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ORIGINAL PAPER

An archaeometallurgical investigation of iron smithing in Swahili contexts and its wider implications

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Abstract

This paper presents the most extensive archaeometallurgical study of iron-smithing debris excavated in East Africa. It presents an integrated methodology, including morphological, chemical, petrographic, and contextual analysis of iron slag excavated from secondary ironworking contexts. Iron slag from three Swahili sites was analysed—Unguja Ukuu located on the southwestern coast of Zanzibar, and Tumbe and Chwaka situated in the north-east of Pemba Island. The results suggest that Unguja Ukuu smithing is associated with oxidising hearth atmospheres and high amounts of CaO, while slag from Tumbe and Chwaka indicates reducing hearth atmospheres and high silica:alumina ratios, potentially pointing to the use of a flux. Distinct technical traditions can be seen at Unguja Ukuu when compared to Tumbe and Chwaka, suggesting a regional rather than chronological pattern. Temporal continuity is evident throughout the occupation of Unguja Ukuu and between sites of different periods in north-western Pemba. The spatial distribution of iron slag at these sites suggests that smithing was taking place across the extent of Unguja Ukuu, while slag scatters were more localised and disassociated from domestic contexts at Tumbe and Chwaka. The wealth of information on technological and organisational aspects of smithing obtained during this study indicates that an integrated methodology can yield valuable data for a variety of smithing sites, irrespective of excavation strategies.

Keywords Swahili · Ironworking · Archaeometallurgy · Iron Age · Zanzibar · Tanzania

Introduction: Research rationale and setting

The East African coast has for ~ 1500 years been home to a shared cultural tradition known as Swahili. From around 600 CE, the coast and the adjacent islands were settled by fishing, farming, and ironworking communities that quickly became brokers of trade with the Indian Ocean mercantile world. Evidence for both the smelting and smithing of iron has been suggested in these East African contexts, but smithing is particularly ubiquitous, found at virtually every excavated site in this region (e.g. Chittick 1974, 1984; Horton 1987; Chami 1999; Fleisher 2014). Here we attempt to demonstrate the potential for archaeometallurgical studies to explore the technology and social setting of iron smithing. The paper proposes a new perspective towards smithing in African contexts; presents the results of the first comparative archaeometallurgical research project carried out on Swahili material; and outlines the outcome of the most extensive study of smithing debris performed on the eastern coast of Africa to date.

Iron smithing technologies and their role in societies are rarely studied from archaeological and metallurgical standpoints. While this is less true for other parts of the world such as European and Near Eastern contexts (e.g. Veldhuijzen and Rehren 2007; Eekelers et al. 2016; Portillo et al. 2018), smithing slag in Africa remains widely understudied, especially when compared to the volume of research

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on iron smelting (e.g. Friede 1979; Kiriama 1987; Schmidt 1997; Rehren et al. 2007; Iles and Martinón-Torres 2009; Lyaya 2020). At coastal sites, considerations of smithing have rarely gone beyond quantifying and weighing iron slag resulting from metal production processes.

The reasons for this lack of attention are myriad, but one important factor is simply that evidence of iron smithing is more difficult to find than evidence of smelting. Across the African continent, smelting is often associated with furnaces, their debris, slag heaps or scatters that transform the landscape and are a visible surface feature (e.g. Trigger 1969; Togola 1993; Miller et al. 2001). This makes smelting evidence a more attainable objective when surveying landscapes for archaeometallurgical research. It can also be difficult to differentiate between smelting and smithing slag. Miller and Killick (2004) presented a valuable debate on this subject in southern African contexts highlighting the complexity of this process that has helped inform our methods. Here we outline a comprehensive methodological approach that facilitates identification of both processes, but this paper concerns only pieces of slag consistent with smithing practices. Smithing activities tend to leave less prominent material remains and are usually found as the by-product of an excavation that has an entirely different research focus. In addition, when smithing slag is analysed, relatively small numbers of obtainable samples can make it difficult to draw conclusions about associated technology (e.g. Chirikure 2006), or the material is studied as part of the wider metallurgical assemblage with limited focus on its technological implications (Miller and Whitelaw 1994). In addition, the secondary nature of this process might translate to secondary importance for archaeometallurgists and result in lower volumes of research on smithing slag. However, possibly the key factor behind the lack of research into smithing slag is that most researchers do not see the material as interesting. The internal chemistry and petrography of smithing slag is highly variable. This inherently high variability means that any meaningful patterns hinting at technological choices are considered difficult if not impossible to distinguish using traditional archaeometallurgical methods. This may also help explain why much of the archaeological research on smithing in African contexts has a strong ethnographic focus (Brown and Sassoon 1995; Kusimba 1996; LaViolette 2000; Soulignac and Serneels 2013; Mtetwa et al. 2017). Ethnographic methods allow us to obtain information that goes beyond slag chemistry, contextualise the craft in its social setting and provide data not readily accessible in archaeological smithing contexts.

This paper challenges the notion that limited information can be acquired from smithing slag. We argue that an integrated methodological approach proposed here can provide meaningful insights into smithing technologies, craft traditions, and settlement dynamics. The research presented here was completed as part of a PhD project focused on reconstructing iron production technologies, and their role in society and in exchange networks in 500–1500 CE coastal Tanzania (Baužytė 2019). We present case studies focused on ironworking at three Swahili archaeological sites—Unguja Ukuu, Tumbe, and Chwaka, located in Zanzibar and Pemba islands (Fig. 1). The sites chosen have been the subject of contextual excavations, with careful spatial and stratigraphic recording. This allows the reconstruction of technologies as part of a detailed understanding of chronological and social factors. They cover two different settings in the Zanzibar archipelago, and span two periods—the seventh to tenth centuries (Unguja Ukuu, Tumbe) and the eleventh to fifteenth centuries (Chwaka), spanning a period of enormous social and economic change on the coast more generally. Iron slag from each of these sites was assessed using an integrated archaeometallurgical approach. Four key steps examining morphological, petrographic, chemical, and contextual information of the slag were performed and are described in detail in the methodology section. As a result, we were able to characterise singular technical traditions for Zanzibar and Pemba islands, furthering the existing approaches to smithing slag analysis such as slag identification studies (e.g. Miller and Killick 2004). Slag identification is a critical first step in characterising the technological process. Studies of settlement organisation as a proxy for social structures also rely on correct slag identification; an example would be the Central Cattle Pattern model, which is informed by the placement of iron production activities in relation to other settlement components (e.g. Huffman 1989, 2001). The present study showcases how developing slag identification methodologies can help understand the social context of iron production and inform these models. Furthermore, this study contributes to the analysis of spatial organisation of craft activity at these sites, evidencing different practices across time and space.

The comparative methodology was tested by the particularities of the sites included in this study, which yielded diverse results attributable to distinct technologies. We might expect similarities in technological traditions between these sites, due to similar sociocultural influences from the African interior and the Indian Ocean trading connections. Nevertheless, the sites have different temporal, environmental, and geographic contexts and were excavated using different archaeological methods and the uncovered material was curated in ways that proved challenging for research. In addition, the inherent variability in iron slag composition is often regarded as hindering differentiation of technological traditions. Thus, the sites present not only a unique potential for comparison but also a set of challenges for the analysis of smithing slag. Distinct technological patterning has been identified among the sites, nonetheless, illustrating that smithing slag can be a highly informative material.

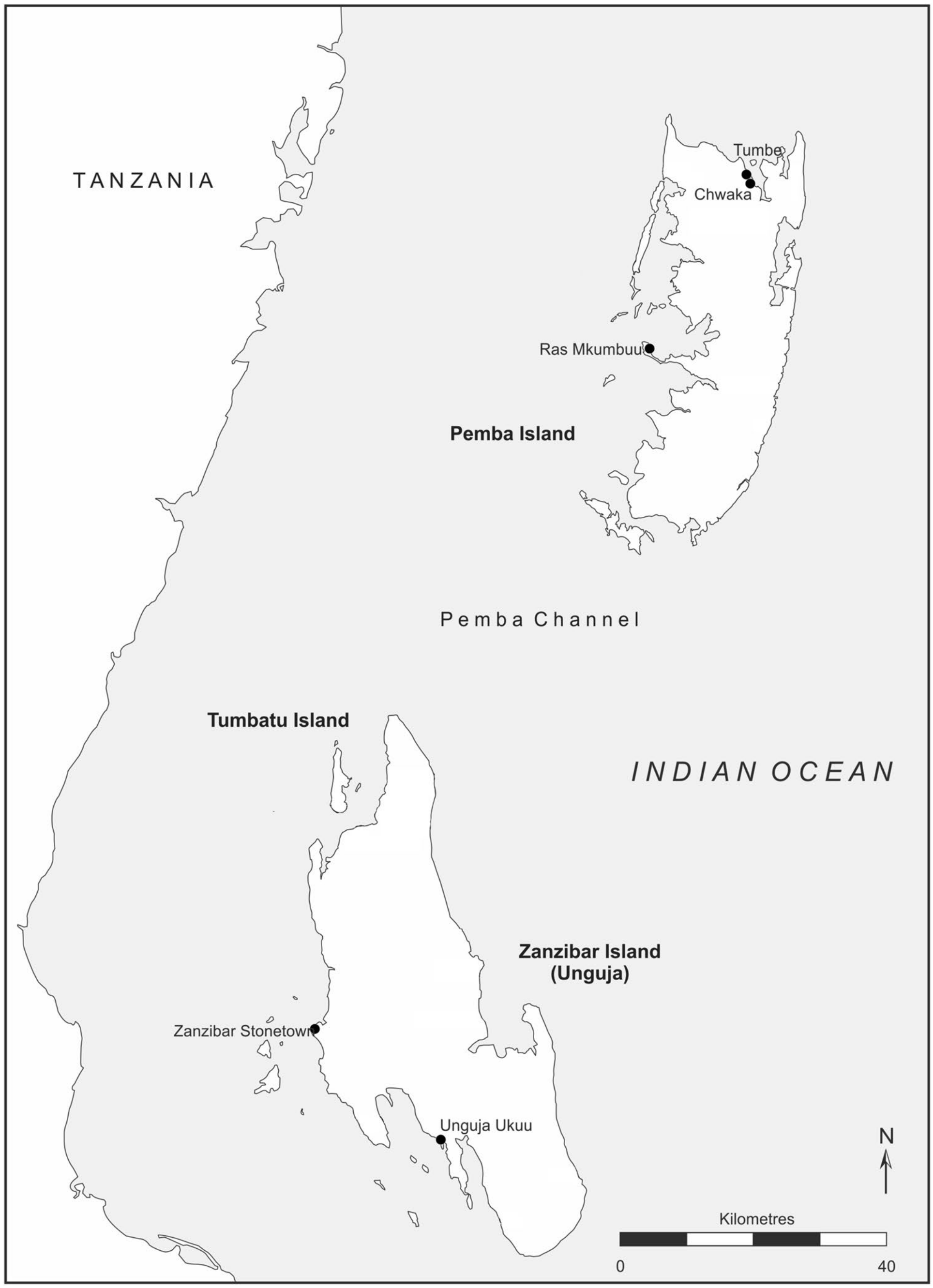

Fig. 1 Map of Zanzibar Archipelago marking locations of Unguja Ukuu (latitude 6° 19′ 04.1″ S, longitude 39° 22′ 31.9″ E), Tumbe (latitude 4° 57′ 50.67″ S, longitude 39°47′ 53.87″ E), and Chwaka (latitude 4° 58′ 6.06″ S, longitude 39°48′ 16.07″ E) sites

Archaeological excavations at Unguja Ukuu, Tumbe, and Chwaka

The Zanzibar archipelago is well known for its archaeological heritage. Although evidence for occupation at cave sites on both Unguja and Pemba dates back many thousands of years (Chami 2001, 2009; Sinclair et al. 2006; Shipton et al. 2016), it is from the seventh century CE that a record of consistent settlement can be traced. It is these communities that developed the Zanzibar Archipelago as an important gateway between the Indian Ocean world and continental Africa. Early sites are found along the coasts of both Zanzibar and Pemba, associated with Early Tana Tradition ceramics, evidence for external trade with the Persian Gulf and India, and the manufacture of iron and shell beads. The population of these sites had a mixed diet that involved some hunting, consumption of fish on a substantial scale, keeping of some chicken, and crops such as pearl millet and sorghum (Juma 2004; Walshaw 2010; Crowther et al. 2016a). In the 1st millennium, the architecture was made of daub, timber, and—by inference—thatch. Many of these sites were substantial even at this early date covering around 4 ha—and can be best described as large villages with a population of up to 1600 (Juma 2004). From the eleventh century onwards, the entire East African coast experienced a shift in forms of settlement, with 'stonetowns' developing at key locations: often the sites of earlier settlements. These towns contained architecture of coral and lime, including mosques and palaces, and assumed a key role in overseas trade (Wright 1993; LaViolette and Wynne-Jones 2018).

Unguja Ukuu

The site of Unguja Ukuu (Fig. 2) has been the subject of detailed archaeological excavations (Juma 2004; Horton and Clark 1985; Crowther et al. 2016a). It was first investigated during a survey of sites on the Zanzibar archipelago (Horton and Clark 1985) and later excavated significantly during the 1990s (Sinclair and Wandibba 1988; Juma 2004). Data from these excavations have been supplemented in recent years by detailed studies of artefacts

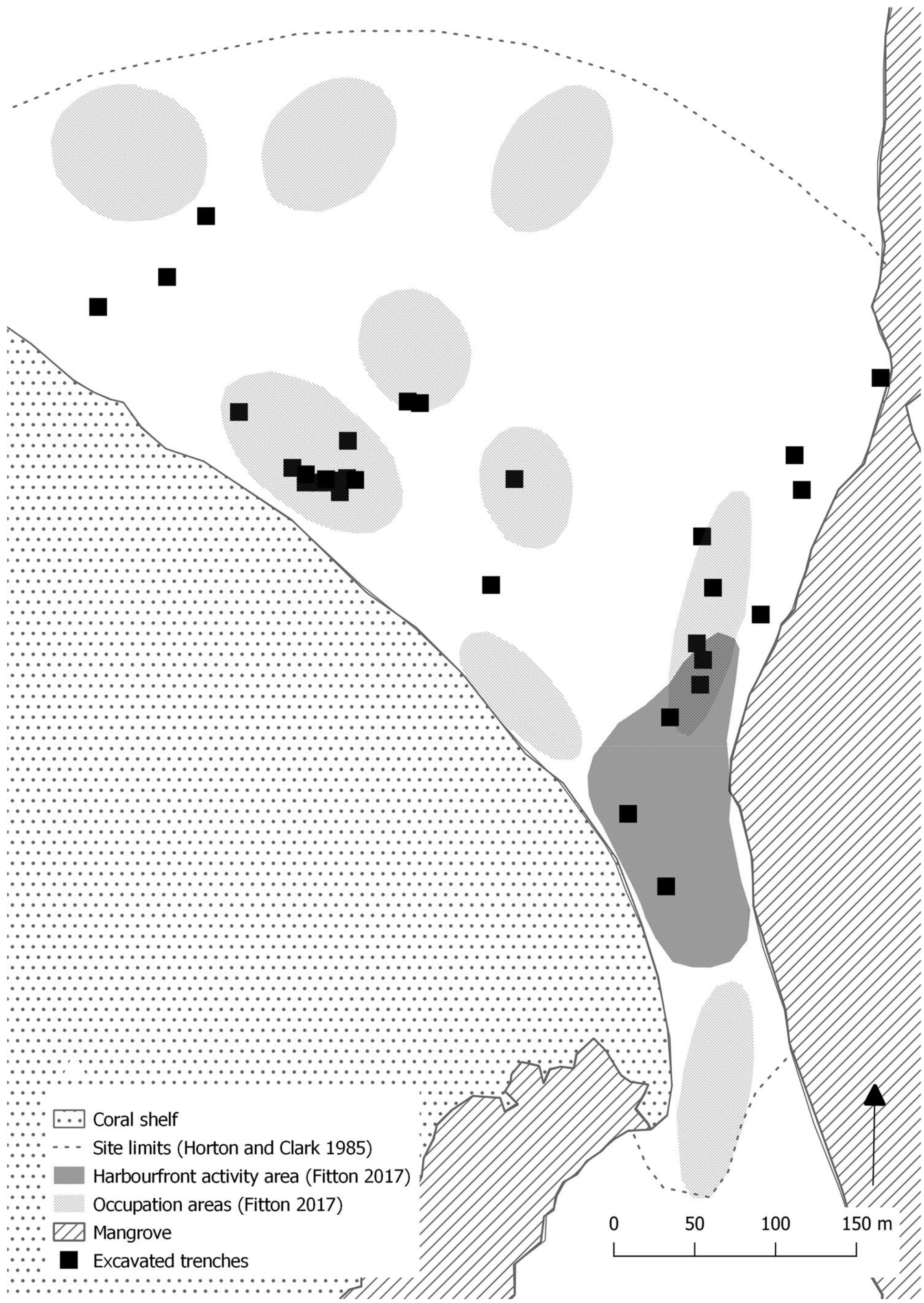

Fig. 2 Map of Unguja Ukuu marking approximate limits of the archaeological site, excavated trenches, occupation, and harbourfront activity areas (after Fitton 2017)

and bioarchaeological material from middens. A study of the imported ceramics and beads has suggested that the site held a prominent place in international trade networks (Juma 2004; Crowther et al. 2015; Wood et al. 2016; Priestman 2018; Wood 2018). This is complemented by botanical data for early imported rice (Crowther et al. 2016a, b; see also Walshaw 2005, 2010). In recent years some of the authors have conducted a series of investigations at Unguja Ukuu aimed at exploring domestic life and resource use in context. These have involved a geophysical survey and test excavations exploring the urban layout (Fitton and Wynne-Jones 2017; Fitton 2018); and two seasons of excavations focusing on domestic structures (Wynne-Jones and Sulas 2017; Wynne-Jones et al. 2020). In sum, these studies gave a better sense of the areas of domestic occupation and craft activity at the site, elaborated on how the inhabitants drew on a wide set of local resources (Sulas et al. 2019; Faulkner et al. 2017), and clarified a chronology for the developing settlement (Wynne-Jones et al. 2020). Samples for the current study were derived from several of the previous excavations, as well as data from one house excavated in 2017.

Tumbe

On the northeast tip of Pemba Island is a small peninsula on which the sites of Tumbe and Chwaka sit adjacent to one another (Figs. 3 and 4). Tumbe was the earlier of the two (Fleisher and LaViolette 2013), with the main occupation 600–950 CE, and therefore broadly contemporary with early centuries at Unguja Ukuu (Juma 2004), Manda (Chittick 1984), and Shanga (Horton 1996); it was one of the largest first-millennium settlements on the coast, and certainly the largest on Pemba for its time. It came to the attention of researchers in 1997 through exposed roadside deposits followed by shovel-test pit surveys and studied further through two seasons of test units and large-exposure excavations in 2002 and 2004 (Fig. 3), the latter as part of a household-based study which included Chwaka and two other sites (Fleisher and LaViolette 1999; LaViolette et al. 2003; LaViolette and

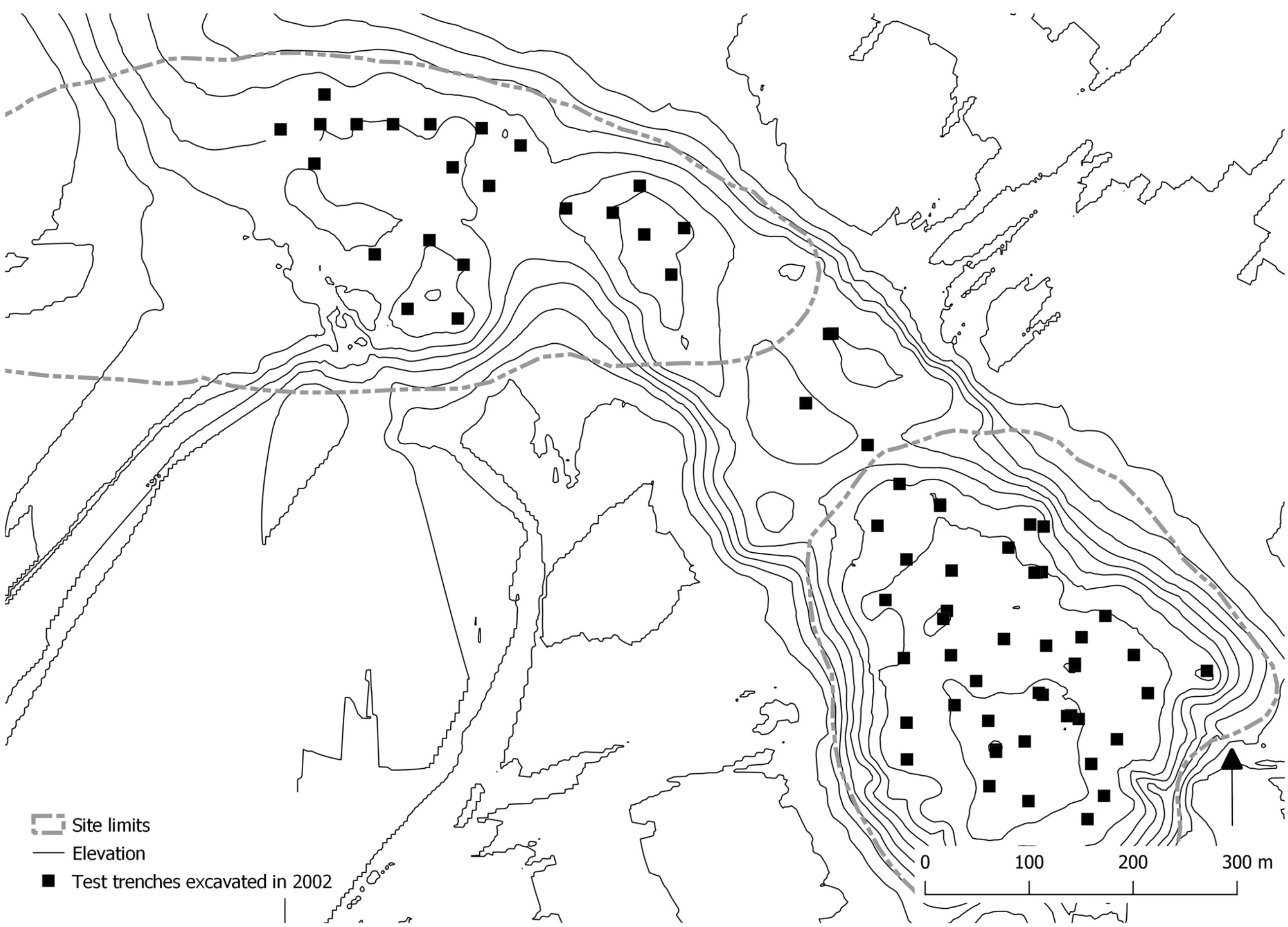

Fig. 3 Map marking location and extent of Tumbe and Chwaka sites and distribution of test trenches excavated at the sites

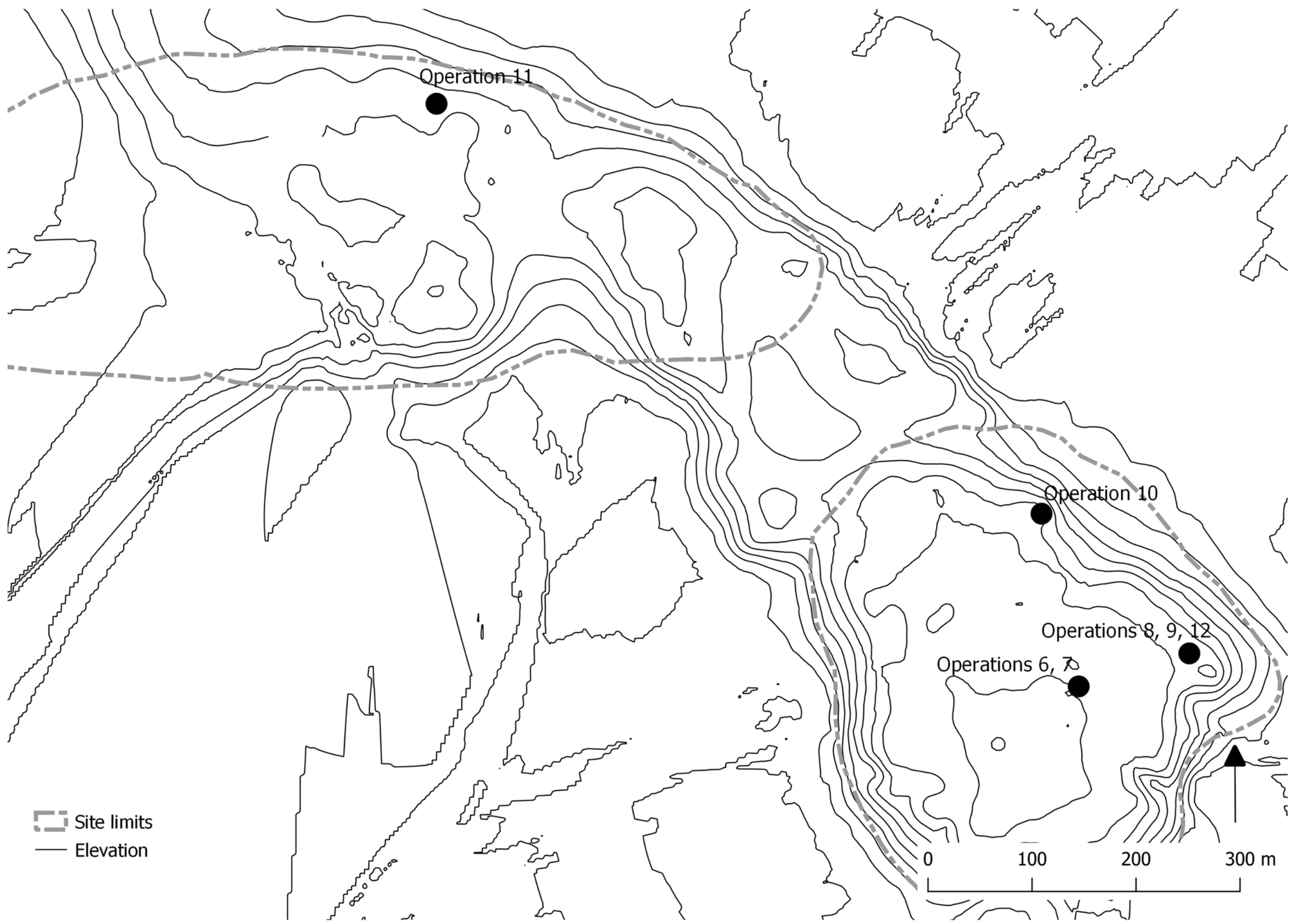

Fig. 4 Map marking location of 2006 operations excavated at Tumbe and Chwaka sites

Fleisher 2018); waterfront modifications were examined by Fitton (2017). Tumbe was a large farming and fishing settlement covering 20-30 ha in a low-density spread of structures and middens; the agricultural base was millet, with a significant component of rice, legumes, and other plants (Walshaw 2010). In addition to evidence for ironworking as focused on here, insights into 1st-millennium life recovered from the deposits included extensive evidence—more than 3600 bead grinders, the largest coastal assemblage to date—for shell-bead production at the household level (Flexner et al. 2008). A wide range of imported goods recovered include large, turquoise-glazed jars and other ceramics, small glassware, stone and glass beads, lead strips, and copper alloy artefacts. While there may have been ties between people living at Tumbe and those who later founded Chwaka, as explored below, Tumbe was not a nascent stonetown but rather a dynamic village with its own life history (Fleisher and LaViolette 2013). Long after the original settlement was buried, eighteenth to nineteenth century Mazrui Arab settlers from the mainland built a mortared-coral fort and group of tombs on a small portion of the uninhabited landscape, which is today largely agricultural land. Samples related to ironworking for the current study came from Operation 11 excavated in 2006 (Fig. 4). Operation 11 was a 5 × 7 m trench focused on revealing portions of a Mazrui-era fort at the site of Tumbe. Slag from this trench comes from a dark brown loamy sand midden sealed below the Mazrui fort deposits. Artefacts from this layer include Early Tana Tradition pottery and turquoise alkaline-glazed and opaque-glazed ware pottery, all materials indicating an eighth to ninth century CE date.

Chwaka

The site of Chwaka was documented by Pearce (1920) and other colonial-era writers, drawn to its standing mortared-coral ruins; portions of three mosques still stand as well as two pillar tombs and some ten smaller tombs. Garlake (1966) documented two of the standing mosques; Horton and Clark

(1985) further surveyed the site. In the late 1990s, additional exploratory work took place there, followed by intensive excavations—30 test units and additional large-scale exposures—from 2002 to 2006 (Figs. 3 and 4) as part of the household-based study of regional political organisation and economy mentioned above (Horton 2004; LaViolette and Fleisher 2009, 2018; Fleisher and LaViolette 2013). In total, multiple superimposed earthen houses, a coral house and mosques, and several community middens were excavated. While the analysis is ongoing, we can say that in the eleventh century, likely shortly after Tumbe was abandoned, a community founded Chwaka on the highest and easternmost portion of the peninsula. The predominantly earth-and-thatch settlement was anchored by a series of enlarging coral mosques and grew steadily through the twelfth to thirteenth centuries. It reached its maximum size of 12 ha in the fourteenth to fifteenth centuries, just before abandonment (Fleisher 2010). Its medium size and dearth of stone houses suggests it was less a commercial centre than a thriving agricultural/fishing town that invested heavily in religious architecture and social practice such as public feasting. Yet, imported goods flowed steadily into Chwaka; a wide range of pottery and glass, stone and glass beads, and personal items of many kinds came from deposits throughout the site. Farmers based their agriculture increasingly on Asian rice (Walshaw 2010), grown just south of the peninsula in a shallow brackish inlet. In the 500 years of Chwaka's existence, it shared Pemba with some 6 other towns of its size or larger as well as many villages. Though only half as large as Tumbe, the likely larger population at Chwaka lived in a more densely settled community as evidenced in the 3 m of deposits in some parts of the site. Evidence for pottery and lime making, feasting, and fibre/fabric production was recovered in addition to iron production. The slag samples used in the present analysis came from Operations 6–8, 10, and 12 excavated in 2006 (Fig. 4). Large-exposure excavations focused on areas with earthen architecture that had been detected through test units. These include Operations 6 and 7; each of these measured 6×6 m and were located just north of the Great Mosque. Excavations revealed successive layers of earthen houses with associated hearths and midden contexts. Similarly, adjacent Operations 8, 9, and 12 revealed dense midden deposits and the remains of earthen structures in the form of daub and postholes as well as a buried coral rag toilet feature. These trenches (5×4.5 m; 7×4.5 m; 4×5 m, respectively) were located in the northeast corner of the peninsula. Finally, Operation 10 was a large exposure of a coral rag mosque at the northern edge of the Chwaka peninsula likely dating to the fourteenth century. The slag analysed from Operation 10 comes from the lowest layers excavated (48, 49, 50), in the main hall in front of the *mihrab*. These deposits predate the construction of the mosque and are thus related to occupation deposits in the area dating to the twelfth to thirteenth centuries.

Materials and methods

Materials

A total of 52 pieces of iron slag from the three sites were collected and examined as part of this study, exploiting stored collections from past excavations. Three key criteria for sample selection were defined at the outset of the study:

1. Samples were to be obtained from secure archaeological contexts.
2. The iron slag fragments were to be representative of the overall range of surface morphologies present in the assemblages.
3. Representative quantities from individual contexts were to be collected; the goal was to select more samples from richer contexts and fewer from deposits where less material was recovered.

However, while accessing the assemblages from the selected sites, a number of challenges were encountered limiting what material was available and requiring a more flexible sampling strategy. The outlined criteria were followed where possible, but where they could not feasibly be met, material was sampled with one criterion in mind—the sampled objects were to be representative of the available material.

Excavated artefacts were kept at and selected from two storerooms. The material from Unguja Ukuu was stored at the House of Wonders in Zanzibar town. With the outlined sampling strategy in mind, the aim was to select iron slag exclusively from archaeological excavations carried out by Juma (2004), the most extensive and comprehensively published excavations at the site to date. Approximately 600 kg of iron slag was excavated during this project, 500 kg of which came from one area corresponding to contexts F, G, H, and I (Juma 2004). Slag from these contexts was explicitly targeted during the search for material. However, material from these particular contexts could not be located. Artefacts had been relocated to the House of Wonders from a previous storeroom, where collections were kept in humid conditions where the wooden storage boxes had started to disintegrate due to insects and humidity. Some plastic bags in which the samples were kept were similarly affected by insects, and contextual information about the samples was no longer legible in several instances. The amount of iron slag found in the storerooms was relatively small compared to the reported 600 kg of slag excavated at the site. While no slag from contexts F-I was located, slag from the majority of other excavated units was present. At this point, it was considered important to sample as broad a variety of contexts as possible. In addition to collecting a representative number of samples from each context from Juma's excavations, a small number of samples excavated by Horton and Clark (1985) were collected. In addition, several pieces of slag from deteriorated bags that no longer held reliable contextual information were sampled to document information about contexts that may not have otherwise been accounted for.

A total of 32 samples were collected from the storerooms. Contextual and chronological information about each sample appears in Table 1.

Following the collection of iron slag samples from the House of Wonders in 2016, a small-scale excavation led by Stephanie Wynne-Jones and Federica Sulas was carried out at Unguja Ukuu in 2017 (Sulas et al. 2019; Wynne-Jones et al. 2020). During this excavation, over 50 kg of slag was found. While the material could no longer be included in the laboratory analysis stage of the project, the archaeological data collected during the excavation are considered here.

Iron slag samples excavated on Pemba Island (Tumbe and Chwaka sites) are stored at Chake Chake Museum, central Pemba. The material is kept in robust wooden boxes stacked in a relatively small storeroom. All boxes associated with Tumbe/Chwaka were searched for iron slag material. Contextual information was preserved well in comparison to samples from Unguja Ukuu. However, similar challenges in locating the sought-after contexts were encountered. The initial goal was to access slag from 2002 excavations, during which a total of 18.6 kg (7 kg at Tumbe and 11.6 kg at Chwaka) was excavated between the two sites and during which good spatial and chronological resolution of slag distribution was obtained. However, only materials from the 2006 excavations were located in the storerooms and

Table 1 Unguja Ukuu slag collected at House of Wonders storerooms. Contextual information presented as it was originally recorded by Juma (2004) and Horton and Clarke (1985); [a] analysed with μ-XRF; [b] analysed with optical microscopy

Sample	Excavation director, year	Context	Period (centuries CE)
UU001[ab]	Juma 1989–1993	Unit B, layer 15A	6th–9th
UU002	Juma 1989–1993	Contextual information lost	Unknown
UU003[ab]	Juma 1989–1993	Contextual information lost	Unknown
UU004[ab]	Juma 1989–1993	Unit B, layer 9	6th–9th
UU005[a]	Juma 1989–1993	Contextual information lost	Unknown
UU006	Juma 1989–1993	Contextual information lost	Unknown
UU007[ab]	Juma 1989–1993	Long Trench, layer 4	10th–15th
UU008[ab]	Juma 1989–1993	Surface collection	Unknown
UU009	Juma 1989–1993	Unit B, layer 15A	6th–9th
UU010[ab]	Juma 1989–1993	Unit B, layer 15A	6th–9th
UU011[ab]	Juma 1989–1993	Unit B Layer 6	9th–10th
UU012[ab]	Juma 1989–1993	South long trench, layer 1	10th–15th
UU013	Juma 1989–1993	South long trench, layer 1	10th–15th
UU014[ab]	Juma 1989–1993	Surface collection	Unknown
UU015	Juma 1989–1993	Long Trench, layer 2	10th–15th
UU016	Juma 1989–1993	Long Trench, layer 2	10th–15th
UU017	Juma 1989–1993	Unit M, layer 22	9th–15th
UU018[ab]	Juma 1989–1993	Unit J, layers 7 and 8	9th–15th
UU019	Juma 1989–1993	Unit B, layer 14	6th–9th
UU020[ab]	Juma 1989–1993	Unit B, layer 14	6th–9th
UU021	Juma 1989–1993	Unit B, layer 14	6th–9th
UU022[ab]	Horton and Clark 1985	NO 218, UU01	6th–10th
UU023[ab]	Horton and Clark 1985	UU01 03	6th–10th
UU024	Horton and Clark 1985	NO33, UU01 03	6th–10th
UU025	Juma 1989–1993	Unit B, layer 14	6th–9th
UU026[ab]	Juma 1989–1993	Unit B, layer 14	6th–9th
UU027	Juma 1989–1993	Unit B, layer 14	6th–9th
UU028	Juma 1989–1993	Unit L, layer 9	9th–10th
UU029	Juma 1989–1993	Unit B, layer 15B	6th–9th
UU030	Juma 1989–1993	Unit B, layer 15B	6th–9th
UU031[ab]	Juma 1989–1993	Unit L, layer 2	12th–15th
UU032[ab]	Juma 1989–1993	Unit L, layer 2	12th–15th

sampled. The available assemblage contained slag from most chronological periods and once again, a representative sample of material available was selected. A total of 5 slag pieces were chosen for the study from Tumbe and 15 from Chwaka; their contextual information is provided in Tables 2 and 3. The tables detail the chronological and spatial information associated with each slag piece.

Overall, 52 samples of iron slag from Unguja Ukuu, Tumbe, and Chwaka were selected for the study. The samples originate from a broad variety of spatial and chronological contexts and provides a meaningful representation of craftworking activities over time. The limitations of the material present further challenges to the robustness of the suggested methodology and simultaneously illustrate its potential.

Methods

The analysis of iron slag was performed in 4 key stages: macroscopic analysis of the material that included examination of material dimensions and visual assessment of sample morphology; optical microscopy of sample sections; quantitative elemental analysis; and evaluation of the results in their archaeological context. We discuss these steps in detail in this section.

Table 2 Samples selected from Tumbe assemblage in Chake Chake storerooms. Sample contextual information is presented as it was originally assigned during the excavation; [a] analysed with μ-XRF; [b] analysed with optical microscopy

Sample	Site	Bag number	Operation	Layer	Period (centuries CE)
TBCH007[a,b]	Tumbe	2245	11	11	8th–9th
TBCH009[a,b]	Tumbe	2305	11	20	8th–9th
TBCH010[a,b]	Tumbe	2305	11	20	8th–9th
TBCH011[a]	Tumbe	2305	11	20	8th–9th
TBCH012	Tumbe	2305	11	20	8th–9th

Visual examination and typology

The samples were first washed, photographed, and examined macroscopically. Their dimensions were recorded and morphology was assessed in order to establish typologies. Samples were weighed, and their length, width, and height measured. Their surface features were recorded to make note of any inclusions, charcoal impressions, or adhering sediment or clay. Five morphological types were defined, namely convex bottom slag (CBS), hammerscale, prill, flowed, and non-diagnostic, and are described in detail in Table 4. Only a few of the types of slag described in the table were found at Unguja Ukuu, Tumbe, and Chwaka, but here we detail the comprehensive typology used during the wider PhD research project of which this study formed a part (Baužytė 2019).

Each sample was attributed to one of these categories. To determine whether each piece of slag formed during smithing or smelting processes, its archaeological context was assessed. Differentiating smithing and smelting slag is notoriously difficult. While morphologies can be informative, it is important to note that surface features can usually be used as indicative rather than definitive of specific processes. During this research project, in addition to morphological properties of the material, the archaeological context within which slag was found was considered another key factor in attributing slag samples to these broader categories of smithing, smelting, or non-diagnostic slag. Smelting and smithing contexts are often

Table 3 Samples selected from Chwaka assemblage in Chake Chake storerooms. Sample contextual information is presented as it was originally assigned during the excavation; [a] analysed with μ-XRF; [b] analysed with optical microscopy

Sample	Site	Bag number	Operation	Layer	Period (centuries CE)
TBCH001[a,b]	Chwaka	2283	6	9	14th–15th
TBCH002[a,b]	Chwaka	2208	6	6	14th–15th
TBCH008[a,b]	Chwaka	2370	6	5	12th–13th
TBCH015	Chwaka	2207	6	5	12th–13th
TBCH017[a,b]	Chwaka	2284	6	6	Likely 15th
TBCH022[a,b]	Chwaka	2330	7	12	13th–14th
TBCH016	Chwaka	2032	8	3	14th–15th
TBCH018[a,b]	Chwaka	2296	8	6	14th–15th
TBCH020	Chwaka	2184	8	4	14th–15th
TBCH003[a,b]	Chwaka	2222	10	48	12th–13th
TBCH004	Chwaka	2204	10	49	12th–13th
TBCH005[a]	Chwaka	2204	10	49	12th–13th
TBCH006	Chwaka	2204	10	49	12th–13th
TBCH021[a,b]	Chwaka	2200	10	50	12th–13th
TBCH019	Chwaka	2277	12	5	13th–14th

Table 4 A list of slag sub-types identified during the study, explaining their formation process and identifying features

Convex bottom slag (CBS)	Pieces of slag thought to have formed at the bottom of a smithing hearth or smelting furnace. Their characteristic convex bottom forms as molten slag settles at the bottom of a bowl-shaped hearth or furnace with a slag pit and eventually solidifies preserving the outline of the depression. This type of slag is more commonly referred to as plano-convex in literature (Serneels and Perret 2003; Selskienė 2007; Portillo-Blanco et al. 2020), but due to highly variable degrees of concavity observed on the top part of the slag, the term CBS was thought to more accurately describe the type's morphology. Depending on the archaeological context this type of slag can further be classed as SHB (smithing hearth bottom when found in smithing contexts) (Paynter 2007; Veldhuijzen 2009a, b; Eliyahu-Behar et al. 2013), or FBS[a] (furnace bottom slag when found in smelting contexts) (Coustures et al. 2003; Blakelock et al. 2009)
Hammerscale and droplets	Refers to tiny fragments of slag that flake off the surface or are expelled from inner layers of an iron object during the forging process. These normally measure up to a few mms in size. Flat scale-like/platey hammerscale is detached from the surface of the worked iron object while spherical hammerscale forms when molten slag is expelled from welding lines of the material, and the droplet solidifies when exposed to room temperatures. Highly similar slag fragments can also form during hammering of iron bloom immediately after its extraction from a furnace and may be associated with smelting processes. These fragments are referred to as droplets and unlike hammerscale have multiple mineral phases. (Dungworth and Wilkes 2009; Jouttijärvi 2015)
Prill	Small pieces of slag that form as molten material flows down in a smithing hearth or smelting furnace and solidifies without having settled at the bottom, preserving morphology indicative of vertical flow. In this research, whether a prill is associated with smelting or smithing activities, or is considered non-diagnostic was determined primarily by the archaeological context (Dungworth et al. 2015)
Fuel ash slag	Often grey and pumice-like in appearance, fuel ash slag can form in a smithing hearth or a smelting furnace when fuel and other components fused together. Such slag is usually light, brittle, and amorphous. Friede et al. (1982) describes this type as slag that collected on the surface of molten slag and sintered together without reaching melting temperature
Flowed	When molten slag flows out of a smelting furnace or runs within a hearth and solidifies upon exposure to the atmosphere, horizontal flow features can be preserved in surface morphology. When these are visible on the slag surface, a sample is described as flowed slag. When archaeological context clearly indicates that smelting operations were taking place at the site and this type of slag is found in substantial quantities, it is often identified as tap slag that forms when a smelting furnace is partially broken to release excess slag. In the absence of clear evidence of smelting this type of slag is not considered diagnostic (Sauder and Williams 2002; Miller and Killick 2004)
Non-diagnostic	When no distinctive surface features were observed, the slag sample was simply identified as non-diagnostic

[a]Evidence suggests that iron working in a number of African contexts is a three- rather than two-tier process, involving smelting, refining, and smithing (Lyaya et al. 2012). As the first two are carried out in furnaces and both can result in formation of convex bottom slag, more accurate terms would be Smelting Furnace Bottom Slag (SFBS), Refining Furnace Bottom Slag (RFBS) and Smithing Hearth Bottom Slag (SHBS), or shortened as SBS, RBS, and SHB. However, due to established convention, FBS is used here.

associated with different types of archaeological materials and settings. These are listed in Table 5 and were considered when determining typologies. The relationship between morphological categories listed in Table 4 and broader typologies of the three broad categories of slag are illustrated in Fig. 5.

Quantitative elemental analysis

Following the macroscopic examination, a subsample of 17 pieces of iron slag from Unguja Ukuu, 4 pieces from Tumbe, and 8 from Chwaka were selected for quantitative elemental examination using Bruker Tornado μ-XRF. The analysis was

Table 5 List of archaeological materials commonly associated with smithing and smelting processes. These aspects were taken into consideration when examining whether archaeological context is more suggestive of smithing or smelting processes

Indicative of smelting processes	Indicative of smithing processes
1. Large amounts of tuyère found in association with iron slag	1. Presence of hammerscale
2. Furnace remains	2. Association with settlement activities
3. Fragments of unused iron ore	3. Assemblage dominated by CBS-type slag not measuring more than a few inches in length
4. Dense distribution of iron slag, sometimes in heaps visible above the surface	4. Evidence of a smith's workshop, such as anvil, hammer, hearth
5. Significant presence of large slag blocks or flowed slag	5. Slag found in mixed midden contexts, discrete small-scale concentrations, or scattered individually (not necessarily exclusive to smithing, although more consistent with reported smithing evidence)
6. Absence of domestic activity (although presence of domestic activity does not rule out the possibility of smelting taking place)	6. Absence of types of evidence listed as points 1–3 in 'indicative of melting processes' column of this table

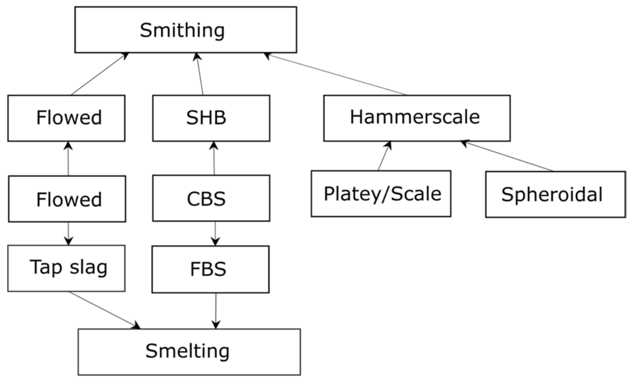

Fig. 5 Table outlining slag type and subtype relationships as they are used in this paper. Morphological types are usually considered undiagnostic, subtypes can further be attributed to smithing and smelting processes and are informed by contextual evidence

done to better understand internal slag chemistry and assess whether distinct chemical fingerprints could be associated with different sites. In preparation for the analysis each sample was sectioned using a lapidary steel saw with a diamond cutting edge to expose a fresh, unweathered surface and access material composition that is more representative of the full production episode than the information that surface analysis would provide. The sections were then roughly polished using a series of SiC grinding papers of 180p, 500p, and 1000p. This was done to obtain an even surface that would minimise scattering of incoming and outgoing X-rays during the elemental analysis.

Samples were analysed at the AGiR (Aarhus University Geochemistry and Isotope Research Platform) centre based in the geoscience department at Aarhus University. Quantitative elemental analysis was performed using Bruker M4 Tornado µ-XRF instrumentation with a single target Rh X-Ray tube. The instrument voltage was set to 50 kV and current to 600 µA. Dual detector mode was selected to mitigate any shadowing effects that occur in samples with uneven surfaces. The samples were analysed using area analysis mode. This means that once an area in the sample was selected, the instrument scanned this area as if reading a book—left to right and top to bottom—analysing 20-µm points across this area, mapping elemental distribution, and quantifying the overall chemical composition of the sample. Each analysis area was scanned twice with analysis time of 3 ms/px. Ten different areas were analysed on each sample. The accuracy of the measurements was first assessed examining three basalt glass CRMs (BCR-2G, BHVO-1G, and BIR-1G). Glass standards were chosen because they were believed to bear the closest resemblance to iron slag in terms of chemical composition and nature of matrix from the standards available. The analytical total ranged from 60 to 65% due to the nature of the analytical instrumentation. Oxygen was added by stoichiometry and the results were normalised to 100 wt%. The results of standard analysis demonstrated that measurements provided consistently accurate quantitative elemental evaluation of sample composition and are summarised in Table 6. When analysing slag samples, each analysis area was selected avoiding any porosity and was located at a distance from the external surface of the sample to avoid any contamination from corrosion layers. The reported results are a mean calculated from 10 measurements carried out on each sample.

Optical microscopy

Following µ-XRF analysis samples were prepared and analysed using reflected light optical microscopy. The purpose of optical microscopic analysis was to understand phase composition, variability, and features. The analytical goal was to examine the obtained micrographs in light of known sample chemical composition and determine whether the results can provide meaningful insights about raw materials and thermal conditions involved in the production process.

Table 6 Results of analysis of three basalt glass CRMs. Reference—presents the certified elemental wt%. Analysed—presents a mean of 10 measurements performed on the CRMs using Bruker Tornado µ-XRF. SD—1σ standard deviation. δ—difference between certified and measured values of elemental wt%. BDL—below instrument detection limits

		SiO_2	MgO	Na_2O	Al_2O_3	K_2O	CaO	TiO_2	MnO	FeO	P_2O_5
HVO-2G	Reference	49.60	7.26	2.22	13.44	0.51	11.40	2.73	0.17	11.14	0.27
	Analysed	50.35	7.44	1.78	13.54	0.54	11.40	2.79	0.17	11.74	0.15
	STDev	0.07	0.05	0.11	0.06	0.01	0.03	0.01	0.00	0.06	0.01
	δ	0.75	0.19	−0.44	0.10	0.03	0.00	0.06	0.00	0.60	−0.12
BCR-2G	Reference	54.00	3.60	3.12	13.48	1.77	7.11	2.27	0.20	12.39	0.36
	Analysed	54.87	3.38	2.96	13.66	2.00	7.04	2.37	0.20	13.25	0.19
	STDev	0.09	0.05	0.18	0.04	0.01	0.03	0.01	0.00	0.07	0.01
	δ	0.87	−0.22	−0.16	0.18	0.23	−0.07	0.10	0.00	0.86	−0.17
BCR-1G	Reference	47.50	9.40	1.85	15.50	0.03	13.30	1.04	0.19	10.40	0.03
	Analysed	47.96	10.10	1.27	15.55	BDL	13.23	0.99	0.17	10.67	BDL
	STDev	0.08	0.07	0.14	0.05	–	0.04	0.00	0.00	0.04	–
	δ	0.46	0.70	−0.58	0.05	–	−0.07	−0.05	−0.02	0.27	–

Fragments from sections previously analysed with μ-XRF were broken off using lineman's pliers and embedded into two component epoxy resin. Resin mounds measured 2 cm in diameter and no piece analysed exceeded those dimensions. Samples were ground down to obtain an even surface using 200p, 500p, and 1000p SiC papers. The samples were subsequently polished to a 1-μm finish employing a series of diamond sprays in order to obtain a mirror-like surface. Struers rotary polishing instrumentation with mountable polishing fabrics and diamond sprays of decreasing particle size (15 μm, 9 μm, 6 μm, 3 μm, and 1 μm) were used.

The polished samples were analysed using a NIKON eclipse E600 pol optical microscope in reflected light mode. The microscope was equipped with a Nikon DS-Fi1 camera which was used to capture images of the observed microstructures. No etching of the samples was performed. Samples were examined using a range of magnifying lenses allowing for × 20 to × 500 magnification. During the analysis, details about types of phases present in samples were recorded, and their size, sample homogeneity, and extent of corrosion were noted. These details were indicative of raw materials used in the production process, redox conditions in the hearths, and cooling rates to which the slag was exposed.

Examining the context

To contextualise the results of the archaeometallurgical analysis, excavation reports and published literature on the sites were examined for any detail relating to iron production activity. Since each site was excavated with different research questions in mind and inevitably different methodological approaches, no single overarching methodology to contextualise iron production could be devised. The key evidence available from archaeological literature was information about the weight of slag excavated from individual contexts. This information was used to interrogate two key aspects of iron production at the sites:

1. Chronology. Weights of slag from different chronological contexts were examined to identify trends in production intensity. The data were evaluated to determine whether the output of slag remained comparable throughout site occupations or intensified/diminished during certain phases of occupation.
2. Spatial patterns. Two questions concerning the spatial distribution of ironworking debris at each site were addressed. The first question was whether discrete areas of iron production could be identified, or if iron smithing was taking place across the sites without any evidence of spatial containment of the activity. Secondly, the spatial relationship between iron production and domestic activity was examined. The distribution of iron slag was assessed against the presence/absence of evidence of domestic structures (remains of daub or coral stone houses). Where relevant, the data were digitised, visualised, and examined using Qgis software.

Results

Unguja Ukuu

Assemblage description and morphological analysis

A total of 32 samples collected from House of Wonders storerooms weighed a total of 2.9 kg. Their mean weight was 93.3 g with a significant standard deviation of 84.6 g and most of the samples weighed less than 100 g. The variation in sizes is also notable in slag length, width, and thickness. Detailed measurements for each sample are provided in Table 7. It is worth noting that slag samples selected for the analysis may not be fully representative of the dimensions of slags found at the site. During subsequent excavations, convex bottom slag pieces weighing up to 1.5 kg were found with average weight of excavated slag being c. 200 g. Due to time and resource restrictions, we were not able to include further samples in the study. While the selected assemblage is representative of the material available from storerooms, the results should be interpreted keeping in mind that the largest slag pieces found at Unguja Ukuu are not represented in this study. Assessment of slag morphology revealed that 21 of the 32 pieces of slag could be characterised as convex bottom slag (Fig. 6). The remaining samples had a variety of surface features and were identified as non-diagnostic. Nineteen samples contained charcoal impressions and 7 bore impressions of wood charcoal. In addition, inclusions of quartz, lateritic soils adhering to the surface of slag, and calcareous particles were noted (Table 7).

Optical microscopy analysis

Sixteen samples of iron slag were subsequently examined using reflected light optical microscopy (Fig. 7). The analysis revealed that most samples (9 of 16) had a wüstite-dominated microstructure. Their matrix mostly consisted of wüstite dendrites and globules surrounded by a glassy phase. Four of the 15 samples were dominated by olivine, most likely fayalite, phases in a glassy matrix, although some small wüstite crystals were present. Finally, the remaining 3 samples had a highly heterogeneous microstructure with relatively even proportions of olivine and wüstite phases. Spinel crystals (likely hercynite) were also noted in some of the samples. Furthermore, significant corrosion was recorded in some of the sections. This was evident from streaks of corrosion product visible in the microstructure and in some cases, preferentially corroded glass phase around

Table 7 Unguja Ukuu sample dimensions, typologies, and surface features recorded during the investigation

Sample no	Type	Impressions	Inclusions	Weight (g)	Width (mm)	Length (mm)	Thickness (mm)
UU001	CBS	Charcoal	Calcareous	167	70	73	11
UU002	CBS	Charcoal	Charcoal	72	33	65	21
UU003	CBS	–	–	133	34	44	29
UU004	CBS	Charcoal	Calcareous, charcoal	186	55	70	35
UU005	CBS	Charcoal	Charcoal, hammerscale, quartz	160	48	55	35
UU006	CBS	–	Quartz	32	32	40	17
UU007	CBS	Charcoal	Calcareous	99	35	61	34
UU008	ND	Charcoal	–	33	26	46	25
UU009	CBS	Charcoal	Hammerscale, quartz	46	40	44	27
UU010	CBS	–	Charcoal	79	34	45	29
UU011	CBS	–	–	61	43	50	22
UU012	CBS	Charcoal	–	46	33	42	22
UU013	ND	–	–	44	32	44	25
UU014	CBS	Charcoal	Calcareous, furnace/hearth lining	466	62	99	56
UU015	Flowed	–	–	59	27	27	25
UU016	ND	Charcoal	–	15	25	41	14
UU017	CBS	–	–	23	29	30	13
UU018	ND	Charcoal	Calcareous	107	43	61	26
UU019	CBS	–	–	72	37	53	24
UU020	CBS	–	Calcareous	64	38	53	20
UU021	CBS	–	–	32	24	41	24
UU022	CBS	Charcoal	–	133	57	75	23
UU023	CBS	Charcoal	Charcoal, quartz	158	41	47	33
UU024	CBS	–	Charcoal, quartz	136	59	84	15
UU025	CBS	Charcoal	Calcareous, quartz	63	38	59	16
UU026	CBS	–	Charcoal	98	47	53	25
UU027	CBS	Charcoal	Quartz	53	31	42	19
UU028	ND	Charcoal	Quartz	75	38	46	35
UU029	CBS	Charcoal	–	23	30	34	14
UU030	CBS	–	Quartz	23	21	49	17
UU031	CBS	Charcoal	–	134	49	60	30
UU032	CBS	Charcoal	–	34	35	42	16
			Min	15	34	21	11
			Max	466	99	70	56
			Mean	93.3	52.7	39.1	24.5
			SD	84.6	15.6	12	9

olivine needles and dendritic wüstite structures. The considerable corrosion may have been propagated by sample porosity and altered sample chemical composition. This is an important consideration when interpreting the results of quantitative elemental analysis. Overall, most samples had well-developed crystals and had some level of heterogeneity in their microstructure.

Quantitative elemental analysis

Seventeen samples of iron slag from Unguja Ukuu were analysed to examine their chemical composition Table 8. Overall, the results of the analysis suggest that elemental concentrations in iron slag from this site are highly variable. The significant variability is seen across the assemblage as well as within individual samples. This variability is well represented by differences in major element weight percentages. The wt% of FeO varied from 58 to 94% while SiO_2 ranged from 1.33 to 23.68 wt% across the assemblage. Similarly, considerable variability was observed in individual samples with FeO relative standard deviation calculated at 2% in more chemically homogeneous samples, while in more variable pieces of slag, FeO relative σ approached 17%. Even higher ranges in relative standard

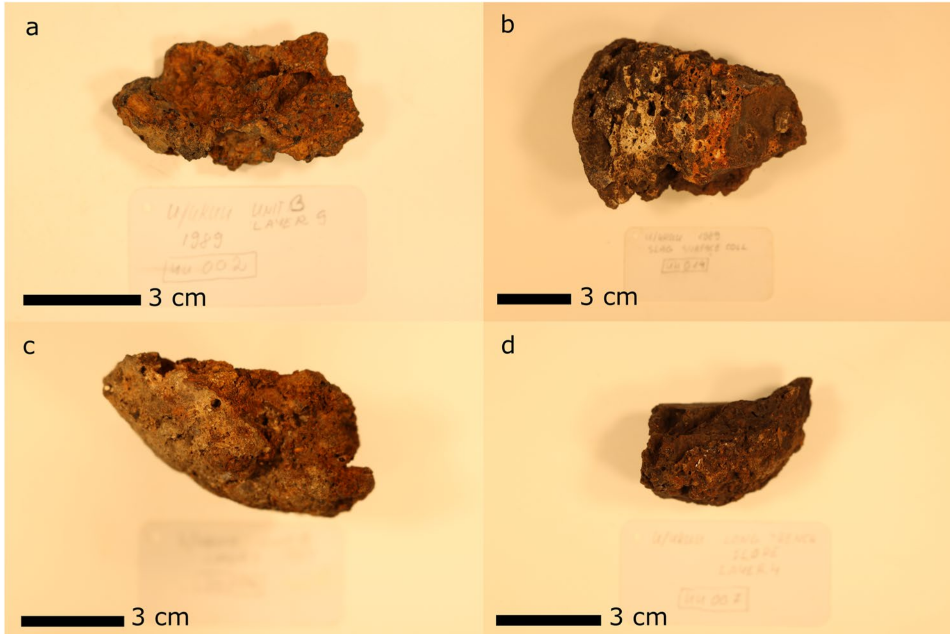

Fig. 6 Images of CBS slag excavated at Unguja Ukuu. **a** UU002. **b** UU014 slag with calcareous inclusions. **c** UU004. **d** UU007

deviation within individual samples were calculated for other compounds.

The results of the quantitative elemental analysis were plotted in a ternary FeO-SiO_2-Al_2O_3 diagram (Fig. 8), so as to examine sample liquidus temperatures and further visualise the wide range of chemical compositions. Most samples plotted in the wüstite temperature region, described by liquidus temperatures ranging from 1148 to 1369°C. Three samples corresponded to the fayalite region associated with melting temperatures of 1088–1178°C, although this does not seem to correlate with micrographs where few fayalite crystals were observed. The remaining three samples were plotted in the hercynite region. Spinel crystals suggestive of hercynite phases were noted in the microstructure of these three samples and the results of optical microscopy are consistent with the elemental analysis.

Examination of archaeological context

To identify any chronological and spatial patterns in ironworking activity at Unguja Ukuu, data reported from three excavation projects (Horton and Clark 1985; Juma 2004; Wynne-Jones and Sulas 2017) were reviewed. During their 1984–1985 survey of standing monuments on Zanzibar Island, Horton, and Clark excavated three test trenches along the western part of the site. One of the trenches, UU1, situated at the southern end of the site yielded significant amounts of slag (c. 120 pieces for 8.4 m^3 of soil excavated), associated with early occupation of the site (sixth to tenth CE).

The most abundant evidence of ironworking amounting to approximately 600 kg of iron slag was recovered during the excavation project led by Juma. Some 82% of this volume (500 kg) was excavated in trenches F–J. These trenches cut through several different layers and features of different time periods, meaning that the excavated slag could not be attributed to a chronological occupation period of the site. It is worth noting that even though the largest amount of slag was retrieved from these units, the trenches also accounted for a huge portion of the soil lifted during the excavation. When the cubic area of excavated soil (96 m^3) is factored in, the amount of slag excavated averaged 5.2 kg/m^3. Furthermore, the excavation was limited to the central-northern part of the site limiting the extent to which evidence of the spatial distribution of ironworking activities can be understood elsewhere at Unguja Ukuu. In addition to spatial limitations of the dataset, detailed information about the volume of slag excavated from each archaeological context was not available. However, the samples can be seen in light of how much slag was recovered for each chronological period (Juma 2004: 137). On average, 7 kg/m^3 of slag were found in the sixth to eighth century CE levels, 3 kg/m^3 of slag were uncovered from the eighth to tenth centuries CE and 7 kg/m^3 were found in the eleventh century CE layers. Published data on slag found at Unguja Ukuu was collated and is presented in Fig. 13. Iron slag was uncovered at all parts of the site and no clear spatial concentrations of the material are noted based on this synthesis.

During the 2017 excavation, slag was uncovered in every excavated trench in varying amounts. A relatively small amount, 172 pieces amounting to 2.7 kg of iron slag were excavated in trench UZ001 (1.08 kg/m^3 of lifted soil). Trench UZ002 was particularly rich in iron slag with 2094 excavated pieces weighing a total of 46.93 kg. Most of the

Table 8 Results of μ-XRF analysis of slag samples from Unguja Ukuu. Ten measurements were carried out per sample and the table presents the mean and RSD of those measurements. BDL—below detection limits

Sample		MgO	K_2O	CaO	TiO_2	FeO	Al_2O_3	SiO_2	PbO	MnO	SrO	SiO_2: Al_2O_3
UU001	Mean	BDL	BDL	8.82	0.13	72.53	2.4	13.75	0.03	BDL	0.15	5.73
	RSD	–	–	42%	27%	11%	35%	32%	56%	–	39%	
UU003	Mean	BDL	BDL	6.02	0.16	76.34	3.03	12.04	0.01	0.36	0.09	3.97
	RSD	–	–	33%	23%	8%	21%	27%	58%	15%	33%	
UU004	Mean	1.49	0.42	8.94	0.25	62.7	5.65	19.07	0.02	–	0.15	3.38
	RSD	27%	19%	17%	22%	7%	13%	11%	58%	–	16%	
UU005	Mean	BDL	BDL	1.78	0.17	67.43	4.68	23.68	0.01	BDL	0.05	5.06
	RSD	–	–	30%	28%	5%	34%	3%	102%	–	36%	
UU007	Mean	BDL	BDL	6.08	0.17	74.39	4.9	11.79	0.02	0.44	0.07	2.41
	RSD	–	–	21%	18%	7%	22%	21%	66%	4%	22%	
UU008	Mean	BDL	BDL	0.95	0.19	70.75	3.33	23.65	0.03	BDL	0.03	7.10
	RSD	–	–	54%	42%	17%	56%	38%	129%	–	42%	
UU010	Mean	BDL	BDL	1.33	0.24	85.52	4.33	6.59	0.01	0.64	0.02	1.52
	RSD	–	–	63%	51%	7%	35%	52%	104%	29%	61%	
UU011	Mean	BDL	0.28	5.21	0.16	77.1	2.86	12.01	0.01	0.65	0.08	4.20
	RSD	–	100%	61%	40%	20%	48%	83%	109%	20%	59%	
UU012	Mean	BDL	BDL	2.13	0.09	94.98	BDL	1.33	0.02	BDL	0.01	–
	RSD	–	–	76%	81%	3%	–	137%	66%	–	55%	
UU014	Mean	BDL	0.78	1.86	0.04	75.97	1.13	18.88	0.02	BDL	0.02	16.71
	RSD	–	46%	26%	42%	7%	69%	21%	93%	–	56%	
UU018	Mean	BDL	0.66	2.14	0.33	78.02	5.65	11.58	0.01	0.64	0.03	2.05
	RSD	–	75%	62%	52%	17%	64%	67%	96%	46%	45%	
UU020	mean	BDL	0.23	3.54	0.32	71.08	9.75	13.39	0.01	0.45	0.03	1.37
	RSD	–	85%	37%	23%	11%	41%	34%	48%	13%	41%	
UU022	Mean	BDL	0.32	10.87	0.39	58.27	8.35	18.51	0.02	BDL	0.14	2.22
	RSD	–	24%	24%	16%	13%	14%	17%	59%	–	19%	
UU023	Mean	BDL	BDL	14.2	0.08	73.22	BDL	9.69	0.03	BDL	0.2	–
	RSD	–	–	25%	67%	9%	–	37%	33%	–	27%	
UU026	Mean	BDL	BDL	2.65	0.12	88.6	2.26	3.85	0.02	BDL	0.03	1.70
	RSD	–	–	30%	42%	3%	35%	27%	55%	–	105%	
UU031	Mean	1.06	BDL	7.74	0.09	77.92	1.76	9.78	0.03	BDL	0.11	5.56
	RSD	58%	–	56%	83%	8%	31%	21%	39%	–	59%	
UU033	Mean	1.71	BDL	1.34	0.08	92.68	1.17	1.65	0.02	BDL	0.01	1.41
	RSD	32%	-	25%	23%	2%	27%	56%	41%	–	45%	

slag (1269 pieces with a total weight of 42.66 kg) was excavated in the first three surface layers (#2001, #2002, and #2003) dated to the eighth to tenth CE. Approximately 5 kg/m^3 were excavated from the entire trench.

Tumbe

Assemblage description and morphological analysis

A total of 5 pieces of slag from Tumbe were collected from the Chake Chake museum storerooms, corresponding to the first occupational period of the peninsula (Fig. 9). Detailed results of the morphological analysis and measurements are presented in Table 9. Overall, the assemblage contained samples relatively similar in size and not exceeding 218 g. Diagnostic slag samples were identified as CBS.

Optical microscopy analysis

Three of the slag samples from the Tumbe assemblage were analysed using optical microscopy (Fig. 10). Overall, a variety of microstructural compositions was observed in the samples. One of the samples (TBCH007) was dominated by olivine phases, while the remaining two had relatively equal proportions of olivine and wüstite phases. Slag samples contained mostly relatively large, well-developed phases, although some eutectic wüstite and small dendrites

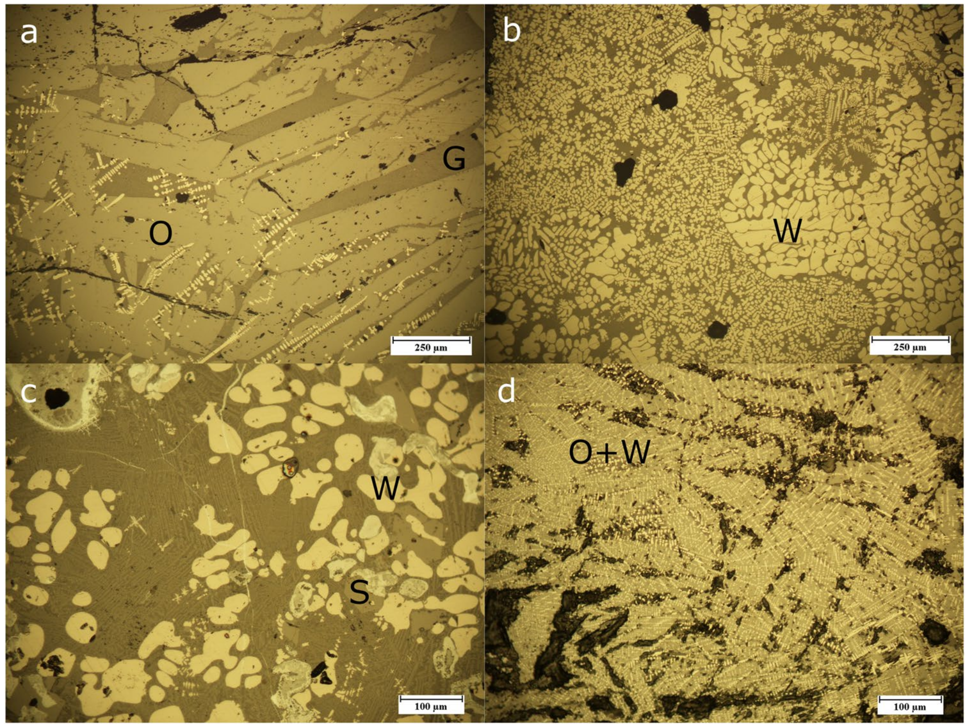

Fig. 7 Images of slag microstructure taken using reflected light optical microscopy. **a** Olivine dominated microstructure with glassy matrix and wüstite dendrites. **b** Slag microstructure dominated by wüstite globules and dendrites. **c** Heterogeneous microstructure with no one dominant phase; wüstite globules and spinel crystals visible in glassy matrix with small olivine needles and mineral inclusions. **d** Olivine crystals and wüstite dendrites in corroded matrix (preferentially corroded glassy phase). W, wüstite; O, olivine; G, glassy phase; S, spinel crystals

are noted in the matrices. Sample TBCH007 contained corrosion bands, and sample TBCH010 had an oxide band indicative of liquefied slag surface exposed to an oxygen-rich environment.

Quantitative elemental analysis

A total of 4 slag pieces recovered at Tumbe were analysed for their quantitative elemental composition. Overall, the results

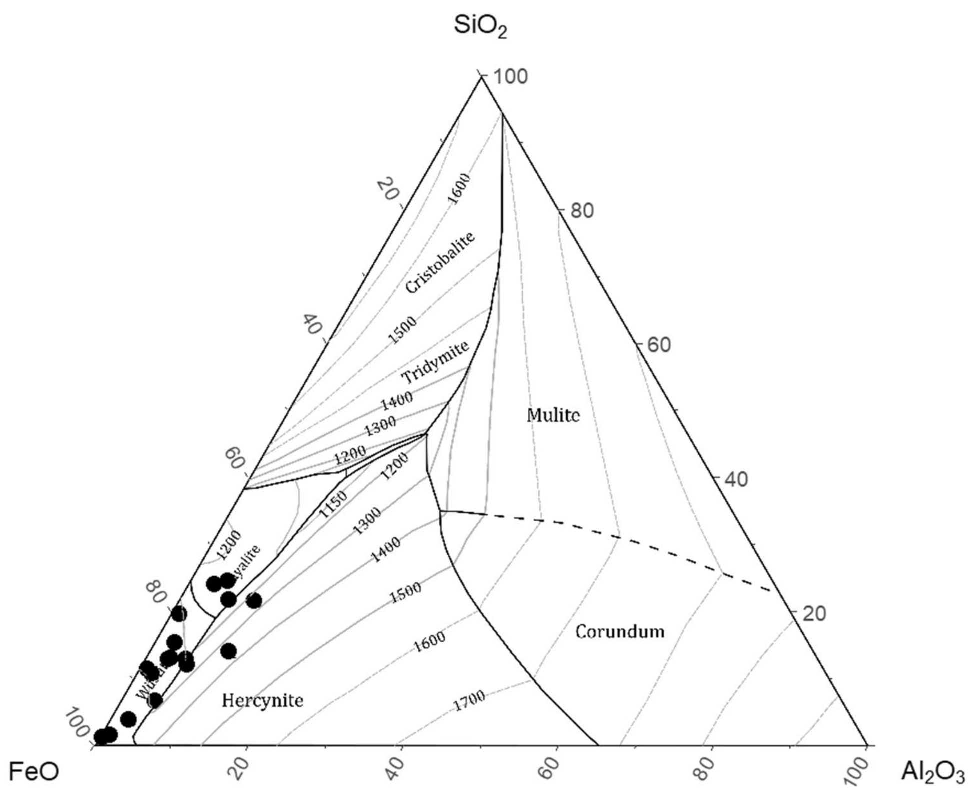

Fig. 8 Ternary FeO-SiO_2-Al_2O_3 diagram showing that most samples from Unguja Ukuu plot in the wüstite, three samples in the fayalite, and three in hercynite temperature regions

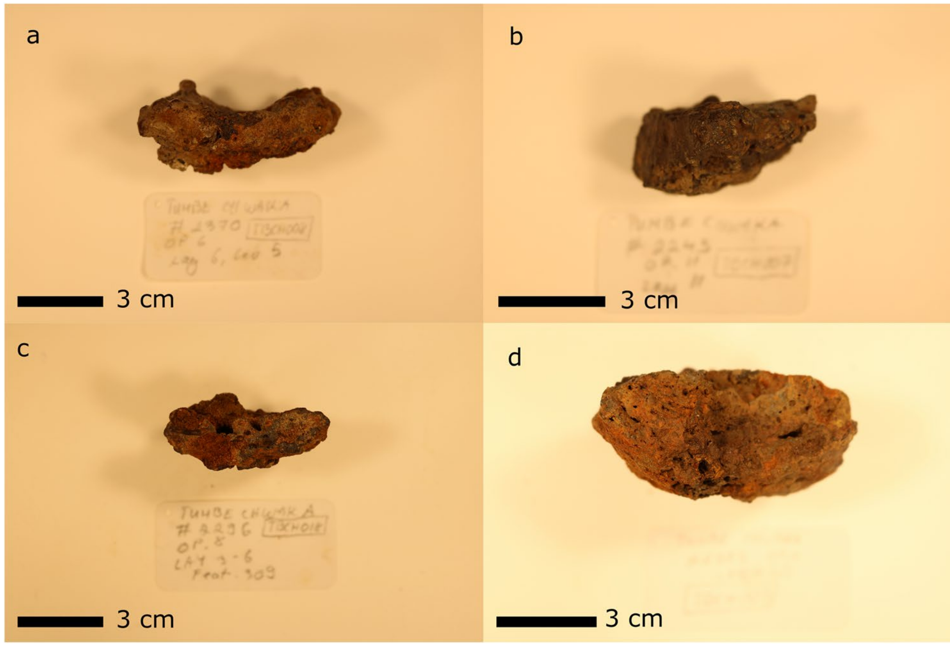

Fig. 9 Images of CBS slag excavated at Tumbe and Chwaka. **a** TBCH008 with spheroidal hammerscale inclusion on the surface. **b** TBCH007. **c** TBCH018. **d** TBCH009

revealed a variable chemical composition of iron slag. Wide ranges of elemental concentrations were detected across the assemblage as well as within individual samples. For instance, average wt% of FeO in Tumbe assemblage varied between 59.52 to 81.33 wt%, with relative standard deviation of FeO within individual pieces of slag ranging from 4 to 26%.

The results of the quantitative elemental analysis were plotted in a FeO-SiO_2-Al_2O_3 ternary diagram (Fig. 11). The diagram indicates that 3 of the samples are plotted in the wüstite temperature region (TBCH007, TBCH009, and TBCH010) and have a melting temperature of 1148–1369°C. The remaining sample TBCH011 plotted in the fayalitic region, suggestive of liquidus temperatures in the 1088–1200°C range. Detailed results of the chemical analysis are outlined in Table 10. Of note are the amounts of CaO and ratios SiO_2:Al_2O_3 present in the slag. Low overall levels of CaO were detected in the slag in comparison to results from Unguja Ukuu, consistently measuring below 1.15 wt%. The SiO_2:Al_2O_3 ratio varies across the assemblage from 5.2:1 to 17.61:1, with most samples having a high silica-to-alumina ratio, above 10:1.

Examination of archaeological context

The 2002 season at Tumbe and Chwaka included a series of some 60 1 × 1-m and 2 × 2-m test excavations distributed across the sites. The results of this survey along with more recent research by Fitton (2017) allow for a discussion of the distribution of slag across the site. At Tumbe, a total of 7035.4 g of iron slag was recovered from excavations.

Table 9 Tumbe sample dimensions, typologies, and surface features recorded during the investigation

Sample no	Type	Impressions	Inclusions	Weight (g)	Width (mm)	Length (mm)	Thickness (mm)
TBCH007	CBS	–	–	155	49	54	26
TBCH009	CBS	–	Soil, quartz	218	218	73	31
TBCH010	ND	–	–	78	26	66	23
TBCH011	CBS	–	–	68	46	66	21
TBCH012	ND	–	–	16	22	36	14
			Minimum	16	22	36	14
			Maximum	218	50	73	31
			Mean	107	38.6	59	23
			STDEV	79.48	13.48	14.56	6.28

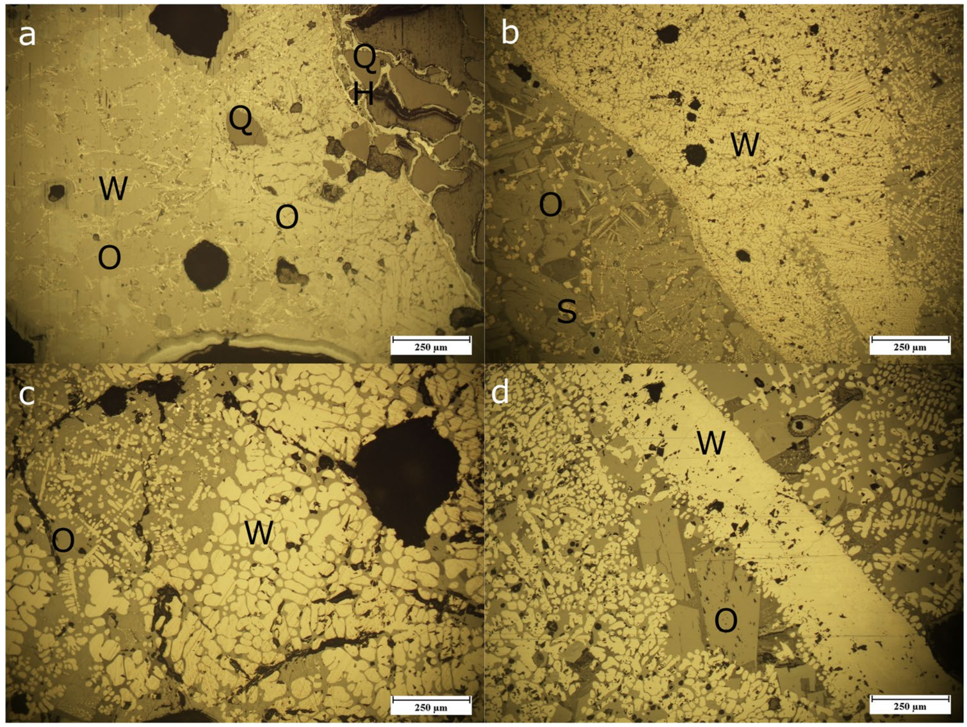

Fig. 10 Microstructure of iron slag from Tumbe and Chwaka sites taken using reflected light optical microscope. **a** Olivine-dominated microstructure with small wüstite dendrites between olivine grains. Hammerscale and quartz inclusions visible on the surface with some of the quartz grains embedded deeper in the slag matrix. **b** Heterogeneous slag matrix with no one dominant phase. Large olivine phases and spinel crystals are present alongside oxide-rich areas dominated by wüstite dendrites and globules. **c** Wüstite-dominated slag microstructure with mostly large wüstite globules and dendritic structures in a glassy matrix. **d** Microstructure with clear oxide band in the matrix of large olivine crystals, wüstite globules, and dendrites dispersed in a glassy phase. W, wüstite; O, olivine; H, hammerscale; Q, quartz, S, spinel

Small amounts of iron slag were found in numerous trenches across the settlement. However, most of the slag, amounting to 5534 g, was excavated from 4 units particularly rich in the material: 45, 46, 48, and 50. Three of the units (46, 48, 50) were situated relatively closely together and in the northeastern part of the site. Unit 45 was located to the south of the three slag-rich trenches, but not far removed. Higher amounts of tuyère fragments were also found in these trenches. The slag samples analysed here, from Operation 11, come from this area.

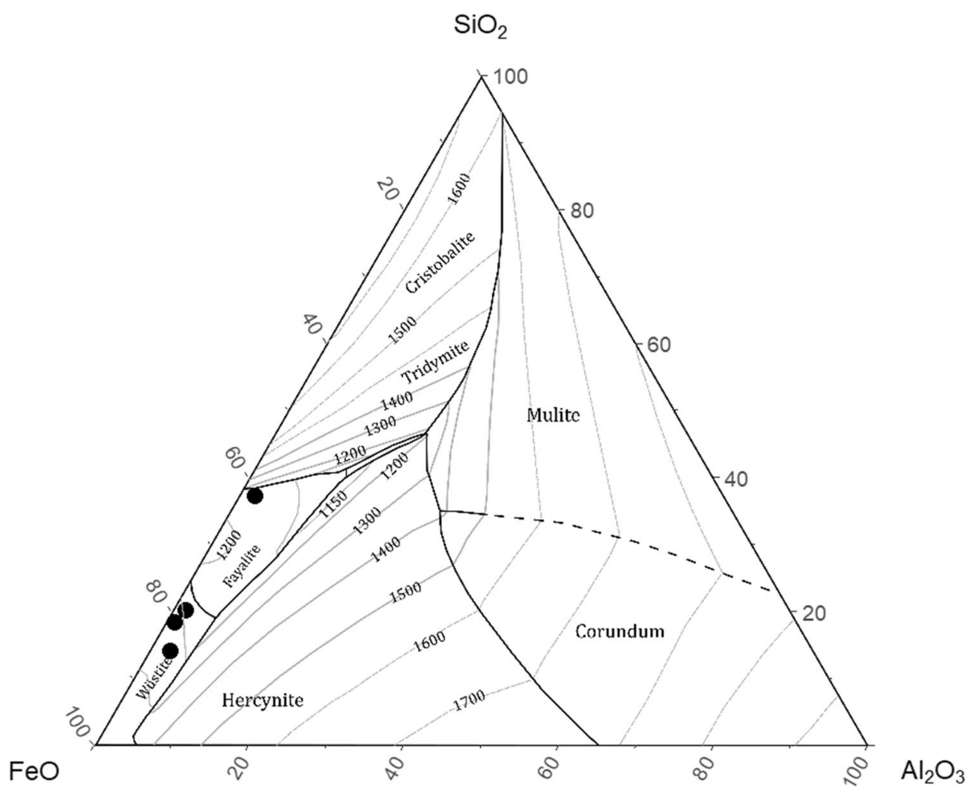

Fig. 11 Ternary FeO-SiO_2-Al_2O_3 diagram showing that iron slag samples from Tumbe plot in fayalite and wüstite temperature regions

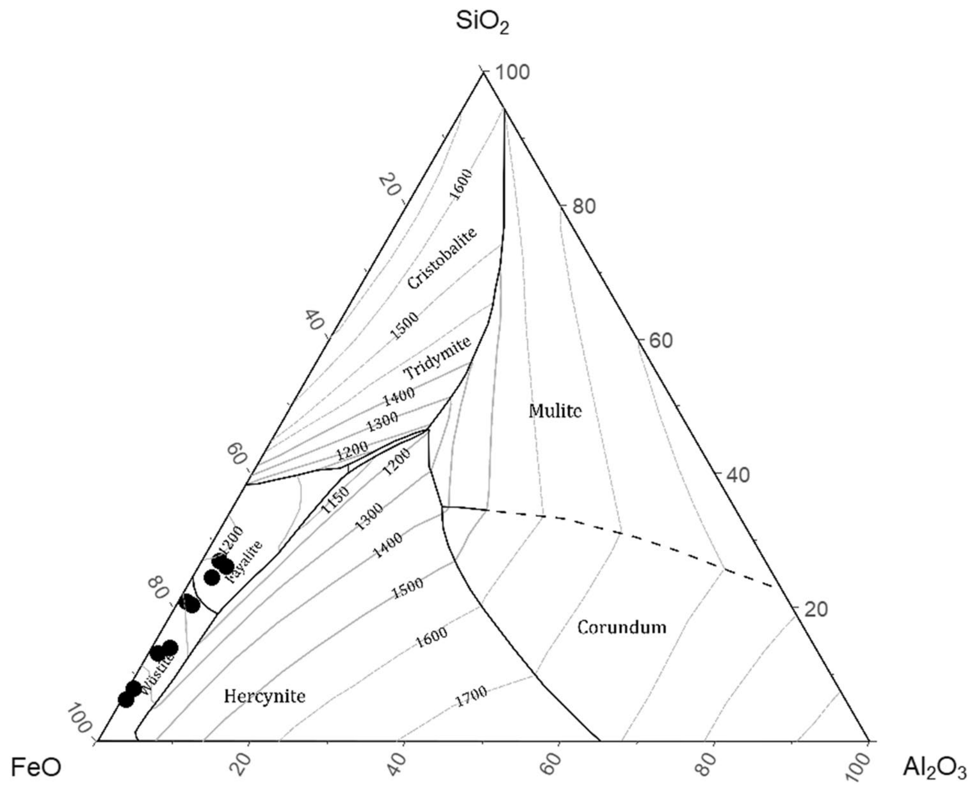

Fig. 12 Ternary FeO-SiO_2-Al_2O_3 diagram showing that iron slag samples from Chwaka plot in fayalite and wüstite temperature regions

LaViolette et al. (n.d.) recorded detailed information about the weight of slag and daub found in excavated contexts. To contextualise ironworking evidence in terms of its proximity to domestic contexts, the first author was then able to plot these data using GIS software (Baužytė 2019). Relatively lower amounts of daub were found in trenches that were rich in ironworking debris. Higher volumes of daub were excavated to the west of the slag-rich area, at the southern part of the site (Fig. 14).

Chwaka

Assemblage description and morphological analysis

A total of 15 pieces of slag from Chwaka were analysed. Seven of the samples were dated between the twelfth and thirteenth centuries, 2 between the thirteenth and fourteenth centuries, and 6 were dated to the last occupation period in the area between the fourteenth and fifteenth centuries. Detailed results of the morphological analysis and measurements are presented in Table 11. Overall, slag pieces are relatively small in size, not exceeding 185 g individually. Diagnostic slag samples were identified as CBS slag and the presence of hammerscale as surface inclusions was observed in three of the samples (Fig. 9).

Optical microscopy analysis

Eight of the slag samples from the Chwaka assemblage were analysed using optical microscopy (Fig. 10). Overall, a variety of microstructural compositions was observed in the samples. Most of the analysed pieces of slag (5 out of 8) had microstructures that were dominated by olivine phases. Two of the 8t samples (TBCH001, TBCH017) contained both olivine and wüstite phases in relatively equal proportions and only one sample (TBCH021) was dominated by wüstite phases. A significant amount of variability was observed within the samples in terms of crystal sizes. Only one of the samples (TBCH018) had a comparatively homogeneous microstructure with mostly large and well-developed phases. The remaining 7 samples exhibited a significant amount of variability in phase dimensions.

Close examination of individual samples revealed interesting details about the use of raw materials and thermodynamic conditions in the hearth. Some samples contained highly reflective spinel crystals (likely magnetite) and inclusions of unreduced iron. One potentially intriguing piece of slag (TBCH022) contained inclusions of what is suspected to be quartz with sharp edges. The implications of the unweathered corners of possible quartz inclusions in the slag are outlined in the discussion.

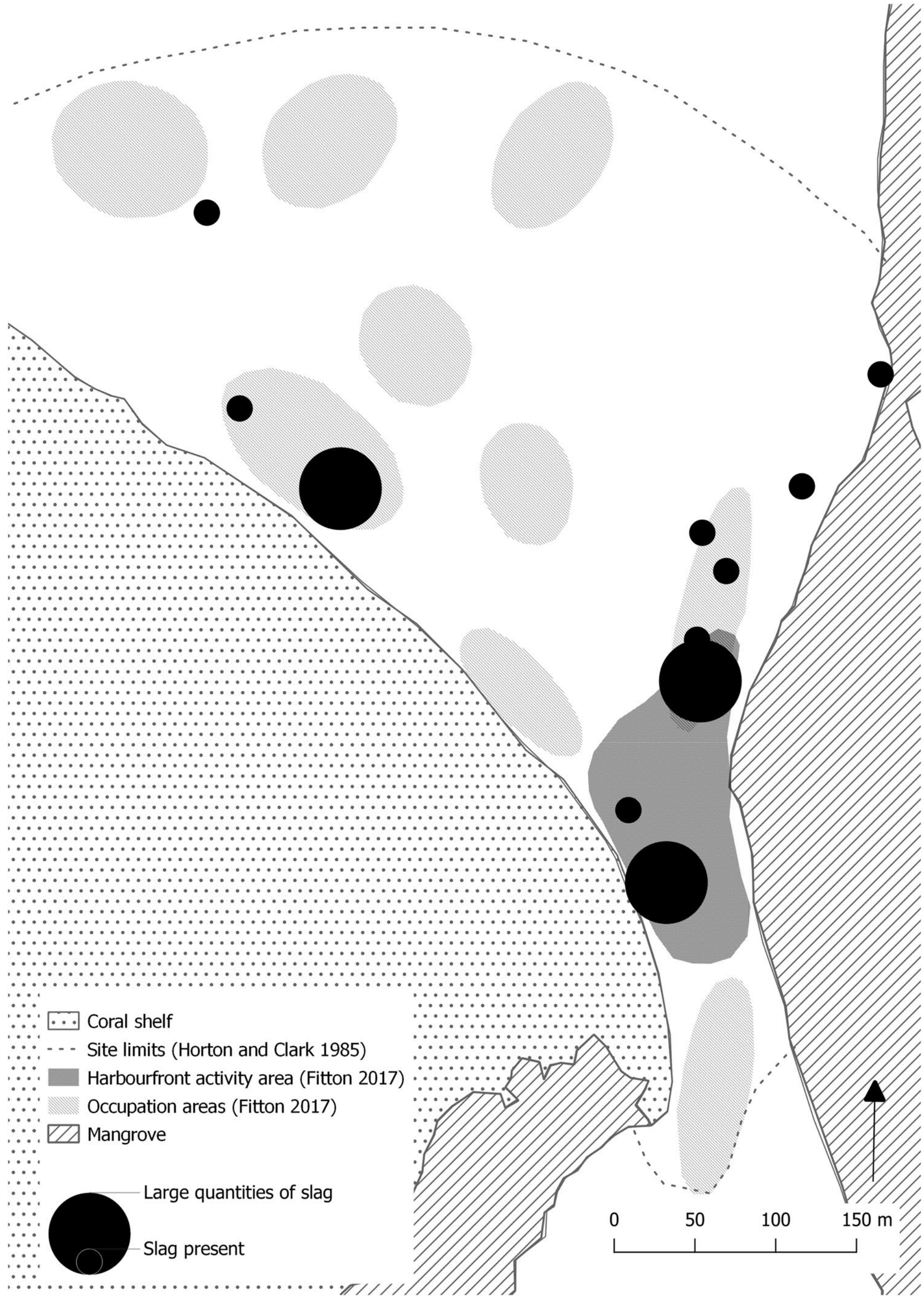

Fig. 13 Map showing approximate locations and amounts of slag found. Quantities are depicted qualitatively with smaller circles representing locations where slag is reported without specifying quantity or where less than 50 kg of slag was excavated from the trench. Larger circles represent locations where slag was found in quantities that exceeded 50 kg or were qualitatively judged as 'huge' quantities by the excavators

Quantitative elemental analysis

A total of 9 slag pieces recovered at Chwaka were analysed for their quantitative elemental composition. Overall, the results revealed considerable variability in the chemical composition of iron slag. The average wt% of FeO in the assemblage varied between 67.31 to 90.52 wt%, with a relative standard deviation of FeO within individual pieces of slag ranging from 2 to 16%. Detailed results of the chemical composition of iron slag are outlined in Table 12.

The results of the quantitative elemental analysis were plotted in a FeO-SiO_2-Al_2O_3 ternary diagram (Fig. 12). The diagram indicates that 6 of the samples plot in the wüstite temperature region and have a melting temperature of 1148–1369°C. The remaining three samples were plotted in the fayalitic region, suggestive of liquidus temperatures in the 1088–1200°C range. Noteworthy are amounts of CaO and ratios SiO_2:Al_2O_3 present in the slag. Amounts of CaO detected were consistently low and measured up to 2.15 wt%. The SiO_2:Al_2O_3 ratio varies across the assemblage

Fig. 14 Map of daub and slag distribution at Tumbe (eighth–ninth century occupation). The map demonstrates that higher concentrations of iron slag were found closer to the shoreline, at the north-eastern part of the site, while daub remains associated with domestic structures were largely found south-west of slag-rich areas

from 5.43:1 to 16.58:1 with most samples having a high silica to alumina ratio above 8:1.

Examination of archaeological context

Similar to the Tumbe data, the spatial distribution of iron production debris across Chwaka, can be analysed from test excavations in 2002. A total of 1168 g of iron slag were excavated from early layers associated with the 1100–1300 CE occupation, with 10,363.5 g from the later settlement dating to 1300–1500 CE. Relatively more iron slag was found towards the western part of the site in the layers associated with the 1100–1300 CE occupation. Meanwhile, iron slag retrieved from later occupation layers (1300–1500 CE) suggested that the material was concentrated towards the northwestern part of the site. In addition, amounts of daub found in excavation units were assessed. As a result of GIS mapping of data recorded by LaViolette et al. (n.d.), building remains were found to be distributed largely towards the eastern portion of the early Chwaka settlement. Evidence from the later occupation layers suggests that smaller amounts of daub were found in the northwest part of the site, rich in iron slag remains (Figs. 15, 16 and 17).

As with Tumbe, the evidence was digitised and plotted using QGIS software (Baužytė 2019) and is discussed further below.

Discussion

Overall, the results of visual, microscopic, and quantitative elemental assessment of slag from the three sites suggested a number of key conclusions about the nature of iron production activities. First, the data suggest that ironworking taking place at Unguja Ukuu, Tumbe, and Chwaka sites was associated with smithing activities. During the morphological analysis of the Unguja Ukuu assemblage, the

Fig. 15 Map of daub and slag distribution at earliest occupation of Chwaka (10th–eleventh centuries). Concentrations of slag and daub are found mostly in the same excavation contexts

majority of slag samples (26/32) were identified as convex bottom slag and are consistent with typical morphologies of smithing hearth bottom slag. In addition, hammerscale inclusions in the slag and overall small sizes of the slag uncovered at the site further support this conclusion. While a small number of possible iron-rich minerals were excavated at the site, these are likely more consistent with pigment production. The few tuyère fragments that have been unearthed were not diagnostic enough to indicate the tuyères' actual size, including length and diameter, let alone allowing determination of whether they were flared or not. The volume of this material, however, was more consistent with smithing than smelting processes. While smelting could not be confidently ruled out, the analysis of the objects and the archaeological context strongly indicate that smithing was taking place at the site.

Similarly, most of the slag pieces from Tumbe were identified as CBS and are consistent with evidence of smithing. The volume of samples and lack of evidence pointing to smelting leads us to conclude that only smithing activities were carried out at Tumbe. Morphological analysis of Chwaka slag led to the same conclusion: a significant portion of the assemblage includes relatively small convex bottom slag consistent with the type of slag forming at the bottom of a smithing hearth. Furthermore, inclusions of spherical hammerscale observed on the surface of slag samples TBCH008, TBCH017, and TBCH018 support this suggestion. The relatively small amount of slag pieces located across the site, their dimension, and lack of any additional evidence pointing to smelting activities strongly supports the likelihood of smithing being the predominant metalworking activity.

Second, the results of the optical microscopy analysis suggested that the Unguja Ukuu assemblage is notably different from the Tumbe and Chwaka assemblages in terms of the microstructural composition of slag. Most samples from Unguja Ukuu had wüstite-dominated microstructures, indicative of slag forming in a relatively oxidising atmosphere. This indicates that sufficient oxygen was available in the hearth for iron oxide phases to form in the slag. It is important to note that significant variability was observed within individual samples, and heterogenous as well as

Fig.16 Map of daub and slag distribution during period 3 of Chwaka occupation (12th–thirteenth centuries). Relatively higher concentrations of iron slag are visible at the western part of the site, while higher amounts of daub were recovered from north-eastern parts of the site

olivine-dominated slag pieces were identified. However, a clear trend of wüstite-rich microstructures was observed in the assemblage.

The significance of oxidised phases being found consistently in smithing slag is difficult to assess. On the one hand, a hearth being a comparatively open environment with constant airflow needed to maintain the heat is expected to have a degree of oxidising conditions. A pertinent, although likely impossible to answer, question is to what extent craftspeople had control of and intentionally manipulated redox conditions of a smithing hearth. An oxidising atmosphere would facilitate the removal of excess carbon from a bloom or bar resulting in softer ferritic iron. However, such efforts would also mean significant losses of iron in the process. While intentional decarburisation is well documented in contexts where otherwise unworkable cast iron would be obtained, such as China (e.g. Liu et al. 2019), the possibility of intentional maintenance of oxidising hearth conditions is considered here with due scepticism. It is worth noting that overall, convex bottom slag from Unguja Ukuu is larger and contains higher amounts of FeO than slag from Tumbe or Chwaka, which may be consistent with higher losses of iron during smithing processes. This supports the suggestion that the atmosphere in smithing hearths was frequently oxidising. However, the degree of intentionality behind redox conditions, while intriguing to consider, is impossible to assess, especially without microstructural analysis of blooms and resulting worked objects.

While only a few samples from the Tumbe site were analysed petrographically, the available data suggest that samples contained more olivine than wüstite phases. Similarly, the microstructural composition of iron slag from Chwaka was dominated by olivine phases with only one sample being dominated by wüstite globules. The abundance of olivine phases in both assemblages suggested that relatively reducing atmosphere conditions were present in smithing hearths at these sites. Olivine forms in reducing conditions and suggests that smithing hearths at Tumbe and Chwaka were operated in an oxygen-depleted environment. While there is a clear overall trend of olivine-rich slag, a degree of compositional heterogeneity was noted in some samples at both sites, indicating that redox conditions in smithing hearths

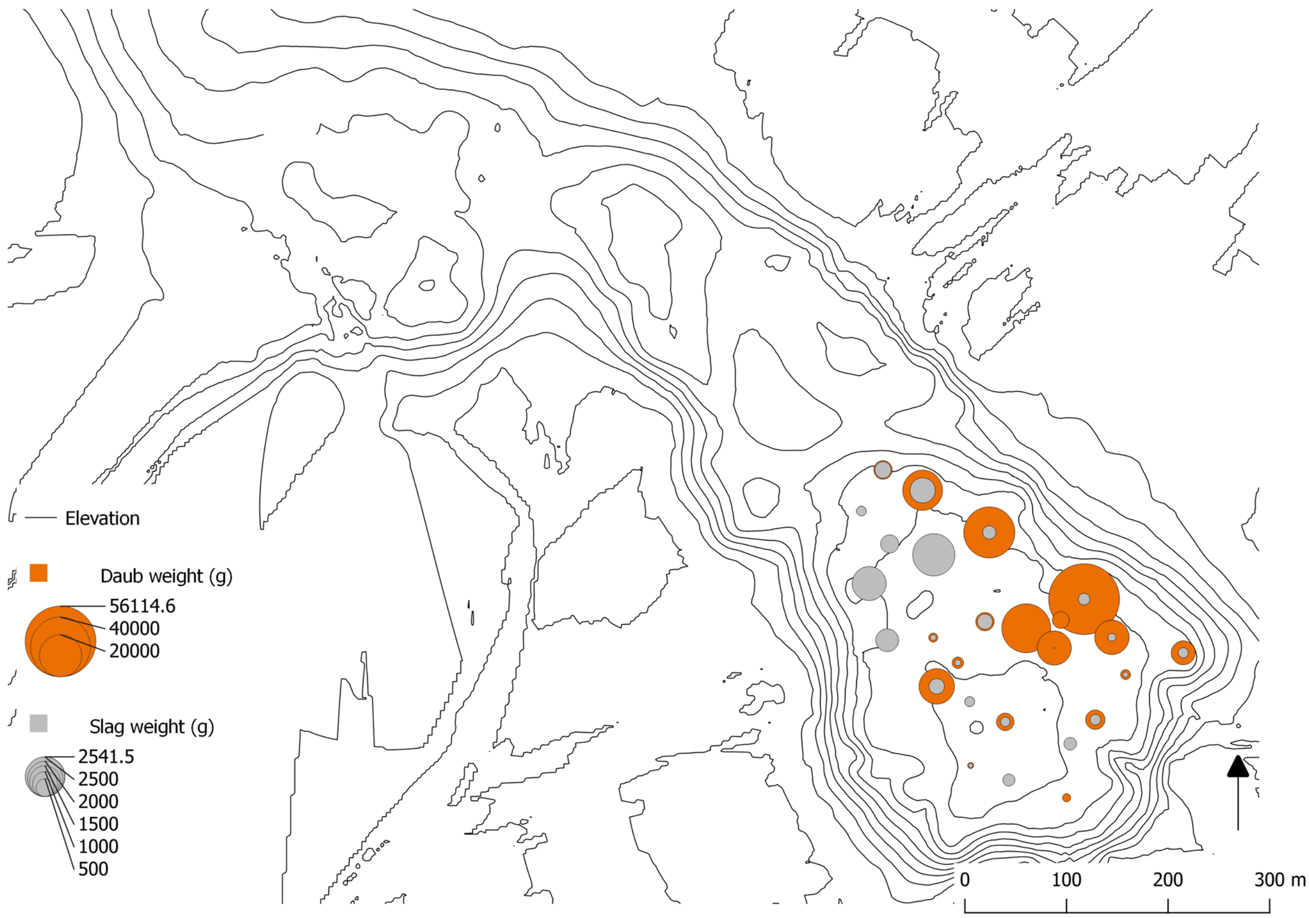

Fig. 17 Map of daub and slag distribution during period 4 of Chwaka occupation (fourteenth–fifteenth centuries). Most of the iron slag is mapped at the north-western quarter of the site, while evidence of daub structures flank this area from east and south

varied throughout the production episode. Relatively comparable microstructural compositions at the two sites may be hinting at temporal continuity of technological traditions in the peninsula.

Third, there are differences between the Unguja Ukuu, Tumbe, and Chwaka assemblages in terms of their variability. Unguja Ukuu's assemblage is highly variable, particularly in its chemical composition. While a significant degree of heterogeneity is observed in sample microstructures, specific trends regarding dominant phases can still be discerned. Chemical composition on the other hand varies widely with FeO wt% ranging from 58 to 94% across the assemblage. In comparison, chemical composition in the Tumbe assemblage has less overall variability with FeO wt % ranging from 59.52 to 81.33 wt%; this may be due in part to the smaller number of samples analysed. The level of chemical variability in the slag assemblage from Chwaka is more comparable with that of Tumbe, with FeO wt% ranging

Table 10 Results of μ-XRF analysis of slag samples from Tumbe. 10 measurements were carried out per sample and the table presents the mean and RSD of those measurements. BDL—below detection limits

Sample		MgO	K_2O	CaO	TiO_2	FeO	Al_2O_3	SiO_2	PbO	MnO	SrO	SiO_2:Al_2O_3
TBCH007	Mean	BDL	0.33	0.90	0.10	76.31	1.68	19.80	0.02	BDL	0.02	11.79
	RSD	–	108%	67%	71%	10%	136%	29%	95%	–	68%	
TBCH009	Mean	BDL	0.26	1.14	0.18	81.33	2.67	13.90	0.01	BDL	0.02	5.20
	RSD	–	37%	37%	29%	4%	29%	15%	118%	–	31%	
TBCH010	Mean	BDL	0.73	0.82	0.09	78.32	1.16	18.00	0.03	BDL	0.02	15.45
	RSD	–	58%	66%	48%	10%	39%	36%	165%	–	49%	
TBCH011	Mean	BDL	0.57	0.67	0.19	59.52	2.08	36.62	0.02	BDL	0.02	17.61
	RSD	–	63%	60%	111%	26%	44%	39%	132%	–	57%	

Table 11 Chwaka sample dimensions, typologies, and surface features recorded during the investigation

Sample no	Type	Impressions	Inclusions	Weight (g)	Width (mm)	Length (mm)	Thickness (mm)
TBCH001	ND	–	–	51	25	60	15
TBCH002	CBS	–	–	38	26	63	17
TBCH003	ND	–	–	31	26	39	11
TBCH004	ND	–	–	26	21	25	20
TBCH005	CBS	–	–	33	31	38	20
TBCH006	ND	–	–	49	36	50	19
TBCH008	CBS	–	Charcoal, hammerscale, soil	152	54	64	19
TBCH015	ND	–	–	23	26	47	16
TBCH016	ND	–	–	54	31	56	18
TBCH017	ND	–	Hammerscale	44	50	50	20
TBCH018	CBS	Charcoal	Hammerscale, soil, quartz	53	41	47	17
TBCH019	ND	–	–	25	32	39	17
TBCH020	CBS	–	–	24	30	34	15
TBCH021	ND	–	–	22	33	39	12
TBCH022	CBS	–	–	185	68	70	23
			Minimum	22	21	25	11
			Maximum	185	68	70	23
			Mean	54	35.33	48.07	17.27
			STDEV	48.28	12.87	12.68	3.17

between 67.31 to 90.52 wt%. While these ranges are still significant, they point to a less variable material in the two latter assemblages. In addition, more consistency is observed in the microstructural composition of iron slag from Tumbe and Chwaka. Most samples from these sites contained relatively large, well-formed crystals indicating that they had ample time to grow as slag cooled down gradually. Cooling rates appeared to vary within individual pieces of slag, with proximity to the surface or oxide bands being a key factor for crystal sizes. However, the overall trend is clear: iron slag from Tumbe and Chwaka is often associated with slow cooling rates. Meanwhile, no conclusion in terms of slag cooling rates at Unguja Ukuu could be suggested. The microstructural variability of slag meant that both larger and smaller

Table 12 Results of μ-XRF analysis of slag samples from Chwaka. 10 measurements were carried out per sample and the table presents the mean and RSD of those measurements. BDL—below detection limits

Sample		MgO	K_2O	CaO	TiO_2	FeO	Al_2O_3	SiO_2	PbO	MnO	SrO	SiO_2:Al_2O_3
TBCH001	Mean	BDL	0.72	1.68	0.18	80.48	2.48	13.45	0.02	BDL	0.03	5.43
	RSD	–	46%	52%	29%	9%	38%	38%	80%	–	45%	
TBCH002	Mean	BDL	0.40	0.91	0.12	75.93	2.28	19.94	0.01	BDL	0.02	8.73
	RSD	–	65%	33%	22%	3%	40%	6%	113%	–	67%	
TBCH003	Mean	BDL	0.89	1.18	0.29	67.31	3.58	25.16	0.01	BDL	0.03	7.04
	RSD	–	78%	62%	29%	16%	46%	28%	83%	–	60%	
TBCH005	Mean	BDL	0.29	0.61	1.52	89.89	BDL	6.14	0.01	BDL	0.03	–
	RSD	–	48%	38%	14%	4%	–	43%	134%	–	25%	
TBCH008	Mean	BDL	1.30	2.15	0.12	67.43	2.49	25.70	0.02	BDL	0.04	10.32
	RSD	–	51%	52%	46%	11%	34%	19%	132%	–	34%	
TBCH017	Mean	BDL	0.31	0.47	0.09	84.40	1.48	12.94	0.01	BDL	0.01	8.73
	RSD	–	68%	68%	17%	6%	39%	33%	124%	–	61%	
TBCH018	Mean	1.07	1.38	0.76	0.12	70.16	2.55	23.64	0.01	BDL	0.02	9.28
	RSD	54%	57%	54%	25%	6%	37%	10%	90%	–	61%	
TBCH021	Mean	BDL	0.21	0.15	0.11	90.52	BDL	7.82	0.01	BDL	0.01	–
	RSD	–	39%	27%	58%	2%	–	17%	113%	–	51%	
TBCH022	Mean	BDL	BDL	0.20	0.11	77.37	1.25	20.76	0.01	BDL	0.01	16.58
	RSD	–	–	66%	80%	5%	95%	16%	139%	–	90%	

crystal phases were observed in the material with no pattern emerging.

Fourth, analysis of the chemical composition of iron slag suggests that Unguja Ukuu, Tumbe, and Chwaka are distinguishable in terms of their CaO and SiO_2 compositions. In the case of Unguja Ukuu, high amounts of CaO are particularly notable. CaO detected in the iron slag varied from 0.95 to 14 wt% with elevated levels of CaO being detected in half of the samples. A few possible explanations for such high CaO amounts can be suggested. High levels of CaO can be contributed to iron slag from fuel when hardwoods are used to produce charcoal for ironworking processes (Van der Merwe and Killick 1979; Jackson et al. 2005). No charcoal analysis was performed as part of the study for tree species identification. Without further information about fuel sources used for iron smithing at the site, the possibility that high CaO amounts contributed to the slag primarily from the fuel cannot be ruled out. However, it is worth noting that high levels of CaO do not appear to correlate with other compounds commonly related to elevated contributions from fuel, such as K_2O.

Alternatively, due to high amounts of corrosion products observed in the slag microstructure during the petrographic analysis, the possibility of post-depositional contributions of CaO to slag composition needs to be considered. CaO may have been leached out of the soil and precipitated in cracks and pores present in the slag. However, close examination of microstructures revealed that phase composition correlates strongly with the amount of CaO present in a sample. Pieces of iron slag with microstructures dominated by wüstite phases contained the highest amounts of CaO. CaO can lower the viscosity of iron slag and affect the formation of phases. When slag microstructure is considered, it appears more likely that CaO was introduced into slag composition during the production process and had a direct impact on the phase composition of iron slag making the possibility of post-depositional contamination less probable.

It could be hypothesised that CaO was added intentionally as a fluxing agent during the smithing process. Calcareous inclusions recorded during the macroscopic analysis would be consistent with the use of lime flux. In terms of resource availability, the underlying bedrock consists primarily of coralline limestone providing ample raw material for possible extraction of lime flux. However, we need to consider what the purpose would be of using lime as a flux. CaO can lower the melting temperature and viscosity of iron slag. While this can be important during the smelting processes, the value of potentially adding CaO during smithing is questionable.

One possible explanation for elevated CaO amounts is that lime flux was added during the smelt or that a calcium-rich ore was used, leading to high levels of CaO in the bloom that were subsequently transferred to smithing slag during forging of the raw metal. Portillo et al. (2018) suggested that high amounts of CaO found in some of the smithing slag could be explained by the addition of flux during the preceding smelting processes or by incorporation of smithing hearth walls. Similarly, Eliyahu-Behar et al. (2013) argued that high amounts of CaO found in convex bottom slag excavated in Israel are likely explained by the use of CaO as a flux during smelting or the use of calcium-rich ore, although it is worth noting that they attributed the convex bottom slag to evidence of smelting. While it is not impossible that CaO may have contributed to the Unguja Ukuu slag from the raw metal, it is important to note that this would signal the use of a relatively impure iron. CaO does not readily precipitate in iron and would likely have been contributed from trapped slag or unreacted inclusions of ore or flux. The feasibility of this suggestion, however, is impossible to confirm or refute without analysis of iron worked at Unguja Ukuu.

One final alternative explanation is the possibility that CaO may have contributed to the slag from hearth walls. Since the underlying geology of Unguja Ukuu is largely made up of coralline limestone, calcium-enriched soils would be unsurprising. While hearth walls have not been found and analysed, the possibility that CaO contributed to the smithing slag from hearth walls remains compelling, if only one of the potential explanations.

In contrast, low amounts of CaO and high levels of silica were detected in the samples from Tumbe and Chwaka sites. Chemical analysis revealed that silica:alumina ratios measured above 5:1 in all samples from Tumbe and Chwaka sites. Slag from Tumbe tended towards higher silica:alumina ratios than slag from Chwaka with most samples containing more that 10:1 ratio of SiO_2:Al_2O_3. While relatively lower ratios were measured in Chwaka samples, they nevertheless largely exceeded the ratio of 8:1 and differed from chemical fingerprint of the Unguja Ukuu assemblage. Silica is contributed to smithing slag primarily from technical ceramics and hearth walls. Without knowing more about the chemical composition of the hearth and sediments, it is difficult to understand the extent to which these silica concentrations can be explained by soil and clay particles permeating into the slag from the surrounding sand and hearth walls. One alternative explanation may be that silica was purposefully added during the smithing process as a fluxing agent. Sand or crushed quartz particles are sometimes sprinkled onto the worked iron bar to facilitate the removal of the FeO scale that forms on the surface of a worked iron bar.

Microstructure of sample TBCH022 is particularly interesting to consider when speculating about this possibility. Mineral inclusions potentially corresponding to quartz particles were identified in the sample during the microscopic analysis, although this could not be confirmed without further analysis. Most of these inclusions were noted at the surface of the sample. Sharper edges were noted in at least one of the inclusions potentially indicating that the mineral was purposefully crushed before being contributed to the ironworking process. Elemental analysis of the sample suggested high levels of SiO_2, particularly with respect to alumina concentrations, supporting the suggestion that the mineral inclusion may be quartz grains. Chemical analysis and microstructure of Tumbe and Chwaka samples present a possibility that silica flux may have been used to facilitate the ironworking process. While contributions from hearth walls and the surrounding sediments may also explain the high silica levels, at the very least, deliberate addition of silica-rich flux by sprinkling silica-rich material onto the worked object could not be ruled out at this time.

Fifthly, different trends in terms of scale of production were noted at Unguja Ukuu, Tumbe, and Chwaka over time. No technological differences were identified in association with different chronological periods at the sites, but changes in spatial and production intensity are evident. There are of course challenges to this process and Unguja Ukuu presents more hurdles for such study when compared to Tumbe and Chwaka. The collage of data providing contextual information about ironworking at Unguja Ukuu was extrapolated from a number of projects motivated by different research questions and using different excavation strategies. This means that information about slag abundance was recorded differently over the course of excavations and prompts a qualitative rather than quantitative approach in collating the data. In contrast, because excavations carried out at Tumbe and Chwaka were consistent in methodology, these sites present excellent case studies for quantitative examination of chronological and spatial trends in the distribution of materials associated with craftworking. Excavation units were situated throughout the extent of the settlements and were highly comparable in size. This allowed for a detailed spatial and chronological mapping of slag distribution. The evidence presents an interesting case for how ironworking areas and the associated debris were managed during different chronological periods.

Overall, slag volumes excavated at Unguja Ukuu suggest no obvious patterns of production intensification or decline and may point to relatively even production rates throughout the occupation of the site. Tumbe's occupation was relatively short and no meaningful temporal trends in terms of production intensity were observed at the site. Meanwhile, the results from Chwaka suggest that the most intensive scale of production was taking place during the latest occupation period: the fourteenth to fifteenth centuries CE. Juma (2004) suggested that ironworking at Unguja Ukuu was more intense during the earliest and latest occupation periods, with respect to the middle occupation period. However, since then, work in 2017 carried out at the site located significant volumes of slag dating to the seventh-ninth centuries CE, corresponding to the middle occupation period. As a result, no conclusive trends of production intensification or scaling down can be supported.

At Tumbe, a total of 7 035.4 g of slag were excavated during the 2002 fieldwork season. Following the abandonment of this early occupation of the peninsula, only 66.2 g of slag were found in the earliest layers of Chwaka, dated to the tenth to eleventh centuries. A mild increase in iron production is notable from 1100–1300 CE, from which a total of 1168 g of iron slag were recovered. The highest volumes of slag were associated with the final occupation period of Chwaka and amounted to 10,363.5 g. These data indicate that the most intensive iron smithing work was taking place from 1300 to 1500 CE. However, whether these increased amounts of iron slag indicate proportional intensification of production at the site or are a result of a growing population density and increased need for iron objects is difficult to determine.

Our final conclusion concerns the spatial distribution of ironworking evidence at these sites. We suggest that at Unguja Ukuu smithing was taking place across the extent of the site with no definitive spatial patterns emerging. In contrast, at Tumbe and Chwaka, the distribution of iron slag indicates designated working areas and separation from domestic contexts. Following fieldwork at Unguja Ukuu, Fitton (2017) suggested that ironworking may have been concentrated at the southern end of the site, on a low-lying area connecting the mainland with the peninsula. He argued that the concentration of metalworking debris, metal objects, and results of a resistivity survey point to iron production taking place at this part of the site, separately from domestic activities at the northern end of the site. The abundance of slag found in test trenches UU1 and UZ002 excavated at the southern end of the site is consistent with this suggestion, although it is worth noting that these concentrated iron slag deposits could be indicative of refuse management practices rather than activity areas. In addition, pieces of slag are found throughout the site (Fig. 13). Wide spatial distribution of iron slag may indicate multiple areas of production rather than a designated point of ironworking activity. Finally, when the extent of soil excavated is taken into consideration, amounts of slag per kilogramme of soil lifted are comparable throughout the site. While one of the authors excavated 500 kg of slag from a discrete area (243 m^2; Juma 2004) at the site, when the amount of soil lifted (100.46 m^3) is factored in, the excavated volume of slag (4.98 kg/m^3) is consistent with amounts of production debris found in other areas of the site. In addition, no evidence of craft production being segregated from domestic contexts has been found at Unguja Ukuu. Fragments of iron slag were found in a variety of contexts, including in association with coral stone building materials and daub. This paints a picture of smithing as a craft activity that was embedded into the spatial and social fabric of the settlement, performed in proximity to other daily activities, and continuously adapting to shifts in settlement structure.

Examination of the spatial distribution of slag from Tumbe and Chwaka reveals a different picture. At Tumbe, the remains of iron smithing are seen concentrated along the shoreline, at the northeastern edge of the site, while evidence of domestic structures was more abundant in the western part of the site (Fig. 14). This indicates that ironworking activities were largely taking place along the waterfront, away from domestic areas.

Different spatial patterns of craftworking emerge during the 2nd-millennium occupation of Chwaka. Evidence from the earliest occupation (1000–1100 CE) suggests that iron smithing was taking place close to domestic contexts, in the western part of the site (Fig. 15), but low quantities of slag dating to this period urge caution when drawing any conclusions about space. From 1100–1300 CE, however, ironworking areas may have been concentrated in the western part of the site, with domestic areas located to the east of craft activity (Fig. 16). The clearest evidence of ironworking areas being segregated from domestic contexts is noted during the final occupation period (1300–1500 CE) at Chwaka. While iron slag is concentrated in the northwestern quarter of the site, remains of daub houses were found largely in the eastern half of the settlement (Fig. 17). However, the northwestern part of the site was associated with extensive midden contexts. Therefore, one explanation for the refuse of ironworking being removed from domestic areas of the site, is that discarded material was systematically managed and disposed of in one place. Thus, it may be argued that this higher concentration of iron slag indicates rubbish management practices rather than a correlation with craft activity areas. Overall, much clearer indications of spatial organisation of iron production and/or management of resulting debris emerge at Tumbe and Chwaka when compared to Unguja Ukuu, where no evidence of spatial organisation of the craft was found.

This study sheds new and interesting light on inferring social structures based on the spatial organisation of iron production. Huffman (2001) advocated for the use of the Central Cattle Pattern model for examining spatial organisation of Iron Age societies in southern Africa. The study associates iron smithing with central settlement spaces—the domain of men, where political decisions are made and disputes are resolved (Huffman 2001). Meanwhile, smelting is surrounded by ritual. It takes place away from settlements, often because of its relationship with procreational symbolism. This study adds complexity to this view—at all three sites, smithing was not restricted to or associated exclusively with a central settlement space. Far more diverse evidence of spatial organisation of the three investigated settlements would be needed to weigh them against larger models of spatial organisation. However, the distribution of smithing debris points to diverging worldviews compared to those captured by the Central Cattle Pattern model (Huffman 2001).

Furthermore, it is debatable to what extent the spatial distribution of iron slag within the settlements points to a clear social structure. Basic assumptions of spatial organisation studies suggest that to create order, people structured their space and designated specific areas for certain activities (Hillier and Hanson 1984; H. Kuper 1972; Lawrence and Low 1990). The extent to which a space is structured, therefore, is considered informative of how ordered a society is and how it practises its belief and class systems. The ubiquity of smithing evidence across the extent of Unguja Ukuu might then point to a low level of social stratification. Meanwhile, clearer patterns of spatial organisation of ironworking emerge in Tumbe and Chwaka. These may indicate an increasingly ordered society that regulates space as well as local lifeways. Interestingly, such different levels of social structure may be reflected in technologies at these sites—the lower level of slag variability at Tumbe and Chwaka may further support the argument for a more regulated social context. This highlights the value of investigating craft technologies along with the spatial distribution of craft materials.

The sites of Unguja Ukuu, Tumbe, and Chwaka are all characterised by distinct material culture and landscapes and were excavated using different archaeological approaches. The goal here is not just to draw parallels and juxtapositions between the sites, but to highlight ways in which studying them with an integrated methodology challenges the expectation that limited information can be extracted from smithing slag.

The study has revealed that smithing slag from Unguja Ukuu suggests technical traditions different from those of Tumbe and Chwaka in several ways. Petrographic analysis suggested that reducing hearth conditions were predominant at Tumbe and Chwaka, while Unguja Ukuu slag indicated oxidising hearth conditions. Elemental composition of slag, while variable at all sites, underscored differences in raw materials that may have been used, particularly with respect to CaO and SiO_2 concentrations. Finally, the examination of slag in its spatial and chronological context revealed that ironworking activity was probably taking place in association with domestic contexts at Unguja Ukuu, while more dynamic spatial organisation of craft activity emerges at Tumbe and Chwaka. The employed methodology allowed for multiple points of comparison of the technological traditions and revealed distinct communities of practice, as defined by Lave and Wenger (1991; Wenger 1998), on Pemba and Zanzibar islands. These findings shed light on a critically understudied subject of Swahili craft production and further our understanding of spatial organisation of archaeological settlements in the region.

While iron smithing receives less scholarly attention than smelting overall, this is particularly apparent in African contexts. A host of researchers have investigated iron smelting in Africa from archaeological and ethnographic points of view (e.g. Van Der Merwe and Avery 1987; Childs 1991; Killick 1991; Herbert 1994; Schmidt 1997; Haaland 2004; Chirikure and Rehren 2006; Rehren et al. 2007; Mapunda 2011; Mtetwa 2017; Lyaya 2019). Their findings invariably illustrate how diverse and innovative technical traditions of iron extraction are across the continent. It has been suggested that the highest variability of technological approaches to iron smelting has been found in Africa (Killick 2015). One could ask whether it is likely that such a fiercely innovative approach to iron production would not spill over into iron smithing as well.

In the future, more holistic strategies for the study of smithing slag and its contexts would help answer this question and shed further light on practices of smithing. While individual methods used in this study are well established, their integration has allowed for a new perspective. Similarly, a pioneering method for collecting and plotting distribution of hammerscale using a magnet (Veldhuijzen 2009a, b; Veldhuijzen and Rehren 2006, 2007) could help locate and map archaeological smithing workshops. Structural remains of smithing workshops are exceedingly rare in African contexts (e.g. McIntosh 1995) and the use of this particular method could transform our ability to find and understand ironworking areas. Furthermore, routinely integrating morphological slag analysis into fieldwork would lead to a more comprehensive understanding of technical traditions than what can be extrapolated from a small number of curated samples. Finally, more archaeometallurgical analysis of smithing slag in the region is needed. While currently available methods have limitations, this study demonstrates that their integration provides a solid approach that can reveal intriguing insights into technical traditions, creative use of resources, and help identify communities of practice.

Conclusion

We present an integrated methodological approach to the study of iron smithing slag from three East African sites. The results suggest that two highly distinct technological traditions can be detected in Zanzibar and Pemba islands. Petrographic analysis of iron slag indicated that different redox conditions were achieved at Unguja Ukuu when compared to Tumbe and Chwaka sites. Quantitative elemental analysis and different chemical fingerprints lay further ground for a hypothesis that distinct technical traditions and communities of practice are associated with Zanzibar and Pemba islands. We suggest that a level of technological consistency is evident at Unguja Ukuu throughout its occupation. Similarly, parallels in slag characteristics indicate that comparable technological approaches were employed at Tumbe and Chwaka sites, hinting at continuity of technical traditions on the peninsula. Finally, investigation of spatial and chronological contexts revealed different traditions of spatial organisation of craft at different sites. The study has wider implications—it demonstrates how an integrated approach can be used to extract valuable information from a challenging material and help address questions of technological practices and work organisation. It also showcases the significance of advancing our ability to differentiate between smithing and smelting slag, by demonstrating how identification and characterisation of these materials can add to our understanding of social structures.

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Data availability All key data are included in the publication and no additional data repositories have been used.

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Declarations

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References

Baužytė E (2019) Making and trading iron in the Swahili world: an archaeometallurgical study of iron production technologies, their role, and exchange networks in 500–1500CE coastal Tanzania. Dissertation, Aarhus University

Blakelock E, Martinón-Torres M, Veldhuijzen HA, Young T (2009) Slag inclusions in iron objects and the quest for provenance: an experiment and a case study. J Archaeol Sci 36(8):1745–1757. https://doi.org/10.1016/j.jas.2009.03.032

Brown J, Sassoon JB (1995) Traditional metalworking in Kenya (No. 38). Oxbow Books Limited, Oxford

Chami FA (1999) The Early Iron Age on Mafia island and its relationship with the mainland. AZANIA: J Br Inst East Afr 34(1):1–10. https://doi.org/10.1080/00672709909511468

Chami F (2001) Chicken bones from a Neolithic limestone cave in Zanzibar. In: Chami F, Pwiti G, Radimilahy C (eds) People, contacts and the environment in the African past. University of Dar es Salaam Press, Dar es Salaam, pp 81–97

Chami F (2009) Zanzibar and the Swahili coast from c. 30,000 years ago. E & D Publishers, Dar es Salaam

Childs ST (1991) Style, technology, and iron smelting furnaces in Bantu-speaking Africa. J Anthropol Archaeol 10(4):332–359. https://doi.org/10.1016/0278-4165(91)90006-J

Chirikure S (2006) New light on Njanja iron working: towards a systematic encounter between ethnohistory and archaeometallurgy. South Afr Archaeol Bull 61(184):142–151

Chirikure S, Rehren Th (2006) Iron smelting in pre-colonial Zimbabwe: evidence for diachronic change from Swart Village and Baranda, northern Zimbabwe. J Afr Archaeol 4(1):37–54. https://doi.org/10.1163/10.3213/1612-1651-10062

Chittick N (1974) Kilwa: an Islamic trading city on the East African coast. British Institute in Eastern Africa, Nairobi

Chittick N (1984) Manda: excavations at an island port on the Kenya coast. British Institute in Eastern Africa, Nairobi

Coustures MP, Béziat D, Tollon F, Domergue C, Long L, Rebiscoul A (2003) The use of trace element analysis of entrapped slag inclusions to establish ore–bar iron links: examples from two Gallo-Roman iron-making sites in France (Les Martys, Montagne Noire, and Les Ferrys, Loiret). Archaeometry 45(4):599–613. https://doi.org/10.1046/j.1475-4754.2003.00131.x

Crowther A, Veall MA, Boivin N, Horton M, Kotarba-Morley A, Fuller DQ, Fenn T, Haji O, Matheson CD (2015) Use of Zanzibar copal (Hymenaea verrucosa Gaertn.) as incense at Unguja Ukuu, Tanzania in the 7–8th century CE: chemical insights into trade and Indian Ocean interactions. J Archaeol Sci 53:374–390

Crowther A, Faulkner P, Prendergast ME, Quintana Morales EM, Horton M, Wilmsen E, Kotarba-Morley AM, Christie A, Petek N, Tibesasa R, Douka K, Picornell-Gelabert L, Carah X, Boivin N (2016a) Coastal subsistence, maritime trade, and the colonization of small offshore islands in Eastern African prehistory. J Island Coastal Archaeol 11(2):211–237

Crowther A, Lucas L, Helm R, Horton MC, Shipton C, Wright HT, Walshaw S, Pawlowicz MC, Radimilahy C, Douka K, Picornell-Gelabert L, Carah X, Boivin N (2016b) Ancient crops provide first archaeological signature of the westward Austronesian expansion. Proc Natl Acad Sci USA 13(24):6635–6640

Dungworth D, Bayley J, Paynter S, Crew P, Fell V, Gilmour B, McDonnell G, Mortimer C, Northover P, Starley D, Young T (2015) Archaeometallurgy: guidelines for best practice. Historic England, Swindon

Dungworth D, Wilkes R (2009) Understanding hammerscale: the use of high-speed film and electron microscopy. Hist Metall 43(1):33–46

Eekelers K, Degryse P, Muchez P (2016) Petrographic investigation of smithing slag of the Hellenistic to Byzantine city of Sagalassos (SW-Turkey). Mineral Soc Am 101(5):1072–1083. https://doi.org/10.2138/am-2016-5390

Eliyahu-Behar A, Yahalom-Mack N, Gadot Y, Finkelstein I (2013) Iron smelting and smithing in major urban centers in Israel during the Iron Age. J Archaeol Sci 40(12):4319–4330. https://doi.org/10.1016/j.jas.2013.06.009

Faulkner P, Harris M, Ali AK, Haji O, Crowther A, Horton MC, Boivin NL (2017) Characterising marine mollusc exploitation in the eastern African Iron Age: archaeomalacological evidence from Unguja Ukuu and Fukuchani Zanzibar. Quat Int 471(Part A):66–80

Fitton T, Wynne-Jones S (2017) Understanding the layout of early coastal settlement at Unguja Ukuu. Zanzibar Antiq 91(359):1268–1284

Fitton, T (2017) Pushing the Boat Out: A study of spatial organisation and harbour spaces in the early Swahili ports of the Zanzibar Archipelago, 550–1100 CE. Dissertation, University of York

Fitton, T (2018) Zanzibar. In Wynne-Jones S, LaViolette A (eds) The Swahili world. Routledge, London, pp 239–244. https://doi.org/10.4324/9781315691459

Fleisher JB (2010) Swahili synoecism: rural settlements and town formation on the Central East African coast, A.D. 750–1500. J Field Archaeol 35(3):265–282

Fleisher J (2014) The complexity of public space at the Swahili town of Songo Mnara, Tanzania. J Anthropol Archaeol 35:1–22. https://doi.org/10.1016/j.jaa.2014.04.002

Fleisher J, LaViolette A (1999) Elusive wattle-and-daub: finding the hidden majority in the archaeology of the Swahili. AZANIA: J Br Inst East Afr 34(1):87–108

Fleisher J, LaViolette A (2013) The early Swahili trade village of Tumbe, Pemba Island, Tanzania, AD600–950. Antiquity 87(338):1151–1168

Flexner JL, Fleisher JB, LaViolette A (2008) Bead grinders and early Swahili household economy: analysis of an assemblage from Tumbe, Pemba Island, Tanzania, 7th–10th centuries AD. J Afr Archaeol 6:161–181

Friede HM (1979) Iron-smelting furnaces and metallurgical traditions of the South African Iron Age. J South Afr Inst Min Metall 79(13):372–381

Friede HM, Hejja AA, Kousaris A (1982) Archaeo-metallurgical studies of iron smelting slags from prehistoric sites in southern Africa. J South Afr Inst Min Metall 82(2):38–48

Garlake PS (1966) The early Islamic architecture of the East African coast. Oxford University Press, London

Haaland R (2004) Iron smelting-a vanishing tradition: ethnographic study of this craft in south-west Ethiopia. J Afr Archaeol 2(1):65–79. https://doi.org/10.3213/1612-1651-10019
Herbert EW (1994) Iron, gender, and power: rituals of transformation in African societies. Indiana University Press, Bloomington and Indianapolis
Hillier BH, Hanson J (1984) The social logic of space. Cambridge University Press, Cambridge
Horton MC (1987) Early Muslim trading settlements on the East African coast: new evidence from Shanga. Antiqu J 67(2):290–323. https://doi.org/10.1017/S0003581500025427
Horton MC (1996) Shanga; the archaeology of a Muslim trading community on the coast of East Africa. British Institute in Eastern Africa, London
Horton MC, Clark CM (1985) Zanzibar Archaeological Survey. Azania 20:161–171
Horton MC (2004) Islam, archaeology, and Swahili identity. In: Whitcome (ed) Changing social identity with the spread of Islam: archaeological perspectives. Chicago, The Oriental Institute of the University of Chicago, pp 67–88
Huffman TN (1989) Ceramics, settlements and late Iron Age migrations. Afr Archaeol Rev 7(1):155–182
Huffman TN (2001) The Central Cattle Pattern and interpreting the past. South Afr Humanit 13(1):19–35
Iles L, Martinón-Torres M (2009) Pastoralist iron production on the Laikipia Plateau, Kenya: wider implications for archaeometallurgical studies. J Archaeol Sci 36(10):2314–2326
Jackson CM, Booth CA, Smedley JW (2005) Glass by design? Raw Mater Recipes Compositional Data Archaeom 47(4):781–795. https://doi.org/10.1111/j.1475-4754.2005.00232.x
Jouttijärvi A (2015) Scales and spheres. Hist Metall 48:41–46
Juma A (2004) Unguja Ukuu on Zanzibar: an archaeological study of early urbanism. Societas Archaeologica Upsaliensis, Uppsala
Killick D (1991) The relevance of recent African iron-smelting practice to reconstructions of prehistoric smelting technology. MASCA Res Papers Sci Archaeol 8(1):47–54
Killick D (2015) Invention and innovation in African iron-smelting technologies. Camb Archaeol J 25(1):307–319. https://doi.org/10.1017/S0959774314001176
Kiriama HO (1987) Archaeo-metallurgy of iron smelting slags from a Mwitu Tradition site in Kenya. South Afr Archaeol Bull, 42(146):125–130
Kuper H (1972) The language of sites in the politics of space. Am Anthropol 74(3):411–425
Kusimba CM (1996) The social context of iron forging on the Kenya coast. Africa: J Int Afr Inst 66(3):386–410. https://doi.org/10.2307/1160959
Lave J, Wenger E (1991) Situated learning: legitimate peripheral participation. Cambridge University Press, Cambridge
LaViolette A (2000) Ethno-Archaeology in Jenné, Mali: craft and status among smiths, potters, and masons. BAR International Series 838. Archaeopress, Oxford
LaViolette A, Fleisher J (2009) The urban history of a rural place: Swahili archaeology on Pemba Island, Tanzania, 700–1500 A.D. Int J Afr Hist Stud 42(3):433–455
LaViolette A, Fleisher JB (2018) Developments in rural life on the Eastern African coast, AD 700–1500. J Field Archaeol 43(5):380–398
LaViolette A, Wynne-Jones S (2018) The Swahili world. In: Wynne-Jones S, LaViolette A (eds) The Swahili world. Routledge, London, pp 1–14
LaViolette A, Fleisher J, Mapunda B (2003) Preliminary report: Pemba archaeological project, first season, June-August 2002. Department of Archives, Museums, and Antiquities, Zanzibar
Lawrence DL, Low SM (1990) The built environment and spatial form. Annu Rev Anthropol 19:453–505
Liu Y, Martinón-Torres M, Chen J, Sun W, Chen K (2019) Iron decarburisation techniques in the eastern Guanzhong Plain, China, during Late Warring States period: an investigation based on slag inclusion analyses. Archaeol Anthropol Sci 11(12):6537–6549. https://doi.org/10.1007/s12520-019-00921-5
Lyaya EC (2019) Archaeology of Hehe iron smelting technology at Kalenga, southern Tanzania. J Afr Archaeol Netw 10:80–106
Lyaya EC (2020) Change and continuity in metal technology: iron production in the first and second millennium CE in Mbinga, southwestern Tanzania. Archaeol Anthropol Sci 12:1–23
Lyaya E, Mapunda B, Rehren Th (2012) The bloom refining technology in Ufipa, Tanzania (1850–1950). In: Robion-Brunner C, Martinelli B (eds) Métallurgie du fer et Sociétés africaines. Archaeopress, Oxford, pp 195–207
Mapunda B (2011) Jack of two trades, master of both: smelting and healing in Ufipa, southwestern Tanzania. Afr Archaeol Rev 28:161–175. https://doi.org/10.1007/s10437-011-9099-z
McIntosh SK (1995) Excavations at Jenne-Jeno, Hambarketolo, and Kaniana (Inland Niger Delta, Mali): the 1981 Season. University of California Press, Berkeley and Los Angeles
Miller D, Killick D (2004) Slag identification at southern African archaeological sites. J Afr Archaeol 2(1):23–47
Miller D, Whitelaw G (1994) Early Iron Age metal working from the site of KwaGandaganda, Natal, South Africa. South Afr Archaeol Bull 49(160):79–89. https://doi.org/10.2307/3889226
Miller D, Killick D, Van Der Merwe NJ (2001) Metal working in the Northern Lowveld, South Africa AD. J Field Archaeol 28(3–4):401–417. https://doi.org/10.1179/jfa.2001.28.3-4.401
Mtetwa E, Maposa YC, Manyanga M, Chirikure S (2017) When the smith is a woman: innovation, improvisation and ambiguity in the organisation of African iron metallurgy. In: Manyanga M, Chirikure S (eds) Archives, objects, places and landscapes: multidisciplinary approaches to decolonised Zimbabwean pasts. Langaa Research & Publishing CIG, Mankon, Bamenda, pp 295–318
Mtetwa E (2017) Technology, ideology and environment: the social dynamics of iron metallurgy in Great Zimbabwe, AD 900 to the present. Dissertation, Uppsala University
Paynter S (2007) Romano-British workshops for iron smelting and smithing at Westhawk Farm. Kent Hist Metall 41(1):15–31
Pearce FB (1920) Zanzibar: the island metropolis of Eastern Africa. Frank Cass and Company, London
Portillo H, Zuluaga MC, Ortega LA, Alonso-Olazabal A, Murelaga X, Martinez-Salcedo A (2018) XRD, SEM/EDX and micro-Raman spectroscopy for mineralogical and chemical characterization of iron slags from the Roman archaeological site of Forua (Biscay, North Spain). Microchem J 138:246–254. https://doi.org/10.1016/j.microc.2018.01.020
Portillo-Blanco H, Zuluaga MC, Ortega LA, Alonso-Olazabal A, Cepeda-Ocampo JJ, Martínez Salcedo A (2020) Mineralogical characterization of slags from the Oiola site (Biscay, Spain) to assess the development in bloomery iron smelting technology from the Roman period to the Middle Ages. Miner 10(4):1–17. https://doi.org/10.3390/min10040321
Priestman S (2018) Quantitative evidence for early long-distance exchange in eastern Africa: the consumption volume of ceramic imports. In: Wynne-Jones S, LaViolette A (eds) The Swahili world. Routledge, London, pp 472–484
Rehren Th, Charlton M, Chirikure S, Humphris J, Ige A, Veldhuijzen HA (2007) Decisions set in slag: the human factor in African iron smelting. In: La Niece S, Hook DR, Craddock PT (eds) Metals and mines – studies in archaeometallurgy. Archetype British Museum, London, pp 211–218
Sauder L, Williams S (2002) A practical treatise on the smelting and smithing of bloomery iron. Hist Metall 36(2):122–131

Schmidt PR (1997) Iron technology in East Africa: symbolism, science, and archaeology. James Currey Publishers, Oxford
Selskienė A (2007) Examination of smelting and smithing slags formed in bloomery iron-making process. Chemija 18(2):22–28
Serneels V, Perret S (2003) Quantification of smithing activities based on the investigation of slag and other material remains. In: Proceedings of the International Conference Archaeometallurgy in Europe. Associazione Italiana di Metallurgia, Milano, pp 469–479
Shipton C, Crowther A, Kourampas N, Prendergast ME, Horton M, Douka K, Schwenninger JL, Faulkner P, Morales EMQ, Langley MC, Tibesasa R, Picornell-Gelabert L, Wilmsen EN, Doherty C, Veall MA, Ali AK, Petraglia MD, Boivin N (2016) Reinvestigation of Kuumbi Cave, Zanzibar, reveals Later Stone Age coastal habitation, early Holocene abandonment and Iron Age reoccupation. Azania: Archaeol Res Afr 51(2):197–233
Sinclair P, Juma A, Chami F (2006) Excavations at Kuumbi Cave on Zanzibar in 2005. In: Chami F (ed) Studies in the African past. University of Dar es Salaam Press, Dar es Salaam, pp 95-106
Sinclair PJJ, Wandibba S (1988) Urban origins in Eastern Africa: project proposals and workshop summaries. Central Board of Antiquities, Stockholm
Soulignac R, Serneels V (2013) Forging with Dogon smiths (Mali). In: Dungworth D, Doonan RCP (eds) Accidental and experimental archaeometallurgy. Historical Metallurgy Society, London, pp 119–126
Sulas F, Kristiansen SM, Wynne-Jones S (2019) Soil geochemistry, phytoliths and artefacts from an early Swahili daub house, Unguja Ukuu, Zanzibar. J Archaeol Sci 103:32–45
Togola T (1993) Archaeological investigations of Iron Age sites in the Mema region, Mali (West Africa). Dissertation, Rice University
Trigger BG (1969) The myth of Meroe and the African iron age. Afr Hist Stud 2(1):23–50. https://doi.org/10.2307/216325
Van der Merwe NJ, Avery DH (1987) Science and magic in African technology: traditional iron smelting in Malawi. Afr: J Int Afr Inst 57(2):143–172. https://doi.org/10.2307/1159819
Van der Merwe NJ, Killick DJ (1979) Square: an iron smelting site near Phalaborwa. SA Archaeol Soc Goodwin Ser 3:86–93. https://doi.org/10.2307/3858116
Veldhuijzen HA (2009a) Red hot: the smithy at Tel Beth-Shemesh. Near East Archaeol 72(3):129–131
Veldhuijzen HA (2009b) Of slag and scales; micro-stratigraphy and micromagnetic material at metallurgical excavations. In: Kaptijn E, Petit L (eds) A timeless vale. Leiden University Press, Leiden, Archaeological and related essays on the Jordan Valley in honour of Gerrit van der Kooij on the occasion of his sixty-fifth birthday, pp 155–166
Veldhuijzen HA, Rehren Th (2006) Iron smelting slag at Tell Hammeh (azZarqa), Jordan. In: Pérez-Arantegui J (ed) Proceedings of the 34th International Symposium on Archaeometry, Zaragoza, 3–7 May 2004. Institución Fernando el Católico, Zaragoza, pp 245–250
Veldhuijzen HA, Rehren Th (2007) Slags and the city: early iron production at Tell Hammeh, Jordan and Tell Beth-Shemesh, Israel. In: Niece SL, Hook D, Craddock P (eds) Metals and mines: studies in archaeometallurgy. Archetype, London, pp 189–201
Walshaw SC (2010) Converting to rice: urbanization, Islamization and crops on Pemba Island, Tanzania, ad 700–1500. World Archaeol 42:137–154
Walshaw SC (2005) Swahili urbanization, trade and food production: botanical perspectives from Pemba Island, Tanzania, AD700–1500. Dissertation, Washington University
Wenger E (1998) Communities of practice: learning as a social system. Systems Thinker 9(5):2–3
Wood M (2018) Glass beads and Indian Ocean trade. In: Wynne-Jones S, LaViolette A (eds) The Swahili world. Routledge, London, pp 458–471
Wood M, Panighello S, Orsega EF, Robertshaw P, van Elteren JT, Crowther A, Horton MC, Boivin N (2016) Zanzibar and Indian Ocean trade in the first millennium CE: the glass bead evidence. Archaeol Anthropol Sci 9(5):871–901
Wright HT (1993) Trade and Politics on the Eastern Littoral of Africa, A.D.800-1300. In: Shaw T, Sinclair P, Andah B, Okpoko A (eds) The archaeology of Africa: food, metals and towns. Routledge, London, pp 658–672
Wynne-Jones S, LaViolette A (2018) The Swahili world. Routledge, London
Wynne-Jones S, Sulas F, Out W, Kristiansen S, Fitton T, Ali A, Olsen J (2020) Urban chronology on a human scale on the coast of East Africa in the first millennium AD. J Field Archaeol 46(1):21–35
Wynne-Jones S, Sulas F (2017) Archaeological fieldwork at Unguja Ukuu, Zanzibar, July 2017: interim report. Aarhus University, Aarhus. http://ebooks.au.dk/index.php/aul/catalog/book/276. Accessed 7 May 2023