# Innovation, tradition and metals at Kilwa Kisiwani

By Ema Baužytė, Gry Barfod, Stephanie Wynne-Jones

Corresponding author: Ema Baužytė, UrbNet Centre of Excellence , Aarhus University, Aarhus, Denmark.

ema.bauzyte@cas.au.dk

The study of ancient metalworking is an area of study where invention and innovation have been extensively discussed; this has often been seen as the same as discussing creativity.[[1]](#footnote-2) Yet, metal working processes have often been thought of as quite resistant to change: standardized, even ritualized. Less attention has been paid to the repeated acts of creativity that are part of any long-term production in a region. By focusing on these we can also explore connections between different practices, gleaning for example where metalworking processes draw on other craft technologies or materials, which techniques and technologies travel, and how this occurs.

In this paper, we present the results of recent metallurgical analysis of iron slags from Kilwa Kisiwani. Kilwa is not normally thought of as a major centre of early iron production. The excavator of the site stated that ”[i]ron was smelted from the beginning of the settlement … but not, it would seem, on a substantial scale.”[[2]](#footnote-3) The historical and archaeological focus at Kilwa has always been on the activities of the elite, the larger monuments and the site’s role in external trade, despite the reporting of significant quantities of iron slag at the site in 2006.[[3]](#footnote-4) Building on these discoveries by Felix Chami, the data from our own study suggest that this slag should be seen as indicative of a major industry at Kilwa, with evidence for the smelting of iron on an industrial scale. This evidence may date to some of the earliest periods of the site’s occupation. Further, we present the results of morphological and µ-XRF (X-Ray Florescence) analysis on the slag from Kilwa, which suggest significant creativity in the process of production here. Evidence for the use of lime as a flux suggests experimentation towards particular ends and may be evidence for a possible cross-over with copper-working technologies at the site. Lime can be an important flux in the smelting of copper alloys and Kilwa is one of the only coastal sites at which there is evidence for a significant copper industry, both for utilitarian objects and for the active Kilwa coin mint. Morphological analysis of the iron slag also suggests a slag-tapping technology for smelting iron at Kilwa. This is not known elsewhere on the coast, although it is a technology seen in southern Africa at a similar period. Both slag tapping and the use of lime flux for copper are also technologies known from the Near East; previous studies have suggested that the technology might have come from that region. Here we explore these aspects of Kilwa’s iron technology from the perspective of innovation and creativity, turning our attention to the ways that technologies were recreated at Kilwa as a route into considering the importance of expertise at the site. We also suggest that ultimate origins might not be important; Kilwa itself emerges as a town with a significant mineral heritage and a people engaged with metals and metalworking over a long period.

## Metal at Kilwa Kisiwani

The growth and success of Kilwa Kisiwani has often been linked to control over the supply of gold from the Zimbabwe plateau. [[4]](#footnote-5) Swahili towns of the eastern African coast traded between regional and international networks; they often moved commodities from the African interior into Indian Ocean markets. By the 14th century, gold had become a prime commodity in international trade, and Kilwa was able to exploit this, possibly based on control over Sofala (the coast of Mozambique) and hence access to the mineral wealth of the Zimbabwe plateau (Figure 1). This is intimated by the comments reported by Ibn Battuta that “a fortnight’s sail beyond Kilwa lies Sofala, where gold-dust is brought from a place a month’s journey inland”.[[5]](#footnote-6) The relationship between Kilwa and Zimbabwe is also supported by the chronology of growth and decline that links the settlements and the artefacts derived from coastal trade found at the latter site. This association persisted to the end of the 15th century, when Kilwa and Sofala were described by Portuguese visitors: “We found therein such great booty of gold, of silver and pearls, of golden pieces, and of sundry precious wares, that it was impossible to reckon their value.”[[6]](#footnote-7)

These historical mentions relate to the end of the Kilwa sequence and history is not informative on when this supply of gold may have begun. Indeed, the mechanism by which coastal towns gained control over particular resources has rarely been deconstructed beyond a general sense that coastal groups were well-placed to act as middlemen. It is also difficult to recognize the beginnings of the gold trade through archaeology, as there has been almost no trace of gold in any of the excavations conducted at the site, despite the massive scale of work (Chittick reported two gold beads, only one from excavations, and some tiny fragments of gold sheet and wire).[[7]](#footnote-8) Instead, historical and archaeological research has recovered evidence of a town that flourished particularly from the 11th century, built on a mixed economy of farming and fishing. This development is associated with the growth of a sultanate and with evidence for engagement with Indian Ocean networks of trade and religion (Table 1). Kilwa became one of the most elaborate townscapes on the eastern African coast, with buildings in coral and lime on a grand scale. The Great Mosque constructed in the 11th century was augmented with an enormous domed extension in the 14th century; it stands today as one of the most impressive monuments on the coast. To the east of the town, the palace of Husuni Kubwa and the adjacent enclosure known as Husuni Ndogo were also constructed in the 13th–14th centuries. Later the townscape was elaborated with many other stone houses, all built in the area near the Great Mosque, as well as with urban developments on adjacent islands such as Songo Mnara (Figure 2).[[8]](#footnote-9)

## Craft and economy

Craft production was never the focus of historical attention and has been little explored through excavation. As elsewhere on the coast, there is little contextual information for economic activity at the site.[[9]](#footnote-10) Nonetheless, Chittick recorded evidence for several local production processes, each with a distinct chronology.[[10]](#footnote-11) Pottery production was important throughout the sequence. In the early layers, before c.AD1000, numerous bead grinders attest to the production of marine shell beads. These declined after AD1000, alongside an increase in imported glass beads. Spindle whorls attesting to the production of cotton at the site are common from this time and are also found across sites in the adjacent mainland.[[11]](#footnote-12)

In Chittick’s excavations, metalworking did not loom disproportionately large amongst these local forms of production. He mentions iron slag in some of the earliest levels but investigations of these contexts were only ever on a small scale..[[12]](#footnote-13) Copper working is given more prominence, both directly through the evidence for copper slag and crucibles and indirectly through discussion of the many copper alloy coins that are found throughout the deposits at this site, although he did note that copper objects were rare. [[13]](#footnote-14) In this active copper-working industry, Kilwa is unusual among coastal sites, although Chittick could not have known this at the time of his writing. Yet the theme of Kilwa’s metalworking has been picked up more recently by Felix Chami. In particular, he drew attention to an area known as Nguruni, which is immediately adjacent to Husuni Kubwa (Figure 2) and therefore sits between the 14th-century palace and the town proper.[[14]](#footnote-15) At Nguruni there is evidence for ironworking on a large scale. The deposits are difficult to disentangle; they seem to represent repeated episodes of iron slag being dumped from the top of the slope down towards the foreshore. Nguruni is also a very denuded landscape, apparently due to large-scale mining of red lateritic clays in this area which have exposed the rocks beneath (Figure 3). The archaeology of the area is therefore a jumble of iron slag on top of rocks. Chami conducted test excavations in the area, and revealed dense layers of slag with little to separate them. The ceramic record from these layers suggested multiple intersecting deposition events, rather than any occupation or domestic use of this area. He was able to recover charcoal for radiocarbon dating, which gave two dates of AD1283 ±50 and AD982 ± 50. These are difficult dates to use, as their calibration is not reported; nonetheless they raise the possibility that charcoal was being burnt at Nguruni during the earliest centuries of Kilwa’s occupation. Direct dating of charcoal within slag is planned by the current authors to add greater clarity. As part of Chami’s project, Bertram Mapunda also analysed some of the copper crucibles found by his colleagues, and provided the first discussion of Kilwa as a location where copper was being worked on a significant scale, making a connection with the coin mint, as well as with the copper items that have emerged from excavations.[[15]](#footnote-16) This also brings a suggestion of chronology, since copper coins were minted from the mid-eleventh century onwards. It is likely that the scale of copper working was more extensive than has been revealed through archaeology; the present authors have observed quantities of copper crucibles on sale in local curio shops, clearly having been removed from the site.

## Metal traditions

What becomes clear from the Nguruni landscape and Chami’s excavations within it, is that Kilwa was a significant centre of metalworking. Iron smelting was on a large scale, whereas remains analysed from contemporary sites such as Shanga, or Chwaka are suggestive mostly of smithing.[[16]](#footnote-17) The identification of Nguruni as an industrial location allows us to consider anew the overall trajectory for Kilwa Kisiwani, in which metals figure prominently. At Kilwa the evidence for trade with the Islamic world is slight during the earliest centuries; it may therefore be that iron production was a more important aspect of the site’s economy during the earliest occupation and, perhaps, well into the second millennium CE. The importance of metals to Kilwa’s economy also serves to draw attention away from Indian Ocean connections and suggest links to the interior of southern Africa that pre-date the gold trade, since this was the probable source of copper ore.

What makes ironworking at Kilwa particularly interesting is the ways it stands alongside the development of other metal traditions. Copper working and copper objects are prominent here and Kilwa minted cuprous coins on a large scale, for use as a currency in the town itself and in areas where Kilwa held influence.[[17]](#footnote-18) Silver coins are rarer, but also known from the excavations and from an eleventh-century hoard on Pemba at Mtambwe Mkuu.[[18]](#footnote-19) Gold looms large in the histories, yet it is poorly represented in the archaeology. An exception might be the rare Kilwa gold coins that testify to the working of this metal locally.[[19]](#footnote-20) Together, this creates a picture of a site with a significant metal tradition. Kilwa was not just a conduit for commodity metals from the African interior. It was a place where a range of metals was manipulated and with a significant investment of labour and time in the manufacture and trade of metal items.

## Innovation, Creativity and Metal Technologies

How do these metals and metalworking fit into considerations of innovation and creativity? The literature on technological invention in African metalworking is extensive.[[20]](#footnote-21) Archaeology and ethnoarchaeology usefully combine in this field to explore the diversity of African metalworking traditions and there is general agreement on the significance of metalworking–and particularly ironworking–in African contexts.[[21]](#footnote-22) Yet the majority of discussion has been at the level of regional tradition, characterising the technology and social organisation of ironworking in that particular place and time.[[22]](#footnote-23) This acknowledges but does not elaborate on the role of individual creativity and craftsmanship in the production and reproduction of technological processes.

Here we instead draw on two trends in the study of ancient metals. First, a useful distinction drawn between invention and innovation in recent literature.[[23]](#footnote-24) This positions invention as a moment in the process of technological creativity, when novel approaches are created or applied. The inventor negotiates practical considerations of resource availability, the inertia and safety of tradition against the search for improved outcomes and introduces a different approach to making metal. This requires a shift in perception of the landscape, since invention in pyrotechnology requires the transformation of the material world.[[24]](#footnote-25) If these inventions are successfully transmitted they become innovation. What is useful in this formulation is the insertion of time and consistency into the discussion; it draws our attention not just to the origin point of a technology, but instead to how it is recreated over and again through multiple acts of individual creativity. For an innovation to take hold requires people to recognise the value of the initial invention and choose to recreate it repeatedly. This echoes discussion of improvisation and innovation in the literature on creativity, which contrasts the forward-looking qualities of improvisation compared to the more static concept of innovation.[[25]](#footnote-26) Technological innovation, then, contradicts the artistic value system that recognises an original as superior and a copy as inferior. A technological invention only becomes established and thus accumulates value through these individual acts of recreation. This has been explored in relation to style, in work that has explored the socially embedded nature of technical choices and argued for the primacy of learning structures in the creation of particular forms and methods.[[26]](#footnote-27) The process of producing a metal is thus somewhat comparable to such performative actions, and much like following a recipe or attempting to retell a folk tale, it is subject to choices made by individuals. When recreated without changes it is only because of an active choice to do so. The consistency of these choices is what transforms an invention to innovation. It challenges us as archaeologists to account for those choices through both instrumental and cultural logics: “continuity of tradition is due not to its passive inertia but to its active regeneration.”[[27]](#footnote-28)

Second, recent archaeologies have explored the ways that different technologies intersect and cross-fertilise. This is particularly true for pyrotechnologies, where invention in particular crafts can influence other areas. For example, expertise in copper working has been seen to spill over into glass and glaze technologies and into gold working. [[28]](#footnote-29) Scholars of this theme draw significantly on archaeometallurgy and materials approaches to add depth and comparability to their studies. Microscopic analyses of slag and metalworking debris, elemental characterisation of metals and their by-products, and detailed chronologies of development and change have allowed ever greater insight into those ongoing processes of innovation.[[29]](#footnote-30)

At Kilwa, these two approaches lead us towards an interesting area. Using archaeometric studies of iron slag from Kilwa Nguruni, we explore the ongoing process of innovation at the site. This is evident in the technology of iron production on a massive scale, unmatched at any other coastal town. Characterisation of the slag also allows discussion of the elements of this technology, exploring cross-fertilisation between mineral technologies here, notably between iron and copper working at the site and further afield. The result is a recasting of the site itself as a significant centre of technological innovation and skill.

## Iron Production at Kilwa Nguruni

In July 2016, the authors visited Kilwa Kisiwani during the course of excavations at neighbouring Songo Mnara. The area of Nguruni was explored with a view to gathering iron slag samples for a comparative project on coastal metalworking by one of the authors. It was intended that the Kilwa samples would become part of a comparative analysis of smelting and smithing at coastal centres. This is in process, but it has also become clear that the Kilwa material is quite distinct from samples elsewhere. Four key findings about the technology of iron production at Kilwa are suggested in this paper. These findings distinguish the site from any other known iron production site along the East African coast. Firstly, evidence strongly suggests that tapping techniques were used to remove excess slag. Secondly, we argue that a calcium-rich flux was used to facilitate iron extraction due to consistently high levels of CaO wt% detected in iron slag. Thirdly, the huge scale of production taking place at Kilwa is discussed, suggesting that such intensive ironworking is not found elsewhere along the East African coast. Finally, we discuss the resources available at Kilwa for iron production and conclude that at least iron ore would have to have been shipped to the site from the African mainland.

### Sampling and methodology

During the 2016 visit 40 pieces of iron slag exhibiting a range of different morphologies and scattered at various parts of the site were collected for analysis. The samples were then analysed using a range of archaeometallurgical methods in order to identify slag types, evaluate their chemical compositions, and subsequently understand the craftsmens’ decisions encoded in the material. Macroscopic attributes of the slag were noted, enabling differentiation between smithing, smelting, and non-diagnostic slag samples. Fifteen representative samples were then cut using a steel saw with a diamond edge in order to obtain thick sections of samples and an even surface was prepared by grinding the samples using SiC grinding papers of 180p and 500p. The samples were then analysed using Bruker M4 Tornado µ-XRF analytical instrumentation in order to obtain quantitative elemental information.Ten measurements were carried out for each sample.[[30]](#footnote-31)

### Smithing or smelting?

The first analytical aim was to identify whether the slag from Kilwa represented the debris of smithing or smelting activity. A total of 15 slag pieces were identified as plano-convex in shape and therefore, interpreted as smithing hearth bottom slag; 15 were identified as having horizontal flow marks and were attributed to smelting processes. Finally, ten were identified as non-diagnostic. Overall, the morphological analysis indicated that both smithing and smelting processes were carried out at the site, probably intensively.

Moreover, as well as suggesting the presence of a significant iron smelting industry at Kilwa Nguruni, the results further identified some interesting characteristics of the technological process. The horizontal flow morphology noted on the smelting samples suggested that slag may have been purposefully tapped from smelting furnaces. Furthermore, earlier evaluation of a larger slag assemblage from the site (145 samples) carried out by Mapunda and Chami concluded that 74% of the assemblage was constituted of such horizontally flowed slag.[[31]](#footnote-32) This indicates that smelting furnaces at Kilwa likely used a tapping technique to manage excess slag.

Subsequently, 15 samples (ten smelting and five probable smithing) were analysed for quantitative elemental composition. Particularly interesting were the results of smelting slag. The results indicated limited variability within individual samples and across the assemblage. The average FeO wt% of samples remained consistently within the range of 50.21 wt% to 57.44 wt%. Silica:alumina ratios were similarly comparable and measured from 3.06:1 to 3.77:1. CaO quantities were invariably high and fluctuated from 6.20 wt% to 8.01 wt%.% (Table 2). These data therefore point to consistency and potential standardization of process at Kilwa.

## Understanding Iron Production at Kilwa Nguruni

Evidence of iron production uncovered at the site has no known parallels in coastal East Africa. Kilwa Nguruni is distinguishable from other iron production sites by its production scale, its location in relation to the main settlement, and the technology itself.

### Scale

While evidence of iron production is found ubiquitously along the Swahili coast, only relatively small-scale iron working, largely occurring in association with domestic structures, has been unearthed previously.[[32]](#footnote-33) Kusimba states that “no sites of large scale iron production are known on the Swahili coast” and blames a lack of primary research.[[33]](#footnote-34) Iron slag resulting from smithing episodes is found more commonly than evidence of smelting, although the latter has also been found at several Swahili sites, such as Kaole, Tumbe, Bwembeni and from the 16th century onwards at Galu.[[34]](#footnote-35) Dakawa, in the coastal hinterland of Tanzania, is a smelting site with ceramics that have coastal affinities; it has been interpreted as supplying coastal markets.[[35]](#footnote-36) Without systematic survey and excavations the extent of iron production at Kilwa Nguruni cannot be evaluated quantitatively or compared accurately to other sites in the region. Nevertheless, we know that the production site extends for approximately a kilometre along the shoreline. Continuous scatters of slag are found throughout this area and the depth of these deposits is unclear. Excavations carried out by Chami revealed that slag deposits observed on the surface cap dense subsoil layers of iron debris. The excavators were not able to reach the sterile and the precise depth of these deposits remains unknown. However, a huge scale of iron working is evident at the site and presents a stark difference from the household-level craftsmanship more commonly found at Swahili sites.

### Location

The scale of production is undoubtedly an important factor in choosing the location for an iron smelting site and it is hardly surprising that such activity is situated outside the limits of the main Kilwa settlement. Less apparent is the explanation for why iron production developed to such a large extent on Kilwa Island at all. Iron smelting sites are commonly found at a distance from inhabited areas in mainland Tanzania[[36]](#footnote-37). Ethnographic investigations often emphasise cultural taboos associated with iron smelting as one of the reasons why more remote areas are chosen for the work. These taboos frequently exclude menstruating women and women of reproductive age from the smelting process, as it is believed that their presence causes a smelt to fail. Thus, smelting operations are often removed from domestic contexts and performed outside inhabited areas. However, no ethnographic research on iron smelting has been carried out for the Swahili coast and it is unclear to what extent these taboos were ever practiced in the region. Furthermore, there are important practical reasons to position a smelting site outside of a settlement, such as potential dangers of fire, nuisance of smoke and noise associated with smelting operations. Finally, ethnographic accounts focus on far smaller scale individual iron smelting episodes and do not prepare us for the production scale evident at Kilwa. Therefore, cultural aspects related to the location of a smelt commonly considered in ethnographic accounts are difficult to discuss meaningfully in the context of Kilwa.

Kilwa Nguruni does not appear to be an advantageous location for access to raw material sources such as iron ore, fuel, and water. Firstly, no known ore sources are found on the island. During the visit to the site lateritic outcrops were noted within the vicinity of the slag heaps. It was initially suspected that the deposits may have been exploited for iron smelting and samples of the lateritic soil were collected for analysis. However, the subsequent bulk elemental analysis revealed low FeO contents ranging between 1.54 wt% and 1.85 wt% (Table 3). These values indicated that the deposits did not contain nearly enough iron to make a viable ore. It is difficult to rule out the possibility that any viable ore was mined out in its entirety due to the inherent heterogeneity of lateritic soils. More probably, however, the soil was quarried for other purposes, such as the construction of smelting furnaces, production of tuyères, or wattle-and-daub house construction, but this would not have been used to extract iron. In addition, one fragment of a possible iron-bearing mineral was found as part of surface collection and recovered for analysis. Quantitative elemental evaluation revealed that FeO contents ranged from 71.15 wt% to 78.23 wt% (Table 4) and suggested that an analogous type of mineral may have been a suitable material for iron extraction. Furthermore, elemental composition of the mineral was evaluated in relationship to slag composition and no specific reason to rule out the possibility that such mineral may have been used for iron production at Kilwa Nguruni was identified. However, no deposits of such ore have been recorded on Kilwa Island. Thus, it currently appears probable that the raw material for iron extraction was transported to the site from elsewhere.

Since transporting raw materials is logistically and economically more taxing than transporting the smelted iron, it is reasonable to think that this is only done when other resources necessary for iron production, such as fuel, water, clay, or technological know-how are not available locally. For instance, Maggs argued that access to fuel plays a particularly important role in determining the location of a smelting site and a reliable source of charcoal is more important than the site’s proximity to ore deposits.[[37]](#footnote-38) However, it is difficult to argue that the abundance of fuel sources could have been an important factor in choosing the location of smelting activity at Kilwa. The landscape of Kilwa Nguruni is largely dominated by shrubs and grasses rather than hardwoods, which are considered to be the preferred type of wood species for iron smelting.[[38]](#footnote-39) However, ultimately, availability of tree species and their value for other purposes, such as suitability for house construction can play an important role in species selection and mean that more diverse types of wood are used for smelting.[[39]](#footnote-40) Furthermore, it has been argued that various sustainable woodland management strategies may have been employed in the past in order to make the most out of the available vegetation.[[40]](#footnote-41) Thus, the flora available at Kilwa may have been sufficient for iron smelting at the site. Currently no empirical data are available to suggest what fuel sources were used for iron production at Kilwa and analysis of charcoal found in association with smelting debris would provide crucial information in the future. With data available at present, it is argued that while the vegetation at Kilwa Nguruni may have sufficed for the purposes of iron production, it is unlikely to have been the primary reason for the location of the site.

Another significant factor in choosing a location for a smelting site is its proximity to water sources. Iron smelting sites are commonly, although not exclusively, found along rivers and streams.[[41]](#footnote-42) Water is important for production of technical ceramics, can be used to control the fire and facilitate material transport.[[42]](#footnote-43) Kilwa Nguruni is in fact positioned within proximity to the shoreline and has the advantage of reliable access to water and transport, although Nguruni area is hardly unique in this respect and it is unlikely that this alone could have made the laborious transportation of raw material to the island worthwhile. Clays are similarly far from being a scarce resource in the region and are not considered to have affected the choice for site location.

### Technology

The final aspect, and the one we consider most likely to have been the reason for the site’s location and ultimately the huge scale of production, is the technological expertise that would have been available at Kilwa. While iron smelting is common in the region, several technological aspects that single Kilwa out from other sites have been uncovered during this research.

The most apparent distinction is the discovery of tapping technology at the site. According to previous archaeological research in the wider region of East Africa, by far the more common approach to managing excess slag was excavation of a slag pit, where material would accumulate during the smelt.[[43]](#footnote-44) Tapping has occasionally been found archaeologically on mainland East Africa in areas from Buganda, southwards to west Tanzania and Zimbabwe, although smelting at Kilwa mostly predates these mainland sites.[[44]](#footnote-45) Tantalising new evidence is emerging from the Zimbabwe plateau, where research has identified slag-tapping technologies on sites dated to the 10th and 11th centuries.[[45]](#footnote-46) Evidence of slag-tapping technology predating the 2nd millennium CE is also found at archaeological sites in the Middle Eastern region and Northern Africa.[[46]](#footnote-47) It is tempting to think of Kilwa’s technologies as derived from an early connection with the Zimbabwe plateau, and to see these technologies as evidence for that. Yet, technological inspiration could also have reached the site from the Red Sea region. It is also difficult to rule out definitively the possibility that slag tapping techniques could have been invented at Kilwa independently. Accidental slag tapping can occur without human intervention when liquid slag flows out of a furnace due to a weakness in a furnace wall. It is conceivable that iron smelters would have observed this process, recognised its value and begun applying the technique purposefully. However, even such seemingly minor shifts in iron production process can be difficult to implement and can prove detrimental to the outcome of the smelt. If the furnace is tapped too early, iron will not have had the time to precipitate out of the slag and will be removed from the furnace alongside the slag. Late tapping can prove similarly catastrophic to the smelt. Such inherent risks associated with the independent invention of slag tapping lead us to speculate that in the case of Kilwa, a site known to have been in contact with contexts that already had knowledge of tapping techniques, transfer and adaptation of this technology may be the more plausible explanation .

In truth we cannot know from where the practice of slag-tapping at Kilwa came. More important here is that the craftsmen at Kilwa recognised the value of such an iron production technique and chose to recreate it. Establishing an innovative practice in a new setting is an inherently creative process. Regardless of the degree to which a craftsperson may attempt to recreate a specific technology in a different geographical context, various aspects of the process may have to be renegotiated through consideration and incorporation of local material and human resources. These instances of creative engineering may then become more definitive of the technology than its links to prototype technologies. As discussed in the introduction to this volume, the genealogy of practices is important, but is only one factor in the composition of knowledge, materials and skills that make up the creative process in a particular time and place. At Kilwa there was clearly a high degree of technological skill in evidence among these early smelters. This may have been the most compelling reason for the craft being located at the site. Bulk elemental analysis also demonstrated similarity between chemical compositions of samples. This suggests that a level of production standardization had occurred and craftsmen were able to reproduce successfully the parameters of the process. This is well illustrated by the results of the quantitative elemental analysis presented earlier in this paper. Overall, the relative similarities observed between samples indicate that similar raw materials and comparable production parameters were used during separate production episodes. Limited variability within individual samples suggests that production parameters were kept consistent throughout the process. Thus, an image of a highly controlled operation aimed towards recreating the same parameters emerges.

### Furthermore, tentative evidence has been presented suggesting that this impressive iron production activity was carried out alongside copper production. For this study we have not been able to examine the remains of copper working from Kilwa. Yet in 2006, Mapunda analysed a series of slags from excavations at Nguruni which he identified as stemming from the smelting of copper. In these samples, Mapunda identified evidence for slag tapping in copper working at the site; this further supports the idea that Kilwa had developed an early and prodigious metalworking industry that moved across different types of metals.[[47]](#footnote-48)

### Creativity across media

The key area in which we may see evidence for this intersection between iron and copper technologies is in the levels of calcium found in Kilwa’s iron slag; this may have been added deliberately or achieved through the use of a particular fuel. All analysed samples of smelting slag were found to contain relatively high amounts of CaO reaching up to 8.01 wt%. Iron slag excavated in East Africa does not commonly contain such high amounts of CaO and the significant quantities have to be explained .[[48]](#footnote-49)

Calcium is understood to be contributed to slag composition either from fuel or through the use of calcium-rich flux, although potential additions from technical ceramics and ore have to be considered. The low amounts of CaO (invariably below 0.5wt%) detected in the iron-bearing mineral collected at the site and the surrounding lateritic deposits with low FeO amounts present an argument against the ore and possibly technical ceramics being the source of high CaO content. This supports fuel or flux as the more likely source of CaO in the slag material. Authors who have previously identified elevated Ca concentrations in iron slag in East African contexts have argued that this may indicate the use of hardwoods as a fuel source.[[49]](#footnote-50) Some hardwoods have been found to contain Ca amounts in excess of 50 wt% and their use for iron smelting would certainly explain the high levels of CaO detected in the iron slag. However, hardwood species are not widely available at Kilwa; if these were the source then the landscape must have been substantially different, or they must have been brought into the site from mainland Africa. .[[50]](#footnote-51)

Alternatively, deliberate addition of a flux may explain a relatively high concentration of CaO. Calcium facilitates the iron extraction process by reacting with and thus removing impurities, lowering the viscosity of slag and acting as a catalyst in the process of slag and metal separation. It effectively raises the amount of iron retrieved during the process. It is therefore possible that lime flux was deliberately added to the furnace charge in order to increase the amount of iron resulting from the smelt. Craftspeople at Kilwa Nguruni would have had ample access to lime sources, such as shell or coral. Lime would have been routinely produced at Kilwa for coral-stone building construction by burning coral, as evidenced by a number of lime kilns excavated at the site.[[51]](#footnote-52) Hence, attempting to explain high amounts of CaO detected in iron slag with resource availability in mind, it may be more likely that lime was used as a flux, rather than hardwoods as fuel.

It is interesting to consider the elevated amounts of CaO with respect to the slag tapping technique. Addition of lime to the smelting system renders the slag less viscous and may contribute to slag properties that render the material easily tappable from the furnace. Whether amounts of CaO in the smelting system contributed towards the choice to adopt slag tapping is difficult to answer. Engineering solutions are not exclusively influenced by practical considerations and cultural contexts play a significant role in technological choices[[52]](#footnote-53).

Parallel production of copper at Kilwa is particularly interesting to discuss in relationship to the high CaO values. The extent to which fluxes were used in the process of iron smelting is still debated. Iron ores are not uncommonly self-fluxing due to presence of SiO2. Silica present in the ore effectively reduces slag-melting temperature to approximately 1200°C and facilitates the removal of gangue materials leaving behind the precipitated iron bloom. Additional silica contributions from reacted technical ceramics can also help this process along and use of lower grade ores alongside higher grade ones can function as fluxes.[[53]](#footnote-54) Furthermore, contributions of higher levels of CaO due to the use of hardwood fuels play a similar role.[[54]](#footnote-55) However, addition of a separate material, such as crushed quartz or lime exclusively for the purposes of fluxing has not been recorded frequently. A few rare examples of this from African contexts include an ethnographic account from Mbeere iron smelters in Mount Kenya region recorded by Brown and a speculation brought forward by Kiriama that calcium-rich flux may have been used for iron smelting at Saghasa, Kenya[[55]](#footnote-56). Possibility of an added silica flux was more cautiously proposed by Friede *et al[[56]](#footnote-57).* when studying slag from Southern African contexts. In addition, Mtetwa[[57]](#footnote-58) speculated that elevated amounts of CaO in several of the iron smelting sites excavated in Zimbabwe may be connected to the use of ritual medicines that had fluxing properties. However, few case studies where slag chemistry suggests use of fluxes are known, particularly when use of lime as a flux is in question. During a comparative study carried out by one of the authors[[58]](#footnote-59) on iron slag from 7 different sites in East Africa, only slag from Kilwa contained such consistently high levels of CaO wt% and indicated use of lime as a fluxing material.

More widely discussed has been the use of a variety of fluxes for copper smelting .[[59]](#footnote-60) Use of calcium-rich materials as possible fluxes has been suggested by numerous authors.[[60]](#footnote-61) The proximity with which iron smelting and copper production (possibly including copper smelting; Mapunda 2006) took place at Kilwa, suggests a hypothesis that certain technological aspects, such as the possible use of lime-flux for copper production may have informed the technology of iron making at the site. Such hypothesis is difficult to support or dispute given the lack of research into copper production at Kilwa. At present, it poses an intriguing possibility that the coexistence of two mineral technologies at the site may have led to innovative approaches across and between media.

## Re-casting Kilwa

The evidence presented here builds a case for understanding iron working at Kilwa in terms of technological innovation and creativity. We draw on the archaeometallurgical evidence which shows a significant, specialised industry at the site from early times. It is difficult to assign a chronology to this industry, since the deposits at Nguruni are so mixed. The C14 dates obtained by Chami, combined with the presence of iron slag in the earliest levels at Kilwa might suggest that it occurs early in the Kilwa sequence. The ceramics at Nguruni position activity there at least contemporary with the construction of adjacent Husuni Ndogo in the 13th century and probably before. Direct dates on charcoal inclusions and the slag itself will add to this picture immensely, but the indication is that iron smelting on a large scale was associated with Kilwa Kisiwani from early in its sequence. We explore innovation of iron production processes at Kilwa through a discussion of two key findings: evidence of slag tapping, and use of lime as a flux. The latter of these may have been used to increase Fe yield. In addition, the use of a lime flux might point to shared technologies between Kilwa’s other industries; the technique was known for copper smelting. In a less direct way, it may also draw on the significant engagement with coral and the lime it produces at Kilwa, which is one of the sites along the coast with the clearest investment in mining and working the reef for architecture and mortar. These suggestions remind us of the importance of material properties in shaping and directing technological decisions.

Most important for the purposes of this paper, we suggest that this tradition at Kilwa was based on a high degree of technical skill and that it was this human factor that may have recommended the site as such a large production centre. The invention of the technologies seen at Kilwa may have their initial inspiration elsewhere. Here the emerging results from Zimbabwe are fascinating as they begin to suggest an axis of connection that pre-dated the large-scale gold trade with that region, perhaps including the transfer of technological knowledge.[[61]](#footnote-62) Yet we stress the aspect of innovation at Kilwa itself: the repeated and standardised process of making high-grade iron. At Kilwa the constellation of connectivity (to ore sources, to transit routes) and craftsmanship came together in a way that is unique for the coast and means that we must fully acknowledge the skills of local craftspeople and the power of local knowledge networks in our explanations of the growth of centres in this region.

Finally, there is the standardisation of iron production at Kilwa. The creative moments in the conception of Kilwa technology are evident and have resulted in a collage of technological and material influences. These inventive instances then accumulate and culminate in a large-scale repetitive recreation of the technology. Encoded in the material is the determination of craftspeople to produce iron using the same technology over and over again through individual episodes of creativity.

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