, and its nutritional value with a protein content ranging from 19 to 28% (Burt 2023; Mujiono 2009; Pape et al. 2008; Pasaribu, Buyang, and Monika 2019; Samsi et al. 2020). While *Hexaplex* was historically used for dye production in the Mediterranean, in Southeast Arabia it appears to have been consumed as food, supported by the absence of tools associated with dye extraction and the widespread distribution of *Hexaplex* shells, which argues against centralised processing (Çakırlar 2011; Oliver 2015; Sukenik et al. 2017; Surowiec, Nowik, and Moritz 2012). Analyses of *Ostreoidea*, *Marcia* and *Hexaplex* showed them to be very nutritious and a significant source of proteins, amino acids and minerals, and therefore a suitable food source (Ashja Ardalan et al. 2004; Kumar Sethukali and Darshaka Jayasena 2022; Suja and Muthiah 2010; Valenzuela et al. 2022; Vasconcelos et al. 2009; Zarai et al. 2011).

A high degree of fragmentation and surface abrasion, particularly in gastropods which must be broken to access the edible tissue, provide general evidence for the utilisation of these species as a food source (Händel 2015; Lidour, Pellegrino, and Charbonnier 2023; Müller García and Nebelsick 2024; Prieur 2005). Fragmentation patterns not only reflect flesh extraction processes but also the variable preservation potential of different shell regions depending on shell thickness (Müller García and Nebelsick 2024; Vermeij 1979; Zuschin and Oliver 2003; Zuschin and Stanton 2001). Methods of detaching soft tissue from the shell, such as using pointed sticks or pins, as documented among Aborigines, can produce fine superficial cracks on interior shell surfaces (Aldeias et al. 2019; Meehan 1975; Milano et al. 2018; Müller García and Nebelsick 2024). Cooking processes may alter shell colouration or result in grey or blackened burned shells (see below). Distinguishing these from the effects of natural fires or non-culinary burning events can be challenging, however, especially given the low likelihood of such traces being preserved and identified in archaeological contexts (Aldeias et al. 2019; Milano et al. 2018; Müller García and Nebelsick 2024). Burned shells may also result from accidental post-depositional burning or deliberate waste disposal practices. At present, there is no direct evidence for such processes in the assemblage, and the coexistence of burned and unburned shells is difficult to reconcile with systematic burning. Additionally, experimental studies suggest that direct exposure of mollusk shells to fire often leads to fragmentation or destruction, biasing their archaeological visibility (Lindauer et al. 2018; Milano, Prendergast, and Schöne 2016, 2018; Müller et al. 2017). Even though these factors limit confident interpretation of burning as unequivocal evidence of cooking activities, evidence from other archaeological contexts indicates that mollusks were commonly cooked or grilled during preparation, producing colour alterations comparable to those observed here, which therefore most plausibly reflect culinary processing (e.g. Händel 2015; Houbrick 1991).

Some littoral bivalves, such as *Anadara*, *Pinctada*, and *Asaphis violascens*, are also known to have been consumed (e.g. Beech et al. 2005; Beech and Kallweit 2001; Biagi 2020; Bosh et al. 1995; Glover 1995; Lidour, Pellegrino, and Charbonnier 2023). Their utilisation for sustenance is further suggested by the absence of indicators of post-mortem collection, such as encrustations or predatory boreholes (see above); the good preservation of interior shell surfaces regarding ablation and shininess, as well as colour changes potentially linked to cooking processes. The low frequency of these species, however, suggests that they were not a staple food source. Alternative uses may also explain their presence: *Pinctada* sp., for example, could have been used for pearl harvesting or fishhook production (e.g. Biagi 2020; Lidour, Pellegrino, and Charbonnier 2023; 2024), while *Asaphis violascens* may have been repurposed as a tool (Beech et al. 2005; Lidour and Cuenca Solana 2024; Lidour, Pellegrino, and Charbonnier 2023, 2024). Some studies also report the use of live-collected bivalves as tools (Lidour and Cuenca Solana 2024; Lidour, Pellegrino, and Charbonnier 2023, 2024), suggesting that all these species may have been utilised in this way, instead of, or in addition to, being consumed.

Other bivalves, such as *Callista*, *Dosinia tumida*, *Vesticardium assimile lacunosum*, and several *Veneridae* species, show similar preservation patterns but originate from sublittoral to offshore environments. This makes their collection as bycatch or via diving unlikely (Bosh et al. 1995; Carlén and Ólafsson 2002; Lindauer et al. 2018). Instead, they were most likely collected after being washed to the beach by onshore transport (see Figure 7 A). The same applies to the remaining bivalves, *Barbatia*, *Glycymerididae*, *Mactra lilacea*, *Mytiloidea*, *Pectinidae*, and *Spondylidae*, which exhibit evidence of post-mortem collection, such as serpulid worm encrustations on interior surfaces and predatory boreholes. Their poor state of preservation, including strong ablation as well as loss of shininess and colouration, makes their use as ornaments or decorative objects unlikely.

Some of the above mentioned taxa, such as *Glycymeris*, are known to have been repurposed as tools or containers (Hutterer, Schröder, and Linstädter 2021; Lidour and Cuenca Solana 2024; Lidour, Pellegrino, and Charbonnier 2023). Shell tools were also often collected from beaches after the animal's death (Álvarez-Fernandez, Barrera, and Fernández-Gómez 2019; Lidour and Cuenca Solana 2024; Romagnoli et al. 2017), which is consistent with the results of the bivalves mentioned above. These specimens may therefore represent former tools later discarded along with kitchen waste. There is currently, however, no direct evidence of tool use, such as wear patterns or modifications indicative of handling or processing (Álvarez-Fernandez, Barrera, and Fernández-Gómez 2019; Lidour and Cuenca Solana 2024; Romagnoli et al. 2017).

Unlike most of the mentioned bivalve taxa, the gastropods *Cypraea* sp. and *Conus* sp. are well known for their ornamental use (Bar-Yosef Mayer 2002; Çakırlar 2011; D'Errico and Backwell 2016; Del Cerro 2013; Gardner 2005; Glover 1995; Prust 2020). Perforations in *Cypraea* sp. shells may be linked to jewelry production, as their position allows suspension. Previous studies show that natural perforations typically occur in structurally weak zones, whereas anthropogenic holes also appear in more stable shell areas, tend to vary less in location, and are frequently positioned for suspension. Human-made perforations may additionally display diagnostic traces such as microchipping, impact scars, rounding traces around the hole, or faceting (e.g. Bosch, Buck, and Strauss 2019, 2023; Douka and Spinapolice 2012; Szabo and Koppel 2015). The perforation in the present *Cypraea* shell is surrounded by a smooth surface, which could indicate faceting and thus possible attachment to clothing; however, natural processes cannot be excluded as an alternative cause. Because only few perforated *Cypraea* sp. shells are available, statistical assessment of perforation placement is not feasible. Overall, such perforations may reflect jewelry production, though natural openings later reused as ornaments remain equally plausible.

Additionally, members of the family *Strombidae* were frequently used as bowls or containers and may have served for storage purposes (Bar-Yosef Mayer 1997; Gensheimer 1984; Glover 1995). The remaining gastropod taxa were likely not used for decorative purposes or as food sources, despite good preservation regarding shininess and ablation, due to their small size and the absence of modifications typically associated with jewelry production. An overlap between elevated concentrations of *Pirenella cingulata* and *P. conica* and the presence of floor samples in Buildings VI and VII may indicate mixing of beach-derived flooring material with food waste. Given their littoral origin, another plausible explanation, suggested by Glover (1995), is that these small gastropods were unintentionally transported to the site by adhering to larger collected species.

Results of Differential Cooking Techniques

As mentioned above, the gastropods *Terebralia palustris* and *Hexaplex kuesterianus* show higher degrees of fragmentation, surface abrasion, and superficial interior surface cracking indicative of detaching the flesh from the shell, compared to the more easily prepared bivalves *Marcia cordata* and *Ostreoidea* sp. (Aldeias et al. 2019; Meehan 1975; Milano et al. 2018; Müller García and Nebelsick 2024). Among the two gastropods, *T. palustris* fragments show more frequent signs of surface abrasion than *H. kuesterianus*, which may be due to the generally poorer preservation, for example regarding ablation, of the latter, which can obscure evidence of surface wear. It remains uncertain to what extent differences in shell stability contribute to this pattern, as both species possess a crossed-lamellar shell structure (Lahbib et al. 2022; Müller García and Nebelsick 2024).

Both gastropods also display a range of colour alterations: a shift from white to beige of colourless shell areas as well as the disappearance of original colouration and, in rare cases, grey-black discolouration combined with a bad state of preservation regarding ablation and shininess. *T. palustris*, however, also occurs in fragments with relatively good preservation regarding ablation, shininess, and colouration. These colour alterations reflect temperature dependent shell alterations related to different cooking methods: (1) boiling preserving shininess and original colouration (~100°C), (2) grilling leading colour alterations and stronger ablation with a lack of shininess (200–300°C), and (3) burning (400–500°C) changing the shell to greyish black with a bad state of preservation regarding ablation and shininess (Aldeias et al. 2019; Händel 2015; Houbrick 1991; Lindauer et al. 2018; Loch 1987; Meehan 1975; Milano,

Prendergast, and Schöne 2016, 2018; Müller et al. 2017; Müller García and Nebelsick 2024). Accordingly, the different colour alterations of *T. palustris* and *H. kuesterianus* may indicate grilling, and burning to a minor degree, as well as possibly boiling in the case of *T. palustris*, as likely cooking methods. Identifying the specific cooking methods remains challenging, however, as cooking temperatures are influenced by factors such as the distance between the shells and the heat source and the type of fuel (Hanson and Cain 2007; Wolf et al. 2013).

As previously mentioned, both *Ostreoidea* sp. and *Marcia cordata* are less fragmented than *T. palustris* and *H. kuesterianus*, and they appear disarticulated but without surface abrasion, puncturing, or bioerosion. *M. cordata*, like *T. palustris*, occurs in both well and poor states of preservation regarding surface ablation and shininess. In contrast, *Ostreoidea* sp., similar to *H. kuesterianus*, is only found in a poor state of preservation. Additionally, superficial cracks on the internal surfaces are more frequently observed in *M. cordata* than in *Ostreoidea* sp., likely due to the more intense surface ablation of the latter. The complete loss of original colouration in *Ostreoidea* sp., as also seen in *H. kuesterianus*, suggests grilling as the primary preparation method. A few *M. cordata* fragments retain traces of their original colour, though much less frequently than *T. palustris*, indicating grilling and, to a lesser extent, boiling (Aldeias et al. 2019; Händel 2015; Houbrick 1991; Lindauer et al. 2018; Loch 1987; Meehan 1975; Milano, Prendergast, and Schöne 2016, 2018; Müller et al. 2017; Müller García and Nebelsick 2024). Burned specimens are rare among both *M. cordata* and *H. kuesterianus*. Overall, *M. cordata* and *T. palustris* share more similarities in terms of cooking temperature and method, while *Ostreoidea* sp. aligns more closely with *H. kuesterianus*.

In contrast to the previously discussed species, *Anadara*, *Pinctada*, and *Asaphis violascens*, which were possibly used to a lesser extent for sustenance, exhibit frequent surface alterations, e.g. strong ablation and colour alteration, but no evidence of burning, which suggests grilling as the preferred cooking method (Aldeias et al. 2019; Händel 2015; Houbrick 1991; Lindauer et al. 2018; Loch 1987; Meehan 1975; Milano, Prendergast, and Schöne 2016, 2018; Müller et al. 2017; Müller García and Nebelsick 2024). The variation in cooking techniques may reflect differences in taste preferences or possibly the socio-economic status of the site's inhabitants.

These observations, taken together with the broader assemblage characteristics, point to a nuanced pattern of mollusk use at Muweilah, where environmental accessibility, species-specific processing requirements, and potential cultural preferences appear to have influenced both collection and preparation strategies. While dominant taxa such as *Terebralia palustris* and *Marcia cordata* were likely staple food sources, the presence of less abundant, post-mortem collected bivalves and ornamental gastropods suggests multifunctional uses extending beyond mere sustenance, although direct evidence of tool or ornament production remains absent. Further insights are expected from ongoing comparative studies within the settlement and with regional assemblages, which aim to contextualise the findings from Muweilah within broader patterns of mollusk exploitation in southeastern Arabia.

Although this study refrains from explicit interpretations regarding social organisation at Muweilah, the observed variation in species use, collection strategies, and processing techniques may hint at differentiated practices related to labour, access, or consumption. In the absence of textual sources (e.g. Karacic et al. 2018; Magee 1996, 2002, 2004), such implications necessarily remain cautious; however, further intra-site analyses – currently in preparation – may offer new perspectives on the socio-economic dimensions of mollusk use within the settlement context.

Comparisons to Other Sites in the Region

When compared with other sites in the region (see Table 3), the taxonomic composition at Muweilah shows the highest similarity with sites in its immediate vicinity, while dissimilarities increase with distance. The dominant species identified at Muweilah (*T. palustris*, *H. kuesterianus*, *Ostreoidea* sp. and *M. cordata*) corresponds most closely with the nearby sites Al-Hamriyah (UAE, Neolithic to Iron Age), Tell Abraq (UAE, Bronze Age), Akab (UAE, Neolithic), and Ed-Dur (UAE, Neolithic to Iron Age). Notable differences occur nonetheless, such as additional dominant taxa at these sites, for instance, *Callista erycina* and *C. umbonella* at Tell Abraq, and *C. erycina* at Akab (Händel 2015; Lidour et al. 2020; Prieur 1990; Van Neer and Gautier 1993). A further distinction between these four sites and Muweilah concerns the genus *Marcia*, which is dominant across all sites but represented by different species: at Al-Hamriyah and Ed-Dur, *M. hiantina* prevails, whereas *M. opima* is dominant at Tell Abraq (Prieur 1990). At Akab (Lidour et al. 2020), the taxon has not been identified to the species level (*Marcia* sp.). Glover (1995), however, has proposed that these taxa may represent regional variants of a single species. Temporal differences are also evident between Muweilah and Al-Hamriyah: at the latter site, *T. palustris* dominated during the Neolithic period, while *Marcia* prevailed in the Iron Age (Händel 2015). This pattern contrasts with Muweilah (Iron Age), where *T. palustris* remains the clearly dominant species over *M. cordata*.

Table 3. Comparison in species composition per site mentioned in the text, with references, location of the sites, chronology, dominant taxa and total amount of taxa for each site.

Site	References	Location	Chronology	Dominant Taxa	Total Taxa
Muweilah	—	U.A.E.	Iron Age	*Terebralia palustris*, *Hexaplex kuesterianus*, *Ostreoidea* sp., *Marcia cordata*	54
Al-Hamriyah	(Händel 2015)	U.A.E.	Neolithic – Iron Age	*Terebralia palustris*, *Hexaplex kuesterianus*, *Ostreoidea* sp., *Marcia hiantina*	Not reported
Tell Abraq	(Prieur 1990)	U.A.E.	Bronze Age	*Terebralia palustris*, *Hexaplex kuesterianus*, *Ostreoidea* sp., *Marcia opima*, *Callista erycina*, *Callista umbonella*	37
Akab	(Lidour et al. 2020)	U.A.E.	Neolithic	*Terebralia palustris*, *Hexaplex kuesterianus*, *Ostreoidea* sp., *Marcia* sp., *Callista erycina*	Not reported
Ed-Dur	(Van Neer and Gautier 1993)	U.A.E.	Neolithic – Iron Age	*Terebralia palustris*, *Hexaplex kuesterianus*, *Ostreoidea* sp., *Marcia hiantina*	20
Mahleya	(Al-Jahwari 2011)	Oman	Neolithic	*Odostomia eutropia*, *Mactra ovalina*	18
Saar	(Glover 1995)	Bahrain	Bronze Age	*Hexaplex kuesterianus*, *Marcia flammea*, *Pinctada radiata*, *Amiantis umbonella*	49
Dosariyah	Nebelsick, Drechsler, and Albano 2018	Saudi Arabia, near Arabian Gulf	Neolithic	*Hexaplex kuesterianus*, *Pinctada radiata*	44

Comparations also reveal taxonomic distinctions between the Arabian Gulf, the Gulf of Oman, and the Arabian Sea, which contribute to differences in species composition between Muweilah and more distant sites in Oman. Species such as *Architectonica perspectiva* and *Telescopium telescopium*, which occur in the Gulf of Oman and the Arabian Sea, are entirely absent from the Arabian Gulf (Bosh et al. 1995; MolluscaBase 2025). At Mahleya (Oman, Neolithic), for example, *Ostomia eutropia* and *Mactra ovalina* are dominant, species not found at Muweilah (Al-Jahwari 2011). Intra-regional variations are also evident within the Arabian Gulf itself, particularly between its western and eastern coasts. These differences are reflected in the species assemblages identified at sites such as Saar (Bahrain, Bronze Age) and Dosariyah (Saudi Arabia, Neolithic, near the Arabian Gulf), which show partial overlap with species that are rare or absent at Muweilah. In addition, the dominant taxa at these sites differ substantially from those at Muweilah, where *T. palustris*, *Ostreoidea*, *H. kuesterianus*, and *M. cordata* predominate. At Saar, for instance, *Pinctada radiata* (present only in low concentrations at Muweilah) and *Amiantis umbonella* (absent at Muweilah) are dominant, together with *Marcia* and *Hexaplex kuesterianus*, which are also abundant at Muweilah (Glover 1995). At Dosariyah, *H. kuesterianus* dominates alongside the infrequently occurring *Pinctada radiata* (Nebelsick, Drechsler, and Albano 2018).

Differences such as those observed between Dosariyah and Muweilah may also be attributed to chronological variation, particularly between Neolithic and Iron Age contexts. As noted above, temporal shifts between these periods are also documented at Al-Hamriyah (Händel 2015). Such diachronic changes may reflect both cultural developments (e.g. the transition to a sedentary lifestyle, technological innovations, or the domestication of the dromedary) and environmental transformations (e.g. increasing aridity, rising sea surface temperatures, and resource overexploitation) (Feulner 2006; Fleitmann et al. 2022; Händel 2015). The Umm an-Nar period (~4200 BP), for instance, has frequently been associated with the onset of drier climatic conditions (Berger et al. 2013; Fleitmann et al. 2022; Händel 2015; Karacic et al. 2018; Magee 2014; Parker et al. 2006a, 2006b). To date, the only species for which a direct correlation with climatic change has been demonstrated is *T. palustris* (e.g. Aspinall et al. 2002; Glover 1998).

Beyond natural spatial and temporal distribution patterns across and within marine environments, differences between Muweilah and other sites in the region also reflect divergent criteria in species selection. These distinctions relate to the varied purposes for which mollusks were exploited – subsistence, ornamentation, or tool production. Dietary species were likely selected according to their availability, nutritional value, ease of collection, size, human preference, and the site's proximity to the coast (e.g. Albert, Bujeng, and Chia 2022; Gazzo et al. 2025; Hutterer, Schröder, and Linstädter 2021). Conversely, aesthetic and cultural considerations appear to have guided shell selection for ornamental purposes (O'Connor 2010; O'Connor, Spriggs, and Veth 2002; Steele, Álvarez-Fernandez, and Hallett-Desguez 2019; Vitezović 2022), while morphology, size, and durability were decisive factors in the choice of shells for tool manufacture (Lidour et al. 2024; Romagnoli et al. 2017). Examples include *Strombus* finds in Mahleya (Oman, age), a species which is known for its use as ornamentation or decoration, which accounts for a

higher proportion of the total shell quantity in Mahleya compared to Muweilah (11.11% vs <0.01%), where mollusks were predominantly used for sustentation (Al-Jahwari 2011).

Overall, the comparisons indicate that the mollusk assemblage from Muweilah broadly aligns with regional trends while retaining site-specific characteristics shaped by local environmental conditions and species availability over time. Despite generally similar arid conditions along the eastern Arabian Gulf, the data suggest that mangrove remnants and stable populations of *Terebralia palustris* persisted in restricted ecological niches. More broadly, the comparisons highlight how mollusk assemblages across southeastern Arabia were influenced by settlement location within distinct geographical zones, with clear differences between coastal and inland sites that likely reflect varying resource-use strategies. In this context, Muweilah provides a useful case study for assessing both regional continuity and local variability in mollusk exploitation during the Iron Age and contributes to a more nuanced reconstruction of human–environment interactions in southeastern Arabia.

Conclusion

The molluscan assemblage from the Iron Age site of Muweilah includes 54 taxa dominated by *Terebralia palustris*, *Marcia cordata*, *Ostreoidea* sp. and *Hexaplex kuesterianus*. Most shells originate from mangrove and littoral environments, reflecting the dominance of the four main species. Looking at the taxa instead of number of individuals, however, most species inhabit littoral and sublittoral habitats, as the only taxa from mangrove environments besides *T. palustris* are *Pirenella cingulata*, *P. conica*, *Mytoloidea* sp., and *Ostreoidea* sp. The dominance of the four main species correlates with their ease of collection, whereby only *M. cordata* requires active hunting due to its burrowing lifestyle. Nowadays, only three of the four main species occur in the region, while *T. palustris* is extirpated except for occurrences in Khor Kalba.

Both *T. palustris* and *H. kuesterianus* exhibit high degrees of fragmentation as well as superficial internal cracks as a result of flesh extraction methods. Differences in the states of preservation regarding colouration, ablation and shininess combined with the presence of burned specimens suggests boiling, grilling and to a minor degree burning as possible cooking methods. The differences in preservation quality between species indicates a species-specific selection of cooking methods.

The bivalve species *Anadara*, *Pinctada*, and *Asaphis violascens* may also have been used for sustenance, albeit to a lesser extent. Key factors influencing species selection for consumption likely included their edibility, availability, as well as ease of collection and preparation. In contrast, bivalves such as *Callista*, *Dosinia tumida*, and *Barbatia* appear to have been collected post-mortem and may have served as tools, although there is currently no direct evidence such as wear patterns or modifications. Other species were likely used for decorative or utilitarian purposes, for instance, *Cypraea* sp., *Conus* sp., and members of the *Strombidae* family may have functioned as ornaments or bowls. Small gastropods such as *Priotrochus kotschyi*, *Pirenella cingulata*, *P. conica*, *Mitrella blanda*, and *Nassarius* spp. were either used as flooring material or unintentionally introduced to the site by adhering to larger specimens.

Muweilahs mollusk assemblage exhibits the highest degree of similarity with sites in its immediate vicinity, including Al-Hamriyah, Tell Abraq, Akab, and Ed-Dur, while showing greater dissimilarity to more distant sites along the Gulf of Oman, the Arabian Sea, and the western Arabian Gulf. These differences correlate with variations in species distribution patterns, divergent selection criteria, as well as distinct cultural developments and environmental transformations over time. Against the wider regional backdrop, the mollusk assemblage in Muweilah reflects overarching Iron Age patterns while also highlighting the importance of local environmental conditions in shaping resource use. The persistence of restricted mangrove habitats despite generally arid conditions along the eastern Arabian Gulf underscores the environmental variability communities navigated. As such, Muweilah provides a key reference point for understanding regional continuity, local adaptation, and human–environment interactions in southeastern Arabia during the Iron Age.

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Appendices

Appendix 1. Literature used to classify gastropods and bivalves into individual habitats

Family	Genus and Species	Literature
Gastropod		
Columbellidae	*Mitrella blanda* (G. B. Sowerby I, 1844)	(Abdul-Salam and Al-Khedery 1992; Al-Kandari et al. 2020; Bosh et al. 1995; Ebadzadeh, Shojaei, and Seyfabadi 2024; Nebelsick, Drechsler, and Albano 2018)
Conidae	*Conus* sp. (Linnaeus, 1758)	(Bosh et al. 1995; El-Sorogy et al. 2019)
Cypraeidae	*Cypraea* sp. (Linnaeus, 1758)	(Bosh et al. 1995)
Littorinidae	*Littoraria intermedia* (Philippi, 1846)	(Bosh et al. 1995; Cook 1986; Reid 1985)
Muricidae	*Hexaplex kuesterianus* (Tapparone Canefri, 1875)	(Beech and Kallweit 2001; Bosh et al. 1995; El-Sorogy et al. 2019, 2020; Häussler, Nebelsick, and Drechsler 2018; Hellyer and Aspinall 2006; Nebelsick, Drechsler, and Albano 2018)
	Rapana sp. (Schumacher, 1817)	(Bosh et al. 1995)
	Rapana venosa (Valenciennes, 1846)	(Bosh et al. 1995)
	Tylothais savignyi (Deshayes, 1844)	(Bosh et al. 1995)
Nassariidae	*Nassarius fissilabris* (A. Adams, 1852)	(Bosh et al. 1995)
	Nassarius sp. (Duméril, 1805)	(Bosh et al. 1995)
Naticidae	*Neverita didyma* (Röding, 1798)	(Al-Kandari et al. 2020; Bosh et al. 1995; El-Asmar, Taha, and El-Sorogy 2016; Munandar et al. 2017; Yu et al. 2020)
Neritidae	*Nerita albicilla* (Linnaeus, 1758)	(Al-Kandari et al. 2020; Bosh et al. 1995; El-Sorogy et al. 2019; Feng et al. 2019; Hong et al. 2023; Manaa et al. 2016 Nebelsick, Drechsler, and Albano 2018; Tan and Clements 2008;)
Potamididae	*Terebralia palustris* (Linnaeus, 1767)	(Bosh et al. 1995; Carlén and Ólafsson 2002; Fratini, Cannicci, and Vannini 2000, 2001, 2004; Händel 2015; Kendrick and Morse 1990; Lindauer et al. 2017; Mujiono 2009; Pape et al. 2008)
	Pirenella cingulata (Gmelin, 1791)	(Bosh et al. 1995; El-Sorogy, Demircan, and Alharbi 2020; Nebelsick, Drechsler, and Albano 2018)
	Pirenella conica (Blainville, 1829)	(Al-Kandari et al. 2020; Bosh et al. 1995; Nebelsick, Drechsler, and Albano 2018)
	Pirenella sp. *(Gray, 1847)*	(Bosh et al. 1995)
Siphonariidae	*Siphonaria* sp. (G. B. Sowerby I, 1823)	(Al-Kandari et al. 2020; Bosh et al. 1995)
Strombidae	*Strombidae* sp. (Rafinesque, 1815)	(Bosh et al. 1995)
Turbinidae	*Lunella coronata* (Gmelin, 1791)	(Afsar et al. 2022; Al-Kandari et al. 2020; Bosh et al. 1995; El-Sorogy et al. 2019; Nebelsick, Drechsler, and Albano 2018)
Trochidae	*Priotrochus obscurus* (W. Wood, 1828)	(Bosh et al. 1995)
	Umbonium vestiarium (Linnaeus, 1758)	(Bosh et al. 1995)
Bivalves		
Arcidae	*Acar plicata* (Dillwyn, 1917)	(Al-Kandari et al. 2020; Audino, Serb, and Marian 2019; Bosh et al. 1995; Graham et al. 2023; Nebelsick, Drechsler, and Albano 2018; Yasser et al. 2023)
	Anadara antiquata (Linnaeus, 1758)	(Abdullah, Nurjanah, and Yusefi 2013; Afiati 2007; Azmi et al. 2021; Bosh et al. 1995; El-Asmar, Taha, and El-Sorogy 2016; El-Sorogy et al. 2019, 2020; Graham et al. 2023; Jahangir, Siddiqui, and Ayub 2014; Manaa et al. 2016; Mayoma et al. 2020; Mzighani 2005; Nurdin et al. 2006; Toral-Barza and Gomez 1985; Wanjeri et al. 2023)
	Anadara sp. (J. E. Gray, 1847)	(Bosh et al. 1995)
	Anadara uropigimelana (Bory de Saint-Vincent, 1827)	(Bosh et al. 1995; Dolorosa and Dangan-Galon 2014 El-Asmar, Taha, and El-Sorogy 2016;; Graham et al. 2023; Lindauer et al. 2017, 2018; Tebano and Paulay 2000)
	Barbatia foliata (Forssk ål, 1775)	(Agüera and Oliver 2008; Bosh et al. 1995; Paulay 1996; Souji, Vardhanan, and Radhakrishnan 2014)
	Barbatia obliquata (W. Wood, 1828)	(Bosh et al. 1995; Prieur 2005; Souji, Vardhanan, and Radhakrishnan 2014)
	Barbatia sp. (Gray, 1842)	(Bosh et al. 1995)
Cardiidae	*Vasticardium assimile lacunosum* (Reeve, 1845)	(Bosh et al. 1995; El-Sorogy et al. 2019; Graham et al. 2023; Nebelsick, Drechsler, and Albano 2018)
Glycymerididae	*Glycymerididae* sp. (Dall, 1908)	(Bosh et al. 1995)
	Glycymeris arabica (H. Adams, 1871)	(Bosh et al. 1995; El-Asmar, Taha, and El-Sorogy 2016; El-Sorogy et al. 2019; Zuschin and Ebner 2015)
	Glycymeris livida (Reeve, 1843)	(Bosh et al. 1995; Callapez and Dinis 2020; El-Asmar, Taha, and El-Sorogy 2016; El-Sorogy et al. 2016, 2019; Lidour, Pellegrino, and Charbonnier 2023)
	Glycymeris sp. (da Costa, 1778)	(Bosh et al. 1995)
	Tucetona pectunculus (Linnaeus, 1758)	(Bosh et al. 1995; El-Sorogy, Demircan, and Alharbi 2020; Nebelsick, Drechsler, and Albano 2018)
Mactridae	*Mactra lilacea* (Lamarck, 1818)	(Al-Kandari et al. 2020; Bosh et al. 1995; El-Asmar, Taha, and El-Sorogy 2016; El-Sorogy et al. 2019; Matthews et al. 1989)
Margaritidae	*Pinctada margaritifera* (Linnaeus, 1758)	(Bosh et al. 1995; El-Sorogy et al. 2019; Elen 2002; Le Moullac et al. 2016; Yukihira, Klumpp, and Lucas 1999, 2000, 2006)
	Pinctada sp. (Röding, 1798)	(Bosh et al. 1995)
Mytiloidea	*Mytiloidea* sp. (Rafinesque, 1815)	(Bosh et al. 1995)
Ostreoidea	*Ostreoidea* sp. (Rafinesque, 1815)	(Bosh et al. 1995)
Pectinidae	*Chlamys* sp. (Röding, 1798)	(Bosh et al. 1995; Waller 1993)
	Pectinidae sp. (Rafinesque, 1815)	(Bosh et al. 1995)
	Scaeochlamys livida (Lamarck, 1819)	(Ali et al. 2017; Bosh et al. 1995 Dijkstra 1990; El-Sorogy et al. 2019; Zuschin and Piller 1997)
Psammobiidae	*Asaphis violascens* (Forsskål, 1775)	(Al-Kandari et al. 2020; Bird et al. 2002; Bird and Bird 1997; Bolasina 2022;; Bosh et al. 1995 Domaneschi and Shea 2004; El-Sorogy et al. 2019; Nebelsick, Drechsler, and Albano 2018; Tilley et al. 2021; Widiastuti 2023; Zhang et al. 2019)
Spondylidae	*Spondylus gloriandus* (Melvill & Standen, 1907)	(Bosh et al. 1995; El-Sorogy et al. 2016)
	Spondylus spinosus (Schreibers, 1793)	(Aksit, Mutaf, and Balci 2013;; Al-Kandari et al. 2020 Bosh et al. 1995; Ghosn et al. 2020; Lamprell 1998; Nebelsick, Drechsler, and Albano 2018)
Veneridae	*Callista erycina* (Linnaeus, 1758)	(Bosh et al. 1995; Dolorosa and Dangan-Galon 2014; Potts et al. 1996; Prabhakar 2011)
	Callista florida (Lamarck, 1818)	(Al-Kandari et al. 2020; Bosh et al. 1995; El-Sorogy et al. 2019; Mohammad and Yusuf 2015)
	Dosinia tumida (Gray, 1838)	(Bosh et al. 1995; El-Sorogy et al. 2019; Kumar, Panda, and Sen 2023; Robba et al. 2005)
	Marcia cordata (Forsskål in Niebuhr, 1775)	(Bosh et al. 1995; Carpenter et al. 1997; El-Sorogy et al. 2016; Feulner and Hornby 2006; Glover 1995; Jahangir et al. 2012; Nebelsick, Drechsler, and Albano 2018)
	Veneridae sp. (Rafinesque, 1815)	(Bosh et al. 1995)

Appendix 2. Habitats of Origin of Gastropod Species, Divided into Mangrove, Littoral, Sublittoral, Offshore, and Undetermined, with und. = Undetermined

Gastropods		Habitat				
Family	Genus	mangroves	littoral	sublittoral	offshore	und.
Columbellidae	*Mitrella blanda*		X			
Conidae	*Conus* sp.		X			
Cypraeidae	*Cypraea* sp.		X	X	X	
Gastropod indet.	*Gastropod* indet.					X
Littorinidae	*Littoraria intermedia*		X			
Muricidae	*Hexaplex kuesterianus*		X			
	Rapana sp.			X	X	
	Rapana venosa				X	
	Tylothais savignyi		X			
Nassariidae	*Nassarius fissilabris*		X			
	Nassarius sp.		X		X	
Naticidae	*Neverita didyma*		X			
Neritidae	*Nerita albicilla*		X			
Potamididae	*Terebralia palustris*	X				
	Pirenella cingulata	X	X			
	Pirenella conica		X			
	Pirenella sp.	X	X			
Siphonariidae	*Siphonaria* sp.		X			
Strombidae	*Strombidae* sp.		X		X	
Turbinidae	*Lunella coronata*		X			
Trochidae	*Priotrochus obscurus*		X			
	Umbonium vestiarium		X			

Appendix 3. Habitats of Origin of Bivalve Species, Divided into Mangrove, Littoral, Sublittoral, Offshore, Undetermined, with und. = Undetermined

Bivalves		Habitat				
Family	Genus	mangroves	littoral	sublittoral	offshore	und.
Arcidae	*Acar plicata*		X	X		
	Anadara antiquata		X		X	
	Anadara sp.		X		X	
	Anadara uropigimelana				X	
	Barbatia foliata		X	X		
	Barbatia obliquata		X	X		
	Barbatia sp.		X	X	X	
Bivalve indet.	*Bivalve* indet.					X
Cardiidae	*Vasticardium assimile lacunosum*				X	
Glycymerididae	*Glycymerididae* sp.		X			
	Glycymeris arabica		X			
	Glycymeris livida		X			
	Glycymeris sp.		X			
	Tucetona pectunculus				X	
Mactridae	*Mactra lilacea*				X	
Margaritidae	*Pinctada margaritifera*		X	X		
	Pinctada sp.		X	X		
Mytiloidea	*Mytiloidea* sp.	X	X		X	
Ostreoidea	*Ostreoidea* sp.	X	X	X		
Pectinidae	*Chlamys* sp.		X	X	X	
	Pectinidae sp.		X	X	X	
	Scaeochlamys livida		X		X	
Psammobiidae	*Asaphis violascens*		X			
Spondylidae	*Spondylus gloriandus*				X	
	Spondylus spinosus		X	X		
Veneridae	*Callista erycina*				X	
	Callista florida				X	
	Dosinia tumida				X	
	Marcia cordata		X			
	Veneridae sp.		X	X	X	

4. Shell Remains from the Archaeological Site of Muweilah: Sustentation and Socioeconomic Distribution Patterns

Inés De La Fortuna Müller García and James H. Nebelsick

In preparation

4.1 Context and Scope

This manuscript examines spatial variation and habitat associations within the molluscan assemblage of Muweilah, extending the insights of the previous manuscripts. Building on Manuscript 2, it extends the comparative analysis by examining species composition and habitat associations of the shell remains in relation to other archaeological contexts across the Arabian Gulf, the Gulf of Oman, and the Arabian Sea. Leveraging the taphonomic framework established in Manuscript 1, this study also considers the site's location and distance from the coastline and mangrove habitats, discussing in detail potential factors underlying differences in species distributions. The study aims to identify socioeconomic distinctions within the site and integrates archaeomalacological data with broader archaeological evidence to provide a more comprehensive understanding of site use and organization.

This manuscript builds on the results of Manuscript 1, where *Terebralia palustris* was established as a taphonomic reference framework, and on the broader assemblage analysis presented in Manuscript 2. By examining spatial variation in species composition, habitat associations, and site-specific distributions, it extends the interpretation of shell exploitation and resource use across Muweilah. The analysis further highlights the site's proximity to mangrove habitats and the coastline while being situated within an aeolian sand dune belt, providing insight into ecological and socioeconomic factors influencing species distributions.

The manuscript is included here in draft form as part of the dissertation.

4.2 Manuscript Draft

Abstract

The study of archaeological shell remains offers a valuable means to reconstruct subsistence strategies, cultural traditions, and interactions between communities and coastal ecosystems, as well as to trace environmental and climatic shifts. This research investigates a large assemblage of molluscan remains from Muweilah, an Iron Age II (1000–600 BC) settlement in the Emirate of Sharjah, United Arab Emirates. The analysis focuses on spatial variation in shell distribution within the site and compares species composition with that of other archaeological contexts across the Arabian Gulf, the Gulf of Oman, and the Arabian Sea.

The spatial distribution of molluscan remains within the site reflects socioeconomic distinctions, characterized by 1) a ceremonial columned hall marked by elevated oyster frequencies and comparatively low species diversity; 2) a residential sector with high species diversity; and 3) concentrations near gates, possibly indicating refuse disposal areas.

Comparisons with other archaeological and modern sites along the Arabian Peninsula suggest that the mollusks were collected from coastal and mangrove habitats of the Arabian Gulf located near Muweilah. The closest parallels in species composition occur at nearby archaeological sites, whereas the most pronounced differences are found at sites in Oman and in present-day contexts. These spatial and temporal variations are attributed to differing modes of shell use, cultural practices, human preferences, and environmental changes, most notably the decline of mangroves, which led to the local extirpation of the gastropod *Terebralia palustris* from much of the Gulf.

Introduction

Archaeological studies in the Arabian Peninsula have highlighted the importance of molluscan remains as indicators of subsistence strategies in arid environments and of cultural practices such as symbolic shell use. Mollusk remains recovered from settlements and middens are typically interpreted as food waste, offering valuable insights into human–environment interactions, environmental change, and resource use under challenging climatic conditions (e.g., Uerpmann 1992; Biagi 1999; Kuhn et al. 2001; Prieur 2005; Parker and Goudie 2007; Häussler et al. 2018; Hausmann et al. 2019; Berger et al. 2020; Müller García and Nebelsick 2024). Additionally, the spatial distribution of mollusk remains within settlements has also come to be usedd to interpret mollusk remains as potential evidence of social organization, economic practices, and spatial use within past communities (e.g., Prieur 1990; Glover 1995; Beech and lover 2005; Händel 2013; Çakırlar 2019). Variations in the spatial distribution of shells within archaeological sites are often attributed to factors such as environmental change, modifications in subsistence strategies, or intensive resource use (e.g., Prieur 1990; Glover 1995; Beech and Glover 2005; Händel 2013; Çakırlar 2019). The present study applies this framework to analyze the shell assemblage from Muweilah.

Study site

The Iron Age II settlement of Muweilah, located approximately 15 km inland in the Emirate of Sharjah (UAE), lies within a landscape of aeolian sand dunes (Figure 4.1). The site was first occupied in the 10th century BC and remained inhabited until its abrupt destruction by fire, likely between the 8th and 6th centuries BC (Magee 1996, 2004; Blau et al. 2000; Magee et al. 2018; Karacic et al. 2018). At the onset of the Iron Age II, climatic conditions began to resemble those of the present day. The earlier environment, dominated by widespread mangroves, remnants of Pleistocene dune systems, and a strong Indian Ocean monsoon, gradually gave way to a regime influenced by low-pressure systems from the eastern Mediterranean. Following these climatic changes, the formation of sabkhas, the reactivation of dune systems, and a transition to scrubland interspersed with residual mangrove stands took place (Glover 1998; Staubwasser 2002; Parker et al. 2006, 2020; Berger et al. 2013; Händel 2013; Karacic et al. 2018; Fleitman et al. 2022).

This environmental shift impacted local resource availability, settlement patterns, and subsistence strategies. Communities adapted to the increasingly arid conditions through technological and socio-economic innovations, such as the domestication of camels, improved herd management, as well as the introduction of *falaj* irrigation systems, which allowed for the extraction and redirection of groundwater from distant aquifers (Magee 1998, 2004, 2014; Potts 2001; Magee and Thompson 2001; Benoist 2008; Boivin & Fuller 2009; Uerpmann et al. 2013; Moussa 2019). Combined with advancements of navigational skills in seafaring, these developments positioned Muweilah advantageously near the coast, allowing participation in maritime trade while offering protection from coastal threats such as piracy (Potts 2001; Magee and Thompson 2001; Magee 2004, 2014; Benoist 2008; Boivin & Fuller 2009; Uerpmann et al. 2013). The site's inland location, close enough to the coast to access trade routes, yet far enough to ensure security, was likely a key factor in its strategic importance (Potts 2001; Magee 2004, 2014).

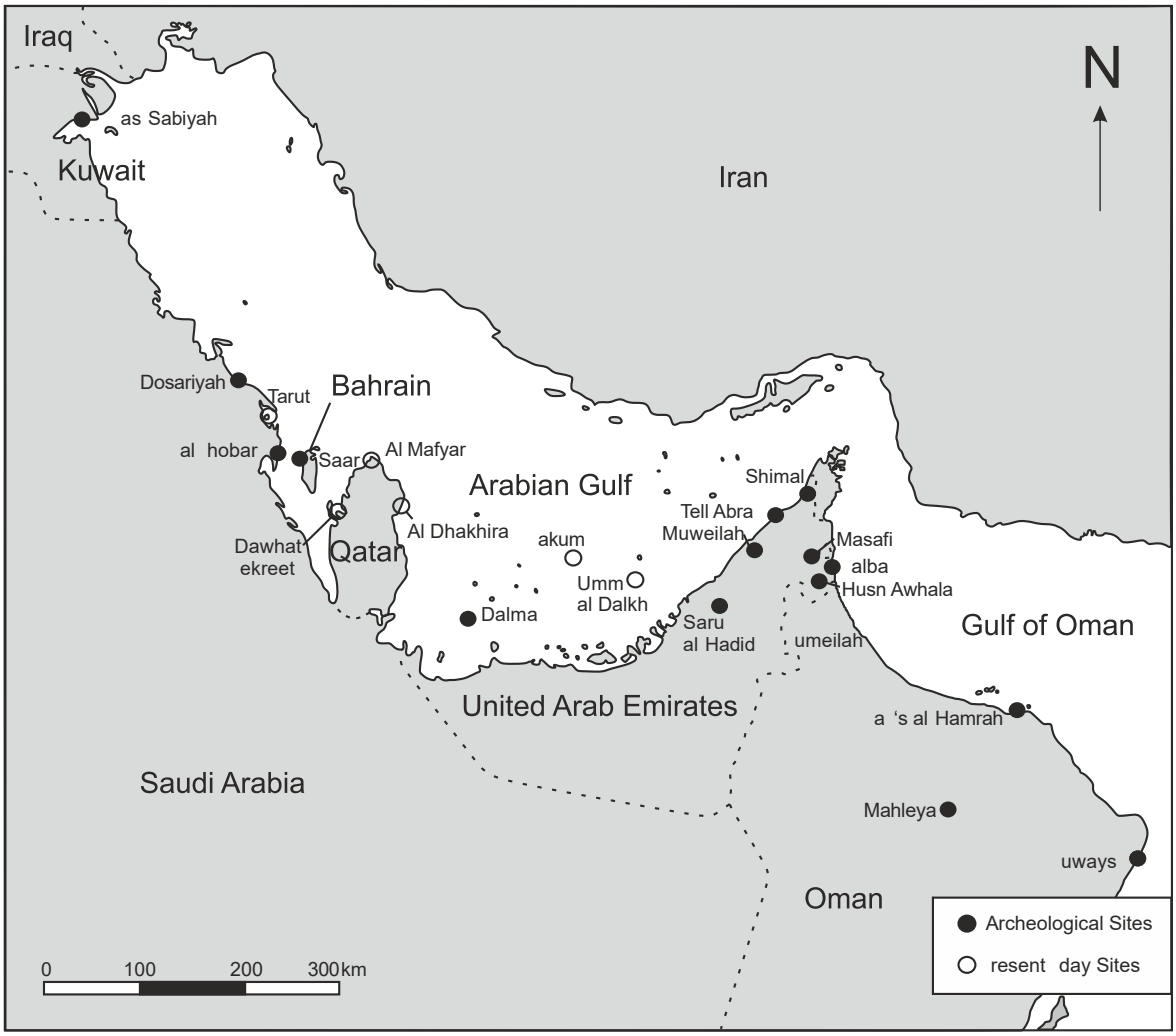

Figure 4.1 Position of the archaeological site of Muweilah in the Arabian Peninsula as well as relevant archeological and present-day sites of the region. Illustration based on Magee 2004; Karacic et al. 2018; and Lidour et al. 2024.

Architecture of Muweilah

Muweilah was divided into a Western and a Central Area, covering approximately 1 hectare enclosed by two chronologically consecutive surround walls with access provided by three gates (Figure 4.2). This fortification stands out among contemporary sites in Southeast Arabia due to the architectural complexity of its gateways and the combined use of stone and traditional mudbrick in construction (Magee 1996, 2002, 2004; Blau et al. 2000; Benoist 2008; Karacic et al. 2018). The Western Area, separated from the rest of the site by the first wall and enclosed again by the second, includes the West Gate as well as Buildings IX, X, and II. Building II is interpreted as a place of significant social and economic importance and consists of a columned hall supported by 20 wooden columns arranged in a 4×5 grid on a sand floor, along with several adjacent, elevated rooms featuring *pisé* (rammed earth) floors, storage jars, as well as banqueting paraphernalia. As the largest free-standing structure at the site, Building II follows a layout commonly found elsewhere in Arabia (Magee 2002, 2004; Karacic et al. 2018; Magee and Thompson 2001). Similar structures in Rumeilah have been interpreted by Boucharlat and Lombard (2001) as storage rooms or elite residences linked to the management of irrigation systems, however, despite architectural parallels suggesting comparable ritual practices, Magee (2003) argues for an elite use of Muweilahs column hall in the context of controlling and distributing local and supra-regional luxury goods. Northeast of Building II lies a large pit, approximately 4 meters in diameter, referred to here as Building II b, which may have served as a lime plaster production area. This location yielded large quantities of shells, pottery, and animal bones, with significantly lower evidence of burning compared to Building II itself (Magee 2002).

The Central Area can be further subdivided into a Southern Area (comprising the South Gate and Buildings I, VI, VII, VIII, and XII), an Eastern Area (East Gate, Buildings XI and V), and a Northern Area (Buildings III and IV). One characteristic feature of the Central Area is a recurring architectural se uence of “main room - corridor-ancillary room(s)” (highlighted in red in Figure 4.2) (Karacic et al. 2018; Magee et al. 2018). This layout typically includes a large main room with external access and pyrotechnic installations (e.g., hearths or fire pits), adjoining ancillary rooms equipped with large flat stones likely used to support storage jars, and approximately 2-meter-wide corridors formed by freestanding walls, which are

thought to have facilitated roof access, improved natural lighting, and enhanced air circulation (Karacic et al. 2018; Magee et al. 2018). An exception to this layout is Building VIII, which contains a higher number of pyrotechnic features and deviates from the standard configuration with only one possible corridor (Room 124), positioned at the far end of the building with just a single doorway (Karacic et al. 2018; Magee et al. 2018).

The “main room-corridor-ancillary room” configuration is absent in the Western Area, nevertheless, evidence suggests roof-related activities in Building II, where roof access may have been provided through an external Room 38 rather than internal corridors (Karacic et al. 2018). Following these observations, four levels of access to different areas of the site emerge: (1) access to the Central Area only, (2) access to the Western Area only, (3) access to both the Central and Western Areas, and (4) no access. The restricted and spatially segregated access to the Western Area underscores its significance, although it remains unclear who exactly was permitted entry (Magee 2002; Karacic et al. 2018; Magee and Thompson 2001).

Archeological remains

Pottery constitutes the majority of archaeological finds at Muweilah and includes sandy wares for everyday use, ceramics with white calcareous inclusions, and fine painted wares, for example vessels used in banqueting. These ceramics originate from a variety of production centers, including the Al-Ain oasis, the Al-Hajar Mountains, Mesopotamia, and Bahrain, reflecting Muweilahs strategically favorable position for both regional and long-distance trade. The fine painted wares are more frequent at Muweilah compared to other sites such as Tell Abraq and are especially concentrated in Building II, pointing to differentiated social and political structures within the settlement and other regions and emphasizing Muweilahs connections in Southeast Arabia (Magee 1996, 2004, 2014; Magee and Thompson 2001).

Building II also provides evidence for both bronze and iron production for local use and trade. The discovery of imported iron from Iran is particularly significant, as iron remains rare in Southeastern Arabia during this period, despite the term “Iron Age” (Magee and Thompson 2001; Stepanov et al. 2020). Dromedary figurines found in Building II further highlight the importance of camel domestication (Potts 2001; Magee 1996, 2002, 2014; Magee and Thompson 2001). Of equal importance is the identification of the earliest known South Arabian inscription on a locally produced vessel, which indicates cultural interactions with Yemen occurring approximately 300–400 years earlier than previously assumed (Müller 1999; Magee 1999, 2014).

Botanical and faunal remains

Botanical and faunal remains, including dromedaries, goats, fish, and wild game, as well as plant species such as date palm, tamarisk (*Tamarix* sp.), jujube (*Ziziphus* sp.), and acacia (*Acacia* sp.), have provided important insights into subsistence strategies and environmental conditions in Muweilah (Magee 1996, 2014; Magee and Thompson 2001; Tengberg 2009). Previous research on mollusk remains has focused on taxonomic identification and taphonomic analysis, with *Terebralia palustris*, *Hexaplex kuesterianus*, *Marcia cordata*, and *Ostreoidea* sp. identified as the most frequently consumed species. In addition to these, a wide variety of other taxa have been recorded, likely serving diverse functions such as ornamentation, flooring, or tool production (Magee and Thompson 2001; Müller García and Nebelsick 2024). The distribution, diversity, and habitat origin of mollusk remains across different areas of the site have, however, not yet been systematically examined. Such comparative analyses are crucial for identifying broader regional patterns of resource exploitation, trade networks, and human-environment interactions during the Iron Age.

Aims

This study aims to: (1) identify differences in species diversity, equitability, and habitat origin within the settlement, and (2) further contextualize the results within the broader archaeological state of knowledge of Muweilah and Southeastern Arabia. By doing so, the analysis seeks to clarify the function of individual buildings and site areas, particularly in relation to the Central and Western Areas, in relation to differences in access within the settlement. The study further examines interregional differences between Muweilah and contemporary Iron Age sites, as well as Neolithic and modern sites, to assess temporal change and regional connectivity. It also aims to enhance our understanding of the socio-cultural significance of mollusks in Southeast Arabia, particularly regarding trade, social status, and ritual practices. In addition, the manuscript also seeks to draw conclusions about potential shell collection locations. In doing so, the study builds on and deepens the analytical results presented in previous publications (Müller García and Nebelsick 2026).

Such an in-depth analysis will contribute to a more comprehensive understanding of both the site itself and Southeastern Arabia as a whole. Building on previous research concerning taphonomic and ecological investigations (Müller García and Nebelsick 2024, 2026), this manuscript seeks to further investigate human-environment interactions, interregional trade networks, as well as the climatic and cultural contexts that shaped these dynamics.

Methods

A total of 40,668 shells from 541 loci were analyzed across multiple architectural contexts at Muweilah, including Buildings I–X and XII, the East, West, and South Gates, and Building II b (Appendix 4.1). Species-level identifications were conducted following Bosch et al. (1995), with nomenclature verified using MolluscaBase (2025). The primary aim of the study was to compare assemblage composition across different architectural units. Due to previously documented differences (Magee 2002), Building II b was treated as a separate analytical unit. For loci containing large numbers of specimens, subsampling was performed using a sediment splitter (5 cm slat interval). Floor deposits containing exclusively micro-gastropods from Building VI, as well as samples of uncertain provenance, were excluded from the analysis.

Building on the habitat analysis presented in Manuscript 2 (Müller García and Nebelsick 2026; details see below), this study expands the investigation of species' ecological origins and interregional comparisons. Habitat data were recorded for each specimen, distinguishing between mangrove, littoral, sublittoral, offshore, and undetermined environments. Taxa occurring across multiple habitats were assigned to all relevant categories to reflect their ecological range, with habitat classifications based primarily on Bosch et al. (1995) and supplemented by additional sources (see Appendix 1 in Müller García and Nebelsick 2026). The current analysis extends the previous work in several ways. First, it includes a more comprehensive comparison with additional contemporary and modern sites from the region. Second, species present at the compared sites but absent from Muweilah are discussed in terms of age and habitat of origin.

Assemblages were analyzed at both site-wide and building-specific levels, including Buildings I–X, XII, the East, West, and South Gates, and Building II b. The following parameters were recorded: total number of individuals, bivalve-to-gastropod ratio, number of taxa (overall, bivalves, and gastropods), and species frequency distributions. Species distributions were visualized using histograms for selected structures (Buildings II and VI, West Gate, and South Gate; see Appendices 4.2–4.6 for complete data). To assess diversity patterns, rarefaction curves and sample coverage were calculated using the iNEXT online platform (Chao et al. 2014, 2016). Shannon diversity and equitability indices were calculated

separately for bivalves, gastropods, and combined assemblages. Diversity values were evaluated in relation to taxonomic richness across buildings. Statistical analyses were performed using RStudio (version 2024.12.1), Excel (version 1808), and SPSS (version 29), and figures were prepared using CorelDRAW (version 24.3.0.571).

The assemblage from Muweilah was compared with 32 sites spanning the Neolithic to the present across the Arabian Gulf, Gulf of Oman, and Arabian Sea (Appendix 4.7). For Tell Abraq, Bronze Age data were used due to better preservation and documentation. Dominant taxa from each site were compared with the most common species at Muweilah and visualized in a heatmap. Sites lacking data on dominant species were excluded. For comparative purposes, closely related taxa (e.g., *Marcia cordata* and *M. hiantina*, *Saccostrea cucullata* and *Ostrea* sp.) were grouped at the genus or higher taxonomic level. Taxa absent from Muweilah but present at other sites were further analyzed in terms of their habitat affiliation and chronological range. These analyses were conducted using Excel (version 1808), SPSS (version 29), as well as RStudio (version 2024.12.1) and formatted with CoralDraw (version 24.3.0.571).

Results

Distribution within the site

Most buildings show a broadly similar species composition across the site, which is divided into several spatial areas (Figure 4.2). The assemblages are consistently dominated by *Terebralia palustris* and *Marcia cordata*, indicating a relatively uniform baseline community structure across the site. Among the remaining taxa, *Ostreoidea* sp. and *Hexaplex kuesterianus* are generally the most frequent (Figures 4.2–4.5; Tables 4.1–4.2; Appendix 4.2–4.6).

Deviations from this overall pattern are summarized in Table 4.4 and are not evenly distributed across the site. Building II in the Western Area (see Figure 4.2) stands out due to the strong dominance of *Ostreoidea* sp., which accounts for 79.82 % of all bivalves and thus represents a markedly skewed composition compared to other structures. Elevated proportions of this taxon are also observed in several other western structures (Buildings IX, II b, X, and the West Gate), as well as in Building IV (Northern Area), although less pronounced. In contrast, Buildings III (Northern Area) and VII (Southern Area) show reduced frequencies of *M. cordata* without a corresponding increase in *Ostreoidea* sp.; instead, other taxa such as *Callista erycina*, *Vasticardium assimile lacunosum*, and *Anadara uropigimelana* occur more frequently.

In addition to these deviations, several taxa show clear spatial concentration (Table 4.5). Building I is characterized by high proportions of *Lunella coronata*, *Pinctada margaritifera*, and *Callista erycina*, whereas the South Gate shows elevated frequencies of multiple gastropod taxa. Buildings VI and VII are distinguished by high abundances of *Pirenella cingulata* and *P. conica*. These patterns indicate that certain taxa are not evenly distributed but are instead associated with specific structures.

The number of individuals and taxonomic richness vary considerably across the site, ranging from 105 to 9,478 individuals and from 8 to 33 taxa (Table 4.3). The highest values are recorded in the Southern Area, with a general decline toward the east and, more markedly, toward the west. Among the western structures, Buildings IX and II b show comparatively high numbers of individuals relative to the surrounding buildings. In contrast, Building VII combines a relatively low number of

individuals compared to the remaining Southern Area with reduced gastropod diversity but a comparatively high number of bivalve taxa.

Bivalve and gastropod distributions also show a clear spatial pattern (Figure 4.2). Bivalves dominate in the eastern part of the site, whereas gastropods increase in relative abundance toward the western and northern areas. Overall, while a consistent baseline composition characterizes most buildings, the observed deviations and spatial concentrations demonstrate a pronounced intra-site variability.

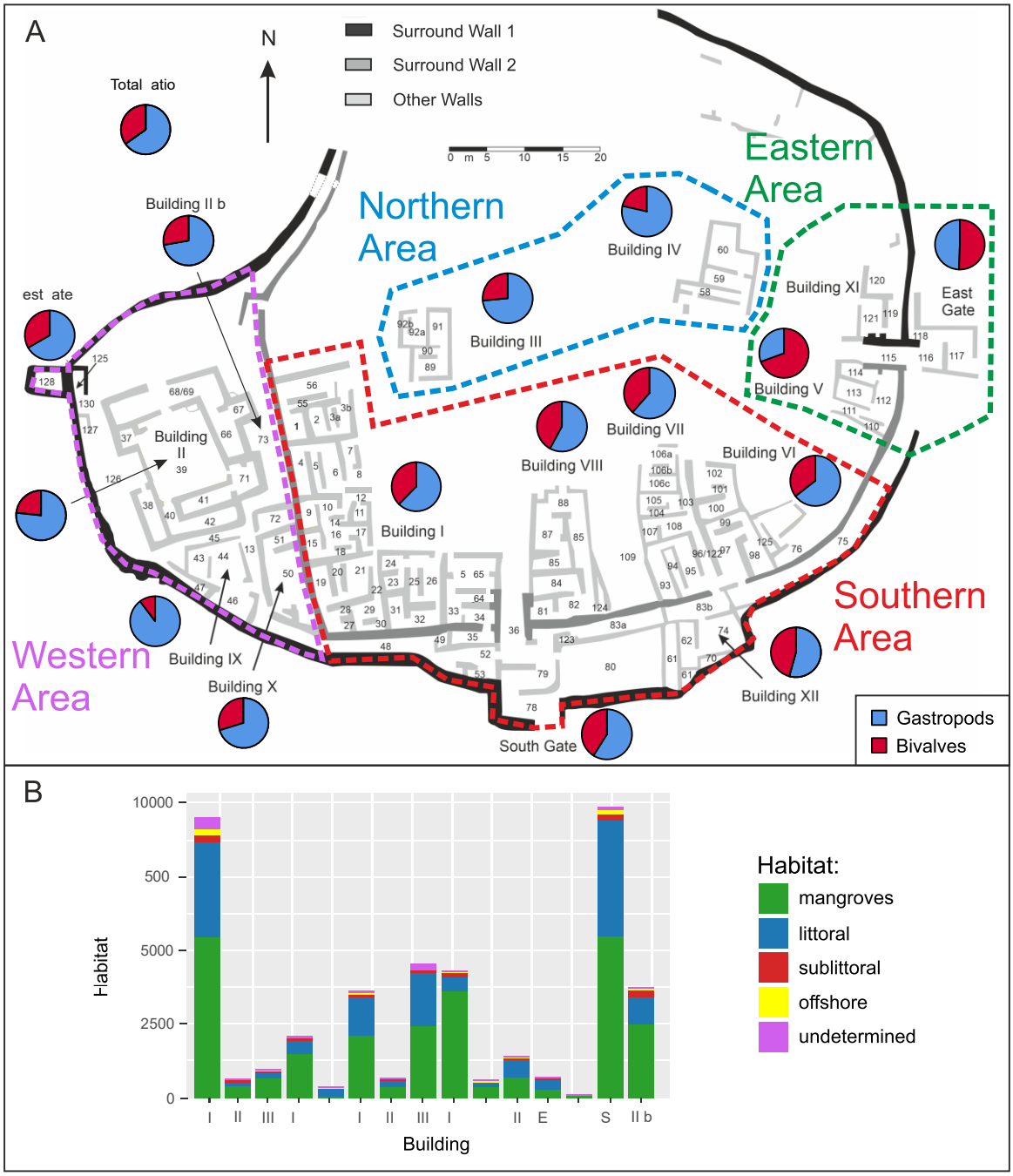

Figure 4.2 A) Map of Muweilah with different areas of the site, with Southern (red), Northern (blue), Western (purple) and Eastern Area (green) and gastropods-bivalves' ratios of the Buildings I-X, XII, Building II b, East, West and South Gate. Illustration based on Karacic et al. 2018. B) Habitats (mangrove/littoral/sublittoral/offshore/undetermined) of both gastropods and bivalves for the analyzed buildings of Muweilah (see above). Classification was primarily based on Bosh et al. (1995), alongside numerous other publications listed in Müller García and Nebelsick (2026) (Appendix 1). With EG = East Gate, SG = South Gate, WG = West Gate, and roman numbers = Building numbers.

Figure 4.3 Map of Muweilah with A) gastropod and B) bivalve ratios of selected Buildings. Taxa occurring in less than 1 % summarized as Remaining species.

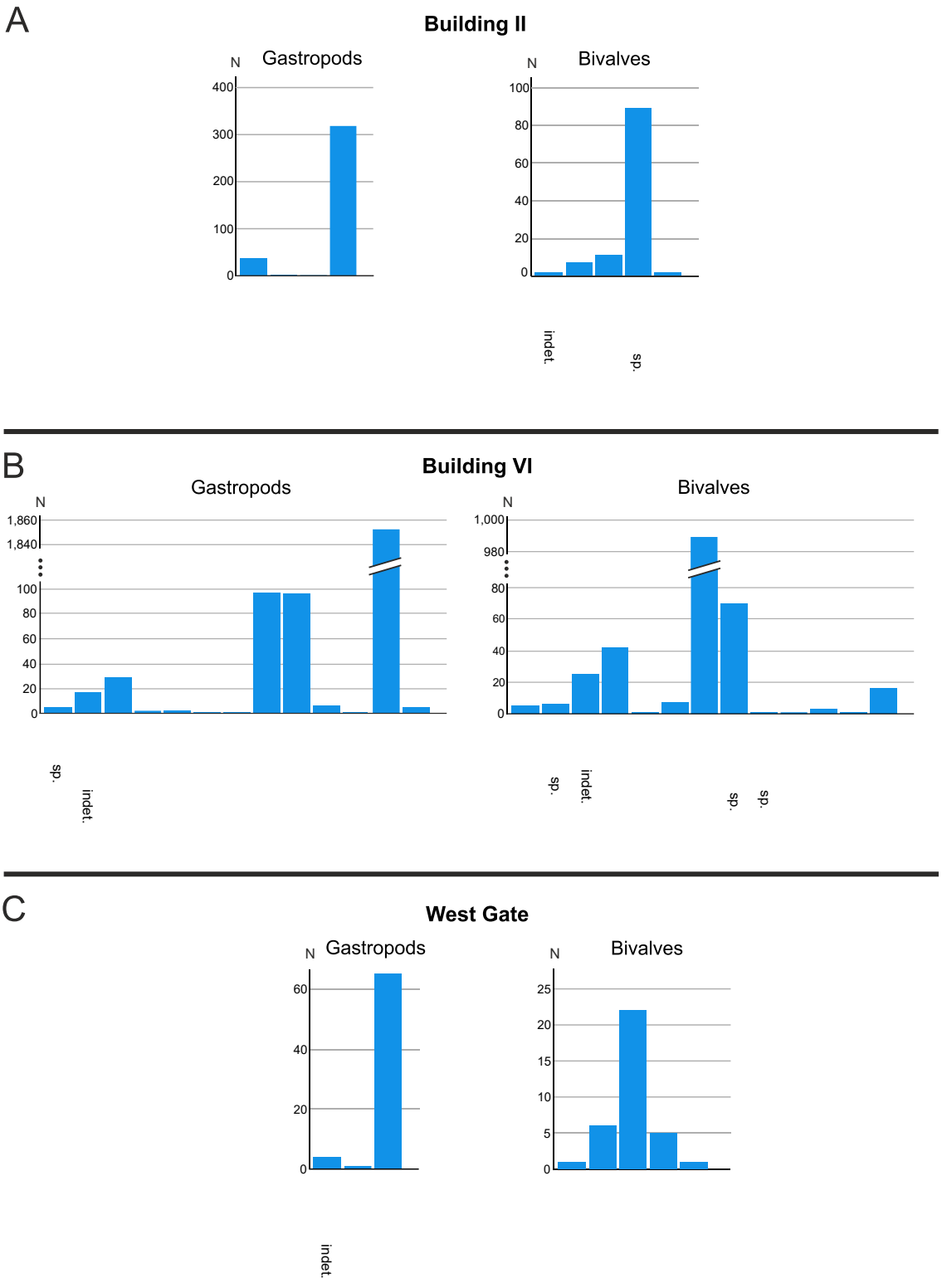

Figure 4.4 Species histograms of A) Building II, B) Building VI, and C) West Gate from the archaeological context of Muweilah.

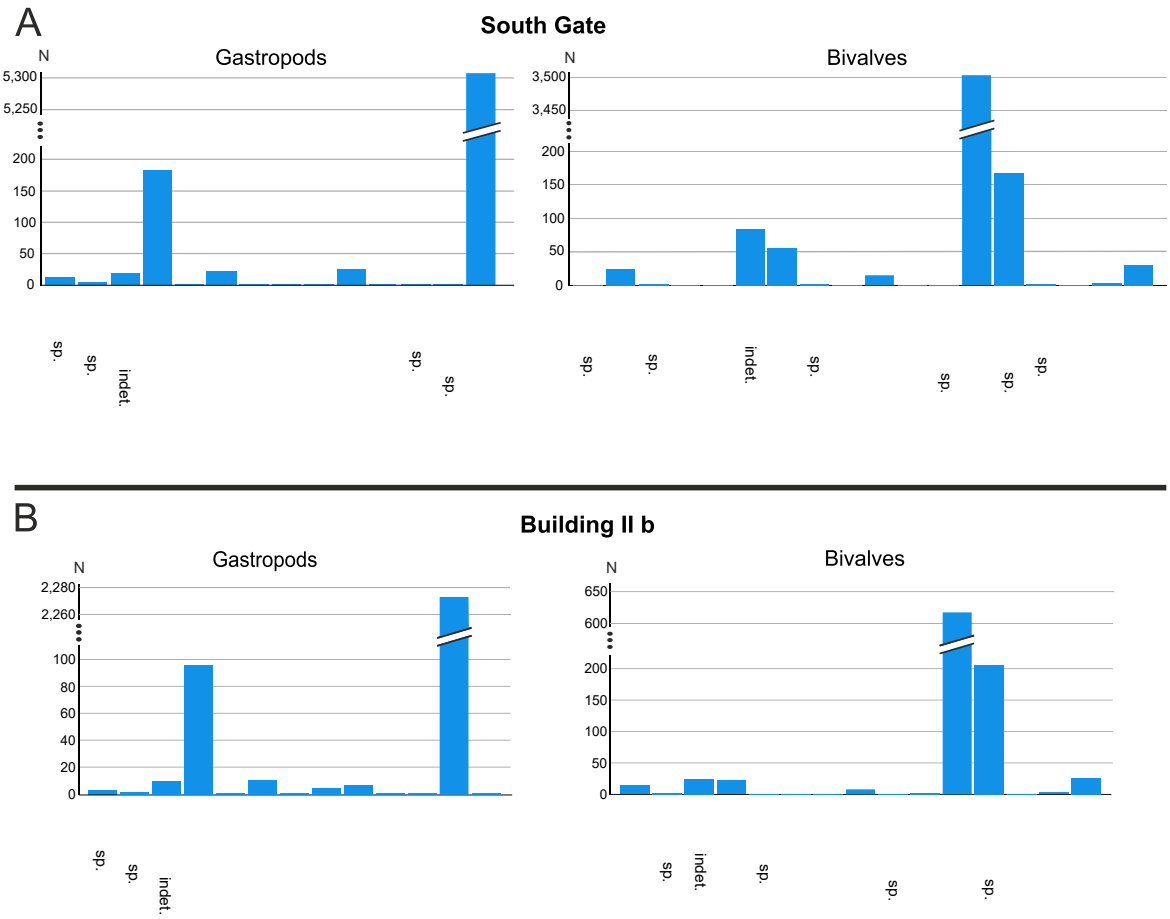

Figure 4.5 Species histograms of A) South Gate and B) Building II b from the archaeological context of Muweilah.

Table 4.1 Gastropod taxonomy of each analyzed Building from the archaeological context of Muweilah, with no. indiv. = number of individuals, EG = East Gate, SG = South Gate and WG = West Gate.

Family	Genus and Species (author)	Total	Buildings [no. indiv.]														
			I	II	III	IV	V	VI	VII	VIII	IX	X	XII	EG	WG	SG	II b
Columbellidae	*Mitrella blanda* (G. B. Sowerby I, 1844)	5	1	—	—	—	—	—	—	1	—	—	1	—	—	1	1
Conidae	*Conus* sp. (Linnaeus, 1758)	52	5	—	3	4	2	5	6	5	—	3	1	1	—	14	3
Cypraeidae	*Cypraea* sp. (Linnaeus, 1758)	11	1	—	—	—	—	—	—	1	—	—	—	2	—	5	2
Gastropod indet.	*Gastropod* indet.	296	176	—	7	18	4	17	2	9	21	4	1	3	4	20	10
Littorinidae	*Littoraria intermedia* (Philippi, 1846)	25	8	—	—	4	—	2	1	2	3	—	2	—	—	2	1
Muricidae	*Hexaplex kuesterianus* (Tapparone Canefri, 1875)	810	143	37	17	41	7	29	10	133	63	3	28	19	1	183	96
	Rapana sp. (Schumacher, 1817)	1	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—
	Rapana venosa (Valenciennes, 1846)	2	—	—	—	—	—	1	—	—	—	—	—	—	—	—	1
	Tylothais savignyi (Deshayes, 1844)	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1
Nassariidae	*Nassarius fissilabris* (A. Adams, 1852)	10	1	—	1	2	—	1	—	2	1	—	—	—	—	2	—
	Nassarius sp. (Duméril, 1805)	1	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—
Naticidae	*Neverita didyma* (Röding, 1798)	3	—	—	—	—	—	—	—	1	—	—	1	—	—	1	—
Neritidae	*Nerita albicilla* (Linnaeus, 1758)	1	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—
Potamididae	*Terebralia palustris* (Linnaeus, 1767)	24797	5271	318	625	1450	123	1852	313	2361	3475	364	685	315	65	5307	2273
	Pirenella cingulata (Gmelin, 1791)	217	19	1	6	9	1	97	27	9	10	1	4	2	—	26	5
	Pirenella conica (Blainville, 1829)	138	4	—	2	1	1	96	17	6	1	—	1	1	—	1	7
	Pirenella sp. *(Gray, 1847)*	1	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—
Siphonariidae	*Siphonaria* sp. (G. B. Sowerby I, 1823)	1	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—
Strombidae	*Strombidae* sp. (Rafinesque, 1815)	1	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—
Turbinidae	*Lunella coronata* (Gmelin, 1791)	112	30	2	1	10	1	2	2	11	8	7	4	1	—	22	11
Trochidae	*Priotrochus obscurus* (W. Wood, 1828)	9	2	—	—	—	—	6	—	—	—	—	—	—	—	—	1
	Umbonium vestiarium (Linnaeus, 1758)	10	2	—	—	—	1	5	1	—	—	—	—	1	—	—	—

Table 4.2 Bivalve taxonomy of each analyzed Building from the archaeological context of Muweilah, with EG = East Gate, SG = South Gate and WG = West Gate.

Family	Genus and Species (author)	Total	Buildings [number of individuals]														
			I	II	III	IV	V	VI	VII	VIII	IX	X	XII	EG	WG	SG	II b
Arcidae	*Acar plicata* (Dillwyn, 1917)	1	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—
	Anadara antiquata (Linnaeus, 1758)	1	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—
	Anadara sp. (J. E. Gray, 1847)	6	—	—	—	1	—	—	2	1	—	1	—	—	—	1	—
	Anadara uropigimelana (Bory de Saint-Vincent, 1827)	112	15	—	7	2	1	5	12	12	—	3	12	4	1	24	14
	Barbatia foliata (Forssk ål, 1775)	2	—	—	—	—	—	—	—	—	—	—	1	—	—	1	—
	Barbatia obliquata (W. Wood, 1828)	2	—	—	—	—	1	—	—	—	—	—	—	—	—	1	—
	Barbatia sp. (Gray, 1842)	47	5	—	5	3	6	6	7	4	—	1	4	2	—	2	2
Bivalve indet.	*Bivalve* indet.	715	226	2	19	35	16	25	25	186	15	8	12	33	6	83	24
Cardiidae	*Vasticardium assimile lacunosum* (Reeve, 1845)	190	41	2	10	7	5	16	24	9	3	5	6	5	1	30	26
Glycymerididae	*Glycymerididae* sp. (Dall, 1908)	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1
	Glycymeris arabica (H. Adams, 1871)	69	16	—	4	1	1	7	9	5	—	—	3	—	—	15	8
	Glycymeris livida (Reeve, 1843)	2	—	—	—	—	—	—	—	—	—	—	1	—	—	1	—
	Glycymeris sp. (da Costa, 1778)	2	—	—	—	—	—	—	—	—	—	—	—	—	—	1	1
	Tucetona pectunculus (Linnaeus, 1758)	15	1	—	—	—	—	1	3	—	—	—	3	1	—	3	3
Mactridae	*Mactra lilacea* (Lamarck, 1818)	4	1	—	—	—	—	—	1	—	—	—	—	—	—	—	2
Margaritidae	*Pinctada margaritifera* (Linnaeus, 1758)	30	25	—	—	4	—	1	—	—	—	—	—	—	—	—	—
	Pinctada sp. (Röding, 1798)	2	—	—	—	—	—	—	—	—	—	—	—	—	—	2	—
Mytiloidea	*Mytiloidea* sp. (Rafinesque, 1815)	1	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—
Ostreoidea	*Ostreoidea* sp. (Rafinesque, 1815)	1074	175	87	18	61	7	70	5	75	146	23	23	8	5	165	206
Pectinidae	*Chlamys* sp. (Röding, 1798)	6	—	—	2	—	—	—	1	—	—	—	—	—	—	2	1
	Pectinidae sp. (Rafinesque, 1815)	1	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—
	Scaeochlamys livida (Lamarck, 1819)	11	10	—	—	—	—	—	—	1	—	—	—	—	—	—	—
Psammobiidae	*Asaphis violascens* (Forsskål, 1775)	9	3	—	—	—	—	—	—	—	—	—	1	5	—	—	—
Spondylidae	*Spondylus gloriandus* (Melvill & Standen, 1907)	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	1
	Spondylus spinosus (Schreibers, 1793)	9	—	—	—	1	1	3	2	—	—	—	—	1	—	1	—
Veneridae	*Callista erycina* (Linnaeus, 1758)	370	126	7	18	10	11	42	6	23	10	5	23	12	—	55	22
	Callista florida (Lamarck, 1818)	3	1	—	—	—	—	1	1	—	—	—	—	—	—	—	—
	Dosinia tumida (Gray, 1838)	6	—	—	—	1	—	—	1	1	1	—	—	—	—	1	1
	Marcia cordata (Forsskål in Niebuhr, 1775)	11470	2778	11	156	296	268	989	139	1534	235	116	525	281	22	3503	617
	Veneridae sp. (Rafinesque, 1815)	1	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—

Table 4.3 Number of Individuals, gastropod and bivalve ratios, total number of taxa, gastropod and bivalve taxa as well as Shannon Diversity and Equitability Indices of bivalves, gastropods and total for each analyzed building, with EG = East Gate, SG = South Gate and WG = West Gate.

		Buildings															
		Total	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XII**	**EG**	**WG**	**SG**	**II b**
Number of Individuals		**40668**	9087	467	902	1962	458	3281	617	4394	3993	544	1343	697	105	9477	3341
[%] of individuals	Gastropods	**65.17**	62.32	76.66	73.50	78.53	30.57	64.44	61.43	57.84	89.71	70.22	54.28	49.50	66.67	58.95	72.19
	Bivalves	**34.83**	37.68	23.34	26.50	21.47	69.43	35.56	38.57	42.16	10.29	29.78	45.72	50.50	33.33	41.05	27.81
Taxa	Gastropods	**25**	16	4	9	10	8	13	9	13	8	6	12	9	3	14	14
	Bivalves	**30**	14	5	9	12	11	13	15	13	7	8	12	10	5	18	15
	Total	**54**	30	9	18	22	19	26	14	26	15	14	24	19	8	32	29
Shannon Diversity Index	Gastropods	**0.35**	0.35	0.39	0.31	0.32	0.57	0.56	0.73	0.33	0.17	0.26	0.31	0.41	0.29	0.26	0.30
	Bivalves	**0.81**	0.80	0.73	1.29	1.05	0.73	0.82	1.56	0.68	0.96	1.02	0.70	0.84	1.08	0.50	1.07
	Total	**1.16**	1.18	1.01	1.15	1.06	1.29	1.26	1.72	1.16	2.07	1.09	1.18	1.32	1.19	1.03	1.10
Shannon Equitability Index	Gastropods	**0.11**	0.13	0.28	0.14	0.14	0.27	0.22	0.33	0.13	0.08	0.14	0.13	0.19	0.27	0.10	0.11
	Bivalves	**0.24**	0.30	0.46	0.59	0.42	0.30	0.32	0.58	0.26	0.50	0.49	0.28	0.36	0.67	0.17	0.40
	Total	**0.29**	0.35	0.46	0.40	0.34	0.44	0.39	0.54	0.36	0.76	0.41	0.38	0.45	0.57	0.30	0.33

Table 4.4 Spatial concentration of selected taxa within the site of Muweilah.

Taxon	Individuals (n) Total	Building	% of total site specimens of this taxon
Lunella coronata	112	Building I	26.79
Pinctada margaritifera	30	Building I	83.33
Callista erycina	370	Building I	34.05
Cypraea sp.	11	South Gate	45.45
Conus sp.	52	South Gate	26.92
Marcia cordata	11470	South Gate	30.54
Ostreoidea sp.	1074	South Gate	15.36
Pirenella cingulata	217	Building VI	44.70
		Building VII	12.44
Pirenella conica	138	Building VI	69.57
		Building VII	12.32

Table 4.5 Structures showing deviations from the side-wide bivalve composition with elevated concentrations of *Ostreoidea* sp. or reduced frequencies of *Marcia cordata*.

Structure	Area	Ostreoidea sp. (%)	*Marcia cordata* (%)	Other notable Taxa
Building II	West	79.82	10.09	—
Building IX	West	35.52	57.18	—
Building II b	West	22.17	66.42	—
Building IV	North	14.45	70.14	—
West Gate	West	14.29	62.86	Bivalve indet.: 17.14 %
Building X	West	14.20	71.64	—
Building III	North	7.53	65.27	Bivalve indet.: 7.95 %; *Callista erycina*: 7.53 %; *Vasticardium assimile lacunosum*: 4.18 %;
Building VII	South	2.10	58.40	Bivalve indet.: 10.50 %; *Vasticardium assimile lacunosum*: 10.08 %; *Anadara uropigimelana*: 5.04 %
Average distribution per structure		7.58	80.99	—

Diversity and equitability

Sample completeness curves indicate near-complete sampling for most structures, with slightly lower completeness in Building V (Figure 4.6). Rarefaction curves further show clear spatial differences in taxonomic diversity. The lowest diversity is observed in the Western Area, the East Gate, and Building III (Northern Area), whereas the Southern Area exhibits the highest diversity. Within the Western Area, Building II b shows comparatively higher diversity than adjacent structures.

Shannon diversity index values (Figure 4.7 A) range from 0.5 to 0.8 for bivalves and from 0.26 to 0.35 for gastropods, indicating overall higher diversity and greater variability among structures for bivalves. Spatially, bivalve diversity generally increases from east to west, with additional local maxima in the north (Buildings III and IV) and in the southeast (Building VII). In contrast, gastropod diversity shows an opposing trend, decreasing from east to west and reaching its highest values in the southeastern structures (Buildings V–VII). Overlapping diversity peaks of both groups occur particularly in Buildings IX and VII.

Equitability values (Figure 4.7 B) broadly follow the same spatial patterns. Bivalves exhibit higher evenness than gastropods (0.17–0.67 vs. 0.10–0.27) and show greater variability between structures. Evenness in bivalves increases from east to west, with localized deviations in the northern structures and at the West Gate. Gastropod evenness displays a weaker decline along the same gradient. Combined equitability values are highest at the West Gate and in Buildings IX and VII.

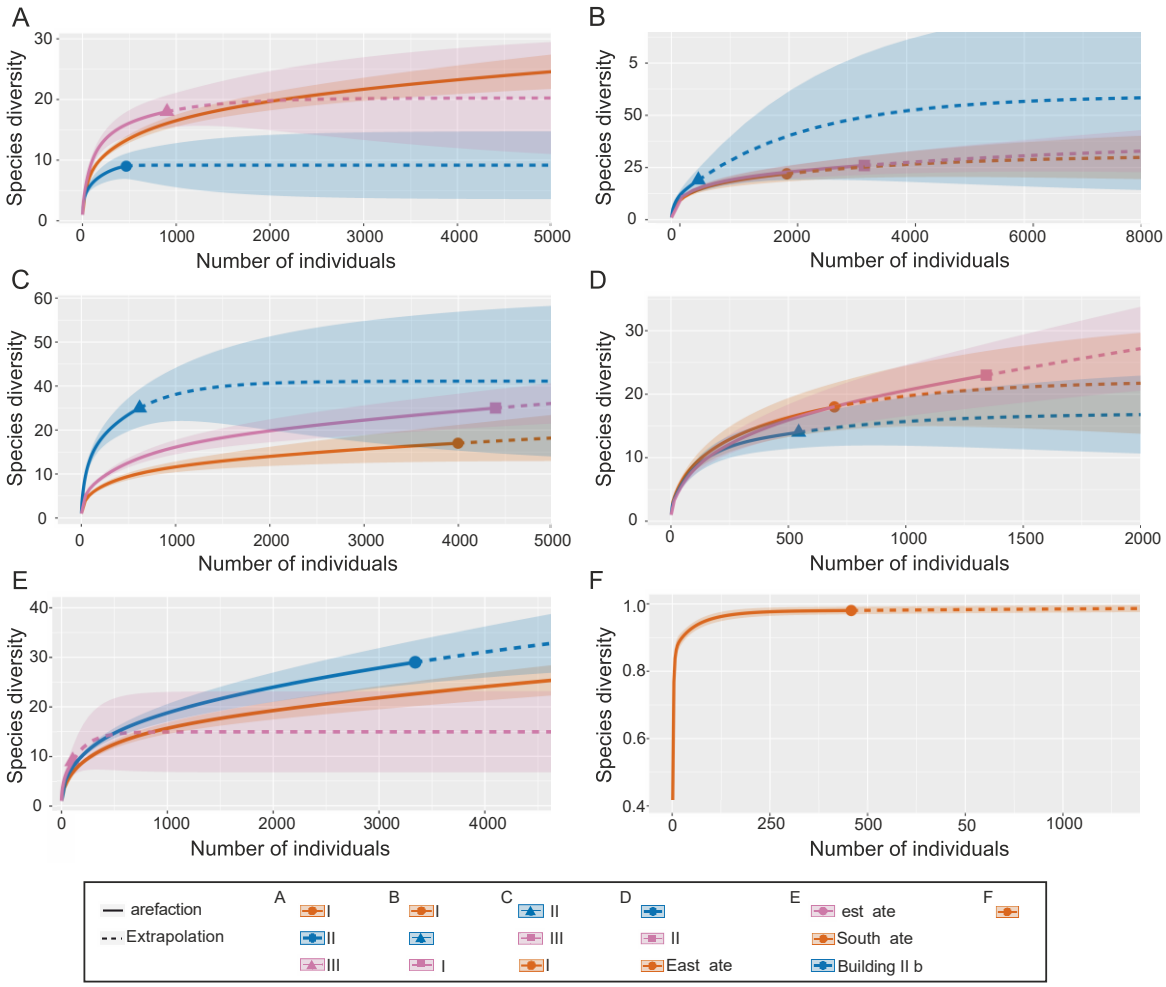

Figure 4.6 Rarefaction curves for the Buildings of Muweilah, with A) Buildings I-III, B) IV-VI, C) VII-IX, D) X, XII and East Gate, E) West Gate, South Gate, and Building II b, and F) sample coverage curve for the Building V, with roman numbers = Building numbers.

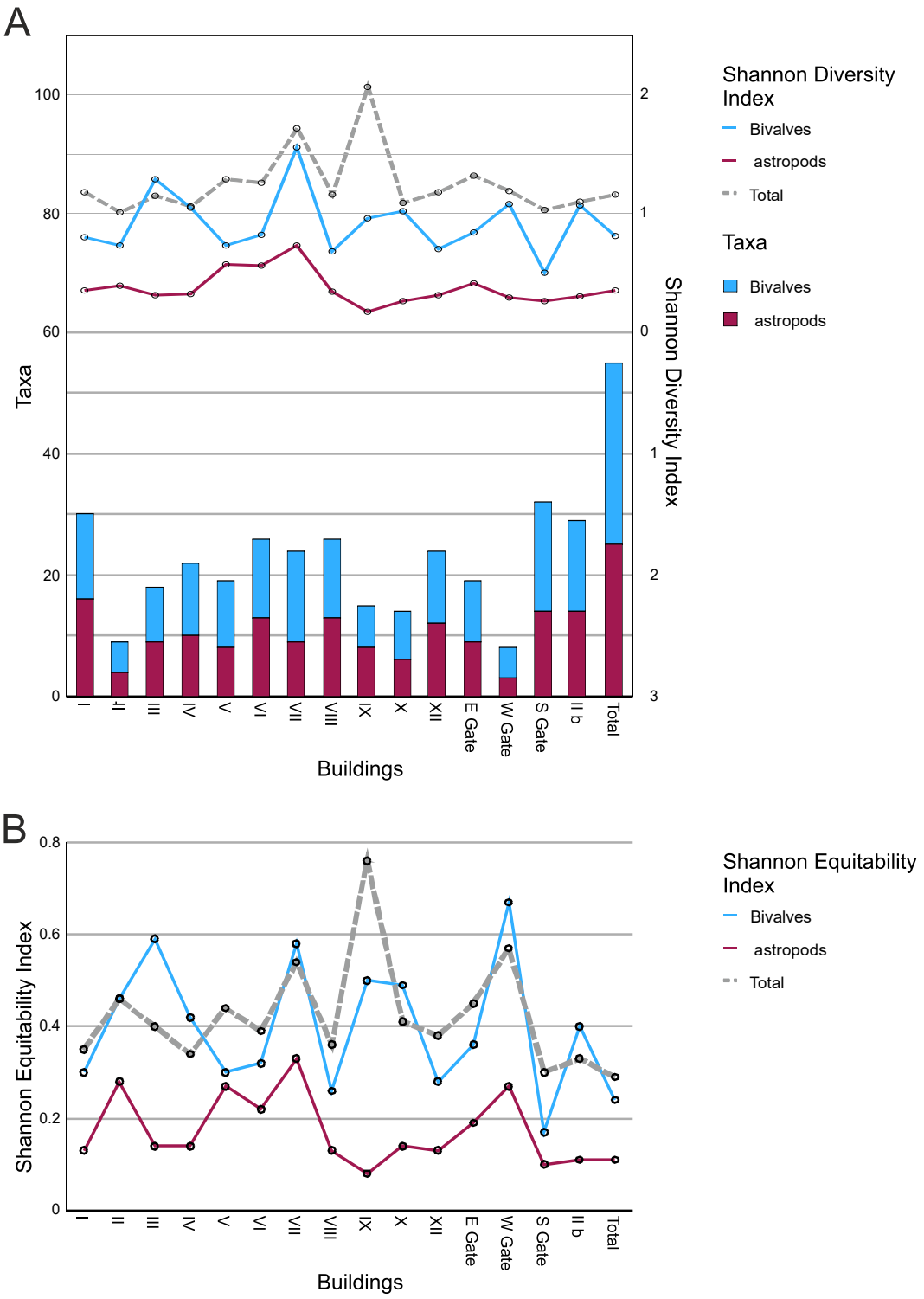

Figure 4.7 A) Top: Shannon Diversity Index graph for bivalves, gastropods and both categories for the Buildings I-X, XII, Building II b, East, West and South Gates of Muweilah. Bottom: Taxa quantities for these Buildings. B) Shannon Equitability Index graph for bivalves, gastropods and both categories for Buildings I-X, XII, Building II b, East, West and South Gates of Muweilah. With E Gate = East Gate, S Gate = South Gate, W Gate = West Gate, and roman numbers = Building numbers.

Environmental composition

Assemblages are generally dominated by mangrove and littoral taxa (Figure 4.2), with clear spatial differentiation between these groups. Mangrove taxa are most prevalent in the Western and Northern Areas, whereas littoral taxa dominate in the Eastern and Southern Areas. Littoral species are particularly abundant in Building V.

In contrast, sublittoral and offshore taxa are comparatively rare and do not exhibit a consistent spatial pattern. Slightly higher proportions of sublittoral taxa, however, are observed in the Western Area, as well as in Building I and at the South Gate. Offshore taxa occur most frequently in the Southern Area and in Building II b but are absent from Building II and the West Gate.

Comparison with other archaeological sites

Sites with similar dominant taxa (*Terebralia palustris*, *Hexaplex kuesterianus*, and *Marcia cordata*) are primarily located in close geographic proximity to Muweilah, including Al-Hamriyah (Neolithic to Iron Age), Tell Abraq (Bronze Age), Akab (Neolithic), and Ed-Dur (Neolithic to Iron Age) (see Figure 4.1 and 4.8). Notable chronological differences are, however, evident within these sites. At Al-Hamriyah, for example, *T. palustris* dominates in the Neolithic but is replaced by *Marcia hiantina* in the Iron Age, whereas at Muweilah *T. palustris* remains the dominant taxon.

Assemblages from more distant sites within the UAE, such as Al-Madam (Iron Age), show little similarity to Muweilah. Even greater differences are observed in sites from Oman and the western Arabian Gulf, where dominant taxa often include species that are rare or absent in Muweilah, such as *Pinctada radiata* and *Amiantis umbonella*. Exceptions to this pattern include *Hexaplex kuesterianus* and *Marcia* sp., which are also common at sites such as Saar (Bahrrain, Bronze Age), Dosariyah (Saudi Arabia near the Arabian Gulf, Neolithic), and Ruways 1 (Oman, Neolithic).

Modern assemblages show the strongest divergence from Muweilah. None of their dominant species correspond to the most common taxa identified at the site. While some species (e.g., *Mitrella blanda*) occur in low frequencies, many dominant modern taxa, such as *Bulla ampulla* and *Clypeomorus bifasciatus persicus*, are entirely absent.

Most taxa recorded across comparative sites but absent at Muweilah are associated with littoral, sublittoral, and offshore habitats, while other habitat categories remain marginal (see Table 4.6). Notably, most offshore taxa derive from present-day marine assemblages, whereas archaeological sites (Neolithic, Bronze Age, Iron Age) show a comparatively lower presentation of offshore species. The assemblage at Muweilah itself shows a broadly comparable habitat distribution (see also Figure 4.2), although with a slightly higher representation of offshore taxa. Those mollusks absent from Muweilah derive predominantly from modern assemblages, with smaller contributions from Neolithic, Bronze Age, and Iron Age contexts. The comparative dataset also includes additional sites that are not part of the analysis of the most frequent taxa mentioned above, as the available literature in these cases provides species lists only, without associated abundance data.

Table 4.6 Habitat distribution and total counts of taxa recorded across comparative assemblages but absent from Muweilah. Rare habitat categories (terrestrial, freshwater, and fossil) are grouped under “Minor Habitats”.

Site	Chronology	Location	Habitat of taxa absent in Muweilah				
			Mangroves	Littoral	Sublittoral	Offshore	Minor Habitats
Tell Abraq	Bronze Age	U.A.E.	1	16	4	2	–
Akab	Neolithic	U.A.E.	1	1	–	–	–
Ed-Dur	Neolithic-Iron Age	U.A.E.	–	2	–	–	1 freshwater
Jazirat al-Hamrah	Neolithic	U.A.E.	–	3	–	–	–
Kalba	Bronze Age	U.A.E.	2	2	–	1	–
Shimal	Bronze Age	U.A.E.	1	19	3	1	–
Husn awhala	Bronze Age	U.A.E.	1	4	–	1	–
Al madam	Iron Age	U.A.E.	2	19	8	8	–
UAQ38	Neolithic	U.A.E.	1	2	1	–	–
FAY-NE 15	Neolithic	U.A.E.	–	3	1	1	–
Saruq al-Hadid	Bronze – Iron Age	U.A.E.	–	17	6	5	–
Dosariyah	Neolithic	Saudi Arabia	–	25	5	2	–
As Sabiyah	Neolithic	Kuwait	–	17	5	1	1 freshwater
Saar	Bronze Age	Bahrain	–	24	5	3	4 freshwater 1 fossil 1 terrestrial
Nafun	Iron Age	Oman	–	6	1	–	–
Ruways 1	Neolithic	Oman	–	4	–	–	–
Mayhleya	Neolithic-Iron Age	Oman	–	2	1	3	–
Zakum	Present	U.A.E.	–	4	4	7	–
Umm al-Dalkh	Present	U.A.E.	–	4	4	5	–
Dawhat Zekreet	Present	U.A.E.	1	24	3	4	–
Dalma Island	Present	U.A.E.	–	12	1	–	–
Umm Al-Quwain, Ajman and Sharjah	Present	U.A.E.	–	1	–	1	–
Al Mafyar	Present	Qatar	2	35	7	14	–
Al Dhakira	Present	Qatar	2	41	15	15	–
Umm Aladam	Present	Qatar	–	5	1	1	–
Hadeed	Present	Qatar	–	18	16	2	–
Halul	Present	Qatar	–	19	15	11	–
Halut Al-Asere	Present	Qatar	1	19	16	2	–
Qatar	Present	Qatar	–	41	17	4	–
Tarut Island	Present	Saudi Arabia	–	35	7	10	–
Al-Khobar	Present	Saudi Arabia	–	33	6	9	–
Tarut Bay	Present	Saudi Arabia	1	9	6	6	1 fossil
Total (absent taxa)			16	466	158	119	9
Total taxa in Muweilah			5	39	13	21	–

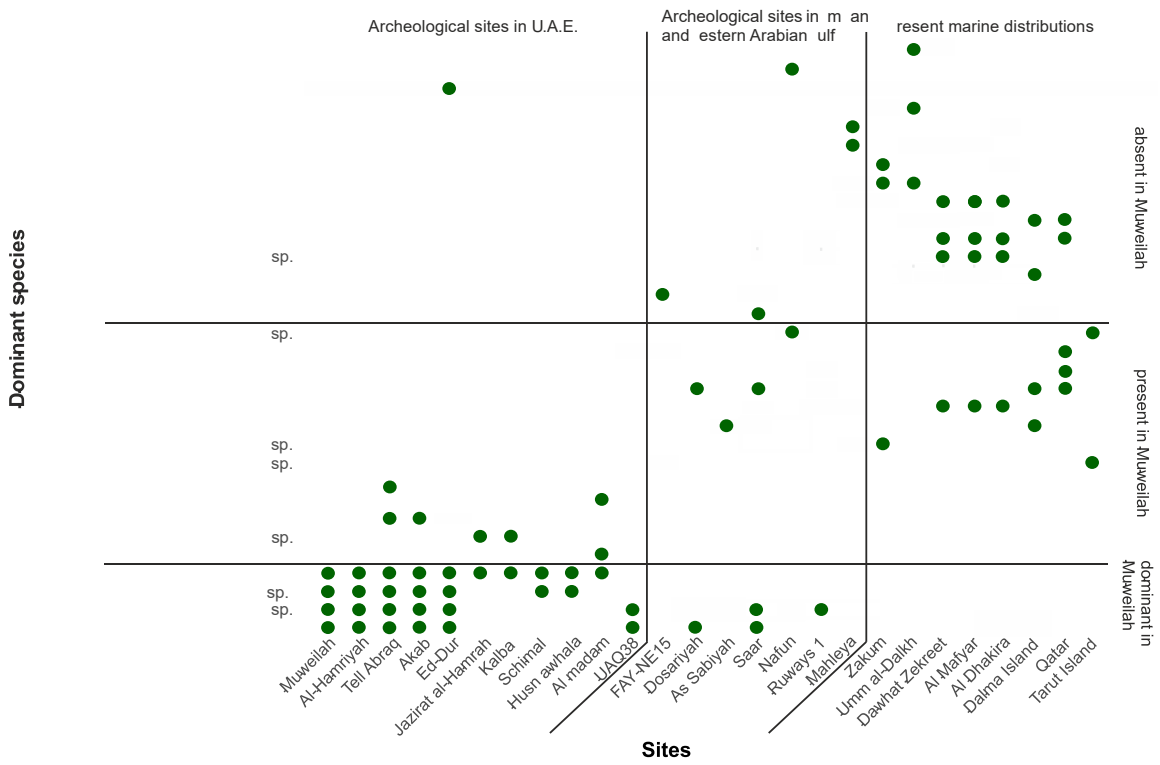

Figure 4.8 A) Dominant species of archeological sites in the United Arab Emirates (U.A.E.), archeological sites in Oman and western Arabian Gulf, as well as present marine distributions. Oyster species were collectively categorized under the family name *Ostreoidea* sp., as well as all *Marcia* species under the genus name. Dominant species are separated into three categories: 1) dominant in Muweilah, 2) present in Muweilah and 3) absent in Muweilah.

Discussion

The spatial distribution of molluscan remains at Muweilah reveals clear functional and social zoning within the settlement, as well as marked contrasts with assemblages from the western Arabian Gulf, the Gulf of Oman, and the modern Arabian Gulf. These patterns reflect a combination of environmental conditions, selective resource use, and socioeconomic differentiation, offering insights into the interplay between coastal ecology and community organization in Iron Age Southeastern Arabia.

Intra-site variation and socio-economic differentiation

Patterns of molluscan abundance underscore the particular significance of the Western Area within the settlement (see Figures 4.2–4.7; Tables 4.1–4.5). This area is characterized by generally low specimen counts and reduced species diversity (as indicated by rarefaction curves, as well as Shannon diversity and Equitability indices), a pronounced dominance of *Ostreoidea* sp.— especially in Building II — a decline in *Marcia cordata*, and a relative increase in *Terebralia palustris*. In addition, mollusks associated with littoral and sublittoral habitats are less frequently represented. Together, these features point to a distinct functional role of the Western Area. These differences correspond closely with architectural characteristics, including the presence of a surrounding wall separating the Western and Central Areas, the absence of the typical “room–corridor–ancillary room(s)” layout, and the inclusion of a columned hall in Building II (Magee 1996, 2002, 2004, 2014; Magee and Thompson 2001; Potts 2001; Karacic et al. 2018). The presence of banqueting paraphernalia further underscores the high socioeconomic significance of this structure and suggests a potential link between shell deposition and communal or ceremonial feasting activities (Magee 2002, 2004; Karacic et al. 2018; Magee and Thompson 2001).

The comparatively low quantity of shell material in the Western Area may reflect restricted access, while the dominance of *Ostreoidea* sp., in contrast to the more widespread *Marcia cordata*, points to selective collection or consumption preferences. Building II b constitutes a notable exception, with its high species diversity, large number of individuals, and broad ecological spectrum resembling

patterns observed in Building I and the South Gate. The continued prominence of *Ostreoidea* sp., however, aligns it more closely with the Western Area. Although this building has been tentatively associated with lime plaster production (Magee 2002), its precise function remains uncertain.

Within the Central Area, the Southern Area, but particularly Building I and the South Gate, stands out for exhibiting the highest species diversity and specimen counts across the site (as indicated by rarefaction curves and Shannon diversity and equitability indices), combined with a low proportion of offshore taxa (see Figures 4.2–4.7; Tables 4.1–4.5). These patterns correspond with greater architectural complexity compared to the East Gate (Karacic et al. 2018; Magee et al. 2018) and may indicate more intensive activity or the use of these areas for refuse disposal. Buildings VI and VII in the eastern part of the Southern Area are further distinguished by elevated frequencies of *Pirenella cingulata* and *P. conica*. These elevated frequencies may reflect the mixing of food waste with construction materials or, as proposed by Glover (1995), incidental introduction.

In contrast, the Eastern and Northern Areas show higher proportions of gastropods and *T. palustris*, resembling patterns observed in the Western Area, though without the pronounced dominance of *Ostreoidea* sp. The function of the Northern Area remains difficult to assess due to limited excavation. Despite these differences, the recurrence of the “main room–corridor–ancillary room” layout (Karacic et al. 2018; Magee et al. 2018) suggests an overall structural continuity within the Central Area.

Environmental vs. cultural drivers of intra-site variation

In general, archaeomalacological studies rarely address intra-site variation, tending instead to focus on taxonomic identification or chronological aspects (e.g., Van Neer & Gautier 1993; Bar-Yosef Mayer 2002; Boivin & Fuller 2009; Al-Jahwari 2011; Benítez-Gale et al. 2025). Where intra-site variability is considered, it is most often approached from a diachronic perspective, emphasizing temporal changes within a site. Such variations are typically explained in terms of environmental change, shifts in subsistence strategies, or processes of overexploitation (e.g., Prieur 1990; Glover 1995; Beech and lover 2005; Händel 2013; Çakırlar 2019). At Al -Hamriyah, for instance, a settlement occupied from the Neolithic to the Iron Age, the replacement of *T. palustris* by *M. cordata* has been linked to the decline of mangrove habitats (Händel 2013). At Muweilah, however, environmental degradation alone is unlikely to account for the observed variability. Despite regional evidence for mangrove decline, *T. palustris* remains consistently abundant across all areas of the site.

Another common explanation for intra-site variation relates to disposal practices, as observed on Dalma Island and at Saar. On Dalma Island, accumulations of *Pinctada* sp. have been interpreted as the result of deliberate removal of sharp shells from activity areas (Beech and Glover 2005). Similarly, at Saar, shell remains are predominantly found outside domestic structures, which has likewise been attributed to the clearing of sharp shell material (Glover 1995). In contrast, at Muweilah, shell remains were predominantly recovered from interior contexts across the site. Even large and spiny species, such as *T. palustris* and *H. kuesterianus*, occur mainly indoors. Only the South Gate, with its large accumulation of shells and greater species diversity compared to interior contexts, may have functioned as a designated disposal area, indicating a localized clearing or deposition practice distinct from the more dispersed indoor assemblages.

Functional differentiation between buildings has also been proposed as a driver of intra-site variation. At Saar, for example, marked differences between the temple and other structures have been noted, with the former containing significantly fewer shell deposits, few edible species such as oysters, and high quantities of freshwater snails such as *Melanoides* (Glover 1995). A comparable pattern can be observed at Muweilah, where functional distinctions between buildings, particularly between the Western and Central Areas, and most notably in the columned hall

(Building II), likely contributed to the spatial patterning of shell remains. The composition of the assemblage, however, differs markedly between the two sites. While the temple at Saar is characterized by the presence of freshwater snails, the columned hall at Muweilah is dominated by species associated with subsistence activities, primarily *Terebralia palustris*, *Ostreoidea* sp., and *Hexaplex kuesterianus*, and lacks freshwater taxa entirely. At Saar, the presence of freshwater snails within the temple has been interpreted as evidence for the use of water in flooring construction (i.e. freshwater used to mix floor and wall plaster) or maintenance (Glover 1995). The absence of freshwater snails in Muweilah may instead be related to the sand-floored nature of the columned hall (Magee 2002, 2004; Magee and Thompson 2001; Karacic et al. 2018), which would have rendered the use of water for construction or cleaning purposes unlikely.

Finally, intra-site variation has also been linked to craft activities such as ornament production. On Dalma Island, for instance, the distribution of species such as *Lunella coronata* has been associated with the manufacture of ornaments (Beech and Glover 2005). At Muweilah, however, only a small number of species in low quantities may have been used for ornamental purposes (Müller García & Nebelsick 2026), and the archaeological record (e.g., Magee 1996, 2002, 2004; Blau et al. 2000; Karacic et al. 2018) provides no indication of large-scale production. Ornament manufacture is therefore unlikely to have significantly influenced the observed distribution patterns.

Taken together, these observations point to distinct cultural practices governing shell use and disposal, which in turn structured the spatial distribution of shell remains within the settlement. The patterns observed at Muweilah are best explained as the result of selective resource use combined with socially structured activity areas, rather than environmental constraints alone, although further research will be necessary to refine these interpretations.

Regional and diachronic comparison of Molluscan assemblages

Archaeological assemblages most closely resembling the molluscan record from Muweilah are found at nearby sites within the Arabian Gulf, particularly Al-Hamriyah (Neolithic to Iron Age), Tell Abraq (Bronze Age), Akab (Neolithic), and Ed-Dur (Neolithic to Iron Age). In contrast to Muweilah, sites along the Gulf of Oman and the Arabian Sea show markedly lower similarity. Several factors underline this pattern, beginning with broader biogeographic differences between the adjoining marine environments from which mollusks were sourced, as demonstrated by the absence of several species characteristic of the Gulf of Oman, such as *Architectonica perspectiva* and *Telescopium telescopium*, in the Arabian Gulf (Bosh et al. 1995; MolluscaBase 2025). At the same time, variation in dominant taxa among sites within the Arabian Gulf itself, especially between the western and the eastern coast (see Figure 4.7), highlights considerable intra-regional diversity. These differences cannot be explained solely by habitat, as most assemblages, including Muweilah, show broadly comparable ecological compositions (see Table 4.6). This suggests that factors beyond environmental availability, particularly differences in site function and patterns of resource use, as discussed above for Muweilah, played a key role in shaping assemblage composition. Only in specific cases, such as modern offshore sites including Zakum and Umm al-Dalkh, does habitat appear to be the dominant factor, with assemblages characterized by offshore taxa reflecting their environmental setting.

Inter-site differences also reflect patterns of species selection. Modern ecological studies typically record the full range of species present within a habitat, whereas archaeological assemblages represent selective choices related to subsistence, ornament production, or tool manufacture. These choices are influenced by factors such as availability, nutritional value, and ease of collection (e.g., Hutterer et al. 2021; Albert et al. 2022; Gazzo et al. 2025). At inland sites such as FAY-NE15 or Mahleya, mollusks were primarily used for ornamentation, resulting in a preference for visually distinctive or culturally meaningful taxa (itezović 2016; Steele et al. 2019; Gazzo et al. 2025). In contrast, species selected for tool production tend to reflect functional criteria such as size, shape, and durability (Romagnoli et al. 2017; Lidour and Solana 2024). More broadly, species use is shaped by distance to the coast, site function (e.g., domestic vs. funerary), and long-

term socioeconomic developments. In particular, the transition from mobile to more sedentary lifeways between the Neolithic and Bronze Age, as well as increasing settlement intensity and the domestication of dromedaries during the Iron Age (Magee 2014), likely influenced resource exploitation patterns.

The strongest deviations from species composition as observed in Muweilah, are shown by modern assemblages (Figure 4.7 A, D), which may in part reflect environmental changes, such as the decline of mangrove habitats due to aridity and the associated local extirpation of *Terebralia palustris* (e.g., Glover 1998; Aspinall et al. 2002; Bejarano et al. 2023). It is unclear, however, how much of the habitat shifts are a direct result of environmental change and how much anthropogenic handling impacted species distribution. Human overexploitation is, for example, also considered a contributing factor to the decline of mangroves. Other potential factors include shifts in ocean currents and rising sea temperatures (Feulner 2006; Händel 2013; Fleitmann et al. 2022). Environmental change may also have contributed to diachronic differences between archaeological sites. The transition from the Neolithic to the Iron Age coincides with a shift toward increasingly arid conditions, characterized by alternating wet and dry phases and the expansion of sabkha environments. The end of the Umm al-Nar period, for example, corresponds to a marked arid phase around 4200 BP (Parker et al. 2006; Berger et al. 2013; Fleitmann et al. 2022). Direct archaeological evidence linking environmental change to species composition, however, remains limited, with the decline of *T. palustris* as the clearest documented case.

Finally, differences between Muweilah and comparative sites may also result from variation in taxonomic resolution. For example, *Ostreoidea* sp. at Muweilah may correspond to *Saccostrea cucullata* identified at Akab, while *Mitrella blanda* may be recorded more generally as *Mitrella* sp. at other sites. Such discrepancies are largely influenced by preservation, including fragmentation, ablation, and color alteration, resulting from both natural processes and human activities such as cooking (Vermeij 1979; Zuschin et al. 2003; Milano et al. 2016, 2018; Dyer et al. 2018; Aldeias et al. 2019; Müller García and Nebelsick 2024). Post-depositional processes, including waste management practices, may further affect preservation and identifiability (Ford 1989; Povey & Keough 1991; Rossi et al. 2007; Plicanti et al. 2016; Hausmann et al. 2019; Nicastro et al. 2019). In addition, some taxa may

represent local variants rather than distinct species; for instance, several *Marcia* species reported from Southeastern Arabia may in fact belong to a single taxonomic entity (Glover 1995).

Reconstructing Sea-Level, Mangrove Use, and Coastal Proximity

The increasing similarity of assemblages with decreasing distance to Muweilah suggests that molluscan resources were primarily collected from nearby coastal environments along the Arabian Gulf. This interpretation is further supported by the greater dissimilarity observed in assemblages from more distant regions, such as the Gulf of Oman. The consistent presence of *Terebralia palustris* indicates access to mangrove habitats, despite the site's present location approximately 15 km inland (Magee 1996, 2002, 2004; Blau et al. 2000; Benoist 2008; Karacic et al. 2018; Müller García and Nebelsick 2024). To assess this apparent proximity, the paleogeographic context of the Iron Age must be considered. Sea level had largely stabilized by this period, although minor shoreline shifts cannot be excluded due to the region's low relief (arker et al. 2006; Lokier et al. 2015; Damien et al. 2020). As a result, Muweilah may have been situated somewhat closer to the coast than at present, although the extent of this difference remains difficult to quantify (Bernier et al. 1995; Magee and Thompson 2001; Al-Farraj 2005; Lokier et al. 2015; Paul and Lokier 2017; Rutkowski and Kiersnowski 2025).

Even so, the exploitation of mangrove resources does not necessarily imply immediate proximity. The domestication of dromedaries at the beginning of the Iron Age would have enabled transport over distances of 25–30 km per day, making regular access to coastal environments feasible even from inland locations (Magee 2004). The archaeobotanical record, however, provides an important constraint. While mangrove species such as *Avicennia marina* are common at contemporary coastal sites, they are absent from the charcoal assemblage at Muweilah. Instead, the botanical remains are dominated by date palm, tamarisk (*Tamarix* sp.), jujube (*Ziziphus* sp.), and acacia (*Acacia* sp.) (Magee 1996, 2014; Magee and Thompson 2001; Tengberg 2009). Given that mangrove wood was widely used as fuel and construction material during the Iron Age, its absence suggests that mangrove stands were not located within an economically viable range for regular timber exploitation (Willcox and Tengberg 1995).

Altogether, the evidence indicates that Muweilah was situated within logistical reach of mangrove environments, sufficient for the procurement of species such as *T. palustris*, but not in the immediate vicinity. Overall, this pattern points to a system of targeted resource acquisition rather than the presence of a direct coastal settlement. Further paleoenvironmental research is, however, necessary to refine reconstructions of mangrove distribution and coastline dynamics in Southeastern Arabia during the Iron Age.

Conclusion

The distribution of molluscan remains at Muweilah highlights the distinctive character of the Western Area, which differs markedly from the Central Area. This zone is defined by higher frequencies of *Ostreoidea* sp., a reduced presence of *Marcia cordata*, lower species diversity and abundance, and a narrower range of associated habitats, patterns that correspond closely with architectural differentiation. The presence of banqueting paraphernalia suggests a link between shell deposition and communal or ceremonial consumption, while the dominance of *Ostreoidea* sp. points to selective collection practices, likely reflecting consumption preferences. Building II b represents a notable exception within the Western Area. Its higher species diversity and broader ecological spectrum align it more closely with the Southern Area, particularly Building I and the South Gate, while the continued prominence of *Ostreoidea* sp. maintains its connection to the Western Area.

Within the Central Area, the Southern Area occupies a key position, with the highest species diversity and specimen counts across the site. Together with its architectural complexity, this pattern suggests intensive use, possibly related to residential activities and refuse disposal. In contrast, the Eastern and Northern Areas share certain characteristics with the Western Area, such as higher frequencies of gastropods, but lack the pronounced dominance of *Ostreoidea* sp. The function of the Northern Area remains uncertain due to limited excavation. Despite these differences, the recurring “main room–corridor–ancillary room” layout indicates overall structural continuity within the Central Area. Overall, intra-site shell distribution patterns are best explained by a combination of environmental factors, selective resource use, and socioeconomic differentiation, with building function playing a central role in shaping assemblage composition.

Regional comparisons indicate that molluscan resources were primarily collected along the Arabian Gulf, likely within logistical proximity to the site. The greatest differences are observed in assemblages from Oman and modern contexts, reflecting both biogeographic variation and recent environmental change. More broadly, spatial and temporal patterns in Southeastern Arabia point to the combined influence of cultural practices, site location, and environmental shifts, including mangrove regression and the associated decline of *Terebralia palustris*.

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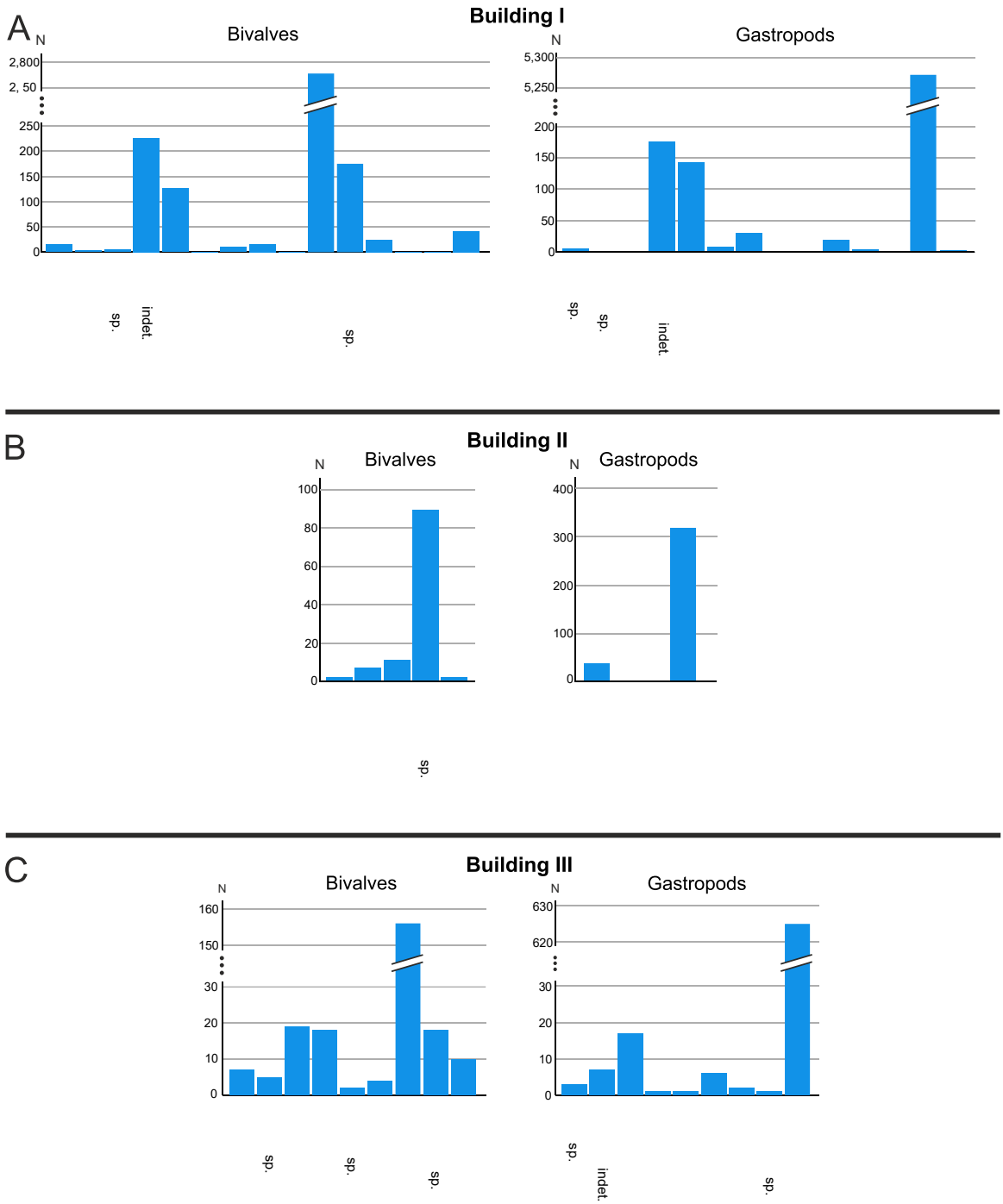
Appendix

Appendix 4.1 Analyzed room numbers and loci of each building from the site of Muweilah.

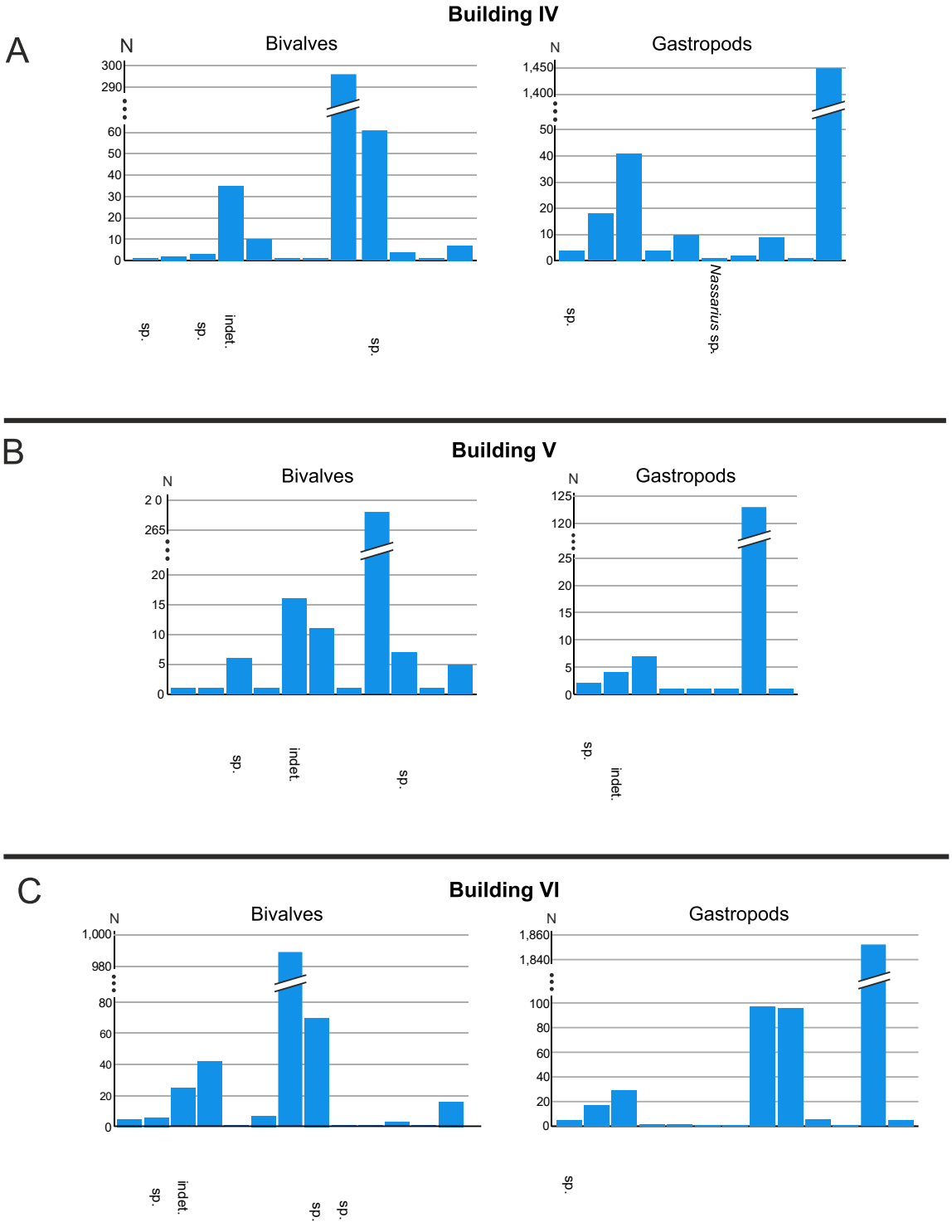
Buildings	Rooms	Loci
I	1–12, 14–18, 20–22, 24–31, 33–34, 55–57, 64–65	2112, 2119, 2300, 2302, 2303, 2307, 2702, 2905, 3100, 3106, 3108, 3109, 3300, 3301, 3303, 3304, 3307, 3310, 3707, 3708, 3722, 3727, 4700, 4703, 4704, 4706, 4708, 4709, 4711, 4900, 5000, 5100, 5107, 5111, 5112, 5300, 5303, 5311, 8001, 8002, 8006, 10025, 11018, 11033, 13001, 13002, 13003, 13005, 13006, 13008, 13010, 13014, 13020, 13022, 13027, 13028, 13029, 13030, 13031, 13032, 13033, 13034, 13036, 14010, 14011, 50020, 50023, 50042, 50048, 50056, 50057, 50058, 50063, 50064, 80006, 81011, 81012, 81015, 81020, 81025, 81026, 81028, 81029, 81031, 81032, 81040, 81041, 81042, 81043, 81301, 90000
II	38–39, 41–42, 68–69, 71	6065, 6091, 6019, 6113, 6118, 12025, 12026, 14008, 14012, 14028, 17027, 22008, 35104, 35105, 45002, 45005, 45016, 45025, 45027, 45029, 45044, 45055
III	89–92	81052, 81053, 81054, 81055, 81056, 81057, 81058, 81059, 81060, 81062, 81078, 81079, 81082, 81087, 81088
IV	58–60	70000, 94006, 94007, 94008, 94010, 94011, 94013, 94017, 94018, 94019, 94021, 94022, 94023, 94034, 94035, 94036, 94037, 94038, 94039, 94045, 94046, 94066, 94068, 94069, 94070
V	110, 112–114	84014, 84016, 84018, 84021, 84024, 84028, 84033, 84037, 84038, 84056, 84066
VI	76–77, 97–102	85001, 85006, 85007, 85009, 85024, 85029, 85030, 85031, 85034, 85036, 85039, 85102, 85111, 85116, 85120, 85125, 85126, 85131, 85132, 85133, 85136, 85137, 85138, 85139, 85141, 85144, 85148, 85149, 85156, 85157, 85165, 85168
VII	93–96, 103–104, 106	85038, 85041, 85042, 85043, 85047, 85503, 85512, 85514, 85517, 85520, 85524, 85525, 85526, 92001, 92002, 92003, 92004, 92005, 92007, 92008, 92009, 92015, 92021
VIII	81–82, 84–88	50038, 50081, 50087, 50089, 50095, 50107, 50110, 50111, 50115, 50116, 50120, 50124, 50128, 50130, 50132, 50133, 50134, 50140, 50147, 50151, 50156, 50157, 50158, 80002, 80003, 80008, 80013, 80016, 80017, 80019, 80029, 98008, 98009
IX	43–47	1710, 6005, 6006, 6008, 6011, 6012, 6014, 6015, 6016, 6018, 6019, 6021, 6026, 6027, 6029, 6030, 6031, 6032, 6033, 6034, 6036, 6039, 6040, 6041, 6042, 6044, 6045, 6048, 6052, 6063, 6102, 6108, 12001, 12003, 12004, 12011, 12013, 12014, 12015, 35000, 35001, 35002, 60000, 60006, 60007, 60008
X	13, 50, 72	2120, 2500, 2502, 2507, 2512, 2513, 2517, 2521, 2522, 2709, 2710, 30001, 98050, 98052, 98053, 98061, 98062, 98063, 98064
XII	61–63, 70, 74–75, 83 b	50001, 92117, 92118, 92128, 92132, 92133, 92134, 92138, 92139, 92141, 92146, 92147, 92157, 92161, 92162, 92163, 92168, 92171, 92173, 92174, 92177, 92178, 92186, 92187, 92188, 92191, 92194, 92195, 92196, 92197, 92210, 92216, 92217
East Gate	116–118	84017, 84019, 84020, 84023, 84029, 84030, 84031, 84032, 84036, 84053, 84054, 84057, 84064, 84068
West Gate	125	85109, 85110, 85169, 85172

Buildings	Rooms	Loci
South Gate	35–36, 48–49, 52–54, 78–80, 83 a, 123	2504, 2519, 2523, 2524, 2527, 2534, 2707, 6038, 6047, 7000, 7004, 7005, 7006, 7007, 7009, 7011, 7016, 7019, 7021, 7024, 7025, 7027, 7029, 11003, 11004, 11005, 11014, 11017, 11020, 50002, 50003, 50005, 50006, 50007, 50012, 50013, 50015, 50016, 50017, 50019, 50021, 50024, 50029, 50030, 50032, 50033, 50034, 50035, 50043, 50046, 50047, 50050, 50051, 50053, 50054, 50055, 50060, 50061, 50062, 50066, 50068, 50069, 50070, 50075, 50083, 50084, 50085, 50086, 50093, 50096, 50097, 50098, 50109, 50112, 50113, 50117, 50118, 50119, 50121, 50122, 50126, 50127, 50129, 50131, 50138, 50143, 50144, 50145, 50148, 50149, 50154, 50161, 50164, 50168, 50173, 80004, 80005, 92102, 92103, 92108, 92110, 92111, 92112, 92120, 92121, 92135, 92136, 92149, 92150, 92152, 92156, 92169, 92170, 92172, 92174, 92176, 92181, 92182, 92185
Building II b	73	5306, 5308, 5310, 5312, 30003, 30004, 30006, 30007, 30008, 30009, 3011010, 30012, 30014, 30015, 30017, 30020, 30021, 30022, 30023, 30025, 30026, 30027, 30040, 30041, 30042, 30044, 30047, 30048, 30049, 30050, 30051, 30052, 30053, 30054, 30055, 30056, 30057, 45004, 45006, 45008, 45012, 45034, 45048, 45049, 81000, 81004, 81008, 81010, 81013, 81014, 81017, 81019, 81022, 81023

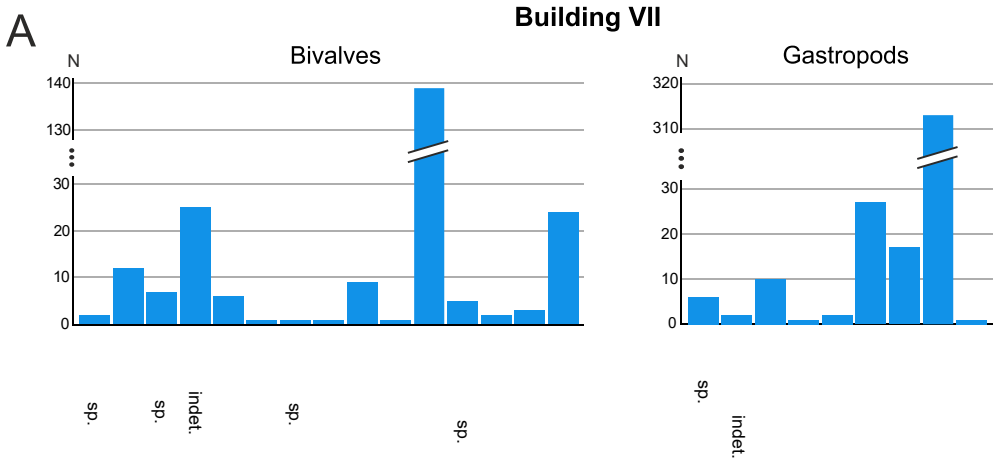
Appendix 4.2 Bivalve and gastropod histograms of A) Building I, B) Building II, and C) Building III from the archaeological context of Muweilah.

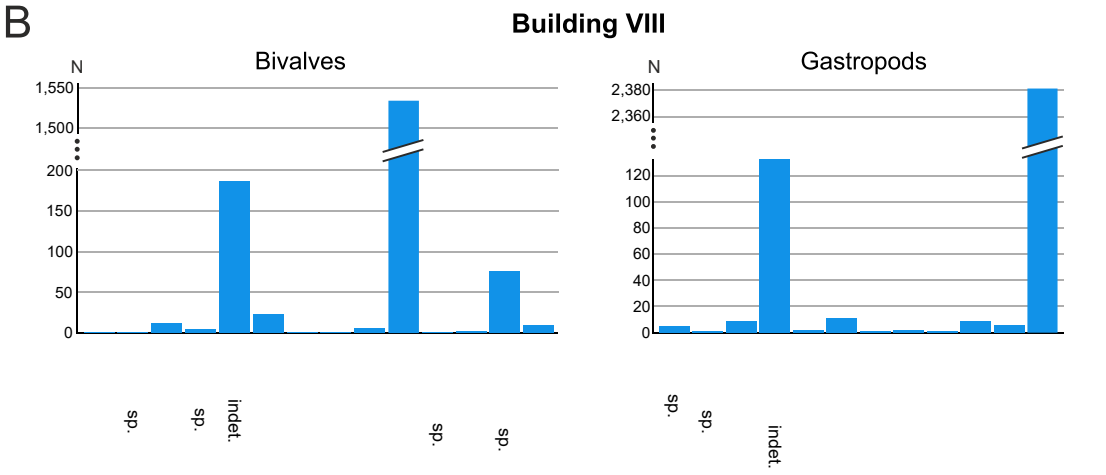


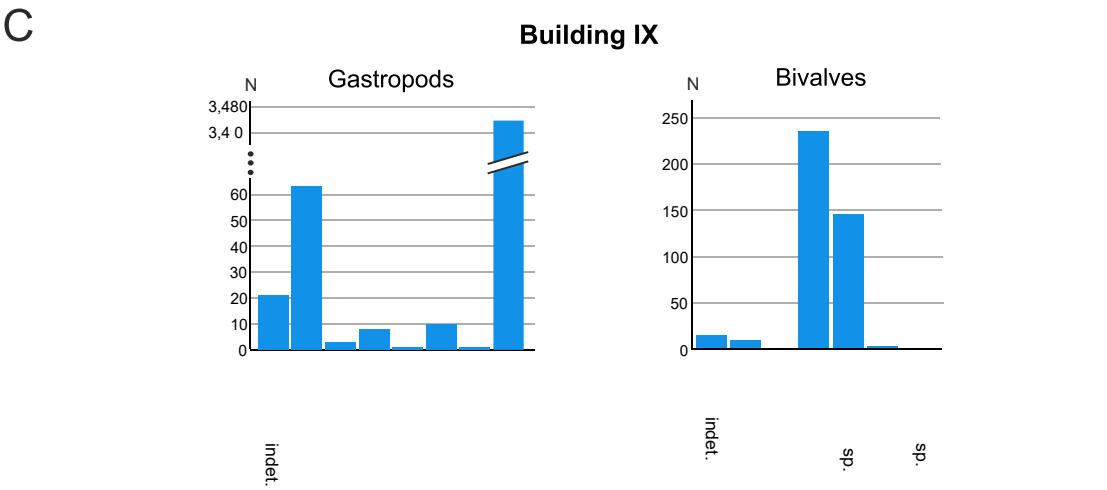
Appendix 4.3 Bivalve and gastropod histograms of A) Building IV, B) Building V, and C) Building VI from the archaeological context of Muweilah.



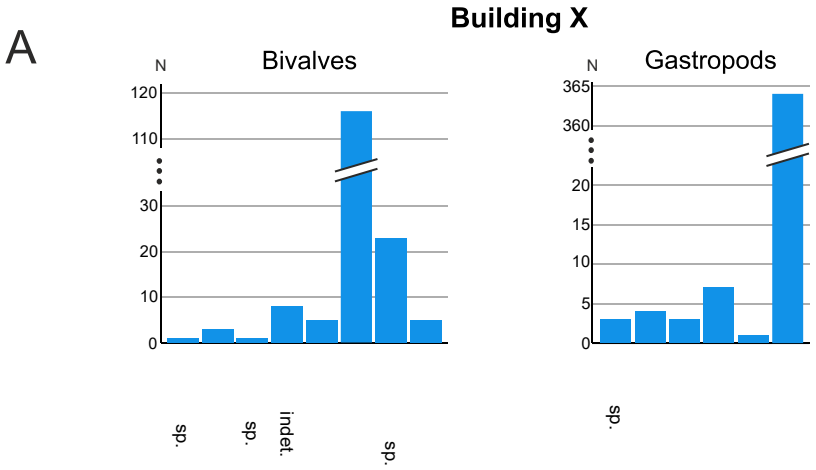
Appendix 4.4 Bivalve and gastropod histograms of A) Building VII, B) Building VIII, and C) Building IX from the archaeological context of Muweilah.

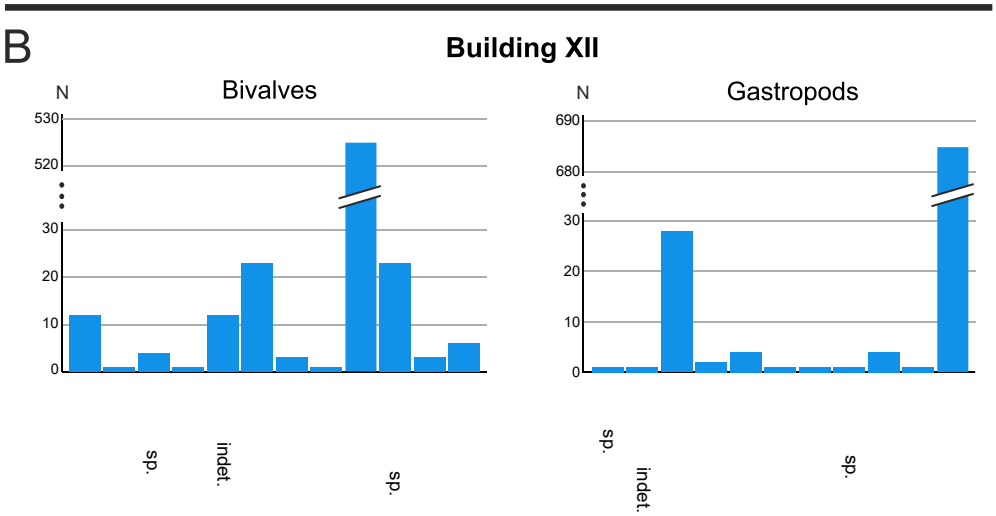


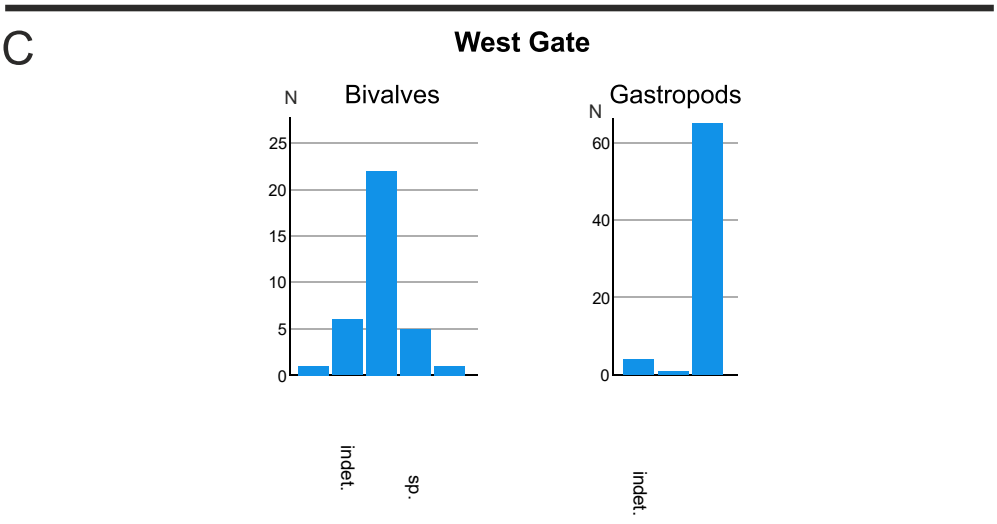




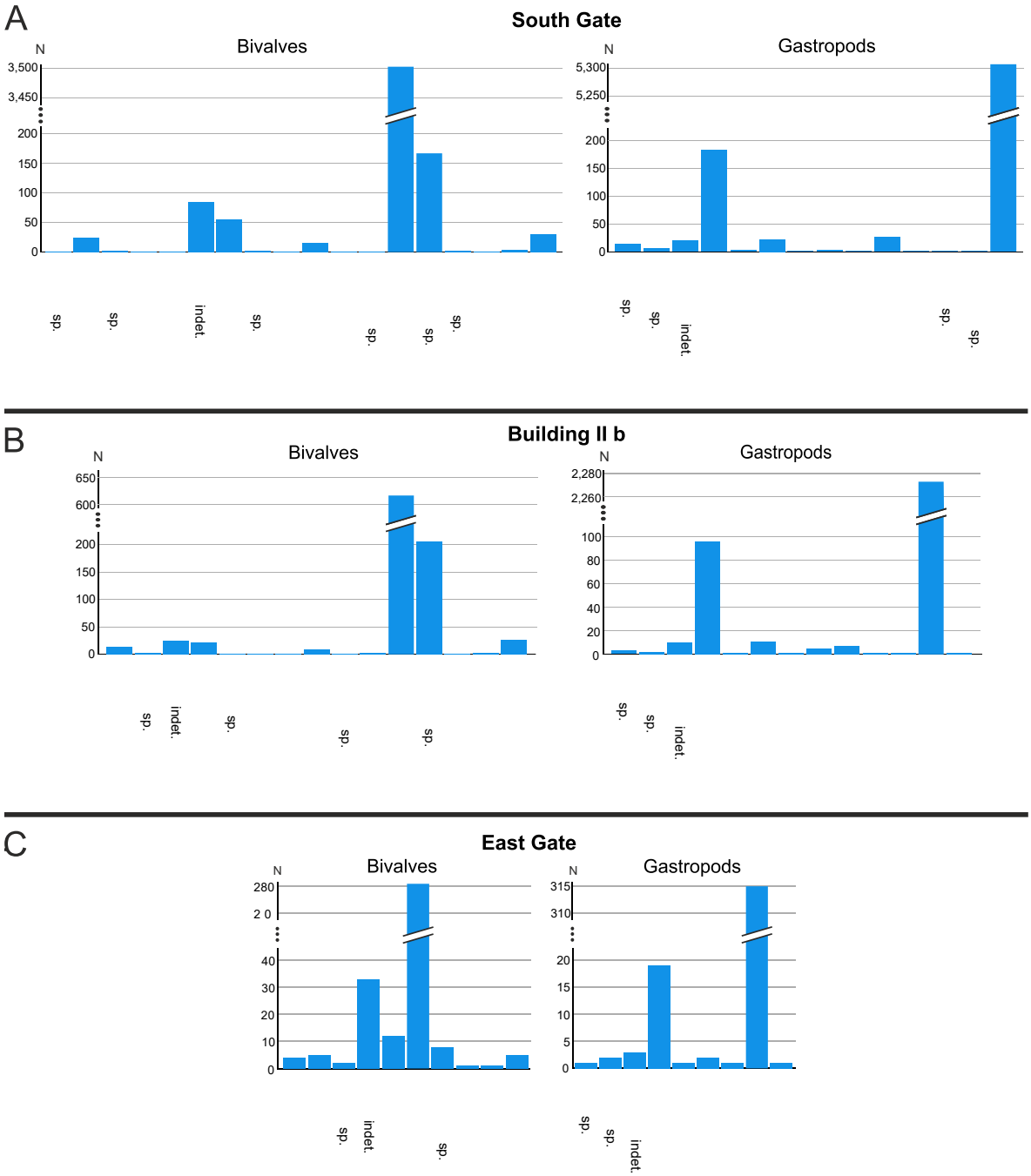
Appendix 4.5 Bivalve and gastropod histograms of A) Building X, B) Building XII, and C) West Gate from the archaeological context of Muweilah.







Appendix 4.6 Bivalve and gastropod histograms of A) South Gate, B) Building II b, and C) East Gate from the archaeological context of Muweilah.



Appendix 4.7 Literature of archeological sites and present marine distributions used for comparative analysis with Muweilah.

Site	Literature
Al-Hamriyah	Händel 2013
Tell Abraq	Prieur 1990
Ed-Dur	Van Neer and Gautier 1993
Jazirat al-Hamra	Beech and Kallweit 2001
Husn Awhala	Potts et al. 1996
Masafi	Decruyenaere et al. 2022, Lidour et al. 2023
Shimal	Glover 1991
Al-Madam	Del Cerro 2013
Nafun	Danielisová et al. 2024
Mahleya	Al-Jahwari 2011
Saruq al-Hadid	Roberts et al. 2019
Umm al-Qaiwain	Prieur and Guerin 1991
UAQ38	Degli Esposti et al. 2020
Kalba (3^{rd}–4^{th})	Phillip et al. 2005
As-Sabiyah	Glover 2010
Dalma Island	Beech and Elders 1999, Beech and Glover 2005
Saar	Glover 1995
Dosariyah	Nebelsick et al. 2018
Ruways1	Berger et al. 2020
Akab	Lidour et al. 2020
FAY-NE15	Uerpmann et al 2012
Zakum, Umm al-Dalkh	Albano et al. 2016
Tarut Island	El Sorogy et al. 2016
Tarut Bay	El Gendy et al. 2015
Qatar	Mohamed and Al-Khayat 1994
Al Mafyar, Dawhat Zekreet and Al Dhakira	Al-Khayat et al. 2021
Al-Khobar	El-Sorogy et al. 2019
Umm al Quwain, Ajman and Sharjah	Samara et al. 2023
Halul, Umm Aladam, Halut Al-Asere, Hadeed	Al-Ansi and Al-Khayat 1999

5. Discussion

The present research provides new insights into the exploitation of coastal resources during the Iron Age in Southeast Arabia, a period marked by increasing aridification and technological innovations that intensified settlement activity and reliance on marine resources (Magee 2014; Boivin & Fuller 2009; Charbonnier 2015; see Introduction). The substantial shell assemblage from Muweilah offers a detailed perspective on the influence of shell morphology on fragmentation and preservation, mollusk use, handling techniques, and subsistence practices. In comparison with other archaeological sites, the assemblage reveals both shared and site-specific patterns, thereby situating Muweilah within a broader regional framework. It further demonstrates how intra-site variation in shell remains correlates with selective resource use in combination with socially structured activity areas, rather than being driven by environmental constraints alone. The following sections briefly summarize the main findings of both manuscripts, which are then integrated into a broader discussion of their implications for human-environment interactions, resource use, and cultural practices in Iron Age Southeast Arabia.

5.1 Patterns of Mollusk Exploitation at Muweilah

Dietary Use and Subsistence Strategies

The mollusk assemblage was dominated by *Terebralia palustris*, *Marcia cordata*, *Ostreoidea* sp., and *Hexaplex kuesterianus* – species which are commonly reported as food resources (Ashja Ardalan et al. 2004; Vasconcelos et al. 2009; Suja & Muthiah 2010; Kumar Sethukali & Darshaka Jayasena 2022). Fragmentation, surface abrasion, ablation, and color alteration reflect both morphological constraints as well as cooking techniques. Gastropods required breakage to access the retractable flesh, producing characteristic fractures and surface abrasion, whereas bivalves could be opened easily with minimal damage. Cross-lamellar shell structures increased resistance to deep fractures, as shown by previous studies (e.g. Carter 1990). Color changes indicate exposure to temperatures below 400 °C, suggesting boiling (~100 °C) or grilling (200–300 °C), while burning was rare. Ethnographic parallels (Meehan 1975) support targeted extraction methods. The results indicate species-specific culinary strategies and nuanced subsistence practices shaped by morphological traits, environmental availability, and cultural preferences.

Non-Dietary Uses and Secondary Functions

A smaller portion of the assemblage, including 28 bivalve and 22 gastropod taxa, was likely collected for non-dietary purposes. Bivalves with post-mortem indicators (e.g. predatory boreholes, serpulid encrustation) were probably beach-collected following onshore transport. Taxa lacking such markers may have served as supplementary food sources or tools, though no use-wear was observed. Larger gastropods (*Cypraea, Conus, Strombidae*) are commonly reported as being used for ornament or container purposes (Bar-Yosef Mayer 2002; Gardner 2005; Çakirlar 2011; Del Cerro 2013; D'Errico 2016; Prust 2020); and the present specimens were likely collected for similar uses, with some perforations suggesting suspension. Smaller gastropods may have arrived incidentally, adhering to larger specimens or via sediment (Glover 1995). Overall, non-dietary use was secondary, and functional roles remain partly unresolved.

Collection Strategies and Habitat Use

Most specimens originate from coastal habitats, more precisely from mangroves (60.3 %) and littoral zones (32.7 %), reflecting targeted collection of abundant and accessible species. The dominant gastropod *T. palustris* can be gathered directly from mangrove floors, whereas the burrowing *M. cordata* required active extraction (Rao 1938; Burt 2023; Carpenter et al. 1997; Oliver et al. 2023). Offshore species were likely opportunistically collected post-mortem on beaches. Larger gastropods were probably collected intentionally, while smaller species may have been transported incidentally. The data indicates predominantly active coastal procurement, supplemented by opportunistic collection and limited non-dietary use, demonstrating both environmental access and selective human exploitation strategies.

Intra-site Variations

The spatial distribution of molluscan remains at Muweilah underscores pronounced functional differentiation within the site, particularly between the Western and Central Areas. The Western Area is characterized by lower diversity and a strong dominance of *Ostreoidea* sp., patterns that, in combination with associated material culture such as banqueting paraphernalia (Magee 1996, 2004, 2014; Magee and Thompson 2001; Magee et al. 2002; Potts 2001; Karacic et al. 2018), point to selective consumption practices and possibly communal or ceremonial activities. In contrast, the Central Area, especially the Southern Area, shows higher species diversity and abundance, supported by rarefaction and diversity metrics, consistent with more intensive and likely domestic use. While certain structures, such as Building II b, deviate from these broader patterns, the overall distribution highlights a close relationship between architectural organization and assemblage composition. Taken together, these patterns suggest that intra-site variability is best explained by the interplay of environmental availability, selective resource use, and socioeconomic differentiation, with building function as a key structuring factor.

Regional and Temporal Comparisons

Muweilahs assemblage shows the closest affinities with nearby coastal sites (e.g. Al-Hamriyah, Tell Abraq, ed-Dur, and Akab; Van Neer & Gautier 1993; Magee 1996, 2004; Glover 1995). The dominance of key taxa (*Terebralia palustris*, *Hexaplex kuesterianus*, *Ostreoidea* sp., *Marcia cordata*) remains stable throughout the Iron Age, in contrast to the temporal shifts observed at other sites. Assemblages from Oman and the eastern Gulf (El-Sorogy et al. 2015; Albano et al. 2016), by comparison, display clear biogeographic differences, with certain taxa absent from Muweilah due to environmental constraints. At the same time, intra-Gulf variation and chronological differences (e.g. Neolithic vs. Iron Age) indicate that these patterns cannot be attributed to habitat alone. Most assemblages, including Muweilah, derive from broadly comparable ecological settings, while the most pronounced contrasts emerge in comparison with modern ecological datasets. This suggests that the differences between Muweilah and other sites result from a combination of broader biogeographic patterning, selective species use, and diachronic environmental change, as well as differences in taxonomic resolution. Overall, variation in assemblage composition is best explained by cultural factors, such as site function and patterns of resource exploitation, rather than environmental availability alone, with habitat exerting a decisive influence only in specific contexts (e.g. offshore sites).

5.2 Mollusk Use in Broader Contexts

The results presented above demonstrate that marine mollusks constituted a structured and recurrent component of human engagement with coastal environments during the Iron Age II at Muweilah. Rather than reflecting isolated or incidental exploitation, the assemblage points to systematic interactions with marine resources embedded within broader subsistence and material practices. At the same time, the interpretation of mollusk exploitation benefits from consideration of environmental conditions, subsistence diversification, mobility between coastal and inland zones, and the social and economic contexts in which marine resources were procured, transported, and used. While these factors have been mentioned in previous studies (e.g. Meehan 1975; Erlandson 2001; West et al. 2017), they are rarely explored in a systematic or integrated way. The significance of mollusk remains thus extends beyond their immediate economic role and touches upon wider questions of human–environment interactions and Iron Age lifeways in Southeast Arabia.

The following sections build on these considerations by situating the archaeomalacological evidence from Muweilah within broader discussions of environmental change and resource use, social and economic organization, as well as the methodological limits and future potential of archaeomalacological research.

Environmental Drivers and Adaptation

Environmental change and increasing aridification during the Iron Age fundamentally shaped subsistence strategies in Southeast Arabia (Magee 1998; Potts 2001; Al Abed et al. 2006). The archaeomalacological evidence from Muweilah demonstrates that marine mollusks constituted a resilient and low-risk resource within this environmentally constrained setting. Rather than indicating dietary specialization or economic intensification, the exploitation of mollusks at Muweilah reflects an adaptive strategy aimed at mitigating environmental uncertainty through the use of predictable and locally abundant coastal resources.

Although mollusks are prominently represented in the archaeological record, their quantitative contribution to the regular diet cannot be reconstructed with precision. Shell remains are inherently biased by their high preservation potential compared to other food resources, such as plant remains or vertebrate bones (Szabó et al. 2014; Rick & Waselkov 2015; Rick et al. 2024; Hausmann et al. 2019; Callapaz & Dinis 2020). The assemblage moreover represents the cumulative outcome of repeated harvesting and consumption events over extended periods rather than discrete meals (see Chapter 2). Mollusks should therefore be understood as part of a diversified subsistence system that also included dates, domesticated animals, and hunting (Magee 1998; Potts 2001; Al Abed et al. 2006; see Introduction), rather than as a primary dietary staple.

The results from Muweilah suggest that spatial and temporal variation in mollusk species composition across Southeast Arabia is closely linked to environmental parameters, particularly the availability of specific coastal habitats. The presence and subsequent disappearance of *Terebralia palustris*, as observed in Muweilah, is often explained with the expansion and decline of mangrove environments (e.g., Pawlik et al. 2015; Douglass et al. 2017), underscoring the sensitivity of mollusk exploitation patterns to environmental change. At the same time, differences between contemporaneous sites, such as between Muweilah and Al-Hamriyah (see Chapter 3–4), demonstrate that environmental conditions varied regionally and did not affect all areas synchronously. These patterns caution against interpreting taxonomic differences solely as cultural choices (see below), highlighting instead the interplay between local environmental availability and human selection.

The assemblage indicates that collection strategies were strongly affected by environmental constraints. Taxa that were abundant, easily accessible, and nutritionally rewarding were preferentially exploited, particularly species occurring in large and predictable quantities. Cultural preferences and functional considerations (see Chapter 3–4), however, also influenced species selection, especially where shells were collected for purposes beyond subsistence, such as ornament production or container use. In these cases, morphological characteristics, including shell size, thickness, and shape, likely played a decisive role in determining archaeological representation (e.g., itezović 2016; Steele et al. 2019; azzo et al. 2025).

The extensive fragmentation and surface abrasion observed in the gastropod assemblage from Muweilah provide compelling evidence for on-site processing of mollusks rather than coastal pre-processing. This pattern contrasts with ethnographically documented strategies in which mollusks are processed at the shore prior to transport (Meehan 1975; Hausmann et al. 2019; Biagi et al. 2021). The biology of key taxa, particularly *Terebralia palustris*, which can survive extended periods without water or food (Rao 1938; Soemodihardjo and Kastoro 1977, Bosh et al. 1995), facilitates such inland transport. This practice implies regular logistical movement between coastal and inland zones and highlights the role of mollusk exploitation within broader mobility and land-use strategies during the Iron Age.

Taken together, the evidence from Muweilah illustrates how mollusk exploitation was embedded within a flexible and environmentally responsive subsistence system. The observed patterns reflect neither opportunistic scavenging nor specialized production, but a stable and adaptive practice that linked coastal ecosystems to inland settlements and contributed to the resilience of human communities in the face of climatic stress.

Social and Economic implications

The presence of marine mollusks at Muweilah has broader social and economic implications that extend beyond their role as a subsistence resource. Regardless of whether mollusks were collected directly by the inhabitants of the site or obtained through exchange, their systematic presence within an inland settlement at Muweilah may be understood as an additional indicator of increased mobility and integration into regional interaction networks during the Iron Age in Southeast Arabia, which are documented in the archaeological record through the distribution of other material categories such as pottery (Magee 1998; Boivin & Fuller 2009; Eddisford 2020). In this sense, mollusk exploitation serves as an indicator of intensified connections between coastal and inland zones rather than as evidence for specialized coastal economies.

The geographic position of Muweilah, located between the coast and the interior desert, would have facilitated both direct procurement and exchange-based acquisition of marine resources. The accessibility of the coast by dromedary makes regular coastal foraging logistically plausible, while archaeological evidence for long-distance exchange, such as the circulation of pottery (see Introduction), demonstrates the site's participation in wider economic networks (Magee 1996, 2004, 2014; Magee & Thompson 2001). Mollusks thus form part of a broader material record that reflects increased mobility, circulation of goods, and economic integration characteristic of the Iron Age, independent of the specific mode of acquisition.

Beyond subsistence, the contextual distribution of shell remains suggests that mollusks may also have held social or symbolic significance, a possibility well established in archaeological research on shell use (e.g. Glover 1995; Bar-Yosef Mayer 2002). The occurrence of shell remains within the columned hall of Building II, a structure interpreted as having a prominent communal or institutional role (Magee 2004; Magee et al. 2002; Karacic et al. 2018), raises the possibility that mollusks were involved in practices extending beyond everyday food consumption. In light of the pronounced functional differentiation observed across the site (see Chapter 4), this pattern is unlikely to be incidental: the concentration of selected taxa, particularly *Ostreoidea* sp., within the columned hall, as supported by quantitative distributional and diversity analyses, together with associated

banqueting paraphernalia, points to context-specific consumption practices linked to the building's role. hile the available evidence does not allow a definitive interpretation of symbolic or ritual use, this patterned distribution underscores the likelihood that mollusks carried socially differentiated meanings, reflecting not only dietary practices but also context-specific modes of consumption within the settlement.

The assemblage also raises questions regarding labor organization and social practice. The collection, transport, and processing of mollusks would have required coordinated effort, yet the current evidence does not permit the identification of gender- or age-specific divisions of labor. Nevertheless, the scale and regularity implied by the assemblage suggest that mollusk exploitation was embedded in routine social practices rather than representing occasional or ad hoc activity. Considered alongside the spatial patterning discussed above, these practices appear to have been structured not only functionally but also socially, with marked differences between architectural areas indicating a non-uniform organization of mollusk-related activities across the settlement. This uneven distribution, which also underpins the association of shell remains with specific consumption contexts (e.g. communal or possibly ceremonial settings), points to an integrated system in which procurement, processing, and consumption were closely intertwined and shaped by the functional and social organization of space. While such patterning may reflect differences in access, activity areas, or status, the available archaeological evidence remains insufficient to draw firm conclusions, particularly given the uneven state of excavation (Karacic et al. 2018, Magee et al. 2018), most notably in the Northern Area. Future analysis of intra-site variation and household-level contexts may therefore further clarify how these tasks were organized within the community.

To summarize, the archaeomalacological evidence from Muweilah indicates that marine mollusks were integrated into the social and economic fabric of the settlement in multiple, spatially structured ways. They reflect patterns of mobility, exchange, and selective resource use, as well as intra-site differentiation linked to the functional organization of architectural space. Together, these patterns point to a close interrelationship between procurement, processing, and consumption practices, suggesting that marine resources played an active role not only in subsistence but also in structuring economic interactions and socially differentiated practices within the settlement and across environmental zones in the Iron Age of Southeast Arabia.

5.3 Study Limitations

The principal limitations of this study relate to taphonomic processes affecting shell preservation and, consequently, taxonomic resolution. Extensive fragmentation, surface ablation, and weathering limit the identification of heavily altered and very small specimens, particularly gastropod remains intentionally broken during processing. This limitation, however, primarily affects minor fragments and does not compromise the identification of the dominant taxa that structure the assemblage and underpin the main interpretations.

Comparative analyses are further constrained by variability in preservation conditions and analytical practices across published archaeomalacological assemblages in Southeast Arabia, as illustrated by existing studies (e.g. Prieur 1990; Al-Jahwari 2011; Lidour et al. 2023). Differences in taxonomic resolution, quantification methods, and reporting standards limit dataset comparability, requiring a cautious assessment of regional patterns but not negating the broader trends identified in this thesis.

Recovery methods represent an additional source of bias, as manual collection favors larger and more robust specimens and may underrepresent small or fragile taxa. While this may affect assessments of species richness, it has limited impact on interpretations of subsistence strategies, which are driven primarily by abundant and morphologically robust taxa. In addition, highly fragmented gastropod remains produced during shell breakage would remain unidentifiable regardless of recovery method, thus not substantially altering the interpretive framework.

At the intra-site level, interpretations are further constrained by the uneven state of excavation and documentation across the settlement. While recent analyses highlight spatial patterning and functional differentiation between architectural areas, these interpretations remain provisional, particularly for poorly explored zones such as the Northern Area. More extensive excavation and integrated contextual analyses would be necessary to refine interpretations of activity areas and building function.

More broadly, published archaeological studies in the region have often prioritized architecture, ceramics, or other material categories, while detailed archaeomalacological analyses remain comparatively limited. This restricts the

resolution at which intra-site variability and functional differentiation can be assessed across sites and highlights the need for more systematically integrated studies of faunal and material assemblages.

Finally, the archaeological record itself is inherently incomplete, and not all mollusks collected, processed, or consumed in the past would have been preserved or recovered. Nevertheless, the large sample size of more than 40,000 individuals provides a robust empirical basis for identifying dominant patterns in mollusk exploitation, processing, and deposition. Although absolute quantification of past behaviors remains unattainable, the scale and consistency of the dataset support the reliability of the conclusions.

5.4 Future Research Directions

Future research building on the results of this study should aim to identify the seasonality of mollusk collection. The application of stable isotope analyses (e.g. Eerkens 2013) could refine interpretations of harvesting schedules and mobility patterns, shedding light on the temporal structuring of coastal–inland interactions. In parallel, expanded scanning electron microscopy studies on a wider range of taxa could further help to clarify the relationship between shell morphology, processing techniques, preservation, and heat-induced alterations, contributing to more precise reconstructions of cooking practices.

More broadly, the results highlight the need for systematic and methodologically consistent archaeomalacological research across Southeast Arabia. Many existing studies remain limited to basic taxonomic identification, often lacking quantitative and taphonomic detail (e.g., Händel 2013; Lidour et al. 2020). Comprehensive analyses from additional sites, employing standardized recording and reporting protocols, would facilitate more robust inter-site comparisons and for identifying regional and diachronic trends in mollusk exploitation during the Iron Age. Emphasis should be placed on linking inter-site variability with intra-site patterning, to assess whether differences observed between sites reflect environmental conditions, site function, or broader socioeconomic organization. In this context, the integration of high-resolution spatial analyses across multiple sites would be especially valuable, allowing for more direct comparison of activity areas, depositional practices, and consumption patterns.

Finally, future research would benefit from closer integration of archaeomalacological data with other archaeological and environmental datasets, including archaeobotanical, zooarchaeological, and geoarchaeological evidence. Such interdisciplinary approaches are crucial for reconstructing subsistence systems in their full complexity and for situating mollusk exploitation within broader economic and ecological frameworks.

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6. Conclusion

This study examined the collection, processing, and use of mollusks at Muweilah, focusing on how taxonomic composition and preservation patterns reflect human activity. The results demonstrate the selective exploitation of a limited range of food species, combined with species-specific processing and cooking practices, whose archaeological signatures are shaped by both culinary behavior and shell morphology. Non-dietary use appears to have been limited, with most bivalves likely collected post-mortem, while larger gastropods may have been selectively used for functional or ornamental purposes.

Regional and chronological comparisons reveal strongest similarities with nearby coastal sites, contrasted by greater variability in assemblages from Oman and the eastern Gulf. These patterns reflect the combined influence of biogeographic constraints and cultural choices, while also demonstrating that taxonomic variability cannot be explained by environmental availability alone. In particular, the results highlight the importance of intra-site variation, showing that differences in assemblage composition are closely linked to the functional organization of space and patterns of resource use within the settlement. This is most evident in the contrast between the Western Area, characterized by low diversity, high frequency of *Ostreoidea* sp., and absence of the typically dominant *Marcia cordata*, and the more diverse and abundant assemblages of the Central Area.

Taken together, these findings show that mollusk exploitation at Muweilah was not a uniform subsistence activity but a spatially structured and socially embedded practice integrating procurement, processing, and consumption. Marine resources were incorporated into inland lifeways in ways that reflect both environmental constraints and local socioeconomic organization, contributing to risk reduction strategies while also indicating patterns of mobility and regional connectivity during the Iron Age.

More broadly, this study demonstrates the need for systematically integrated and methodologically consistent archaeomalacological research across Southeast Arabia, as well as closer integration with archaeobotanical, zooarchaeological, and geoarchaeological datasets. Such approaches are essential for refining interpretations of subsistence systems and human–environment interactions in the region. Ultimately, the mollusk assemblage from Muweilah shows that even fragmented and contextually complex marine remains can provide robust insights into human adaptation, spatial organization, and the integration of inland and coastal economies, underscoring the value of archaeomalacological evidence for understanding Iron Age societies in Southeast Arabia.

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