UNIVERSITY OF OKLAHOMA GRADUATE COLLEGE

UNDERSTANDING MULTI-SCALAR EXCHANGE NETWORKS ALONG THE TANZANIAN SWAHILI COAST THROUGH THE GEOCHEMICAL EXAMINATION OF COPPER-BASED METALS, 7th-15th CENTURIES CE

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UNDERSTANDING MULTI-SCALAR EXCHANGE NETWORKS ALONG THE TANZANIAN SWAHILI COAST THROUGH THE GEOCHEMICAL EXAMINATION OF COPPER-BASED METALS, 7th-15th CENTURIES CE

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BY THE COMMITTEE CONSISTING OF

Dr. Thomas Fenn, Chair

Dr. Kary Stackelbeck

Dr. Claire Nicholas

Dr. Jay Stephens

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Abstract

Throughout the Global Middle Ages, Swahili Coast towns were key in articulating long-distance and regional trade that linked Eastern and Southern Africa with triangular Indian Ocean networks extending to India and the Persian Gulf and Red Sea. Copper and copper-based metal alloy objects were likely imported through these trade networks and reworked locally, but the role these metals played in local Swahili economies as well as global exchange systems remains unclear. Therefore, the examination of copper-based metals can shed light on the impact of multi-scalar trade connections within Swahili communities. To that end, this thesis used a combination of solution-mode inductively coupled plasma mass spectrometry (ICP-MS) and multi-collector ICP-MS (MC-ICP-MS) to perform geochemical and lead isotopic analyses of a collection of 28 copper-based artifacts from five different sites along the Tanzanian Swahili Coast, dating from the 7th-15th centuries CE. The results of the bulk elemental analysis reveal a variety of metal types, including pure coppers, brasses, bronzes, as well as ternary, quaternary, and highly leaded alloys, attesting to the prevalence of mixing and recycling practices surrounding the production of these copper-based metals. Trace element compositions were examined alongside lead isotope ratios in order to discern possible geological provenances of the copper and added lead, revealing likely connections with ore sources in Southwest Asia, India, and possibly the African Interior as well. The results of this research demonstrate the potential of combined isotopic and geochemical analyses to aid in understanding copper exchange in the medieval African and Indian Ocean worlds, the Swahili Coast's role in these historic multi-scalar economic networks, and the role of nonlocal trade items such as copper within Swahili communities.

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Chapter 1: Introduction

The Swahili Coast of East Africa is widely recognized for its historic involvement in long-distance Indian Ocean trade networks that spanned the Global Middle Ages (500-1500 CE). The Indian Ocean world during this time became a thriving international economic sphere, and trans-oceanic communication across vastly different cultural regions was facilitated by monsoon winds that blew from India to the eastern coast of Africa and back each year (Fig. 1). The rise of Islam played a major role in shaping this global economy from the 7th century onwards, as Arab and Persian dynasties drove trade around the Persian Gulf and Red Sea. Much of the research to date on Indian Ocean trade has approached the study of these networks from a Middle Eastern Islamic lens. Other major players in these maritime connections included the several dynasties in northwestern and southern Indian as well as Tang, Song, and Ming China (Beaujard 2019).

By comparison, the role of East Africa in the Indian Ocean maritime economic sphere is often overlooked. However, the Swahili Coast, which extends along the eastern coast of Africa from Mogadishu in southern Somalia south to Mozambique (Fig. 2), was unmistakably involved in these global maritime networks as well as terrestrial networks that reached far within the African interior. Visitors from the Middle East documented trade with coastal East Africa as early as the 1st century CE, and records of continued contact from several Arab travelers were documented throughout the medieval period. The Swahili Coast's long history of contact with the Islamic world in particular is evidenced by their shared tradition of Islamic faith, the incorporation of Arabic borrow words in the Swahili language, and similarities in medieval stone architectural styles. This evidence of Islamic influence has, in the past, been used to attribute the Swahili Coast's cultural development and economic success during the medieval period almost entirely to their Middle Eastern connections. However, a plethora of imported ceramics, glass, and other objects that have been recovered from excavations at Swahili archaeological sites attest to diverse Indian Ocean trade networks that extended beyond the Islamic world to India and China as well.

Amid the abundant evidence of Indian Ocean trade, the Swahili Coast's connections with the African interior are often overlooked. Historical and archaeological evidence attest to the terrestrial trade networks through which the Swahili people sourced products such as ivory and gold from further inland to trade with Indian Ocean merchants. In addition to the trade in luxury goods and despite the strong Islamic cultural influences, the Swahili are known to be an African people that shared many cultural characteristics with other East African groups. The proto-Swahili coastal peoples were eastern Bantu agriculturalists that settled in the region in the late centuries BCE and early centuries CE. Early Swahili sites dating to the 7th century such as Unguja Ukuu, Tumbe, Mso Bay, and Maganbani are characterized by agricultural/fishing subsistence economies, iron smelting industry, wattle and daub house construction, and Triangular Incised Ware (TIW) ceramics, characteristics they shared with contemporary hinterland East African groups. These local traditions persisted in Swahili communities throughout the medieval period.

This thesis incorporates an integrative approach to investigating Swahili trade networks through the lens of copper-based metal objects, which were in common circulation throughout this period, and considers a variety of potential sources and trajectories through which these materials might have arrived on the East African coast. Although many classes of imported and local material culture have been studied, the role of copper in medieval Swahili economies and how it connected and positioned the Swahili Coast within long-distance trade networks has not been comprehensively addressed. Despite the fact that copper and copper-based alloy objects are found at almost every Swahili Coast archaeological site, there are no copper ore deposits in the near-coastal regions of eastern Africa, and sparse evidence of local copper smelting activity. Therefore, it stands to reason that copper and other non-ferrous metals must have been imported over long distances. Many archaeologists have assumed an Indian Ocean origin for these non-ferrous metals, and others have argued for southern African origins. In addition, the extent of local copper working technology and the role of this nonlocal material within Swahili societies is poorly understood.

The purpose of this thesis is to improve archaeological understanding of the relationship between historic long-distance trade networks and local Swahili technological and economic practices. This study will achieve this goal through the chemical and isotopic characterization of a collection of 28 copper-based metal objects from five different archaeological sites along the Tanzanian Swahili Coast. To provide background for this study, Chapter 2 will establish a broad overview of the historic Swahili Coast and its role in Indian Ocean trade networks as it is currently understood. Second, it will discuss important theoretical advances and challenges that have influenced study of Swahili Coast economies in the past and position the current study within useful theoretical frameworks. Thirdly, a literature review of previous research from the five archaeological sites will provide site-specific context for the objects analyzed in this study, and a brief overview of metallurgical traditions in East Africa contextualize copper as a material within this region. Next, the analytical methods used in this study will be discussed and sample preparation and analysis procedures are detailed for each in Chapter 3. Results of chemical and isotopic are presented and reviewed in Chapter 4. Chapter 5 discusses phenomena and trends observed within the results and interprets then within their archaeological contexts, employing elements of the theoretical framework presented in Chapter 2. Chapter 6 reviews the results site by site, summarizes the insights gleaned from this research, and proposes future work that can continue to shed light on questions of copper within Swahili economies.

Ultimately, through the examination of the elemental compositions and lead isotope signatures of these objects, this thesis identifies a variety of copper and copper alloy types in use. The elemental chemistry suggests that copper alloy mixing and recycling practices likely took place on site and strongly supports the idea that Swahili copper working activity was used to shape copper metals into objects of local and regional significance. Trace element and lead isotope signatures indicate a common source for multiple copper objects from different Swahili sites, attesting to regionally intertwined networks. Furthermore, geochemistry and lead isotope ratios point towards copper and lead ore sources in the Arabian Shield, Tethyan Metallogenic Belt, and potentially the southern African interior as well, indicating a broad diversity of long-distance copper trade routes. Thus, these combined elemental and isotopic data provide important new insights into the flow of copper through the interplay of local, regional, and global economies within medieval Swahili Coast communities and positions the Swahili as key agents within a complex multi-scalar system of exchange through their consumption, modification, and use of this dynamic imported material.

Chapter 2: Archaeological Background

The Swahili Coast Cultural Sphere

The Swahili are a people that inhabit the immediate coastal regions and offshore islands in East Africa. The Swahili Coast extends from Mogadishu in southern Somalia southward through coastal Kenya and Tanzania and into the northern coast of Mozambique. It also encompasses the Comoros Islands and the northwestern coast of Madagascar (Fig. 2). Shared use of the language Kiswahili, an East African Bantu language that incorporates many Arabic-borrow words, defines them as an ethnic group (Kusimba 1999, 23). Due to their proximity to the Indian Ocean and rich history of maritime and terrestrial trade connections, the distinctive Swahili culture that emerged during the early Global Middle Ages developed into a complex tapestry of interwoven social and cultural characteristics. Monge et al. (2020) asserts the Swahili people are "by religious identity Islamic, by social identity African but biologically very heterogeneous" (65). Kusimba et al. (2014) describes the historic Swahili Coast region as a "cultural mosaic", where communities were interconnected economically but, for the most part, politically independent (4). While rooted in African origins, these mosaic cultural identities have been shaped throughout the centuries by a complex history of trade connections spanning the African and Eurasian continents.

Origins. The origins of the Swahili people have been debated by archaeologists for decades. Historically, these interpretations were often skewed by residual problematic colonial biases throughout the 20th century and the Swahili Coast stone towns were believed to have been part of an "Arab-Persian empire" (Chami 1998). Many early archaeological studies of the

Swahili Coast favored the view that Arab influence and colonization was the primary source of technological, cultural, and sociopolitical development in the medieval Swahili Coast (Robertshaw 1990). Despite the mounting contradictory evidence being recovered from archaeological studies, these views persisted due to long-held racist assumptions about the technological inferiority of African cultures (Schmidt 1997). However, in 1990’s and early 2000’s this harmful paradigm began to shift as archaeologists pursued more questions about the Swahili Coast’s African connections. Subsequent linguistic, genetic, and material culture studies have shown that, despite extensive long-distance cultural exchange, the origins of the Swahili people are undoubtedly African, and that many of their innovations were inspired by these origins.

Linguists and archaeologists trace the origins of Swahili culture to the divergence of the Proto-Sabaki languages around the 6th century CE along with the more or less contemporaneous emergence of early Tana Tradition Ware (ETT) or Triangular Incised Ware (TIW) ceramics (Walsh 2018, Beaujard 2019, 106). Bantu-speaking agriculturalists migrated across sub-Saharan Africa in the 2nd and 1st millennia BCE, bringing with them their farming practices and iron-working technology. They arrived in eastern Africa probably between the 1st century BCE and the 2nd century CE, although this topic is still debated, as archaeological evidence from that time period is sparse.

An in-depth study of Kiswahili language morphology, conducted by Derek Nurse and Thomas J. Hinnebusch in 1993, traced the language’s origins and development. It showed that the first Bantu languages present in East Africa rapidly distinguished themselves from Bantu languages in other regions of Africa, becoming the Northeast Coast Bantu language group, which then diversified into four subgroups in the coastal and hinterland regions. One of these Northeast

Coast Bantu subgroups, Sabaki, includes Kiswahili as well as Comorian and several other closely related languages still spoken in Eastern Africa (Nurse & Hennebusch, 1993). The linguistic evidence indicates that Kiswahili had differentiated from its fellow Sabaki languages by the 9th century CE (Nurse & Hennebusch 1993). Modern-day Kiswahili includes many Arabic borrow words, a testament to the centuries of contact between the Swahili Coast and the Arab world that would follow.

Archaeological evidence shows the distinctive Tana Tradition or Triangle Incised Ware (TIW) ceramics appearing across the East African littoral and its hinterland more or less contemporaneously with the emergence of the Kiswahili language. These ceramics appear in a variety of necked jar and bowl forms and are characterized by the distinctive crisscross and zigzag designs incised on their exterior surfaces (Beaujard 2019, 106). TIW became the common ceramic style produced throughout East Africa sometime between the 6th-9th centuries, apparently "uniting" proto-Swahili groups as one cultural tradition (Wynne Jones & Fleisher, 2013). However, the spread of the TIW tradition was likely disjunctive with the emergence of the Kiswahili language, and its production was not exclusive to coastal groups, as early TIW ceramics have been discovered at nearby inland sites in Tanzania as well (Beaujard 2019, 107). This shared ceramic tradition between coastal and hinterland groups demonstrates that early Swahili Coast inhabitants, or proto-Swahili peoples, were of the same northeastern Bantu cultural origins as their inland East African neighbors (Horton & Middleton, 2000).

Recent ancient DNA studies have corroborated the primarily African origins narrative that is illustrated by the linguistic and material culture evidence. While still a very new line of evidence, these DNA studies have shown primarily West African-related Bantu genetic markers among medieval Swahili populations, as well as some contribution from early East African pastoralist populations, especially in individuals from Swahili archaeological sites in Kenya (Brielle et al. 2023). However, they also reflect some genetic influence from the Middle East, India, and Southeast Asia. One study compared mitochondrial, Y-chromosome, X-chromosome, and autosomal DNA from the remains of 80 Swahili individuals from medieval Kenya and Tanzania (Brielle et al. 2023). Their results show almost entirely African genetic markers on the mitochondrial DNA and X-chromosome, and significant genetic influence from Middle Eastern and Indian sources on the Y-chromosome and autosomes. This study demonstrates significant genetic admixture from Persia and India prior to 1000 CE in male lineages, indicating that it was not uncommon for male traders from abroad to intermarry with African Swahili women (Brielle et al. 2023).

Other DNA studies have shown that the Comoros Islands and northwestern Madagascar have much smaller Southwest Asian and Indian genetic influence but instead demonstrate significant Southeast Asian and Austronesian admixture (Brucato et al. 2018). Despite the regional differences in source and degree of foreign gene flow into the Swahili Coast, these DNA studies agree on a primarily Bantu African genetic origin for all medieval Swahili populations. Foreign admixture appears to be highly variable depending on the region, and the discovery of individuals from similar archaeological contexts with different genetic makeup attests to the continued exchange and migration along Indian Ocean and inter-Swahili trade networks (Brielle et al. 2023). This genetic variability between and within sites during the medieval era corresponds with a complex network of foreign contact and exchange and highlights the diversity of these connections.

The Development of Indian Ocean Connections

The linguistic, genetic, and archaeological evidence work in tandem to affirm the African origins of the Swahili people and their culture. However, historical and archaeological evidence also reflects significant contact with communities across the Indian Ocean world, including the Middle East, India, and Southeast Asia, that originated long before and persisted throughout the medieval period. Thus, the increasingly cohesive Swahili culture that emerged in East Africa between the 6th and 10th centuries did so amid an already interconnected Indian Ocean world.

Several lines of historical and archaeological evidence indicate long-distance trade connections stretching back many millennia. The earliest written document that describes the East African coast is *Periplus Maris Erythraei*, a 1st century CE account from a Greek-speaking merchant or sailor who recorded his journey in detail from the Red Sea south to Mozambique and eventually across the Indian Ocean to India (Chami 1999). The geographic descriptions in *Periplus* match sites we now know to be in southern Somalia, the Lamu Archipelago in Kenya, and Pemba Island, Tanzania, overlapping with areas that would become important Swahili sites in the following centuries (Horton & Middleton, 2000). The author describes the maritime and fishing technology utilized by the pre-Swahili people he encountered at these sites, and states that these communities were importing goods such as iron tools, glass beads, and wine from abroad (Horton & Middleton, 2000).

Faunal and botanical remains from the archaeological record suggest contact with Southeast Asia, India, and the Middle East as early as the 3rd millennium BCE, demonstrated by evidence of domesticated African millet in Southeast Asia and domesticated cattle breeds from India and the Middle East in East Africa (Boivin et. al. 2013, Kusimba 2009). These exchanges may or may not have been direct, but it is evident that East Africa was economically interconnected with the greater Indian Ocean world long before the Swahili era. Additional archaeological evidence such as glass beads and ceramics from the Mediterranean, date back to the 5th century CE (Horton & Middleton, 2000). Thus, connections between East Africa and other communities across the Indian Ocean had existed for a long time before a distinctive Swahili language and culture emerged. This deep history of interconnection suggests that exchange was an integral aspect of the Swahili culture from its earliest origins. Thus, it is important to consider long-distance trade not only as a system that shaped Swahili culture but also as an integral cultural value.

While ancient East Africa participated in long-distance exchange for millennia, during the early Middle Ages, a distinctly Swahili culture was partially developed around the coast's increasing terrestrial and maritime trade connections. The arrival of Islam at many Swahili sites from the 8th century onwards likely helped to facilitate the expansion of their Indian Ocean connections. Added to the growing cohesion in language and material culture traditions in eastern Africa, the introduction of a new belief system and the trade connections it augmented further distinguished the Swahili Coast as a unique cultural sphere. As summarized by Horton and Middleton, "the Swahili of the East African Coast represent a specialist coastal adaptation of these more widespread farming societies (Bantu agriculturalists), through their participation in long-distance trade, the adoption of Islam, and the development of urban living" (2000, p. 27). Thus, the Islamic faith was another layer adding to the "cultural mosaic" that made up Swahili identity.

The introduction of Islam played an integral role in Swahili history. Archaeological evidence shows the earliest mosques appearing in the 8th – 10th centuries at important Swahili sites such as Shanga, in the Lamu archipelago of Kenya, and Unguja Ukuu on Zanzibar Island (Fitton & Wynne Jones, 2017). Sharing a growing religion with much of Southwest Asia and North Africa likely facilitated more regular communication and cultural exchange between these regions. This contact was documented by Al-Masudi, a 10th century Arab historian from Baghdad, who travelled to Qunbalu (likely located on Pemba Island) several times on trading vessels (Chami 2002). In the 12th century, Arab geographer Al-Idrisi labeled the sites of Qunbalu and Unguja along the Tanzanian coast on his map of the world (Chami 2002). Trade with the Swahili Coast is described in two 12th-13th century Omani writings as well as by the more well-known Moroccan explorer Ibn Battuta (early 14th century), who describes his visits to Mogadishu, Somalia and Kilwa, Tanzania (Wilkinson 1981; Dunn 2012). These accounts attest to the flourishing cultural connections between the Middle East and the Swahili Coast and describe the rich Islamic traditions of the Swahili. In the archaeological record, medieval-era Islamic influence at Swahili coastal towns can be seen in the similarities in architectural styles and an increased quantity of imported goods from Persia and the Arabian Peninsula.

Two of the most common types of imported goods seen across the Swahili Coast are ceramics and glass. Several types of distinctly Islamic pottery have been discovered at most Swahili Coast sites, along with Chinese porcelain and stoneware. Blue-green Sasanian-Islamic ware is usually the earliest type of imported ceramic to consistently appear in Swahili archaeological record around the 7th century CE. Other ceramics from India and the Mediterranean are also found at many sites. Fragmented colored glass vessels and different types of glass beads have been recovered from Swahili sites in great quantities, which stylistic and chemical analyses have shown originated in Persia, the Arabian Peninsula, India, and further afield.

Although in lower densities than imported glass and ceramics, non-ferrous metals also frequently occur in the archaeological record, and are often more difficult to source. Coins are one category that is usually less ambiguous in origin. Gold Fatimid coins from the Mediterranean have been discovered at Swahili sites such as Mtambwe Mkuu on Pemba Island and Manda in Kenya (Horton 1987). Chinese bronze coins have been found at Unguja Ukuu on Zanzibar (Fitton 2017). However, other types of non-ferrous metal objects are likely imported but are often of uncertain origin. One example is the Shanga lion, a lion statuette from the site of Shanga which is made of a highly leaded bronze material. The lion is stylistically characteristic of south-central India and compositionally similar to other bronze statuettes produced in Tamil Nadu, southern India, as well as Chinese bronze coins of the northern Song Dynasty (Horton & Blurton 1988). This unique combination of stylistic and chemical characteristics indicate that the lion may have been imported from India or possibly manufactured onsite at Shanga from recycled Chinese coins (Horton & Blurton 1988). Although most are less stylistically distinct than the Shanga lion, other non-ferrous metal objects, especially those made of copper and copper alloys, are similarly ambiguous in origin, and the extent of non-ferrous metal working technology along the Swahili Coast remains unclear. However, copper-based objects hold great potential for shedding light on the relationships between Swahili towns and their Indian Ocean trade partners as well as local knowledge of and technological and value systems surrounding this dynamic semi-precious material.

Theoretical Framework

Archaeological inquiry regarding the Swahili Coast has largely been focused on understanding its Indian Ocean connections due to historic accounts documenting trade relationships with the Middle East as well as the significant amount of foreign material culture that has been recovered from excavations at Swahili sites. However, for many decades, these inquiries have assumed a somewhat simplistic model of economic relationship, often reflexively placing the Swahili Coast in a relatively minor or intermediary role within the larger scheme of Indian Ocean trade, which was assumed to be primarily driven by the economic 'core' societies (under the world-systems theory model developed by Wallerstein, 1974) of Arabia, Persia, India, and China. Copper and other non-ferrous metals, resources that are not geologically native to coastal East Africa, have often been assumed to be products of these global maritime trade networks, added to lists of imported goods recovered from archaeological excavations, but rarely given much attention. Through the examination of copper-based metal objects from Tanzanian Swahili archaeological sites, this project attempts to illuminate some of the nuance of these trade relationships, reexamine the Swahili Coast's role in Indian Ocean trade, and reveal more clearly the socioeconomic impacts of these long-distance connections on Swahili communities (and vice versa) during the Global Middle Ages (500-1500 CE).

Although largely scientific in nature, the interpretative aspects of this study will be situated within the several anthropological frameworks concerning material culture, market economies, and regional and long-distance exchange networks. Many of these frameworks concerning economic relationships are loosely inspired by Karl Marx's ideas of globalization and development and later expanded upon by Wallerstein in his world systems theory model. In addition to the foundations of these early economic theories, this study will discuss more recent theories of global flows and globalism, the circulation of copper as material culture, and its associated production technologies. Material aspects of copper objects will be examined through the lenses of materiality, processes of making and remaking, and value in local and regional contexts. Furthermore, copper as material culture and its human-object relationships will be approached through the framework of object itineraries to bridge the material and economic aspects of copper in past Swahili Coast communities. This integrated economic and material-based approach will offer a nuanced look at the dynamics of copper as a trade item, its role in Swahili cultural context, and how it was used to articulate and reinforce Swahili identities amid a global economic system.

Part I: Global Economies and World-Systems Theory. Long before archaeological study began in earnest along the Swahili Coast, historians were aware of ancient, long-distance trade connections between the East African coast and the Mediterranean and Middle Eastern worlds. Written records such as *Periplus Maris Erythraei* and several medieval era Islamic accounts document centuries of contact and exchange between these regions. In addition to these historical records, growing archaeological evidence of imported material culture discovered at Swahili archaeological sites during excavations throughout the 1960s and 70s made Indian Ocean trade a prominent point of inquiry in the study of the historic Swahili Coast. These archaeological discoveries aligned with the broader theoretical trends among social theorists at the time. In the archaeological community, traditional processual theory was diversifying, and post-processual approaches began to take root in the 1970s. Archaeologists also borrowed and adapted ideas from other social sciences, where key theorists proposed frameworks to focus on the connections between societies and how far-reaching economic relationships influenced the sociocultural development of a given society. This trend encouraged archaeologists to consider past societies as open instead of closed systems and prompted them ask questions about the connections and influence of apparently 'separate' societies on one another.

One key voice contributing to this diversifying trend in social theory was Immanuel Wallerstein, an American sociologist and economic historian, who proposed his World-Systems Theory (WST) model in 1974. Reminiscent of Marxian economic theories of development and underdevelopment in the context of a rapidly globalizing world, Wallerstein's WST model provided a tidy framework within which to analyze global economic relationships and their impacts on society. World-systems theory is based on the idea that economic interaction within a region between economic core, semi-periphery, and periphery societies results in unequal exchange where the core society controls trade to the disadvantage of the peripheries (Killick 2009). Thus, WST assumes the semi-periphery and periphery societies are 'penetrated' by the more advanced/developed knowledge and forms of specialized material goods brought to them by the core societies. This hierarchical economic structure can be traced back to Marx's ideas of underdevelopment. According to Marx, underdevelopment is generated and reinforced as globalization processes promote an increasingly centralized means of production in the developed societies. The economic success of the developed states in this capitalist system are dependent on the continued subjugation and exploitation of the underdeveloped as the demand for more raw materials increases to sustain the developed areas. In this model, it is the centralized control of labor and resources that drives the development of social complexity (Oka & Kusimba 2008).

Wallerstein used similar ideas to construct his WST core-periphery model, where the core societies are developed, and the peripheries are underdeveloped. This model assumes that the "knowledge-intensive manufacturing" of specialized goods (and thus, the control of production) is concentrated at the cores while raw and semi-processed materials are sourced from the peripheries (Killick 2009). However, Wallerstein designed WST to describe the modern, capitalist economic system. Archaeologists such as Richard Blanton & Gary Feinman (1984) and Philip Kohl (1987) adapted and applied the WST model to analyzing the development of complex societies in tandem with information gathered from the archaeological record. These theorists used WST as a framework within which to understand the economic spheres of ancient Mesoamerica and Mesopotamia, respectively. As evidence for East Africa's involvement in extensive Indian Ocean trade networks grew, WST became an increasingly popular model through which to analyze Indian Ocean economies as they existed prior to European influence.

Wallerstein's WST can be a useful framework and is still used by social theorists who study the rise of economic systems on a global scale. This approach was recently applied to the medieval Indian Ocean sphere by anthropologist and historian Phillipe Beaujard in his book *The Worlds of the Indian Ocean: A Global History* (2019). According to Beaujard, the Indian Ocean became the center of a globalized world-system that developed throughout the mid- first millennium CE as Arabian, Persian, Indian, and Chinese dynastic empires drove long-distance exchange with each other and increasingly outsourced raw material production to peripheral regions (2019). Within this WST model, the Swahili Coast is considered a "semi-periphery" society, gathering raw materials such as ivory from "periphery" groups within the African interior, partially working these materials, and shipping them off to the economic "core" societies in Arabia, Persia and India, where they would be crafted into finished luxury products (Beaujard 2019). In exchange, the Swahili Coast received finished goods such as fine ceramics and glass beads created in Persia or India or obtained by them through further exchange with more distant core societies like China (Beaujard 2019). Through this asymmetrical model of exchange, the Swahili Coast, as a "semi-periphery" economy, is assumed to have been largely dependent on demand for raw materials and unfinished goods from the "core" societies.

Although Beaujard's application of WST attempts to be integrative and considers many aspects of the economic system as a whole, the inherent top-down approach of WST relegates the Swahili Coast to being viewed as a conduit for the development of the larger system. Furthermore, it views the development of the Swahili Coast primarily through the lens of Islam. Beaujard focuses on how Islamic foreigners and merchants "exerted an influence via and within (the) existing social structures" of the Swahili people (Beaujard 2019, 109). His work focuses on understanding how foreign ideological, economic, and political influences created an "East African semi-periphery" that was increasingly dependent on demand from the "cores," (the Middle East, China, and India) and allowed the Swahili Coast to develop (Beaujard 2019, 109). While useful when considering the large scale of Indian Ocean networks or exchange, this approach has some limitations when it comes to understanding the Swahili and their role in global economies.

By its nature, WST implies that the semi-periphery and periphery societies were less technologically and socio-politically advanced than the cores. An early critic of WST, Marshall Sahlins pointed out that it makes "the colonized and 'peripheral' peoples the passive objects of their own history and not its authors" (Sahlins 1988: 2). In the case of the Swahili Coast, this core-driven tributary economic perspective allows for the perpetuation of harmful assumptions rooted in colonialist views that attributed the origins of technological developments and finely crafted luxury goods to their supposedly more advanced Arabian and Persian neighbors (Schmidt 1997: 4). For many decades in early anthropological studies in East Africa, it was assumed that alongside the adoption of Islam, the Swahili people adopted a tidy package of knowledge, technologies, and systems of value as well, thus leading to the growth in population and architectural advancements archaeologists observe in the later phases of Swahili sites. Modern applications of WST move beyond these racist views, but the structure of the model is inherently too simplistic. This type of analysis places nearly all credit for the economic success of the medieval Swahili Coast world into the hands of their colonizers. It overlooks the agency of the Swahili people outside of the imposed Islamic ideological system and the importance of their African connections, and it fails to ask questions about how local Swahili cultural values and economies influenced the Indian Ocean system in addition to the reverse.

While still a useful framework for large-scale economic analyses, WST is an overly simplistic model that tends to perpetuate some problematic assumptions about the dynamics of Indian Ocean exchange and the capabilities of the historic Swahili people. WST reinforces a primary focus on Indian Ocean trade, which, while doubtless an integral part of medieval Swahili economies, was only a part of them. The tendency towards WST applications regarding the Swahili Coast risks losing sight of the importance of their African connections as well as their own intellectual, technological, and cultural innovations. Therefore, it is imperative to integrate more dynamic theories of global and regional exchange, multidirectional flows of materials and ideas, and different systems of value and consumption of material goods.

Part II: Towards Globalism and Multi-Directional Flows. In response to the recognition of the limitations of Wallerstein's WST, several anthropological theorists have adapted models to encompass more nuance in the exchange of goods and ideas and how these long-distance economic systems develop. In the 1980s, anthropologist Eric Wolf drew from both Marx and Wallerstein to call attention back to the inequalities that exist in the world system, and how disciplinary imperialism has obscured these inequalities. While he believed that world-systems theory had some merit, he critiqued it as being another version of diffusionism, and he sees this as a particular problem when it comes to understanding the effects of colonialism on globalization processes in certain communities (Wolf 1982). Rooted in Marxian theory, Wolf argued for the importance of understanding the historical development of capitalist systems and how they exploit some groups disproportionately through centralization of modes and means of production (1982). Furthermore, Wolf was interested in the structural power that these globalized systems hold over the individuals and communities involved in them (Wolf 1982).

This thesis seeks to understand how trade relationships influenced Swahili communities on a local scale and how they developed over time due to a variety of local and non-local factors in process simultaneously. Wolf's interests in structural power create room for more nuance in the study of world systems by breaking down some of the harmful colonial assumptions that considered African groups to not have the intellectual and cultural capacity necessary for technological and social innovation. Instead, Wolf's theory focuses on how the systems perpetuated by capitalism and globalization affect the individuals and lock them into a system of relative underdevelopment. However, despite his argument for the agency of "periphery" peoples in shaping their circumstances according to their own conceptions, which WST tends to overlook, Wolf falls into the trap of supposing people's conceptions are a product of their circumstances (Sahlins 1988). Thus, although the capacity for innovation and influence exists in the underdeveloped societies, their agency is still ultimately taken away by the suppression of the capitalist system.

Almost a decade later, anthropologist Arjun Appadurai contributed his theory of global cultural economy and the 5 "scapes" of global cultural flows to look at complex systems through which ideas, goods, money, and technology can be exchanged over long distances (Appadurai, 1990; Appadurai 1996). One of the most essential aspects of Appadurai's 5 scapes model is that it considers the flow of different aspects of culture, which he divides into 5 broad categories, to be disjunctive, and circulate via different paths and at different rates (Appadurai 1990). This is an important consideration in this thesis. An assumption that is often inherently intertwined with the application of the traditional WST model, especially as applied to archaeological contexts, is that people, money, ideas, technology, knowledge, and goods all traveled together, from the core to the periphery societies, which are categorized as such through the problematic polarization of autonomy and dependence (Wilk 1997, 99). These assumptions have historically led scholars to infer that Persian and Arab technologies and goods were carried along with the Islamic faith by merchants traveling to the Swahili Coast to trade, causing a wholesale transformation of Swahili culture in what economic anthropologist Richard Wilk calls "the impact myth" (1997, 101). While this interpretation may hold some merit, it is certainly not the only path of knowledge transfer that was taking place, and it would be remiss not to consider other potential patterns of exchange.

Wilk argues for breaking down this polarized view and instead considering societies that fall somewhere in between autonomy and dependency, which encompasses the vast majority of cases (1997, 101). The Swahili Coast is certainly one of these cases, autonomous in some regards and dependent in others. Its trade partners in the African interior, Arabia, India, and elsewhere were also partially autonomous and partially dependent, and it would be vast oversimplification to treat any of these societies as only one or the other based on the traditional WST categorizations of "core" or "periphery". Helpfully, Appadurai's 5 scapes model lends us a tool through which to consider the multifaceted reality of the complex exchange systems in medieval

East Africa. Through the 5 scapes and disjunctive flows, we allow for the possibility that the flow of copper metal may not have directly accompanied the spread of Islam, and the goods themselves are not necessarily indicators of unilinear technological and knowledge transfer from the Middle East to East Africa. In this study of copper objects from coastal Tanzania, I will explore the possibilities that these finished products were imported from Indian Ocean trade partners, or that the materials were imported from abroad and worked locally, or that the raw materials were being sourced regionally from within the African interior and worked on site at Swahili towns, and potentially even exported from there.

In recent decades, an increasing number of archaeologists have taken interest in researching coast-hinterland and further reaching interior connections among the medieval Swahili, focusing on the Swahili economy on the local and regional scales. The addition of these more multi-scalar approaches aligns with growing critiques of global economic theories, such as WST, as being too reductionist. Blanton et al. (1997) argue that close study of local economic systems should be used to help develop "more robust theories of the global" in an effort to "counter the excessively simplistic and deterministic ideas" that result from trying to explain everything in terms of how it fits into the dynamics of the larger economic system (viii). Along similar lines, Hall (1997) advocates for the integration of an inductive approach alongside the typically applied deductive, top-down analysis that is often used in WST. A good world-systems analysis takes into account both how the global economy impacts the local but also how local dynamics impact the global system (Hall 1997, 87). This project attempts to expand on this approach to economic anthropology through the close study of the local consumption of copper-based materials and subsequent examination of how these materials may inform our understanding of local, regional, and global trade. By comparing materials recovered from five different Tanzanian Swahili sites, we hope to gain a better understanding of local and regional economies as well as the maritime ones. Furthermore, while it has long been known that Swahili Coast towns were sourcing some raw materials, such as ivory, from the interior reaches of East Africa in order to export them abroad, up until recently, little work had been done to characterize the nature and significance of these regional economic relationships. Therefore, close analysis of Swahili materials and their relationality within the Swahili Coast region is essential to gaining a better understanding of the medieval Swahili economy as a whole, not just how it fit into the larger Indian Ocean economic world-system.

Non-ferrous metals are one of the key types of material culture that may be able to help us better understand interior African connections among Swahili Coast towns. Although copper ore could not have been sourced locally, it may have been imported from the African interior or from overseas via Indian Ocean trade. By using Appadurai's 5 scapes model, the possibility that the flow of these raw materials and the technology and knowledge surrounding their use were disjunctive, and did not necessarily travel to the Swahili Coast from the same location or along the same timeline will be considered.

Another important consideration that critiques and expands the basic WST model is Anna Tsing's idea of globalist circulation. Tsing's theory asserts that it is more accurate and useful to think of global flows as circulation rather than penetration (2000). The circulation model allows for multidirectional exchange of goods and ideas, rather than the unidirectional flow of development from core to periphery that is inherent in the traditional WST model, based on the assumed dichotomy between autonomy and dependence (Tsing 2000). In combination with Appadurai's 5 scapes model, this idea of globalist circulation opens up possibilities for the transfer of knowledge or technologies as well as raw materials from the Swahili Coast to their

Indian Ocean trade partners. Tsing's theory views these global systems as dynamic networks that are constantly changing and sharing ideas back and forth. She also stresses the importance of understanding the terrain of circulation and the social conditions that drive and facilitate the flow of goods and information (Tsing 2000). This focus on social conditions is an important aspect of my research, as the consumption patterns, assigned value, and use of potentially imported goods will help inform my understanding of Swahili attitudes towards trade relations and how it shaped life in early Swahili societies.

While this research is based loosely on Wallerstein's WST framework as applied to the medieval Indian Ocean economic sphere, it will employ several more nuanced adaptations of this model in order to avoid oversimplification and work towards dismantling the colonialist assumptions that were for a long time wrapped up in WST and African archaeology in general. While partially based in Marxian ideas of materialism, control over production, and enforced inequalities in globalized systems and employing Wolf's awareness of disciplinary imperialism, this study will incorporate consideration of disjunctive and multidirectional flows of ideas and goods to and from the Swahili Coast, as inspired by Appadurai's and Tsing's theories of global systems. As it seeks to determine the nature and provenance of copper objects excavated from a variety of contexts along the Tanzanian Swahili Coast, this study considers a variety of possible source localities, both within the African continent as well as abroad, and the multi-directional and complex exchange networks that may have brought them to the coast and shaped their formation before and after their arrival.

Part III: Theories of Commodity Value and Object Itineraries. In any study of economies and the exchange of material culture, it is necessary to consider the value placed on certain objects within a specific socio-cultural context and the many reasons why objects were valued by incorporating theories of commodity value, materiality, and object itineraries. The copper and copper-alloy objects that are the focus of this thesis were crafted into a variety of different forms, some apparently utilitarian in nature, some primarily decorative, many likely a mix of both. These objects may have been assigned value by the Swahili people for a variety of reasons, based on their beauty, function, scarcity of material, or demand from long-distance trade partners. According to the 10th century Arab historian and geographer Mas'ūdī , the "Zanj" (or non-Islamic, early Swahili people) valued copper and iron more highly than gold and silver for ornamentation (Beaujard 2019, 117). Thus, in order to understand the flow of copper and copper-based metal objects into and out of the Swahili Coast region, it is imperative to think about how and why they were valued within their social context.

In attempting to determine the origins of these copper objects, we must examine their life histories in a broader sense, tracing where the materials were sourced and how they came to be finished objects deposited in their archaeological contexts at Swahili Coastal towns. Questions of value get at the causes behind these life history events given what is known of the cultural context and human-material interactions that may have resulted in said value. This master's thesis will contribute insights to larger bodies of knowledge concerning materiality and object value of copper-based metals within medieval Swahili Coast communities.

Multiple approaches have been used by anthropologists to study the exchange and value of objects. One body of theory was derived largely from Georg Simmel's theory of value from his book *The Philosophy of Money*, which establishes that the value of an object is determined through a combination of desire to possess it and its inaccessibility, which can be overcome through economic exchange (Appadurai 1986, 3). These exchanges require the sacrifice of another object to obtain the desired one (Appadurai 1986, 3). Cultural anthropologists Igor

Kopytoff and Arjun Appadurai position the relationship between exchange and value as a process of commoditization that fluctuates over time and is articulated through economic transactions. They explain that the dynamicity of commodity value is a result of shifting politics as people continually renegotiate what constitutes a reasonable “exchange of sacrifices” (Appadurai 1986, 57). As desire for and accessibility to an object shift, the existing social framework around its exchange value is breached and reestablished repeatedly through economic transactions (Appadurai 1986, 57). These social-political processes of exchange are what lend commodities value, and therefore, “Value is embodied in commodities that are exchanged” (Appadurai 1986, 3).

In order to understand the continually shifting value of economic objects and the processes through which they are commodified, Kopytoff argues for the necessity of reconstructing object “biographies” (1986). An object biography is essentially a life history of an object as it relates to human societies and can be defined as a sequence of interactions between humans and thing (Kopytoff 1986). Because commodity value can shift and objects can move in and out of commodity status through transactional social negotiations, piecing together the life history of an object can yield better understanding of an object’s use and value over time (Kopytoff 1986). Thus, by studying often commoditized objects like copper, it is possible to better understand systems of value and exchange among medieval Swahili culture. This theoretical framework surrounding commodity value and exchange provides one of the foundational anthropological justifications for this thesis.

The significant social, political, and economic changes that occurred between the 7th and 15th centuries along the Swahili Coast make it essential to treat the commodity value and cultural value of copper items as highly dynamic, not constant. Kusimba notes that copper, along with other items from the African interior such as gold, iron hoes, salt, and glass and shell beads, were "in high demand, and their context varied as both sources of wealth and as symbolic status markers" (2024, 44). The value of these materials depended on their situational uses and meanings, which was constantly changing as these goods moved through time and space (Kusimba 2024, 44). In his discussion of commodity value, Appadurai asserts that it is through the forms, uses, and *trajectories* of things that we can understand their value (Appadurai 1986, 5). Together, these arguments demonstrate that the exchange value of copper objects was dependent on the time and space they existed within. Since the copper objects in this research study span a 900-year timeframe and traveled far to reach the Swahili Coast, their significance can be better understood by studying their life histories or trajectories. The first step of reconstructing these object trajectories is determining the origins of the copper material.

Building on this approach, archaeologist and materiality theorist Rosemary Joyce discusses the benefits and limitations of considering objects' life histories through different lenses. While useful, treating objects as if they are agential actors with their own "biographies" as Kopytoff (1986) suggests, can be problematic. Joyce argues that "the lives of things can be distorted when forced into the mold of a human life course" (Joyce 2015, 23). Instead of treating object life histories as biographies, Joyce proposes that they be studied as itineraries. Both biographies and itineraries are time-dependent narrative devices used to piece together the life-history of an object. However, a biography is exclusively concerned with how that object has related to humans throughout time, overlooking other potentially important aspects of the object's life history. Joyce's object "itineraries" more comprehensively capture the mobility and transformations of an object over time, from its original source material to its eventual deposition and recovery by archeologists (2015, 29). Studying object itineraries includes "consideration of technologies for circulation; transformations that take place along the way; and the value of circulating objects for the production and reshaping of relations among humans, nonhumans, and other forces" (Joyce 2015, 29). As this thesis studies this collection of copper objects from the medieval Tanzanian coast, the first step is to isotopically and chemically characterize and source the copper material they are made from. This data can then be used as a launching point to explore how and why the copper may have been subsequently transported and transformed to arrive in its final state. Using the object itinerary model provides a framework that includes all aspects of the material provenance, archaeological provenience, and everything in between in the analysis of these objects.

Another advantageous aspect of the object itineraries framework is that it encompasses a collectiveness that biographies do not. Itineraries are "routes that can be followed by individual or multiple objects" (Joyce 2015, 29). Since this study deals with complex and potentially highly diverse networks of copper exchange, as well as five different sites of deposition, when reconstructing the objects' life histories, it is important to examine both their individual and collective aspects. Some copper objects may have traveled along similar maritime routes in bulk shipments, to be reworked and transformed on site. Other copper may have found its way from sources in the African continent. All these potential routes and sequences of production and consumption must be considered, and Joyce's object itinerary framework allows for a multifaceted analysis that takes into account these nuanced possibilities.

In tracing the life history of an object, it is also important to consider the ways in which the object's material composition can exert agency on people. As anthropologist Ian Hodder laid out in his entanglement theory framework, which deals with the relationships between humans and things, things have certain properties that "stand up" against humans in ways that dictate how we perceive them and interact with them as well as how things interact with each other (2012). Similarly, Tim Ingold discusses how the physical properties of materials determine the ways in which humans shape them throughout their making processes and have bearing on the final products created from them (Ingold 2007). These theories allow for the study all aspects of an object's properties and its existence in the world, helping to create an object itinerary such as Joyce advocates for and gain a more comprehensive view of the object's life history from its own perspective, not only through the human lens (Hodder 2012, Joyce 2015). Furthermore, Hodder argues that humans depend on things and vice versa, based on their associated properties (2012, 10). In this thesis, it is through these interdependent relationships between the Swahili people and copper metal "things" that I seek to understand economies and trade, which all ties into the value humans placed on them, which can change over time. As discussed above, humans are often influenced by objects through their social context and the value assigned to a material or object based on negotiations surrounding exchange (Appadurai 1986; Kusimba 2024; Joyce 2015). An object's perceived value is often related to one or more of the properties of the object that are considered desirable, tying the object's physical properties, uses, and perceived value together in a complex tapestry of economic and social meaning.

A desirable material property could be entirely socio-economically constructed, such as a relative scarcity that leads to it being assigned prestige status. Value can also be based on the perceived beauty or utility of a material which are based on its physical properties. The value of different material qualities may be weighted differently depending on the meaning assigned to each quality within a given cultural context (Keane 2003). In the case of copper metal, its color, reflectivity, resonance, weight, strength, malleability, melting point and a host of other material properties that result from its chemical composition may make it appealing to the senses, durable, and easy or difficult to work with depending on the tools used. Properties such as color and reflectivity may give copper a particular meaning, while its malleability and durability are conducive to certain utilities. All of these physical properties have bearing on how people shape things and what they choose to attempt to create from the material (Ingold 2007). Boivin argues that it is the "physicality of matter that gives things agency" (2008, 129). An object's physical properties are, to a certain degree, inherent to the material it is made from, and thus materials can exert agency on people through their properties.

However, material properties are not fixed. Rather, they are relational and dependent on how a material responds to and is affected by the processes occurring in the world around it (Ingold 2007). In the case of copper, its ore mineral malachite is a brilliant green color. When smelted and reduced to its metallic phase, copper becomes a rosy reddish color and quite reflective, along with acquiring a whole host of other new properties. These properties change as a result of outside processes exerted by humans on the original substance. Just as human processes can affect and change a material's properties, so can natural processes, such as weather, geological processes, interaction from other creatures, etc. (Ingold 2007; Joyce 2015). Because the physicality of a material is not dependent solely on an object's relationship to people, an object can be studied outside of its interactions with humans as well as within them, in accordance with Joyce's object itineraries framework. However, it is important to note that the way humans interact with a material is dependent on the relationality of the human body's material properties with the external material (Boivin 2008). Thus, throughout the examination of the chemical compositions of this collection of copper artifacts, this thesis acknowledges their physicality and how these properties may have influenced their value and use by the Swahili people.

Through studying some of the most essential of material properties of these copper-based metal objects, this thesis will shed light on the long-distance and regional connections, systems of exchange, and other socio-economic aspects of Tanzanian Swahili Coast communities across time and space during the Global Middle Ages. Chemical and isotopic analyses help determine the material types, lend insight into manufacturing technologies and human-material interactions, and aid in determining the geological provenance copper metals to begin reconstructing their life histories. The carefully considered application of a variety of theoretical approaches dealing with materiality, commodity exchange and value, and economic systems theories will allow for the interpretation and contextualization of this new geochemical data in a way that is meaningful to the holistic anthropological and archaeological understanding of the medieval Swahili Coast.

Archaeological Background of Five Tanzanian Swahili Sites (Fig. 2)

Copper-based objects are commonly found at Swahili Coast archaeological sites from their earliest phases throughout the medieval period but have rarely been the focus of analysis and discussion. For this study, a variety of 28 copper and copper alloy objects from five different sites along the coast of Tanzania were selected for analysis. The five sites extend in time from the early phases of distinct Swahili cultural traditions in the 7th century CE until right before Portuguese contact around 1500 CE. Collectively, they represent a broad example of the Tanzanian Swahili Coast throughout its adoption of Islam, growing involvement in Indian Ocean trade, and formation of stone towns. Geographically, these sites cluster around two different important regions along the Tanzanian Coast. Mso Bay and Songo Mnara lie in the Kilwa Archipelago on the mid-south coast of Tanzania, while Tumbe, Unguja Ukuu, and Maganbani are clustered around the Zanzibar Archipelago along the northern Tanzanian coast (Fig. 2). It is imperative to keep in mind that most Swahili towns were politically independent from each other and therefore did not necessarily share the same trade relationships. This distinction may be particularly relevant considering the geographic distance between the Kilwa and Zanzibar coastal regions. Therefore, this set of copper samples from these five geographically and chronologically diverse Swahili sites will allow for a temporal and regional comparison of copper-based metals, provide a more representative view of the nature of copper-based metals throughout the Swahili Coast over time, and lend insights into multi-scalar trade systems. In order to properly contextualize and interpret the chemical and isotopic data collected in this study, it is first necessary to review the archaeological background of the five sites from which the copper objects were excavated as well as the broader regional contexts of these locations.

Area 1: The Kilwa Archipelago. Two of these sites in this study, Mso Bay and Songo Mnara, are just adjacent to Kilwa Kisiwani, a well-known Swahili stone town in southern Tanzania that was a prominent player in Indian Ocean trade networks between 800~1500 CE (Fig. 3; Fig. 4). The medieval city of Kilwa Kisiwani (or Kilwa for short) has a relatively comprehensive historical narrative compared to other contemporary Swahili towns. This narrative has been preserved by local oral tradition, the Kilwa Chronicle (first written in the early 16th century in both Arabic and Portuguese), and medieval travelers' accounts such as those of Ibn Battuta. Because of these historical records, Kilwa was one of the earliest Swahili sites to capture the attention of archaeologists. It was systematically excavated by Neville Chittick of the British Institute in East Africa during the 1950s and 60s, and ever since, Kilwa has frequently been used as a model for understanding broader Swahili coastal development (Horton et al.

2022). Recent studies have attempted to fine-tune Chittick's chronology of the site, which was mainly based on imported ceramics, by the addition of high-resolution radiocarbon dates (Horton et al. 2022). Horton et al. caution against using Kilwa as an example to describe other Swahili sites, noting several peculiarities in Kilwa's development over time (2022). However, because of its geographical proximity and temporal overlap with the sites of Mso Bay and Songo Mnara, Kilwa's chronology provides important regional context for our understanding of the economic development of these nearby sites.

Mso Bay & Early Kilwa. Mso Bay sits on the southern edge of the mainland Kilwa Masoko promontory, overlooking the entrance to Kilwa Kisiwani Harbor just across the water from the medieval city of Kilwa (Fig. 4). Any ships entering Kilwa harbor would have passed right by Mso Bay, and thus it is spatially positioned to be directly involved with Kilwa's maritime trade networks. However, Mso Bay's excavation chronology, dating between the 7th and 10th centuries CE, overlaps only partially with the earliest settlement phases at Kilwa. The earliest occupation at Kilwa Kisiwani dates to the early 9th century, with low frequencies of imported ceramics appearing in the 10th century, although local Early Tana Tradition (ETT) ceramics may indicate an earlier occupation at the site as well (Horton et al. 2022; Pollard 2008a). The early stratigraphy from test units around Kilwa's Great Mosque (excavated by Chittick, 1974) is quite similar to that at Mso Bay, characterized by wattle and daub house construction, ETT ceramics, and iron slag (Pollard 2008a). Chittick's work showed that pre-10th century Kilwa was a relatively small settlement with "limited external trade and a subsistence economy based upon fishing, shell gathering, bead grinding, and iron smelting" (Pollard 2008a). It appears that the settlement at Mso Bay was quite comparable to its neighboring Kilwa in most aspects.

Kilwa experienced a significant shift in its material culture in the 980s CE, with the first stone architecture built of *Porites* coral emerging, as well as the appearance of imported sgraffiato ceramics and the first silver coin of Ali bin Al-Hasan, known as the first Persian Sultan of Kilwa according to the Kilwa Chronicle (Horton et al. 2022). However, Mso Bay appears to have been abandoned around this time, and thus did not benefit from the expanding Indian Ocean trade networks that were characteristic of 11th-15th century Kilwa. The late 1st millennium settlement at Kilwa Kisiwani was far less interconnected, with very limited evidence of external trade (Chittick 1974; Pollard & Kinyera 2017). While Mso Bay and early Kilwa may have shared some early maritime trade connections, it is important to note that the economic landscape at both sites was very different during this period than the one that the trade-focused Islamic city-state of medieval Kilwa is known for. Therefore, other possibilities for the origin of Mso Bay's material culture, especially copper, must be considered.

Similarly to early Kilwa, the Mso Bay excavations in 2004 and 2012 discovered minimal evidence of long-distance trade, comprised mainly of two Sasanian-Islamic pottery sherds and one blue glass bead (Pollard 2008a; Pollard & Kinyera 2017). These imported objects attest to the fact that the Mso Bay settlement was economically connected with the Middle East and perhaps the wider Indian Ocean world between the 7th-10th centuries. However, the scarcity of these objects indicates that Mso Bay's maritime trade connections were infrequent and possibly not direct. Most of the material culture discovered during excavations consisted of fish and other animal bones, worked stone, substantial evidence of iron production, bead grinders, and wattle and daub construction (Pollard 2008a; Pollard & Kinyera 2017). The presence of ironstone, slag, and iron objects occurs alongside a high density of worked stone cores, debitage, and hammerstones, indicating that "Stone Age and Iron Age communities lived in close contact" at

Mso Bay (Pollard & Kinyera 2017, 939). A similar multi-ethnic social composition is also evident in the archaeological record of some other 1st millennium Swahili sites such as Shanga in Kenya, although many other towns appear to have been more ethnically homogenous (Pollard & Kinyera 2017). The unusual ethnic diversity at sites like Mso Bay and Shanga further demonstrates the variability between Swahili Coast towns regarding their cultural and economic connections.

This evident diversity of connections at Mso Bay leaves us to consider a variety of possible avenues through which copper may have been transported to the site. The presence of Islamic ceramics leaves open the potential for maritime import of copper from southwest Asia or other Indian Ocean connections. However, the scarcity of these finds along with the robust presence of late stone age groups begs the question of whether copper may have made its way to Mso Bay from the African interior via trade with hinterland hunter-gatherers or other agropastoralist groups. The evidence for each of these possibilities will be examined in detail in a later chapter.

Songo Mnara & Late Kilwa. The site of Songo Mnara, granted UNESCO World Heritage Site status due to its impressive medieval stone architecture, also lies in close geographic proximity to Kilwa Kisiwani. The late 14th -15th century stone town was constructed on the northern end of Songo Mnara Island, just to the south of Kilwa Island (Fig. 3). Despite its geographical proximity, temporally Songo Mnara is quite distant from Mso Bay. Songo Mnara was constructed and populated rather rapidly in the late 14th century and no evidence has been found of earlier occupation at the site (Pollard et al. 2012). Therefore, the town of Songo Mnara overlapped with a much later period in Kilwa's chronology and any imported material culture was a result of a drastically different maritime trading scene than existed during Mso Bay's occupation. Because of its concise chronology with minimal stratigraphic complexity, studies at Songo Mnara have focused on the horizontal layout of urban spaces, involving excavations within and around houses and public use areas as well as geophysical survey and mapping (Wynne-Jones & Fleisher 2010, Fleisher 2014, Welham et al. 2014).

The town of Songo Mnara was built and occupied from about 1375-1500 CE (Fleisher 2014). This time period overlaps with a break in Kilwa's chronology during the late 14th century, discovered during recent excavations, followed by an expansion of rag coral architectural construction in the mid 15th century (Horton et al. 2022). The authors suggest this chronological break at Kilwa may correlate with increased activity elsewhere in the area, including Songo Mnara (Horton et al. 2022). Perhaps a focus on building up other nearby areas in part caused or resulted from this evident lull in the development at Kilwa's city center. However, this lull in Kilwa's development coincides with a period of political instability and economic stagnation described in Kilwa's historical accounts between 1350 and 1420 CE (Horton et al. 2022). Regardless of how this event relates to the early construction at Songo Mnara, it may provide important economic context for understanding trade in the region during that time.

Songo Mnara boasts prominent rag coral architecture including forty houses, six mosques, and numerous tombs, all within a well-defined 7-hectare area (Horton et al. 2017; Fleisher & Wynne-Jones 2013). This high density of stone architecture has in the past led the site to be interpreted as a retreat for high-status individuals from the nearby city of Kilwa, although excavations and surveys throughout the past several decades have shown it to be a fully functioning town (Fleisher & Sulas 2015). The number of mosques and highly visible stone monuments at this site seem to indicate that the residents of Songo Mnara were intentionally signaling their Islamic faith to outsiders and visitors (Horton et al. 2017). The presence of stone houses has long been associated with a mercantile elite population, since most stone architecture was reserved for mosques and tombs. This association with a mercantile population would also indicate a focus on maritime trade at Songo Mnara. However, in addition to the prominent stone architecture, both domestic and public, geophysical surveys have recovered evidence of wattle and daub structures as well, further highlighting class differences and the presence of social complexity at Songo Mnara (Wynne-Jones & Fleisher 2011, Welham et al. 2014).

Systematic excavations and intensive archaeological survey were conducted as part of the Songo Mnara Urban Landscape Project from 2009-2016, directed by Jeffrey Fleisher and Stephanie Wynne-Jones (Wood et al. 2023). Excavations took place within and around stone-built and wattle and daub domestic spaces as well as in public areas. The material culture recovered from these excavations was notably lacking in the frequency of certain classes of imported goods that might be expected at such an architecturally wealthy site with proximity to the well-known trade hub at Kilwa (Fleisher & Wynne-Jones 2010). Imported ceramics, glass vessels, and iron and copper objects were found in very low numbers compared with other similar Swahili sites (Fleisher & Wynne-Jones 2010). However, copper coins and glass beads were recovered in abundance, and were excavated from a variety of different areas all over the site, indicating that coins were in common use as currency and many people had access to beads as well. The 63 coins discovered in the 2009 excavations were mostly of Kilwa-type, minted locally, and represented eight different sultans at Kilwa (Fleisher & Wynne-Jones 2010).

Over 9,000 beads were recovered over 4 seasons of excavations, 7,444 of which were glass, the others made of shell, semi-precious stone, and a variety of other materials (Wood et al. 2023). Chemical analysis via laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was carried out on a broadly representative selection of 140 of the glass beads to characterize their composition and determine their origins. This analysis discovered 4 main glass composition types which chemically and stylistically matched beads manufactured in India, Southeast Asia, and China prior to 1500 CE (Wood et al. 2023). Therefore, despite the relative scarcity of other types of imported materials, the abundance and variety of imported glass beads shows that Songo Mnara was actively involved in Indian Ocean trade. The authors of this analysis postulate that some of the coil-wound potash lead silicate Chinese beads (also found at Kilwa) may have been a gift from Chinese admiral Zheng He, who reportedly reached the East African coast in the early 15th century (Wood et al. 2023). If the authors are correct, this would provide concrete evidence of direct trade contact between the Kilwa archipelago and China.

In addition to imported beads, evidence of local glass bead production was also discovered with the help of chemical analysis. A unique folding technique that has not been found anywhere else in the Indian Ocean world was used to manufacture some of the beads from Songo Mnara as well as Kilwa (Wood et al. 2023). This exclusivity of manufacturing style as well as the presence of glass tubes (which were likely used in bead production) found in one of the wattle and daub structures at Songo Mnara suggests the reworking of imported glass onsite (Wood et al. 2023). Furthermore, two of the folded beads seem to have been rejected due to imperfections caused in production (Wood et al. 2023). Therefore, although the vast majority of the glass beads at Songo Mnara were imported, there was likely some production taking place locally as well.

The abundance of imported glass beads and copper combined with the relative dearth of other imported goods that are commonly found at contemporary Swahili sites (such as ceramics and glass vessels) shows that, like most Swahili coastal towns, Songo Mnara was actively involved in maritime trade. However, the clear preference for certain types of imported goods over others highlights the variability in how different types of foreign material culture was valued between different Swahili towns. This variability underscores the importance of considering how imported objects were assigned value on a case-by-case basis and cautions us against generalizing across Swahili sites.

Area 2: The Zanzibar Archipelago. The other three sites of interest to this study lie within the Zanzibar Archipelago along the northern Tanzanian coastline. These three sites are Tumbe on Pemba Island, Unguja Ukuu on Zanzibar Island, and Maganbani which lies on the mainland just across the Zanzibar Channel from Zanzibar Island, near the modern-day city of Bagamoyo (Fig. 5). These three sites are known to have been involved in Indian Ocean trade networks, similarly to the Kilwa Archipelago sites. While Maganbani is a small and less well-known site, Tumbe and Unguja Ukuu are known to be two of the largest and wealthiest ports in the entire Swahili Coast during the proto-Swahili period (Juma 2004; Fleisher & LaViolette 2013; Fitton 2017). Because of the early economic success of these sites, the Zanzibar Archipelago quickly became an important regional trade hub for the western Indian Ocean throughout the 8th and 9th centuries CE (Fitton 2017). The 10th and 11th centuries saw economic decline and depopulation in the region, visible in the archaeological record at both Unguja Ukuu and Tumbe, followed by the redevelopment of many sites as stone towns in the 12th century (Fitton 2017). This study is only concerned with the early phase (7th-10th century) occupation of Tumbe and Maganbani, but both early and late phases of Unguja Ukuu. Therefore, it is important to consider how the region's trade networks may have shifted over time throughout its decline and redevelopment.

Unguja Ukuu (Zanzibar Island). The site of Unguja Ukuu is located on a peninsula on the southwest corner of Zanzibar Island (Fig. 6). The site has been studied by archaeologists periodically since 1920 and is believed to have been the largest and most important port town on Zanzibar Island during the proto-Swahili period and between the 7^{th}-10^{th} centuries CE (Fitton 2017). In addition, it is widely recognized by archaeologists as one of the earliest trading towns on the Swahili Coast (Crowther et al. 2015; Fitton 2017; Juma 2004; Kotarba-Morley et al. 2022). Unguja Ukuu's name implies it was the capital city on Zanzibar Island, as it translates to "central place" according to proto-Bantu naming systems, or more literally, "The Great/Old Town of Unguja" (Juma 2004; Fitton 2017). After its early initial occupation, the site's chronology shows a break around 900 CE when the site was abandoned, followed by resettlement in the 11^{th} century (Juma 2004; Fitton 2017).

Unguja Ukuu's origins date to around 500 CE, when the site appears to have been permanently settled by a proto-Swahili Late Farming community based on a combination of radiocarbon dates and imported pottery fragments excavated from these early contexts (Juma 2004). A shift in monsoon wind patterns brought more moisture to Zanzibar around this time, increasing agricultural production and thus helping to revive interregional exchange networks (Juma 2004). The town of Unguja Ukuu was likely founded at least in part in order to take advantage of the broadening economic opportunities that these exchange networks provided, and it gradually developed alongside and in response to increasing contact with African and Indian Ocean merchants (Juma 2004). While this early date of origin may be contested among archaeologists, it is generally agreed that by the beginning of the 7^{th} century, Unguja Ukuu was a successful and growing coastal settlement, actively participating in long-distance terrestrial and maritime trade (Horton, Crowther, & Boivin 2018). The prevalence of imported ceramics as well as incense and glass beads attest to Unguja Ukuu's maritime trade connections from these early phases and onwards (Crowther et al. 2015; Wood et al. 2017; Fitton 2017).

From the 6th-10th centuries (period 1 according to Juma's 2004 chronology) the site was characterized by daub and timber construction, evidenced by the excavated reed impressions in middens and packed earth floors (Kenoyer et al. 2024), a subsistence economy, and prevalent iron working activity (Pollard 2008a; Horton & Clark 1985; Horton, Crowther, & Boivin 2018). The non-agricultural material culture recovered from Period 1a (500-750 CE) include a range of locally made shell beads, iron tools and slag, and ceramics (Juma 2004). In addition, "considerable quantities" of copper objects were discovered along with other long-distance trade items such as ivory bracelets from the African mainland, glass vessels and beads, and a few wheel-made ceramics with a white or red slip, likely of Egyptian and Mediterranean origin (Juma 2004). These North African and Mediterranean ceramics likely arrived on Zanzibar Island via Red Sea ports controlled by either Axumite or Persian merchants, who dominated the western Indian Ocean trade during this period (Juma 1996).

One of Unguja Ukuu's early copper-based objects is a brass incense burner grate recovered from a 7th- early 8th century CE deposit during Oxford's Sealinks Project excavations in 2011 (Crowther et al. 2015). Portable-XRF analysis was used to chemically identify this object as a copper-zinc alloy with noteworthy quantities of lead and iron (Crowther et al. 2015). This incense burner was likely imported from Persia, given the Persian preference for brass production and the prevalence of incense burning in Islamic settings (Crowther et al. 2015). The incense trade during this period centered along the coasts of Yemen, Somalia, and Oman, and typically involved resins such as frankincense and myrrh which were derived from shrubs that grew in these regions (Crowther et al. 2015). The incense residue left on this particular brass incense burner was chemically analyzed using gas-chromatography mass spectrometry (GC-MS). The results showed that this incense burner was used to burn Zanzibar copal, a species native to Zanzibar and the wider East African coast, which could indicate the early adoption of Islamic practices at Unguja Ukuu and incorporation of these practices with local resources (Crowther et al. 2015), although incense burning was not unique to Islamic tradition at this time. Another copper object from Unguja Ukuu was analyzed for bulk chemistry and lead isotopic signatures closely linked that object with a copper source in Iran (Crowther et al. 2015; Fenn, unpublished data). The chemical and isotopic results concerning these two copper-based objects closely link the copper trade at Unguja Ukuu with the Middle East.

In contrast, the earliest glass beads from period 1, mostly translucent blue-green drawn beads, are a distinct type of mineral-soda glass, m-Na-Al 1 which was almost certainly imported from Sri Lanka or southern India based on their unique chemical signatures and method of manufacture (Wood et al. 2017). Another early type of drawn glass bead, made of plant ash glass (v-Na-Ca), appears slightly later but overlaps with the mineral-soda beads in Unguja Ukuu's chronology. According to their chemistry, the plant ash glass originated in the Middle East. However, raw glass is known to have been widely traded from the Middle East and circulated throughout the Indian Ocean world (Wood et al. 2017). Considering that the drawn bead method of manufacture was much more prevalent during this time in Thailand and South India, it is possible that the plant ash beads found at Unguja Ukuu may have been manufactured from Middle Eastern glass in South or Southeast Asia before reaching the Swahili Coast (Wood et al. 2017).

Period Ib (750-900 CE) shows a significant increase in site area (likely correlating with population increase), a decrease in on-site craft production, and continued evidence of terrestrial and maritime long-distance exchange (Juma 2004). This combination of factors may indicate a trend of outsourcing craft production activities as the town shifted its focus towards articulating long-distance exchange networks between the African interior and Indian Ocean (Juma 2004). It is known that Islam was introduced to and adopted by many smaller Swahili Coast sites during this period. For example, the earliest mosque at Shanga, initially built from timber and later reconstructed from stone, dates to 780 CE (Horton, Crowther, & Boivin 2018). However, evidence of religious orientation at Unguja Ukuu before the 10th century remains inconclusive, with Unguja's first definitive mosque structure not appearing until the 10th century (Juma 2004; Fitton 2017). Therefore, despite its active trade connections with the Indian Ocean merchants and early exposure to Islam, the process of Islamization at Unguja Ukuu occurred gradually and was likely disjunctive from the flows of material goods coming from the same regions.

Unguja Ukuu appears to have been abandoned around the early-mid 10th century CE for unknown reasons. The period of abandonment is indicated by the relative scarcity of lead-glazed sgraffiato ceramics, an Islamic pottery type that was widely introduced at other Swahili sites during this time period, as well as a gap in radiocarbon dates from excavated charcoal samples (Juma 2004). Fitton suggests that this period of abandonment could be related to the disruption of Abbasid trade and the development of new port towns in the Red Sea, which likely impacted wider Indian Ocean trade connections (Fitton 2017; Horton 1987). Unguja Ukuu was resettled briefly from 1050-1100 CE (Period IIa) and then again from 1450-1600 CE (Period IIb) according to Juma's 2004 chronology (Juma 2004). However, the Sealinks Project excavations identified evidence of low-density occupation in the 10th and 11th centuries, so the site was likely not completely abandoned as previously thought (Crowther et al. 2013; Fitton 2017).

Interestingly, the site's earliest rag coral architecture, a mosque and an aristocratic house (or potentially another mosque given its alignment) dates to the late 9th-early 10th century, right around when the site was apparently abandoned (Juma 2004; Fitton 2017). Most of Unguja

Ukuu's stone architecture, which is rather less prominent than at other Swahili sites, was built later during Juma's Period II (Juma 2004). Given these inconsistencies in chronology and the fact that the site area is rather large, it is possible that Unguja Ukuu experienced some depopulation around the beginning of the 10th century and the remaining population shifted activity areas slightly. Overall, the most well-defined chronology at the site extends from the 7th-10th centuries CE, and the timeline of its later occupations, while unmistakably present, are less well understood, partly due to the fact that the later deposits are often distributed as lenses near the surface, making the stratigraphy difficult to determine (Juma 2004).

A range of different copper and copper alloy objects have been recovered from all excavations throughout all periods at Unguja Ukuu. Juma's excavations identified a variety of copper coins, workshop items such as nails, rivets, awls, chain links, and fishing line weights, adornment items like beads, earrings and finger rings, and spiritual objects like the incense burner (Juma 2004). The beads are of particular interest to this study, as they are very similar in style and contemporaneous (Period Ia) to the beads we analyzed from Mso Bay. Additionally, Juma's copper earring is stylistically quite similar to the earring analyzed from Tumbe. The copper coins are also of interest. Juma interprets the uninscribed copper discs as Kilwa type coins from Period IIa that were intentionally buried in a deeper context (Juma 2004). A fragment of a Chinese bronze coin from the North Sung (Song) Dynasty (960-1127 CE) was also discovered (Juma 2004). The riveted copper plates are similar to an object discovered by Fitton, which was analyzed in this study.

Fitton's survey recovered a similarly wide variety of copper-based objects from Unguja Ukuu. The copper objects from Fitton's "Area A" were located during a metal detection survey and recovered from approximately 10-20 cm below the ground surface (Fitton 2017). Due to their context and association with ETT ceramics, Fitton estimated these copper objects to date somewhere between the 7th-13th centuries (Fitton 2017). Copper objects from "Area D" were also located by metal detector and all found within 10 cm of the surface, although it is important to note that the field had been recently ploughed and therefore the near-surface stratigraphy disturbed (Fitton 2017). Although the inscriptions are quite worn and hard to make out, Fitton interprets these coins to be Kilwa-type coins, which were known to have been minted most consistently between the 13th-15th centuries. He uses that known coin chronology as a basis for temporally placing these finds before and during Juma's Period IIb (Fitton 2017). He argues that the coins and rag-coral walls found in Area D may indicate a shift in the site area rather than complete abandonment between periods IIa and IIb (Fitton 2017). Many of the copper objects from Fitton's "Area A" and "Area D" were chemically and isotopically analyzed in this study.

Tumbe (Pemba Island). The site of Tumbe lies on the northeastern edge of Pemba Island, on a bluff above Micheweni Bay (Fig. 5B). It was first discovered in 1993 by Fleisher and LaViolette during an extensive survey of the island (LaViolette & Fleisher 2009; Fleisher & LaViolette 2013; Fitton 2017). Tumbe is positioned with easy access to the mainland via the Zanzibar/Pemba Channel as well as to the greater Indian Ocean. Similar to Period I at Unguja Ukuu, Tumbe was a large town built primarily of mud and thatch structures between the 7th-10th centuries. Just before 1000 CE Tumbe seems to have been completely abandoned, and not long afterwards a new settlement called Chwaka emerged just a few hundred meters away and dominated the area from the 11th-16th centuries (LaViolette & Fleisher 2009, Fleisher & LaViolette 2013). Tumbe is often compared to Unguja Ukuu given their early contemporaneity, large site areas, and prominent involvement in long-distance exchange networks evidenced by their high densities of imported goods (LaViolette & Fleisher 2009; Fleisher & LaViolette 2013).

Early Tana Tradition (ETT) pottery, iron objects and slag, evidence of a subsistence economy centering around farming and fishing activity, and shell bead making debris characterize Tumbe as a typical early Swahili coastal site (LaViolette & Fleisher 2009).

Radiocarbon dates place the site's layers between the 770-980 CE, and imported ceramics such as turquoise-glazed Sasanian Islamic jars are consistent with these dates, although some evidence of earlier 7th century occupation also exists (Walshaw 2005; Fleisher 2010; LaViolette & Fleischer 2009; Fleisher, personal comm. 2024). The large site area (estimated 20-30ha) and high frequency of midden material suggest Tumbe was a very large site for its time period (LaViolette & Fleisher 2009). Furthermore, imported glass and ceramic sherds are found in extremely high densities at Tumbe in both midden and household contexts, exceeding that found at all other contemporary Swahili sites except for Manda and Chibuene (Chittick 1984; Sinclair et al. 2012; Fleisher & LaViolette 2013). This high frequency of imported goods suggests that Tumbe was one of the wealthiest Swahili sites before the 1000 CE (LaViolette & Fleisher 2009, Fleisher & LaViolette 2013).

Along with the presence of iron slag, the prolific shell bead making debris discovered at Tumbe indicates an active craft industry (LaViolette & Fleisher 2009). A far higher number of shell bead grinders has been found at Tumbe than at any other site in East Africa, indicating that shell beads were likely traded either to the African interior or to Indian Ocean merchants (Flexner et al. 2008; Fleisher & LaViolette 2013). Whether directly or indirectly, the shell bead industry at Tumbe likely helped drive Indian Ocean trade networks (Fleisher & LaViolette 2013). Shell bead production seems to have been carried out within households across the site instead of being concentrated at a few areas of specialized production (Fleisher & LaViolette 2013). In addition, fine imported ceramics, glass, and other goods have been found commonly within the remains of humble daub and thatch house structures. This dispersed evidence of involvement with long-distance trade suggests Tumbe was a relatively egalitarian village where many of its residents were directly participating in and benefitting from trade, and where imported goods had become commonplace (Fleisher & LaViolette 2013). Thus, the people of Tumbe balanced domestic and long-distance economies for centuries without any evident development of significant social stratification, and they were able to engage with the Indian Ocean economic system successfully without it dramatically altering their social structure and lifestyle (Fleisher & LaViolette 2013).

Excavations during the 2002 field season turned up diverse imported and locally crafted material culture, including an unusual number of lead objects as well as fourteen copper fragments from seven different test units, all consistent with the 770-980 CE time frame (LaViolette, Fleisher, & Mapunda 2002; Fleisher, personal comm. 2024). Five of these copper objects were chemically and isotopically analyzed during the course of this study. One is an unidentified fragment. The other four are notable for their decorative nature: two incised finger rings, one undecorated finger ring, and one penannular earring. The designs on the two incised finger rings resemble the hatched triangles found on ETT ceramics and may provide further insights into modification or remaking practices performed on imported materials, specifically non-ferrous metals (Fleisher & LaViolette 2013; Moffett & Walz 2023). The evidence for and potential implications of copper material modifications on the Swahili Coast will be discussed further in a later chapter.

Maganbani (Mainland, Zanzibar Channel). The site of Maganbani lies near the modern-day city of Bagamoyo on the mainland Tanzanian coast, on a cliff edge overlooking the Zanzibar Channel (See Fig. 5A) (Pollard & Kinyera 2017). It is much less extensively studied than the other sites discussed in this thesis. It was discovered in the mid-2000s as part of the Tanzanian Coastal Archaeological Project, which endeavored to determine foreign trading patterns along the Tanzanian coast between the 7th-10th centuries (Pollard & Kinyera 2017). Maganbani was initially identified as a large midden, and subsequent test pit excavations unearthed evidence of early Swahili habitation including daub, postholes, a cooking pit, and ETT ceramics (Pollard 2008a; Pollard & Kinyera 2017). Similarly to our other early Swahili sites, Maganbani appears to have been primarily a subsistence economy relying on terrestrial and marine resources that engaged in both shell bead and iron production (Pollard & Kinyera 2017). The few imported finds included sherds of Sasanian-Islamic ware and a Siraf storage jar as well as some colored glass (Pollard & Kinyera 2017). Pollard (2008a) suggests that the "lookout" at Maganbani may have been a seasonal trading camp, but the presence of wattle and daub structures indicates either repeated or continuous use. Regardless, when combined with trade evidence from a nearby site at Kaole Village, this area just south of Bagamoyo along the Zanzibar Channel appears to have been an early Swahili trading port of some significance (Pollard & Kinyera 2017).

One copper object, a subconical bead similar to those found at Mso Bay, Kilwa, and 9th-10th century deposits at Shanga, was categorized as a local artifact by Pollard and Kinyera (2017). This bead was analyzed alongside those from Mso Bay in this study, and the chemical and isotopic results will be compared later. According to Pollard (2008a), the copper for the sub-conical beads from both Mso Bay and Maganbani may have come from the African interior or from southern Asia. The sub-conical form of these beads is a style commonly found at interior and southern African sites (Moffet & Walz 2023; Walz & Dussubieux 2016; Stephens et al. 2020; Miller 1996; Miller & van der Merwe 1994) and was probably locally modified if imported from abroad.

A Brief History of Metallurgy in East Africa

Sub-Saharan Africa has a long history of iron metallurgy, and the earliest origins of the iron industry have been intensely debated for decades (Killick 2016b). However, it is generally agreed that the Bantu agriculturalists who settled in East Africa brought an ironworking tradition with them to the region. The earliest concrete evidence of iron smelting on the Tanzanian coast dates to the first century BCE (Killick 2009). Ironworking became a central craft industry that is a defining characteristic of early Swahili sites, evidenced at nearly every archaeological site by the presence of slag heaps, crucibles, and iron metallurgical debris (Bauzyte et al. 2023; Mapunda 2017). The iron metallurgical tradition across sub-Saharan Africa is unusual in that it was not preceded by copper metallurgy as it was in Europe and Asia. Instead, the two industries were developed simultaneously in the early 1st millennium CE by Bantu-speaking migrants in southern Africa (Killick 2009; Stephens et al. 2025). This phenomenon has puzzled archaeologists for decades, since copper requires lower temperatures to smelt and is generally much easier to work with than iron and is therefore seemingly the more intuitive first step in the development of metallurgical technologies (Killick 2016b). When combined with the fact that there are several major copper deposits throughout central and southern Africa and thus, copper ore was available in plenty, it is still a mystery as to why copper metallurgy was not developed first.

However, in contrast to the interior of sub-Saharan Africa, the near-coastal regions of East Africa are devoid of any copper, lead, and tin ore deposits (Kusimba et al. 1994). Therefore, any non-ferrous metallurgy occurring around the Swahili Coast would have required the use of ores and metals imported over long distances. The closest well known copper ore deposit that was exploited archaeologically (since the 5^{th}-7^{th} centuries CE (Stephens et al. 2020)) lies within Central African Copperbelt in the southern Democratic Republic of Congo and Zambia, over 2000 km away. No evidence for the movement of copper from this region to the Swahili Coast has yet been documented. Furthermore, there is no evidence for the trade of tin or bronze from southern Africa to the Swahili Coast after it began to be manufactured around Mapungubwe in South Africa in the mid-13^{th} century (Killick 2009). The absence of non-ferrous metal deposits in Eastern Africa, lack of evidence for copper movement from the African interior, and plethora of evidence for Indian Ocean trade has often led to the assumption that copper and copper alloy objects were imported along these maritime trade networks. Some of them undoubtedly were, such as the copper and bronze coins from the Middle East, China, and India (Perkins 2015). However, there is also evidence of established trade with regions of southern Africa that are known to have practiced copper metallurgy using southern and central African ores, so it is likely that the Swahili Coast was able to import copper from the African interior as well. Regardless, the Swahili coast would have had to import copper resources over long distances, whether it was through terrestrial African or maritime Indian Ocean trade networks.

Despite the lack of copper-containing geological deposits in East Africa, copper and copper alloy objects are found at almost every Swahili archaeological site. Although it is much rarer to find evidence of copperworking, it is evident that the Swahili people must have had some knowledge of copperworking since major sites such as Kilwa are known to have minted their own copper coinage consistently from the 11^{th} century onwards, and copper coins were likely manufactured more sporadically on Zanzibar as well (Wynne-Jones & Fleisher 2016; Bauzyte et al. 2021; Perkins et al. 2014; Walker 1936). Therefore, it comes as no surprise that, although infrequent, there have been some archaeological discoveries relating to copperworking technological processes. The most notable of these probably come from Kilwa, where the earliest excavations by Neville Chittick identified evidence of copper slag and copper lined crucibles, and many additional green corrosion-encrusted crucibles have been collected and displayed by local shops (Chittick 1974: 22; Bauzyte et al. 2021; Kusimba et al. 1994). Although the presence of copper slag has been contested and no copper ore has been found at Kilwa (Kusimba et al. 1994), the presence of slag could be a sign of copper smelting activity. Copper lined crucibles could have been produced by remelting and reworking imported metallic copper.

There is also evidence of cross-pollination between the copperworking and ironworking technologies in use at Kilwa. Lime is a historically important flux in the smelting of copper and was often used for this purpose in the Near East but it is not necessary in iron smelting (Bauzyte et al. 2021). Interestingly, pXRF analysis of iron slag from Kilwa detected unusually high levels of CaO, which is likely to have come from the use of lime as a flux during smelting and may indicate the transference of ideas between different metalworking industries that were carried out in close proximity (Bauzyte et al. 2021). In addition to copper and ironworking at Kilwa, some silver and gold coins were also minted there, and Kilwa is known to have been involved in the gold trade between Great Zimbabwe and the Indian Ocean as recorded in the *Kilwa Chronicle*. Together, these lines of evidence illustrate a thriving metalworking community where diverse metal types were produced and worked successfully (Bauzyte et al. 2021; Kusimba 1994). If copper was indeed being smelted on site at Kilwa, the ore may have come along trade networks with southern Africa that predated the gold trade (Bauzyte et al. 2021), as ore is very inefficient to transport especially overseas.

Other important Swahili Coast sites have also produced evidence of copper working processes. Copper lined crucibles have been excavated from Manda, Shanga, Ungwana, and

Mafia (Kusimba et al. 1994; Horton 1996). Additionally, Horton's work at Shanga identified small pieces of copper slag and melted copper pieces that would have been produced as waste from a casting process (Horton 1996: 358). Without the presence of copper ores and considering the scarcity of slag, it is hard to imagine that copper smelting was very common, even if it was experimented with at sites like Kilwa and Shanga. It is also possible that small amounts of slag were produced by remelting metallic copper. The more abundant copper-lined crucibles indicate that imported metallic copper was being remelted and reworked with some frequency throughout the Swahili Coast (Horton 1996; Kusimba et al. 1994).

This evidence is quite significant in how we view the role of copper within medieval Swahili society, as it allows the Swahili people agency in shaping and determining the use of this material within their local societies. Copper trade was not simply a direct transference of a new class of objects from abroad. Rather, copper trade provided the Swahili the opportunity to develop a new craft industry and offered them a new medium with which to express their own signs of value. Evidence of copperworking processes along with the presence of distinctly African style copper beads and jewelry, shows that they took full advantage of this. It also demands consideration of the possibility that copper and copper alloy objects were being melted down and remixed with other copper objects locally along the Swahili Coast, adding an additional layer of complexity to this study's interpretations.

Chapter 3: Methods

Background to the Analytical Methods

Little quantitative analysis has been conducted on copper-based metals from historic Swahili Coast sites to date. However, chemical and isotopic analyses of copper have the potential to yield important information about the types of non-ferrous metals that were in circulation and their origins. Similar chemical and isotopic characterization studies of copper-based artifacts have been shown to be quite informative in a variety of other archaeological contexts, including southern Africa (Stephens et al. 2020; Stephens et al. 2023a; Rademakers et al. 2019), ancient and medieval Iran (Orfanou et al. 2018; Orfanou et al. 2020; Oudbashi et al. 2021; Oudbashi et al. 2023; Oudbashi et al. 2025), China (Chen et al. 2020; Chen et al. 2023; Liang & Parker 2021), ancient and medieval India (Bisht et al. 2015; Law & Renson 2021; Srinivasan 2016b), and numerous others. The geographic diversity of Indian Ocean trade networks during the Global Middle Ages makes these questions of metal type and provenance particularly promising for yielding new information about the Swahili Coast's long-distance connections.

A number of analytical methods have been used by archaeologists to determine metallic composition over time, each method with its own strengths and weaknesses. For this study, scanning electron microscopy with energy dispersive x-ray spectroscopy (SEM-EDS), although a qualitative to semi-quantitative method at best and not sensitive enough to detect trace elements, was chosen as a way to initially assess the metals in this collection, gaining information about the types of alloys we were working with and what metallic phases were present in each. SEM-EDS was the primary method of chemical analysis for one object, SM2, due to large phase differences that made it impossible to harvest a sample representative of the bulk composition for ICP-MS.

For all other objects, we followed this qualitative compositional assessment with a fully quantitative chemical analysis via solution-mode ICP-MS. Although destructive to a small sample from each object, we chose ICP-MS as the most appropriate method for elemental analysis in this situation due to the heterogeneity of many archaeological coppers. This heterogeneity results from the immiscibility of lead in copper as well as the metallic phases resulting from the alloying process and metallurgical techniques used in production. Spot analysis methods such as SEM, electron microprobe analysis (EMPA), or laser ablation ICP-MS rely on averages of data collected from different metallic phases to estimate overall elemental concentrations. This spot selection and averaging process may result in nonrepresentative chemical data depending on the selection of spots analyzed. Therefore, it was necessary to dissolve a small fragment of each artifact in solution to achieve the most accurate possible bulk compositional data. Solution mode ICP-MS has been demonstrated to be a highly accurate and precise method of measuring major, minor, and trace element concentrations in archaeological metals. In addition to determining precise alloy compositions, the abundances and ratios of certain trace elements detected by this sensitive method can aid in characterizing the type of ore deposit the copper originated from (Stephens et al. 2020).

In addition to bulk chemical analysis, we conducted lead isotopic analysis (LIA) on the objects in this collection. LIA has been used by archaeologists since the 1980s, particularly in Europe and the Mediterranean regions, to estimate the geological ore sources of copper artifacts (Killick et al. 2020, Stephens et al. 2023a). This method is useful because all copper ores contain at least trace levels of lead, and lead isotopic ratios vary depending on the age and geological characteristics of the ore deposit they originate from. Furthermore, lead isotope ratios are not altered in the smelting process (Liu et al. 2018; Stephens et al. 2023a). Challenges can arise from this method depending on the geological region in which it is applied, as multiple copper ore sources can have overlapping ranges of lead isotope signatures if they were formed during the same geologic event or at the same time. However, when applied in a region with sufficient geological variability, LIA can be very informative, especially in combination with information from trace element compositions, as demonstrated by the work of Pernicka throughout the 1990s and 2000s (Pernicka 2014, Killick et al. 2020, Stephens et al. 2020). LIA became much more widely used worldwide after 2005 due to the introduction of MC-ICP-MS, a faster and more precise method of measuring lead isotope ratios (Douthitt 2008, Killick et al. 2020). High-resolution MC-ICP-MS instrumentation is now commonly used for LIA because it allows for the simultaneous collection of multiple isotopes, can produce equally precise data measurements as TIMS, and can correct for mass fractionation during measurement by thallium spiking (Rehkämper & Halliday 1998, Vanhaecke et al, 2009).

Background to the Present Study

For this thesis, 28 copper-based metal objects were selected for analysis. These objects were recovered from excavations at five archaeological sites along the Tanzanian Swahili Coast and come from temporal contexts spanning the 7^{th} -15^{th} centuries CE. Two of these objects (UU8 and UU12) were sampled in two locations due to their potentially composite nature, for a total of 30 samples. Descriptions of the samples and contexts can be seen in Table 1. As shown, a wide variety of object types are represented in this collection, including some of primarily utilitarian nature, some ornamental, and some unidentifiable fragments. The following results from our chemical and isotopic analyses address potential variation in copper consumption and use over time as well as between two different regions of the Tanzanian coastline, one centered around the Kilwa Archipelago (Songo Mnara and Mso Bay), and one centered around the Zanzibar Archipelago (Tumbe, Maganbani, and Unguja Ukuu).

General Sample Preparation

All objects were carefully assessed visually in order to select sampling locations that would least impact the overall form and structural integrity of the object. Once sampling location was determined, small fragments were harvested from each artifact by hand using a jeweler's saw, allowing for the most optimal precision and care. Throughout the sampling process, measures were taken to clean the sampling equipment and workspace between each sample to minimize any potential for cross-contamination.

SEM-EDS Procedure

The sample taken from SM2 was mounted in epoxy resin, polished, and carbon-coated under vacuum to prevent charging of the conductive material during analysis under the SEM-EDS system. A ThermoFisher Quattro S field emission environmental Scanning Electron Microscope (SEM) housed at the University of Oklahoma's Microscopy facilities was used to examine samples under high magnification. The accompanying Quasor II CMOS Electron Backscatter Diffraction (EBSD) detector and X-Ray detector were used to image metallic phases and qualitatively measure chemical compositions (Figure 7). To estimate the bulk composition for sample SM2, which could not be accurately measured via ICP-MS due to extremely large phase differences, six area scans were analyzed by the X-ray detector. These area scans measured the weight percent concentration of each element detected in each area, and the values for elemental concentrations in each of the six areas were then averaged.

Elemental Analysis Procedure

The samples for elemental chemistry via the ICP-MS underwent more intensive cleaning procedures to eliminate potential contamination. The superficial corrosion layer on each was removed using a Dremel1 rotary tool, with a new carbide cut-off wheel for each sample. Sample masses of approximately 25–50 mg were removed using a jeweler's saw with a new steel blade for each sample. All samples were cleaned using mQ water (sonication for 10 minutes) and then heated overnight in a drying oven. Once clean and dry, samples were weighed on a mass balance and dissolved in a solution of 1 mL 29M trace metal grade (TMG) HF + 8 mL 8M Optima grade HNO3 to minimize precipitation or volatilization of Fe, Zn, As, Ag, Sn, and Sb, and refluxed overnight at 90℃ (Stephens et al. 2023a, Rademakers et al. 2020). Once cooled, sample solutions were weighed on the mass balance to determine sample density. A 100µg aliquot of each solution was then taken and used to prepare a series of 100x, 1000x, and 30,000x dilutions, each including 0.1g of an internal Be, Sc, Rh, Tl standard solution. Procedural blank solutions were created for each batch of dilutions.

All 3 dilutions of each sample were analyzed on the PerkinElmer NexION 300x quadrupole ICP-MS paired with the SC-4 dx autosampler system housed at the University of Missouri Research Reactor (MURR) laboratory. Analytes and associated limits of detection are shown in Table 2. All analytes were run in a standard, low-helium flow (2.4 ml/min), mode while a select group of analytes (^{31}P, ^{52}Cr, ^{56}Fe, ^{75}As, and ^{77}Se) were re-analyzed in a high-helium flow mode (4 ml/min) to minimize known issues with polyatomic interference. The procedural blanks as well as two unknown standards (Spex-Cal-2 and HP-CB) were run with every batch for quality control. The selection of elements and isotopes analyzed for (shown in Table 2) were chosen because of their propensity to transfer from metallic ores through the smelting process and remain in the finished metal according to the Ellingham diagram (Killick 2014; Pollard 2018).

Raw data was processed in Microsoft Excel to normalize measured values, calibrate each analyte, and convert their measured intensities to concentrations using the calibration curves and known sample masses. First, all intensity values for each analyte, measured by the instrument detector in counts per second (cps), were normalized by comparing the expected vs. measured intensity values for the internal standards and determining the normalization factor, which was then applied to all measured intensities. Outlying values caused by trapped droplets in the PFA spray chamber or other similar errors were removed from the dataset. The 5 intensities measured for each analyte were then averaged, standard deviations calculated, and background counts were subtracted from all averages.

Three calibration standards (MSCS-M, MS-C, and MS-D) at varying dilutions were run with each analytical session and were chosen to represent all analytes of interest at the range of concentration values we expected to see in the archaeological samples. A custom blend standard, Mix J, was used to calibrate Cu, Sn, and Zn, at higher concentrations. The measured intensities for each analyte present in these calibration standards were used to develop calibration curves by plotting the measured intensity vs. known concentration in for each analyte in each standard dilution. These calibration curves were then used to convert the measured intensity values in archaeological samples into concentrations.

Limits of detection were calculated for each analyte using the formula (LOD= 3*SD (5 averaged intensity values for that analyte)) (Table 2). Known dilution factors, sample mass, and sample solution densities were used to back-calculate and determine the concentration of each analyte present in the original solid metallic sample. Any concentration values below the calculated LOD were cut, and our final table of the concentration of each element present in each sample was developed (Tables 5&6). All of the normalizations, calibrations, and conversions for this data set resulting from ICP-MS analysis were carried out by Dr. Jay Stephens at MURR labs.

Lead Isotope Analysis Procedure

The fragments harvested for lead isotope analysis varied in mass from 2-84 mg, due to the significantly different dimensions of each object. Each fragment was digested in a Teflon vial using 16M 2x nitric acid (HNO3) solution and dried down on a hotplate at 90^{o}C overnight. These digested and evaporated copper samples were then transported back to the University of Oklahoma and stored for later Pb isotope analysis.

The digested copper samples that were taken for lead isotope analysis at MURR labs to proceed with lead extraction and isotopic analysis. At MURR, the samples were redissolved in 6M Optima grade HCl and based on the rough lead concentrations estimated according to the previous SEM-EDS analysis, aliquots of approximately 4000ng were taken from each to be dried down again on the hot plate at 90^{o}C overnight. The dry residue was redissolved in 0.5M Optima grade HBr and the lead extraction was conducted using ion exchange chromatography, adapted from Weis et al. (2006), and carried out using 0. 5 ml of AG1-X8 BioRad resin in Bio rad 2 ml polypropylene columns (Renson et al. 2016). A blank was included in every set of samples to evaluate the amount of Pb introduced in the sample during the entire preparation in the clean room (digestion and separation steps). The total procedure blank values are between 0.004 ng and 0.024 ng. The pure lead solutions were evaporated at 120°C, then the dry residues were dissolved in 0.25 ml of 14M Optima grade HNO_3, evaporated at 120°C and finally dissolved in 1.6 ml 0.05N HNO_3 (Renson et al. 2016). After final dissolution, the lead samples were loaded into polypropylene microtubes and centrifuged. All but the last drop of solution was pipetted into another microtube to leave behind any possible remaining solids.

Lead isotope analyses were conducted using a Nu Plasma II (Nu Instruments) multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) in operation at MURR. Instrument parameters and collector configurations are shown in Table 3. The instrument was optimized to obtain a minimum of 100 mV for mass 204. The SRM981 was measured multiple times at the beginning of each analytical session and after every two samples. All samples as well as the standard SRM981 were spiked using a Tl solution (SRM997) to obtain identical Pb and Tl concentrations in the samples and in the standard (approximately 200 ng g^{-1} in Pb and 50 ng g^{-1} in Tl). For the voltage tests, 100x dilutions were prepared in additional 0.05M HNO_3, then run through the MC-ICP-MS. Voltage readings were recorded and used to calculate the dilution factor needed for analysis. Each analysis consisted of 60 cycles (3 blocks of 20 cycles of 10 second integration time each. Three successive wash-outs (3% HNO_3, mQ water and 0.05N HNO_3 were applied after every sample and standard solution. All measured lead isotopes values for the standard and the samples were corrected for mass fractionation using the NIST value for the $^{205}Tl/^{203}Tl$ natural ratio (2.38714) and for Hg isobaric interference at mass 204 using a

0.229883 value for the $^{204}Hg/^{202}Hg$ natural ratio (calculated using the natural abundances of the two isotopes with ^{204}Hg = 0.06865 and ^{202}Hg = 0.29863). The mean values for the SRM981 were 36.683 ± 0.007 (2SD), 15.486 ± 0.002 (2SD), and 16.935 ± 0.002 (2SD) for $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$, respectively (n = 44). The isotope values measured for each sample were corrected by standard-sample bracketing method, using the values published by Galer & Abouchami (1998) to eliminate instrumental drift (White et al. 2000, Weis et al, 2006,).

For this study, all radiogenic isotopes, ^{206}Pb, ^{207}Pb, and ^{208}Pb were compared to lead's only non-radiogenic isotope, ^{204}Pb in order to determine the most accurate possible age of the ore deposit of origin. However, ^{208}Pb and ^{207}Pb were also measured in comparison to ^{206}Pb to maintain consistency and comparability with other archaeological lead isotope studies which often prefer to measure isotope ratios against ^{206}Pb due to its much higher natural abundance (~24.1% as opposed to ^{204}Pb's abundance of ~1.4%) (Pollard & Bray 2015). The use of more abundant isotopes can aid in achieving in higher precision ratio measurements.

So far 23 out of the 30 samples have been analyzed for lead isotopes. Three of the remaining seven samples (UU1, UU6, UU7) were held back due to extremely low lead concentrations which require a specialized sample introduction system to boost the signal output in order for the MC-ICP-MS and achieve accurate measurements. The other four samples (SM3, P464, UU2, and UU14) were detained due to solid precipitates in the sample solution that needed to be removed before analysis. The isotope ratios from these remaining seven samples will be added to the dataset at a later date. Results of all chemical and isotopic analyses are presented in the following chapter.

Chapter 4: Results

Chemical analysis was conducted on all 29 samples (28 objects, one of which was sampled in two different locations), one sample via SEM-EDS and the other 28 samples through solution mode ICP-MS. Chemical results show a variety of copper and copper alloy compositions. Lead isotope (LI) analysis has so far been carried out on 23 of the 30 total samples (28 objects, two of which were sampled in two different locations). Most isotopic ratios are distributed along a trend that overlaps with several potential geological sources, while a couple of outliers indicate interesting divergences from this norm. The results of the chemical and isotopic analyses are detailed below.

Elemental Chemistry

SEM-EDS. The averaged SEM-EDS area scans for sample SM2 showed it to be a high tin bronze with some added lead, with average weight percentages of about 68% copper, 28% tin, 2% zinc, and approximately 1.5% lead (Fig. 7) (although the Pb concentrations estimated by the SEM were shown to be highly unreliable through later comparison to the Pb concentrations measured by the ICP-MS). Through the characterization of each individual phase, shown in Figure 7, we were able to determine that the dark gray vein (region 1) was a copper-rich phase, the medium gray region (region 2) a tin-rich phase, and the light gray region (region 3) was a mix of the two. The white spots throughout region 3 are areas of concentrated lead, demonstrating its immiscibility in copper and copper alloy matrices.

All other objects were similarly imaged and examined via SEM-EDS and were found to contain much smaller metallic phases, making it feasible to extract a 25-50 mg sample from each that would be representative of the bulk composition to dissolve for ICP-MS analysis. Object UU8 was initially thought to potentially contain two different metal types that were soldered together and was therefore sampled in two different locations for lead isotope analysis (UU8A and UU8B). However, the SEM images and composition estimates showed the two regions of UU8 to be microstructurally and chemically the same, and therefore this object was only sampled in one location for bulk composition analysis on the ICP-MS. The quantitative bulk compositional data for the rest of the objects, collected via ICP-MS, is presented below.

ICP-MS. Results from bulk chemical characterization via solution mode ICP-MS are presented in Tables 4 and 5. Elemental concentrations are shown in both ppm (Table 4) and wt% (Table 5). The percent relative standard deviation (%RSD) for all elements was <5%. For all major elements (elements present in concentrations above 1 wt%) the %RSD was <2%. Additionally, with one exception, all analyses totaled up to more than 90% (as shown in the SUM column in Tables 5 and 6). Considering the condition of the archaeological samples utilized for this analysis, with corrosion being avoided whenever possible in the sampling process, these totals accurately reflect the original composition of the object. The remaining percentages not documented in the compositional analyses likely are represented by carbonate and oxide corrosion products. One sample, SM3, resulted in total percent of 70.306%, which is attributed to the extreme corrosion in this bronze. Because the corrosion permeated throughout the core of the sample, the corrosion was not able to be removed completely during the sampling process. Therefore, it is assumed that a large portion of the ~29.7% lost were complex corrosion products including elements not sought during this research.

A selection of metallic and heavy non-metallic elements that are commonly found in copper ore deposits and persist through the smelting process were analyzed for, as determined by the Ellingham diagram (Killick 2014; Pollard 2018). Elements denoted with "<D.L." are below the detection limits for the instrument. Copper concentrations range between 59-99 wt%, with the remainder of each composition being made up of a combination of other major, minor, and trace elements (Table 5). Tin concentrations for this dataset range from <D.L. – 21.69 wt%. Zinc concentrations fall between 0.0003 – 18 wt%. Lead concentrations are from 0.0001 – 18.5 wt%. Other less abundant elements include iron (Fe) (<D.L. – 10990 ppm), cobalt (Co) (0.067 – 2602 ppm), nickel (Ni) (9 – 1961 ppm), arsenic (As) (16 – 6307 ppm), molybdenum (Mo) (<D.L. – 3 ppm), silver (Ag) (<D.L. – 889 ppm), cadmium (Cd) (<D.L. – 14 ppm), antimony (Sb) (<D.L. – 8003 ppm), tellurium (Te) (<D.L. – 62 ppm), tungsten (W) (<D.L. – 0.2 ppm), and bismuth (Bi) (3 – 352 ppm). Phosphorous (P) was below the detection limit for all samples except P464 where it occurs at 1.56 ppm. Chromium (Cr) is below the detection limit for all samples except for SM1, UU4, and P464, where it is present between 0.66 – 2.38 ppm. Selenium (Se) was below the detection limit for all samples.

Major alloying elements (present in >1 wt%) in this collection include tin, zinc, and lead. Figures 8, 9, and 10 show these major element concentrations plotted against each other to show the relationships between these elements in the various alloy types. Five primarily copper-tin alloys constitute high tin bronzes, with measured tin concentrations between 10-22 wt%. Because SM3 had a lower total percent due to prevalent corrosion, its concentration values were normalized to total 100% to estimate the original pre-corrosion composition of the object, yielding a tin content of 14.67%. Bronze compositions are shown in Figures 8 & 9. Five primarily copper-zinc alloys constitute brasses, with relatively smaller concentrations of tin and lead (Figs. 8 & 10). Zinc concentrations range between 4-18 wt%. Four primarily copper-lead alloys constitute highly leaded alloys, with relatively lower proportions of tin and zinc, although one also includes a significant amount of zinc and thus is a leaded brass (Figs. 8, 9, & 10). Major lead concentrations in this group fall between 11-19 wt%. The remaining 15 samples are primarily copper with no significant alloying elements and are therefore unalloyed copper, although they have varying levels of tin, zinc, and lead impurities (Figs. 8, 9, & 10).

In addition to the major elements, each of these samples contains varying amounts of minor (0.1 – 1 wt%) and trace (<0.1 wt%) elements, which may have been included as impurities in the copper or other metallic ores. Trace and minor elements can be grouped into those that are siderophile (elements that have an affinity for iron) and chalcophile (elements tend to concentrate in sulfide ores). Figures 11 shows the log of the sum of siderophile vs chalcophile elements and where the different alloy types fall along this comparison. As Fig. 11 shows, all of the alloys with significant concentrations of tin, zinc, and/or lead tend to have higher levels of both siderophile and chalcophile elements than the unalloyed copper samples. However, some of the chalcophile elements, tin (Sn), zinc (Zn), and lead (Pb) are major alloy elements in some of our samples as shown in Figs 8-10, thus inflating the relative chalcophile element sum values for the alloys. In order to achieve a more accurate comparison of siderophile vs. chalcophile elements that are minor or trace only in all samples, Sn, Zn, and Pb were removed from the chalcophile sum (Fig. 12). This brings down the chalcophile element values for the alloys. As Fig. 12 shows, the highly leaded alloys are still the highest in chalcophile elements, while two of the high tin bronzes and one unalloyed copper are highest in siderophile element impurities. Furthermore, there are three unalloyed copper samples that are significantly lower in both siderophile and chalcophile elements than all other samples (Figs. 11 & 12).

The measured lead concentrations are of particular interest here, as they help inform subsequent interpretations of the lead isotopic ratios. Lead concentrations are highly variable in this collection, ranging from 0.67 ppm which indicates extremely low-lead pure coppers, to more than 18 wt% indicating significant amounts of added lead (Tables 5 and 6).

Lead Isotopes

MC-ICP-MS. Lead isotope ratios from the 23 samples so far analyzed for isotopes plus 2 replicate measurements are presented in Table 6 along with the associated standard errors. Plots for each measured isotopic ratio of the 25 analyses are presented in Figure 13 to Figure 17. As shown, 24 of the 25 measured $^{208}Pb/^{204}Pb$ ratios fall between 38.2 and 39.7, but there is one outlier in MB3B, which falls much lower at 36.9431 (Figure 13). Similarly, among the $^{206}Pb/^{204}Pb$ ratios, most fall between 18.2 and 19.1, but again MB3B is an outlier with a much lower value at 17.4076 (Figure 15). This is a common pattern for all measured isotope ratios, with MB3B being significantly different from the trend shown in the other 24 analyses. $^{207}Pb/^{204}Pb$ values range between 15.6 – 15.75, except for MB3B at 15.48 (Figure 14). $^{208}Pb/^{206}Pb$ values are between 2.069-2.100 except for MB3B at 2.122 (Figure 16), and $^{207}Pb/^{206}Pb$ ratios lie between 0.823-0.855 except for MB3B at 0.889 (Figure 17).

As Figures 13-17 show, the replicate measurements for UU8A and UU9 both fall extremely close to the original measurements for these samples. If plotted separately on bivariate plots with associated 2se error margins (Figures 18-23), we can see that almost all measured isotopic ratios fall within the error margins. Measurements for UU8A and its replicate fall within the error margins except for on the $^{207}Pb/^{206}Pb$, which have much smaller 2se values due to the higher abundances of both radiogenic isotopes. All isotope measurements for UU9 and its replicate also fall within the associated error margins except for the $^{206}Pb/^{204}Pb$ ratio where the replicate only partially overlaps with the error margin. Figure 24 plots both UU8A and UU9 with their replicates and 2se margins. The overlap of the replicate measurements with the 2se margins attest to the accuracy and reproducibility of the data.

Figures 25-27 represent the lead isotopic ratios visually in different common plot formats for presenting lead isotope ratio data. As shown in Figures 25 and 26, most of the isotopic ratios plot along a general trendline, with the one notable outlier falling in the lower left of the plot due to its relatively lower radiogenic isotope abundances compared to ^{204}Pb. Figure 27 shows less adherence to a trendline among the radiogenic-only isotope ratios. These various isotope ratio plots show the variability as well as potential groupings and trends within this data set.

The archaeological significance of the trends and phenomena observed within these elemental and isotopic results are discussed in detail in the following chapter.

Chapter 5: Discussion & Synthesis

Discussion of the trends and phenomena observed in the above results are discussed below, followed by a detailed analysis and contextualization of these phenomena within their broad Indian Ocean and site-specific archaeological contexts. These analyses of the results inform the final interpretations and future directions for this area of research.

Chemistry

The major element compositions measured through solution mode ICP-MS analysis of these 29 copper samples shows the wide variety of metal types represented in this collection. As shown above in our results, many of them are alloys of brass and bronze as well as ternary or quaternary leaded alloy varieties. In addition, several of the objects are made from unalloyed copper. The table below (Table 1) shows the major, minor, and significant trace element concentrations grouped by metal type. Our lead isotopic results from 21 of these objects show a relatively cohesive grouping consistent with most lead isotope ratios from ore sources in the alpine orogeny, with a couple of interesting outliers which may yield insights into the geological provenance of some of these metals. In order to understand the paths and processes that brought this diversity of cuprous metals to the Swahili Coast, we must discuss what these varied elemental compositions can tell us about alloying and metalworking technologies as well as the geological characteristics of copper and lead ores in regions across the Indian Ocean world.

In the medieval world, bronze (Cu-Sn alloy) and brass (Cu-Zn alloy) were popular for their desirable gold color, and lead was a common addition to these alloys due to its advantageous material properties, especially for metal casting, and its abundant supply. The technology required for brass and bronze production as well as the popularity of these different copper alloys fluctuated over time and space, depending on the availability of the primary alloy elements, tin and zinc, as well as the technologies available, especially in the case of zinc, whose smelting process is quite different than that of copper and tin. Therefore, the following discussion will take a closer look at historical trends in copper alloy technologies and popularity in the Islamic world as well as in India and Southeast Asia to determine where these alloys were potentially manufactured before arriving on the Swahili Coast. In addition, the ternary and quaternary alloys of copper, tin, zinc, and lead may be the products of recycled brass and bronze objects that were melted down, mixed, and reused to make something new, necessitating discussion of metal recycling practices and the potential of using mixing lines to deconstruct an alloy's life history. Finally, trace element concentrations and lead isotope signatures will be examined to shed light on the provenance of these metals.

Pure copper always contains at least trace quantities of lead, and sometimes more due to the substitution of lead atoms within copper ores. This endogenous lead is transferred as an impurity from the ore into copper metal through the smelting process (Pernicka 2014). In addition, other impurities are common in copper, such as arsenic, antimony, silver, nickel, and sometimes bismuth, cadmium, and cobalt, among others. The ratios of the lead isotopes and trace element proportions are characteristic of (although not necessarily unique to) the geological source where the copper ore originated. Therefore, the pure copper objects in our collection may be tentatively geologically sourced using lead isotopic and trace element signatures. However, since lead was also commonly added to copper and copper alloys to improve the castability of the metal along with several other factors, before we can attempt to source the pure copper objects in our collection and proceed with interpretation of chemical and isotopic data, it is first necessary to distinguish which of our objects are in fact safe to consider unalloyed or “pure”.

As can be seen in Tables 5 and 6, the copper concentration generally decreases as other alloying elements are mixed in in greater proportions. Table 7 shows a summarized version of the elemental compositions in wt% concentrations, only including trace elements that are of the most significance to this study. In all of these objects, copper is the main element. Tin, zinc, and lead are the major alloy elements, and are present in varying combinations within this collection, which is illustrated in Figures 8-10. Based on the relative concentrations of these major alloy elements, we have defined alloy groups within this collection. In addition to the 15 unalloyed copper samples, we have 4 high tin bronzes, 5 brasses, and 4 high lead alloys. The chemistry of each of these groups is discussed below.

Bronzes. The five bronzes in this collection (sample IDs SM2, SM3, UU2, UU14, and P464) are binary copper-tin alloys with tin concentrations between 14-28%, with an average value of 21.05% Sn. All five of these objects are considered to be high-tin bronzes because their tin content is significantly greater than the other alloys in this collection. As one can see in Figure 1, the high tin bronzes, represented by the light blue dots, contain negligible concentrations of Pb and Zn, except for SM2 which has slightly more lead than the others. High-tin bronze is traditionally defined as bronze with 20% tin content or greater (Scott 1991). Microstructurally, the threshold for differentiating low tin and high tin bronzes is theoretically 17% Sn, as that is the maximum solubility limit of tin in copper, but in practice is the solubility limit is usually closer to 14% Sn (Scott 1991). High tin bronze, especially with 20% Sn or more, is sometimes termed “bell bronze” due to the resonant quality of this alloy, and it was also frequently used to make mirrors due to its high reflectivity resulting from the precipitation of the tin-rich beta phase as the alloy cooled (Craddock 1979; La Niece et al. 2012; Scott 1991; Saraiva et al. 2020).

Three of the objects in this collection, UU2, UU14, and P464, sit right around the typical 20% tin "bell bronze" composition, with 19.19, 21.69, and 21.64 % Sn, respectively, and SM2 sits above that at ~28% Sn as determined by SEM-EDS. Although SM3 has a relatively smaller tin concentration (measured at ~10 wt% Sn), we still consider it to be a high tin bronze. This is because SM3 had a rather poor total recovery percentage (only 70.3% total) under ICP-MS analysis due to its highly corroded nature. To account for the material lost to corrosion product, the measured concentration values of all elements present in SM3 were normalized to total 100%. This normalization allowed estimation of what the original chemical composition of this bronze may have looked like prior to the corrosion processes that resulted essentially in the dilution of its metallic components. Normalization of weight percent values brought up the tin concentration in SM3 from about 10.32% to 14.67% and could potentially have been even higher originally if corrosion processes preferentially removed the tin from the copper matrix over time. Therefore, we still consider SM3 to be a high tin bronze, as its normalized tin concentration value falls within the range for high tin bronzes of 13-26% tin, as defined by Orfanou et al. 2018.

Bronze is not known to have been manufactured in sub-Saharan Africa until the 13th century CE, when it appears around the site of Mapungubwe in South Africa, located along the northern border with Zimbabwe and Botswana (Miller 2001). Although the earliest bronze objects at Mapungubwe were imports from the Islamic world, it is evident that tin began to be mined and smelted locally, and that indigenous production of bronze began in the northwest Limpopo province of South Africa around the mid-13th century (Miller & Killick 2019; Miller

2001; Chirikure 2010; Stephens et al. 2020; Stephens et al. 2023b). Bronze production also began in southeastern Nigeria following the Islamic era (Miller & Killick 2019). However, most southern African bronzes contained much lower percentages of tin (<12 wt%) than the objects in this Swahili collection (Miller & Killick 2019). In addition, two of these bronzes (P464 and UU14) are from pre-13th century contexts. Given these two conflicts, it is expected that the high tin bronzes in the present collection were likely imported from across the Indian Ocean.

Bronze of such high tin content is known to have been manufactured in several locations around the Indian Ocean world throughout antiquity and into the medieval period, including the Eastern Mediterranean, the Middle East, India, and China, most commonly for the manufacture of bells and mirrors due to its reflective and resonant qualities. These high tin bronze objects typically contained between 2-10% added lead (and not uncommonly, up to 20% Pb) to improve the castability and reduce the cost of the alloy (Craddock 1979; Scott 1991; La Niece et al. 2012; Srinivasan 2016b; Saraiva et al. 2020; Chen et al. 2023; Liang & Parker 2021). Binary copper-tin alloys with such high tin content are not as fluid as leaded bronze and thus difficult to cast in intricate molds, and they become quite brittle if not worked properly. However, they can be hot worked above 586°C, and if quenched after hot working they retain the tin-rich beta phase, thus retaining reflectivity and reducing brittleness (Scott 1991). Because of this specialized manufacturing method required to successfully produce binary high tin bronze, or "beta bronze", it was much less common during the medieval period than leaded bronze.

In the early Islamic world, bronze was overwhelmingly replaced by brass as the predominant copper alloy. This was likely due to the scarcity of tin after the dissolution of the western Roman Empire, which effectively cut off the eastern Mediterranean and Middle East from the tin mines in Britain and Western Europe (Craddock 1979; Al-Saad 2000). Since there are relatively few tin deposits in the Middle East whereas zinc is quite plentiful, the early Islamic world turned to brass production for the manufacture of the vast majority of its copper alloys (Al-Saad 2000; Craddock 1979; La Niece et al. 2012). However, despite the scarcity of tin, there were still a few specialized types of objects made from bronze in the Islamic world, including mirrors, goblets, and bowls, some of which were high tin bronzes (Al-Saad 2000; Craddock 1979; La Niece et al, 2012).

It is well known that most Islamic copper-based alloys, including both brasses and bronzes, contained significant quantities of added lead (Craddock 1979; Al-Saad 2000; La Niece et al. 2012; Oudbashi et al. 2025; Orfanou et al. 2020). The practice of adding lead was likely adopted for practical reasons, as small quantities of lead (up to 2%) improve the casting properties of copper, and lead was also cheaper than other alloying metals (Craddock 1979; La Niece et al. 2012; Orfanou et al. 2018). Therefore, it is common to find Islamic bronzes with lead concentrations above 5%, sometimes upwards of 15% or even up to 23% (La Niece et al. 2012; Oudbashi et al. 2025). However, several studies have identified Islamic bronzes produced in medieval Iran that notably do not contain added lead, including a few in the "bell bronze" category (Craddock 1979; Orfanou et al. 2018; Oudbashi et al. 2025). These instances, although uncommon, indicate that Islamic metalsmiths did have the specialized technological knowledge required for hot working binary high tin bronzes.

Another region where these types of bronze alloys were produced is India. The long history of bronze production in India, especially southern India, has been well documented both historically and archaeologically. A series of documents known as the *geniza* letters were written by Jewish merchants based in Cairo between the 11-14th centuries CE. These letters detail the exchange of copper from Aden to the Malabar Coast of southwestern India, where it was made into bronze and subsequently shipped back to the Middle East (Gotein 1954; Chakravarti 2015; Srinivasan 2016b). One of these merchants, Abraham ben Yiju, operated a bronze factory in al Manjarur, India for nearly two decades during the mid-12th century (Chakravarti 2015). This demand for south Indian bronze may have been partially due to the scarcity of tin in the Middle East and because of India's superior bronze production technology, especially for high tin bronzes. In the archaeological record, high tin bronze vessels appear in burials in peninsular India since their Iron Age (c. 1000-500 BCE), specifically binary, unleaded bronzes (Srinivasan 2016a). Thus, the hot working technology required for beta bronze production was well-developed in southern India by the medieval period, along with leaded bronze casting technologies, and these traditional bronze production practices continue today in some areas (Srinivasan 2016b).

The production of high tin bronze in Chinese history has famously been associated with bronze mirrors for over 4000 years (Chen et al. 2023). Mirror production flourished during the Warring States Period (475-221 BCE), the Han Dynasty (206 BCE-220 CE), and more relevantly for this study, the Tang (618-906 CE) and Song (960-1279 CE) Dynasties (Liang & Parker 2021; Chen et al. 2023). Recent chemical analyses of many of these mirrors have shown that prior to and throughout the Tang Dynasty, mirrors were commonly produced with tin concentrations between 18-25% and lead concentrations around 2-5%, but sometimes as great as 10% (Liang & Parker 2021; Chen et al. 2023). However, during the Song Dynasty, there was a notable decrease in the proportion of tin being used to about (5-13%) and increase in the proportion of lead (from 5-20% or even up to 35% in some cases) (Craddock 1979; Liang & Parker 2021). Since these mirrors were usually cast in intricate molds, the addition of lead served to increase the fluidity of the alloy and achieve better casting detail, although it would not have been necessary in such high percentages.

A distinguishing characteristic of the Swahili high tin bronzes examined in this study is the unmistakable absence of added lead in all but perhaps SM2. SM3, UU2, UU14, and P464 all contain only trace amounts of lead at concentrations below 0.1 wt% (between 200-900ppm, average ~580ppm). Since manufacturing these binary high tin bronzes required a unique manufacturing method and was prohibitive of casting, which was the preferred method to produce most copper alloy objects, beta bronze was quite rare across the medieval Indian Ocean world. However, there are instances of such bronzes occurring in Iran as well as southern India during this time period, as well as historical evidence of bronze exchange between these two regions (Gotein 1954; Chakravarti 2015; Srinivasan 2016a; Srinivasan 2016b; Craddock 1979; Orfanou et al. 2018). Therefore, we think it likely that the high tin bronze objects from Unguja Ukuu, Tumbe, and Songo Mnara were likely imported from one of these two regions. Considering that tin's ore, cassiterite (SnO_2) is generally much purer than copper ores and contains very little lead compared to copper (Pernicka 2014; Powell et al. 2024), we can safely assume that the trace element quantities in UU2, UU14, P464, and SM3 originated within the copper metal in each of these bronzes. Therefore, future lead isotope analysis of these objects will allow us to further differentiate potential geographic origins for the copper metal comprising them.

Of these five bronzes, SM2 is the least pure. SM2 was not analyzed by ICP-MS due to its extreme heterogeneity, rendering it impossible to select a sample that would accurately represent the bulk. However, SEM-EDS was used to assess the major and minor element compositions, and SM2 was estimated to contain 2.17% Zn and 1.51% Pb. Given the unreliability of SEM-EDS at measuring these small concentrations accurately, especially with lead due to its immiscibility in copper, these impurity levels could be even higher than measured, and it is possible that SM2 was made from recycled materials and/or contains some added lead. When comparing the SEM images of these high tin bronzes, SM2 is the only one where small globules of lead are visible, scattered throughout the copper-tin matrix. Based on comparisons to the images from our other leaded and non-leaded objects, we expect that the measured lead concentration of 1.51% may be an underestimation. Fe, Co, and As were also detected by the SEM-EDS but their concentrations cannot be quantified.

Of the other four bronzes that were analyzed by ICP-MS, P464 is the least pure, with 1.0990% Fe, 1.2155% Zn, and 0.2602% Co, in addition to trace Ni, As, Ag, Sb, Pb, and Bi. SM3, UU2, and UU14 also contain smaller but varying quantities of these elements, which can be informative about the geology of the ore deposit. If we assume that these impurities all originated within the copper, not the tin, we can determine the approximate original concentrations of each impurity by subtracting out the tin concentration and renormalizing the total to 100% (or 95 in this case since our recovery percentages were slightly lower for the bronzes). Table 8 shows the estimated minor and trace element compositions of the copper component of each bronze.

Notable impurities that are often compared and used to indicate copper source are As, Sb, Ag, Ni, Co, and Zn. As we can see in Tables 4 & 5, P464 has significant iron, cobalt, and zinc impurities but is low in other trace elements. UU14 also contains these impurities at levels >0.1%, in addition to more significant arsenic. SM3 contains the most arsenic and antimony, while UU2 contains slightly more lead than the others. Cobalt in particular may be of significance in the study of high tin bronzes. Other studies have found a positive correlation between higher concentrations of cobalt (between 0.08-0.4%) in Islamic high tin bronze alloys from Iran and Israel, and cobalt-rich ore sources have been identified in Iran and Oman (Orfanou et al. 2018; Ponting 2008 p. 58). UU14 and P464 both fall within this range for cobalt, and UU2 is not far below. These unusually high concentrations of cobalt in high tin bronzes may indicate that copper from certain course was preferred for the production of this high tin bronzes (Orfanou et al. 2018). Cobalt concentrations in South Indian leaded, lower tin bronzes from the 10^{th}-11^{th} centuries had <0.08% Co with much higher proportions of Ni and Sb in comparison (Srinivasan 2016b). Cobalt was not analyzed for in studies of the high tin beta bronzes from this region (Srinivasan 1994).

Brasses. Five of the objects in this Swahili collection can be categorized as brasses; P571, P842, P844, UU8, and UU10. These objects contain between 4 and 18% zinc, which is much lower than the zinc content that can be achieved via the cementation or distillation processes. Unlike copper and tin, zinc is highly volatile and boils at 917°C, meaning much of the zinc will vaporize during a typical smelting procedure in an open crucible (Craddock 1979; Al-Saad 2000). The Ancient Romans developed a process called cementation, which reduces zinc ore and condenses the resulting vapor into molten copper within a lidded crucible. This way, when temperatures above 917°C were reached (which is required for melting copper) the vaporizing zinc could not escape and instead would collect and recondense inside the closed vessel (Craddock 1979; Al-Saad 2000). Islamic metalsmiths inherited the cementation tradition from the Romans and continued the practice throughout the medieval period to produce brass (Craddock 1979). In the ancient and medieval periods, cementation had a maximum zinc uptake of 28% when temperatures of 1000°C were reached (Craddock 1979; Al-Saad 2000; La Niece et al. 2012; Orfanou et al. 2020). However, if significant impurities such as tin and lead exist within the copper metal, the maximum zinc uptake during cementation will be somewhat less than it would have been in purer copper (Orfanou et al. 2020).

A different zinc production process, known as distillation, was developed in India and China at least by the 9th or 10th century CE (Craddock 1979; Al-Saad 2000), and likely much earlier in India. This process involved the distillation of zinc vapor into water, and resulted in pure zinc metal, which could then be alloyed with metallic copper to make brass (Craddock 1979). Many brass objects have been recovered from archaeological contexts between the 4th century BCE and 2nd century CE in Pakistan and northwestern India, a few of which contain zinc in concentrations higher than the 28% maximum that could be achieved by the cementation process (Craddock et al. 1983). These high zinc brass alloys must have been made through the mixing of copper and metallic zinc. Evidence of zinc smelting has been discovered at Old Zawar, a zinc mine in Rajasthan, northwestern India, dating to the 13th-17th centuries in the upper levels (Craddock et al. 1983; Xiao et al. 2020; Ghandi 2014). The *Rasaratnasamuccaya*, a Sanskrit document on alchemy written in the 14th century, describes two different zinc distillation processes in use, and zinc metal production was thriving by this time (Craddock 1979; Craddock et al. 1983; Ghandi 2014). Furthermore, Zawar is adjacent to Khetri, a well-known copper mine, and the bulk of the zinc produced at Zawar was likely used to manufacture brass which was in high demand (Craddock et al. 1983).

Zinc distillation was developed in southwest China probably later than in India, although the origins of the industry are still debated. Zinc metal was commonly used for making brass coins during the Ming and Qing Dynasties (16th – 19th centuries), and evidence of zinc smelting is abundant during this time period (Xiao et al. 2020; Zhou et al. 2012). Radiocarbon dating from one site in Chongqing confirmed that pots used in the zinc distillation process were present from the 15th century onwards (Zhou et al. 2012). Distillation technology used in China was slightly different than in India but still resulted in the production of metallic zinc and could be used similarly to make brass objects of much higher zinc concentrations.

Because zinc is so volatile, each time a brass is remelted, about 10% of its original concentration of zinc will be lost, and further losses can occur during the heat treatment and reworking of brass objects as well (Orfanou et al. 2020). The lower concentrations of zinc found in the Swahili brasses under consideration are likely a result of both reworking and impurities in the copper. These five brass objects all contain between 0.22-1.42% Sn and more significantly, 0.96-4.19% Pb. During the cementation process, the lead presence reduces the maximum zinc uptake by two times the lead concentration, and the tin content reduces the maximum zinc uptake by an amount equal to the tin concentration (Al-Saad 2000). UU10 is the brass in this group with the highest tin and lead impurities at 1.42% Sn and 4.19% Pb. These impurities would have reduced the maximum zinc uptake for this object by about 9.8% (1.42+2[4.19] = 9.8), for a maximum of 18.2%, if it was originally made via cementation. However, since this object only contains 9.69% zinc, it must have also been recycled and reworked, perhaps multiple times, to account for the much lower zinc concentration.

Like UU10, P571, P842, and UU8 fall into a similar category, with very low zinc concentrations (4.2-7.1%) which were probably a product of tin and lead impurities as well as multiple cycles of remelting and reworking the metal. P844 has by far the highest zinc content of these five objects at 17.85% Zn. This object, a penannular earring, contains very little tin (0.22% Sn) but likely added lead (3.58% Pb), which together would have reduced the initial zinc uptake to a maximum of 20.62% Zn. This is close enough to our measured value of 17.85 that the difference could be explained by sub-ideal smelting conditions. If ideal temperatures were not quite reached during cementation, the zinc uptake will also be lower (Orfanou et al. 2020). Alternately, P844 may have been reworked which would also account for the ~3% difference in maximum zinc uptake observed.

Is it difficult to determine whether the brass objects from the Swahili Coast were originally manufactured via cementation or distillation, as both processes afford a much higher maximum zinc proportions than are present in this collection. However, brass recycling has been documented as a common practice in the medieval Islamic world. It is not uncommon to find medieval brass objects at sites the Middle East with lower zinc percentages ranging anywhere between (5-23%), many of which were recycled (Orfanou et al. 2020). If these Swahili brass objects were imported from Persia or Arabia, they may have undergone multiple cycles of remelting and reworking and reached their final forms before ever arriving on the Swahili Coast. However, although there is no evidence of brass production on the Swahili Coast to date, it is possible the Swahili were reworking (hot or cold working) brass objects after they arrived, which would have left little direct trace in the archaeological record. The fact that P844 is a penannular earring, which was a style characteristic of sub-Saharan Africa and has been documented at other contemporary Swahili Coast sites such as Shanga (Horton 1996; LaViolette et al. 2002; other citation??), it seems likely that imported brass was reworked on site once it reached Tumbe to create an object suiting local style preferences. This hypothesis is supported by the fact that the two other brass objects from Tumbe (P571 and P842) are incised finger rings, whose geometric incised designs are reminiscent of the Triangle Incised Ware (TIW) ceramic tradition, a characteristic East African and early Swahili style (LaViolette et al. 2002; Fleisher & LaViolette 2013). Although a small sample size, these three objects point towards a tradition of importing brass from abroad and reworking the metal on site to form decorative objects that suited local style preferences.

As mentioned earlier, brass was the most common copper alloy in production in the medieval Islamic world. Zinc ore deposits are plentiful around the Middle East, especially in Iran and Turkey (Al-Saad 2000). This contrasted with the infrequency of tin deposits in the region, and after the Western Roman Empire fell rendering the tin deposits of Europe essentially out of reach, brass production quickly outpaced bronze production in the Islamic world. Recent chemical studies of early Islamic brass objects have documented a wide variety of compositions, ranging from about 5-25% Zn (Orfanou et al. 2018; Orfanou et al. 2020; Oudbashi et al. 2025). Therefore, the five brass objects in this collection, although tending towards the lower end of this range, are still within the parameters for Islamic brass. Brass was also manufactured on a large scale in northwestern India around the mining sites of Zawar and Khetri (Craddock et al. 1983) and was likely circulated throughout the Indian Ocean trade networks.

Leaded brasses have also been commonly identified in studies of Islamic metal work and tended to have lower concentrations of zinc on average than the non-leaded brasses (Orfanou et al. 2018; Orfanou et al. 2020; Oudbashi et al. 2025). Two of the objects in this collection, UU10 and P844, are considered to be leaded brasses with Pb concentrations greater than 2% (4.19 and 3.58%, respectively). In medieval brass production, lead may have been introduced to the alloy as an impurity within either the copper or the zinc ore minerals (La Niece et al. 2012). Zinc and lead ores are both sulfide minerals that often co-occur geologically, making it much more likely that the non-copper component in brass contributed significant lead content, whereas this is not the case for bronzes. Northwestern India and central Iran are both known for significant zinc-lead deposits that were exploited since antiquity (Craddock et al. 1983; Ghandi 2014). Due to this geological proximity and the visual similarity of lead and zinc ore minerals, particularly galena and sphalerite, lead could have been unintentionally added to brass during the sublimation of sphalerite (Orfanou et al. 2020). Additionally, brass objects were commonly cast, which often motivated the deliberate addition of lead to improve the castability of the alloyed metal, as was the case with cast bronzes as well. Keeping the lead addition relatively low (below 5%) would still have allowed for these brass objects to be cold worked later, whereas very high concentrations of Pb would make the alloy too brittle for cold working (Orfanou et al. 2020).

Notable minor and trace elements in these five brasses include variable Fe (0.06-0.4%), minor As (0.1-0.3%), and trace Co, Ni, Ag, Sb, and Bi. These elements are limited in what they can tell us about the origins of the copper used to create these brasses, especially in cases where lead was added as well. Lead and zinc ores are usually much less pure than tin ores, and therefore brass and leaded brass may contain a mixture of trace elements from all its metallic components, although more research is needed on how many impurities would transfer from the zinc component through the cementation process and into the final product (La Niece et al. 2012; Pernicka 2014). In these cases, it would be impossible to determine how much of each trace element had been contributed by each alloy component.

High Lead Alloys. Four of the Swahili objects (SM5, UU3, UU9, and UU13) are categorized as high lead alloys due to their lead concentrations of greater than 10% (11.6-18.4%). As previously mentioned, in the medieval Islamic world as well as in India and China, lead was commonly added to copper, bronze, and brass to improve the fluidity and castability of the metal. However, lead is only required in very small quantities to achieve this goal, and concentrations greater than 2% do not continue to improve the metal’s casting properties

(Craddock 1979; Niece et al. 2012; Al-Saa'd 2000). Other reasons lead may have been added to copper and copper alloys in concentrations higher than 2% include its lower melting point and abundant supply. For example, the addition of up to 36% lead lowers the melting point of bronze, which made it easier to work with (Craddock 1979, Young 1975). Furthermore, lead was often cheaper and easier to procure than copper and other non-ferrous metals, and it has a long history of being used as ballast for ships in the ancient Mediterranean, a practice which continued into the medieval period (Craddock 1979; Heng 2019). An Arab *dhow* from the early 9th century CE, discovered off the coast of Belitung Island in Indonesia, attests to the use of lead ingots as ship ballast along Indian Ocean trade routes as well (Heng 2019). Discoveries such as this one provide evidence for the abundance and high circulation of lead metal around the Indian Ocean world.

Because of its surplus, lead was probably mixed into copper alloys in many locations to increase the volume of the rarer metals being produced (Craddock 1979; Niece et al. 2012). For these reasons, lead is commonly found in Islamic casting alloys in concentrations of 15% or more (Niece et al. 2012; Oudbashi et al. 2025). The addition of high percentages of lead to copper alloys have also been well documented in South Indian and Chinese metallurgical traditions (Srinivasan 1998; Chen et al. 2020; Chen et al. 2023). Studies from the Islamic world have documented the mixing of scrap brass and bronze with lead metal in quantities greater than 10% (Park et al. 2021). Alloys such as SM5, UU3, and UU9 were probably made from a combination of recycled scrap brass, bronze, and lead metal due to the presence of both Zn and Sn in concentrations greater than 1 wt% along with the significant lead contents. UU13 is probably made from scrap brass and lead. Most of the recycled alloys with added lead analyzed in Park et al. 2021 include zinc or tin concentrations of at least 5% or greater, and most of the recycled quaternary alloys contain both zinc and tin in concentrations greater than 3%. Because UU3 and UU9 both contain Zn and Sn in concentrations below 5%, it is likely that the recycled scrap brass and bronze was also mixed with unalloyed copper as well as lead which would account for the further dilution of the alloy. The scrap brass used in UU13 was also probably mixed with unalloyed copper and lead to account for the very dilute Zn present.

In addition to their high lead contents, the four high lead objects in the collection analyzed here contain varying proportions of zinc and tin as well. Studies from other areas of the medieval Islamic world have documented the practice of mixing of scrap brass and bronze with lead metal in quantities greater than 10% (Park et al. 2021). Therefore, alloys such as SM5, UU3, and UU9 were probably made from a combination of recycled scrap brass, bronze, and lead metal. SM5 is a high lead brass (15.39% Zn, 13.22% Pb) which also contains 4.72% tin, indicating that this object was made by combining recycled brass with scrap bronze and then adding lead. UU9 is also a quaternary alloy with much more similar proportions of zinc and tin, at 3.76% and 4.59%, respectively, also likely produced from the recycling of brass and bronze scrap and mixing with plentiful lead metal and possibly unalloyed copper as well. UU3 and UU13 are almost binary Cu-Pb alloys, with only 1.2-1.5% zinc and 0.6-2.5% tin. These low zinc and tin concentrations could still have been produced by repeated recycling and remixing of brass and bronze with additional copper metal as well as lead to account for the very low Sn and Zn concentrations (Park et al. 2021). However, these smaller percentages could also be impurities that were introduced with the copper or lead. Orfanou et al. 2020 considers concentrations <0.5 wt% to be impurity levels for zinc, while concentrations of >1.5 wt% are likely the results of scrap brass reuse (Orfanou et al. 2020). Other significant impurities in these objects include minor concentrations (>0.1 wt%) of Fe, Ni, As, and Sb, and trace (<0.1 wt%) Ag and Bi.

As with the brasses, minor and trace element concentrations in highly leaded alloys are limited in what they can tell us about the metallic components, a puzzle which is especially complicated in the presence of mixing and recycling. All of the minor element concentrations measured for these alloys, including Fe, Co, Ni, As, Ag, Sb, and Bi, are likely a mixture of trace element signatures from multiple sources of copper, zinc, tin, and lead. There are a few assumptions we could make to try to narrow down the possibilities, such as the fact that lead is unlikely to contribute any nickel or cobalt to the mixture but could alter the antimony and silver concentrations (Pernicka 2014). In the case of a binary Cu-Pb alloy, we could use this information to characterize the copper component based on the unaffected trace elements, Co and Ni. However, with potentially multiple sources of copper coming from recycled scrap bronze and brass, it is impossible to use trace element compositions to yield information about the source of the metals in these alloys (La Niece et al. 2012).

Unalloyed Copper. The final category of metals represented in this collection is unalloyed or “pure” copper and includes 15 of the 28 samples analyzed. These objects all contain <1% of tin and zinc, and <2% lead, except for MB1 which contains 2.1% Pb and UU4 with 2.3% Pb and 1.1% Sn. Although the concentration threshold for the natural occurrence of Pb in copper has been widely debated, for the purpose of this study <2% lead is defined as endogenous to the copper due to the relative purity of this group of metals otherwise. An exception has been made for MB1 since its lead content is so close to this threshold and it contains only trace levels of every other impurity except for just above trace (0.18%) arsenic. UU4 is included in this category due to its lack of significant proportions of other alloy elements, although its slightly higher proportion of tin and higher iron and zinc impurities may indicate some addition of recycled bronze or other source of contamination during the metalworking process. The rationale for choosing 2% as the threshold for lead originating within copper is explained further below.

Allowing for some variability of impurities within copper ores, we consider these 15 objects to be made of unalloyed copper, although the higher tin and lead impurities in UU4 may indicate that some recycled metal was mixed into pure copper. Other minor and trace elements of interest in this collection include Fe, Co, Ni, As, Ag, Sb, and Bi. In addition to Pb, Sn, and Zn, the concentrations of these elements in copper vary depending on geological deposit and they will all transfer through the smelting process into the copper metal according to the Ellingham Diagram (Killick 2014; Pollard 2018). Iron concentration is heavily impacted by smelting technologies and therefore is likely more indicative of the metallurgical process rather than provenance (Craddock & Meeks 1987). Nickel, cobalt, arsenic, and antimony are the trace elements that are often most closely associated with the copper ore minerals, although this correlation depends on the type of deposit (Orfanou et al. 2018; Pernicka 1999, p. 170; Ponting 2003, p. 90). This can make these four elements very informative about the provenance of the copper if sufficient reference material from potential copper ore sources is known.

As, Sb, Ag, and Ni can be used to group copper into sixteen different categories based on their relative concentrations. Cobalt can also be an important trace element for sourcing copper, but it is not always measured in chemical analyses for archaeological metals, whereas arsenic, antimony, silver, and nickel are more commonly measured. This method of grouping copper types, developed by Pollard (2018), was intended to be as widely applicable as possible, and categorizes copper based on the presence (>0.1%) or absence (<0.1%) of each of these four trace elements (Pollard 2018). This study can only confidently apply this method to the pure copper objects, and tentatively to the high tin bronzes. Although the trace elements from the copper component in each bronze has been diluted by the tin that was added, it is possible to estimate the original trace element concentrations by subtracting the tin component and renormalizing the concentrations of the other elements to add up to 100% (or 95% in this case to most closely match the measured recovery percent) (Pollard 2018). This estimation relies on the assumption that the tin was very pure and that all the trace elements were introduced with the copper in bronze production. Although it is true that tin ores are generally purer than copper ores, this is not always the case so the trace element estimations for the bronzes should be regarded cautiously.

When applied to our collection of pure copper objects and the renormalized copper components of our high tin bronze objects, we find only four of the possible categories present among these 19 samples (Table 9). This method is useful primarily to detect changes in trace element patterns over time or space in a large dataset. With only 19 objects viable for this type of analysis in our dataset, it is difficult to identify any clear trends. If we divide these copper groups by our early phase objects (7^{th}-13^{th} century) and late phase objects (13^{th}-15^{th} century), we find that there is a mixture of all trace element groups in each time period (except for CuAsSbNi since there is only one object in this category to begin with, which happens to date to the early time period). However, if we sort our copper groups by archaeological site, some interesting trends begin to appear. While Unguja Ukuu and Pemba both contain a mixture of copper groups, both objects from Songo Mnara fall in the CuAsSb category and five out of six objects from Mso Bay/Maganbani fall in the CuAs category. These similarities within sites could be indicative of a shipment of copper from one location being used to create multiple objects, although comparison with the lead isotope ratios may not support this hypothesis. Regional or temporal trends could be defined more confidently in a larger dataset and could even be used to help identify the mixing and recycling of metals in such cases (Pollard 2018). Once more chemical analyses such as this one have been conducted on Swahili copper-based metals, the data can be compared to hopefully identify regional and temporal trends across the medieval Swahili world.

Another useful way to look at trace element compositions and differentiate copper groups in this collection of Swahili objects is to compare the siderophile element concentrations (iron-loving elements) to the chalcophile element concentrations (elements that tend to form sulfide ore minerals) according to the Goldschmidt classification of elements. Because of the different properties and behaviors of siderophile and chalcophile elements, they will be more common in certain ore sources depending on how the ore was formed and thus can help us distinguish between sources. Since the concentrations between these elements vary widely it is helpful to take the log of the sum of each category.

As shown in Figure 11, tin, zinc, and lead are chalcophile elements, along with arsenic, silver, and antimony. Cobalt and nickel are siderophile elements. Because some of our objects are alloys with significant concentrations of Sn, Zn, and Pb, these elements are greatly inflating the chalcophile component of the alloyed objects. To get a clearer comparison of only elements that are trace in all the samples, it is helpful to remove Sn, Zn, and Pb from Figure 12. As Figure 12 shows, this creates more overlap between the alloys and the pure coppers, although the high lead objects still stand out as the highest in chalcophile elements with their much higher levels of arsenic and antimony, and two high tin bronzes stand out as the highest in siderophile elements with their elevated cobalt concentrations. The one pure copper that is high on the siderophile axis is due to its high nickel content.

Both plots show a noticeable separation between three of the pure coppers that have much lower siderophile and chalcophile element concentrations than the rest of the group. These three data points correspond to UU1, UU6, and UU7, three of our pure coppers that have not yet been analyzed for lead isotopes due to their extremely low Pb concentrations. The significantly low trace element concentrations indicate that these objects are made from far purer copper than our other "pure" coppers in our collection, which is indicative of a much purer copper ore source. Although it is too early to compare this trace element data to the lead isotope signatures for these three objects, it is probable that they will be distinctly different from the isotope ratios for the rest of our objects as well. Impurity levels as low as are present in UU1, UU6, and UU7 may point towards a source within the Central African Copperbelt, which have been shown to contain very trace chalcophile and siderophile impurities in similar concentrations (Rademakers et al. 2019; Stephens et al. 2020; Stephens et al. 2023a). If this were the case, we would expect the Pb isotope signatures to be highly radiogenic as is characteristic of Copperbelt ores (Killick et al. 2020), they could establish the first concrete evidence of copper moving from the African interior to the Swahili Coast. Future LIA of these samples will help confirm or deny this hypothesis.

Lead Isotopes

Introduction. Lead isotope ratios reflect the age of the ore deposit where the metal originated, which can help distinguish between potential geological sources of the metal. All copper ores contain trace to minor concentrations of lead due to substitutional impurities in the copper ore matrix. These impurities carry through the smelting process and remain in the copper metal, allowing for the lead to be extracted from the copper matrix and its isotopic ratios to be measured and inform about the provenance of the copper. However, in cases where lead metal was added to copper from an external (or exogenous) source, it will usually be in far greater quantities than the lead that originated within the copper ore (endogenous lead). Therefore, the isotopic ratios from the exogenous lead metal will overwhelm those from the endogenous lead, and our measured isotopic signatures will reflect the source of the lead metal, not the copper. In cases where two metals containing relatively equivalent trace or minor concentrations of lead are mixed (for example copper and zinc during brass production, or two coppers during recycling) the lead isotope signatures measured from the alloy will reflect a mixture or proportional average of the isotopic signatures of its two (or more) components. Therefore, it is necessary to determine which of the objects in our collection contain exogenous lead and which contain only endogenous lead in order to understand what information we can glean from LIA.

It is generally assumed among archaeometallurgists that lead concentrations lower than 1 wt% in copper metal most likely occurred naturally within the copper ore deposit (Holmqvist et al. 2019; Melheim et al. 2018; Chen et al. 2023). Many archaeologists consider Pb concentrations up to 2 wt% to be naturally occurring in copper ore deposits (Ling et al. 2014; Chen et al. 2023) and suggest that Pb concentrations greater than 2 wt% indicate deliberate alloying with exogenous lead (Liversage 2000; Ling et al. 2014). Copper from production sites in Faynan, Jordan and eastern Anatolia has been found to contain up to and even slightly above 2% Pb (Hauptmann 2007). However, studies have shown that most other eastern Mediterranean sources contained less than 1% (Hauptmann 2007). Some go so far as to consider Pb concentrations up to 5 wt% potentially endogenous to the copper (Pernicka 1999; Pernicka 2014; Al-Sa’aad 2000). Ultimately, endogenous lead concentrations can vary widely depending on the ore deposit, and therefore a different threshold for lead content in unalloyed copper may be more reasonable depending on the geological region one is working within.

The uncertainty in the origins of lead between 1-5 wt% makes it challenging to determine what constitutes a pure, unalloyed copper. Many of the existing studies that discuss the natural occurrence of lead in copper concern European metals, which is not relevant to this study. The diversity of Swahili trade networks creates the potential for copper to be coming from several different geological regions around the Indian Ocean or within the African continent, requiring consideration of the geologic compositions of copper deposits in Southern Africa, Persia and the Near East, the Arabian Peninsula, India, and possibly even Southeast Asia and China. However, not enough work has been done to clearly define parameters for naturally occurring lead in copper in all of these locations. Considering the geological diversity across the potential source areas and the results from the elemental analysis as well as the characterizations of copper sources in the eastern Mediterranean, which shares geological formation types with much of the Middle East, this thesis considers Pb concentrations lower than 2 wt% to originate within the copper, with the noted exceptions of MB1 and UU4 for reasons explained above.

In addition to unalloyed copper with less than 2 wt% lead, it can be assumed that lead in very low concentrations in bronze alloys originated with the copper, since copper and lead ore minerals occur together commonly whereas tin and lead do not. Lead cannot be substituted into tin ores as it can in copper ores, but it can sometimes be present in tin due to uranium or thorium substitutions. In certain geological deposits, radioactive uranium can be substituted into the tin matrix and then the post-crystallization decay of these elements to radiogenic lead, which would subsequently remain trapped within the tin crystal lattice (Powell et al. 2024). However, this phenomenon is uncommon in the Indian Ocean sphere, so the trace lead concentrations within the high tin bronze alloys are probably indicative of the copper source, although four of these objects have not yet been analyzed for lead isotopes. The same cannot be said for the brass objects, as zinc ores often contain some lead, so when combined with copper, the lead from both metals would mix. Similarly, in ternary or quaternary alloys the isotopic signatures will reflect a mixture of components. However, it is still useful to examine these isotope ratios as they may yield information about recycling trends. In the four objects with very high lead concentrations (>10% Pb), the isotopic signatures from the lead metal overwhelm any that was contributed as an impurity by the copper or other alloy components and will reflect only the geologic source of the lead metal, although the possibility of mixing lead from multiple sources remains.

When compared with LIA data from other Swahili Coast copper and lead metals (Fenn, in production), the new lead isotope data presented in this study show general agreement with other metals from Swahili sites in Kenya as well as Tanzania. This broad agreement indicates that Swahili towns along the East African coast sourced their non-ferrous metals from the geological area and/or that they were mixing metals enough to average out the isotopic signatures. The bulk of the isotopic ratios from Swahili metals cluster between 18.2-18.9 in their $^{206}Pb/^{204}Pb$ values, between 15.6-15.75 in their $^{207}Pb/^{204}Pb$ values, and between 38.2-39.7 in the $^{208}Pb/^{204}Pb$ values, with only a couple of outliers. According to the Stacey-Kramers two-stage model for calculating lead isotope ratios based on the ages of ore deposits, these isotopic ranges are consistent with the geologic age of the Alpine orogeny, also known as the Tethyan metallogenic belt (Stacey & Kramers 1975).

The Alpine orogeny (or Tethyan metallogenic belt) is geological formation that spans southern Eurasia from the Alps through the Mediterranean, Middle East, the Himalayas and extending into Southeast Asia. The series of geological events that formed the Alpine orogeny resulted in many mineral deposits throughout Eurasia that have been exploited for metal ores since antiquity. However, since these ore deposits formed during the same geological timeframe, they contain comparable concentrations of radiogenic lead isotopes. Uranium and thorium abundances are relatively constant throughout the earth's crust (with a few notable exceptions in regions that aren't relevant here) and their radioactive decay processes occur according to fixed half-life rates (Faure & Mensing 2005, p. 218-219). Therefore, in ore deposits where mineralization occurred and thus the radioactive decay of uranium and thorium began around the same time, the resulting daughter products of ^{206}Pb, ^{207}Pb, and ^{208}Pb would accumulate at the same rates and in the same relative proportions to each other, making the resulting lead isotope signatures essentially the same. This phenomenon makes it nearly impossible to distinguish between different ore deposits within the same geologic formation, such as the Alpine orogeny, or between any two ore deposits of the same geologic age, based on lead isotopes alone.

When plotted against isotopic data from lead and copper ores from regions spanning the Indian Ocean sphere, we can see that most of the Swahili copper and lead objects plot on top of Alpine orogeny/Tethyan metallogenic belt ores (Figure 29). Because this formation crosses from the eastern Mediterranean through Persia and into northern India and Tibet, which are all possible trade connections for the Swahili Coast, we cannot determine the exact source of these metals based on their isotopic signatures alone. As Figure 30 illustrates, most of the measured isotopic ratios could be from multiple different regions all within the Tethyan metallogenic belt. Despite their inconclusivity, these ratios do yield a broad picture of some trends, particularly when compared with the elemental chemistry, about the possible mixing of metals at these sites.

Arabian Connections

There are a couple of noticeable outliers from the group of Swahili copper objects that matches isotopically with the Tethyan metallogenic belt ores. One of these outliers corresponds to sample MB3B and has much lower radiogenic to non-radiogenic ratios with $^{206}Pb/^{204}Pb$ = 17.4076, $^{207}Pb/^{204}Pb$ = 15.4770, and $^{208}Pb/^{204}Pb$ = 36.9431, signaling a much older ore deposit. These ratios correspond with late Precambrian (Proterozoic) age deposits, with a model age of about 680-685 million years old (Stacey et al. 1980) which exist in both the Indian Shield and the Arabian Shield (Killick et al. 2020). The closest isotopic matches from the reference data comes from galena from the Arabian Shield mining sites of Mahd adh Dhahab and Nuqrah, in modern day Saudi Arabia (Stacey et al. 1980; Killick et al. 2020). While there are other geological deposits of similar ages in northern India, the existing isotopic ratios don't match quite as closely to our Swahili samples as do the Arabian ores. As demonstrated in Figure 31, while MB3B's $^{206}Pb/^{204}Pb$ value is very similar to both Arabian and Indian Shield ores, the $^{208}Pb/^{204}Pb$ and especially the $^{207}Pb/^{204}Pb$ ratios separate out the Indian ores, and we can see that MB3B is a much better match with the Arabian Shield group. Since MB3B is an unalloyed copper with only 0.22% Pb, it is safe to assume the lead is endogenous to the copper ore and therefore that the LI ratios are representative of the copper's provenance.

A mining boom began in the Arabian Peninsula shortly before the rise of Islam and flourished for several centuries. Archaeological evidence shows that several mines within the Arabian Shield in central-western Saudi Arabia, including Nuqrah, were actively exploited throughout the early Islamic period (Morony 2019). Copper smelting slag dating to the 9th and 10th centuries is abundant around many of these mines, and the copper minerals at an-Nuqrah were continuously exploited for at least 500 years (Morony 2019). The popularity of Arabian mining in the medieval period may have been partially because it was one of the few regions where copper oxide minerals such as azurite and malachite were still readily available near the surface. In contrast, many other mining areas in the Mediterranean and Near East had been depleted of copper oxide minerals during antiquity, and by the Islamic period only the harder to access copper sulfide minerals in the hypogene were left (Morony 2019). Mahd adh Dhahab, a well-known gold mine in the region since antiquity, also contains plentiful copper ore minerals (Morony 2019; El shafei et al. 2020). This mine appears to have been abandoned around 830 CE, perhaps in favor of other gold mines in Egypt, but copper mining in the region continued (Morony 2019).

Trade between the early Islamic world and the Swahili Coast is well documented archaeologically. Abbasid plant ash glass vessels as well as Egyptian and Levantine natron glass vessels have been found at 7th-9th century Swahili contexts like Unguja Ukuu, Manda, and Shanga (Siu et al. 2023). However, the chemistry of these glass vessels points towards Mesopotamian origins, and they were probably exported from the Persia Gulf (Siu et al. 2023; Wood et al. 2017). Aden became a prominent Arabian port and was key in articulating trade between the Red Sea and Indian Ocean world, including East Africa and India, from the beginning of the 11th century CE, as documented in the *Geniza* letters (Chakravarti 2015; Gotein 1954). However, it is likely that the Red Sea connections with the Swahili Coast began even earlier. In the early 10th century, Al-Masudi, an Arab historian and traveler, traveled with Omani and Sirafi sailors across the Gulf of Aden and southward along the Zanj (Tanzanian) coast (Pollard & Kinyera 2017). Routes like these may have helped distribute goods from the Red Sea and southwestern Arabia into East Africa. Furthermore, early ties to between Unguja Ukuu and

Red Sea ports have been argued for by Juma (1996) regarding the distribution of Mediterranean ceramics. Considering western Arabia was so well-known for copper mining, it is likely that copper from that region circulated throughout the Islamic and wider Indian Ocean world. Our close isotopic match for MB3B with western Arabian non-ferrous metallic ores provides strong evidence for these connections at Mso Bay, whether direct or indirect.

Radiogenic isotopes

At the other end of the isotopic spectrum in our Swahili copper collection are a few objects with slightly radiogenic ratios. The furthest outlier, MB1 (which is potentially a pure copper object but contains 2.11 wt% Pb) has a $^{206}Pb/^{204}Pb$ value of 19.0973, which correlates to a geologic age that projects slightly into the future according to the Stacey-Kramers two stage model. In fact, any $^{206}Pb/^{204}Pb$ ratios above 18.7 will do the same (Stacey & Kramers 1975). These atypically radiogenic isotope signatures, especially on ^{206}Pb, indicate that MB1 as well as P842, P571, UU12A, UU12B, UU8, and UU10 all contain lead from ore deposits slightly enriched in uranium 238, which resulted in disproportionately more ^{206}Pb accumulating over time than normal. Figure 32A and B show the frequency of this type of deposit throughout the Tethyan metallogenic belt and greater Indian Ocean world. The few isotopic ratios in this range from the Arabian Shield are from an area of Oman where a much later Cretaceous formation that was deposited onto the Arabian Shield (Pearce et al. 1981; Hacker & Mosenfelder 1996), as well as a few unusually radiogenic Precambrian deposits (Killick et al. 2020).

As Figures 32A and 32B show, the radiogenic Swahili copper artifacts follow a trend that overlaps with ores from several different locations, including Iran, NW India and Pakistan, some from the SW China/Tibet region, making it impossible to distinguish the provenance according to Pb isotopes alone. There is also some isotopic overlap with southern African ores although the lead concentrations in these objects are too high to be from southern African sources so this region can be ruled out. In fact, all of these objects aside from UU12A, UU12B, and MB1 are low zinc recycled brasses, some with added lead, and therefore their Pb isotopic ratios likely reflect a mixture from different sources. UU12A and 12B isotopically lie directly amid a cluster of signatures for several sources, mainly Iran and China. Although these overlapping signatures make it impossible to determine the provenance of even the pure copper objects in this group, it does begin to show a possible mixing trend, which will be examined further.

Common copper source and reworking along the Tanzanian coast

Another intriguing phenomenon observed in the isotopic data is the similarity of the isotope signatures of three of the pure copper objects, P738, MG1, and MB4, which plot almost directly on top of each other on all Pb isotope plots. Chemically, these objects contain between 2656-5855ppm Pb (or 0.27-0.59% Pb), 1559-3171ppm As, 399-695ppm Sb, 152-475ppm Ni, and 110-356ppm Ag. MG1 also contains Zn and Sn impurities at 1960ppm and 450ppm, respectively, whereas P738 and MB4 only contain these elements at 31-43ppm and 3-9ppm. Despite the different trace concentrations in zinc and tin, these three objects are isotopically and chemically similar enough to potentially be sourced from a common copper supply. Significantly, they are all decorative objects (two conical beads and a finger ring) that come from different sites along the Tanzanian coastline, all dating between the 7^{th}-10^{th} centuries CE. The three sites represented by this group are Tumbe to the north, Maganbani in the middle along the

Zanzibar Channel, and Mso Bay at the southern end near Kilwa. This suggests that, regardless of where the copper was being imported from, early Swahili settlements were likely exchanging copper objects among themselves, either as a commodified material or through gift exchange. Perhaps a shipment of copper was received at Tumbe and some of the material from that shipment was sent south to trade with the Kilwa archipelago, or vice versa. Alternatively, it is possible that they shared a common copper source, and that one ship bearing Indian Ocean copper made multiple stops to offload goods along the Tanzanian coastline.

Furthermore, like the other objects from Mso bay and Tumbe, P738, MB4, and MG1 are all likely Swahili-made. The two beads, MB4 and MG1, are almost identical in form, just like MB2 and MB3A as well. MB3B is an elongated version of the same form. These types of conical copper beads have been found at other east and southern African archaeological sites, including Kwa Mgogo in the interior of northeastern Tanzania and Divuyu in the Tsodilo Hills region of northwestern Botswana (Moffett & Walz 2023; Walz & Dussubieux 2016; Stephens et al. 2020; Miller 1996; Miller & van der Merwe 1994). This indicates that these cone-shaped copper beads were a style that was valued by several African groups, including the early Swahili, and was likely being manufactured on site or regionally. Combined with the TIW cross-hatched designs incised on the two brass rings as well as the penannular earring from Tumbe (P571, P842, and P844), these collections of decorative objects strongly suggest copperworking activity at Tumbe, Mso Bay, and possibly at Maganbani as well, using imported copper from Indian Ocean trade to create African decorative objects for personal adornment.

Although direct evidence of copper working is not high in frequency among Swahili sites, there have been a few occurrences including copper-lined crucibles and some copper slag at Kilwa, Shanga, Manda, Kisiju, Ungwana, and Mafia (Chittick 1974; Horton 1996; Mapunda

2017; Kusimba et al. 1994). This shows that even if the Swahili were not smelting copper on a regular basis and mostly imported metallic copper, they were experimenting with remelting it in several locations, and clearly were reworking, probably by forging (hot and cold working) much more commonly. Unlike smelting, which produces slag that is left over as a byproduct, or full melting which requires use of a crucible, hot and cold working would not necessarily leave obvious traces in the archaeological record. Therefore, it is likely that copper working occurred much more commonly on the Swahili Coast than previously thought, and copper objects of distinctly African form such as the conical beads from Mso Bay and Maganbani (both 7^{th}-10^{th} century CE) and the incised rings from Tumbe (770-980 CE), attest to this phenomenon.

Site by Site Syntheses

The patterns and unique outliers emerging from this chemical and isotopic data begin to demonstrate the nature of trade relationships among Swahili sites, showing common trade contacts and pointing towards specific connections in some cases. These results also shed light on how the medieval Swahili may have interacted with and used imported copper and other non-ferrous metals. Further insights can be gleaned by assessing and interpreting the chemical and isotopic data within the historical and archaeological context of each site. The chemical diversity of alloy types found within each site are shown in Figures 33A-C. The assemblages from Unguja Ukuu, Songo Mnara, and Tumbe all include alloys containing significant proportions of tin, zinc, and lead, as well as some unalloyed objects. In contrast, the objects from Mso Bay and Maganbani are all very low in these three alloying elements (Fig. 33A-C).

Mso Bay. When the chemical and isotopic data for these objects are viewed as subgroups within their site contexts, Mso Bay immediately stands out as the site with the most cohesive collection stylistically and chemically, but the most diverse isotopically. All five objects are items of personal adornment; four of them are morphologically similar conical beads, one more elongated than the other three, which appear to be standardized in form; the fifth object is a bangle of a size to be worn around a wrist or ankle. All of these objects are made out of unalloyed copper with varying levels of minor to trace element concentrations; MB2 has slightly more Ni, As, and Sb than its counterparts, MB3A with slightly more Fe and Zn impurities. The bangle, MB1, contains just enough lead at 2.1 wt% that we must consider the possibility that it was added from an external source, but the low concentrations of other impurities suggests that it may be from a particularly lead-rich copper source.

These varying levels of minor and trace elements point towards different sources of copper, but it is not until we examine the lead isotope ratios that this becomes unmistakable. The Mso Bay collection contains both endmembers in our isotopic spectrum for the entire Swahili copper collection. The furthest outlier on the radiogenic end is MB1, and on the non-radiogenic end, MB3B. Furthermore, when plotted together, the other three Mso Bay objects fall quite linearly between these two outliers (Fig. 35). Coincidentally, MG1 and P738, MB4's isotopic twins, fall directly along this trendline as well.

The linearity of these Pb isotope ratios (R^2=0.999) may suggest that there were two copper sources, one at either end of the trend, that were mixed to produce other objects that would be isotopically in between the two end values. However, if this were the case, other minor and trace elements from the two copper sources would also be averaged in proportion to the amount of each of the two mixed components. We can see that this is mostly not the case in

Figure 36. MB3A and MB4 (along with MG1 and P738) all contain significantly higher Pb^{206} than MB3B which is not proportional to the amount more lead they contain when compared to MB1. Only MB2 contains isotopic ratios and lead concentration in the correct proportions to potentially be a mixture of MB3B and MB1. However, when we look at the other trace elements in MB2, we observe that it has significantly higher Ni, As, and Sb than both MB3B and MB1, and therefore cannot be a combination of only these two components. MB3A, MB4, MG1, and P738 could still be a mixture of the MB3B copper with another more radiogenic pure copper source that had a more similar Pb concentration, or from a separate source entirely.

Even if they were not mixing two copper sources at Mso Bay, it seems that they were working imported copper into locally valued objects. Conical copper beads have been discovered at Swahili and other African sites.

Maganbani. Although the site of Maganbani has not been extensively excavated and is less well understood than other Swahili Coast sites, it is positioned as an intermediary connecting the Zanzibar Archipelago with the Kilwa Archipelago. Hypothetically, if one wanted to travel from Pemba Island to Kilwa by land, one would have to pass right through Maganbani and the nearby settlement of Kaole. In addition, Maganbani lies almost directly across the Zanzibar Channel from Unguja Ukuu and could potentially have been used as a staging area or launching point for island inhabitants seeking to trade with other Swahili towns and non-Swahili mainland groups. Although the present study only analyzed one object from Maganbani, this small bead seems to support this hypothesis. Chemically and isotopically similar to a bead of the same form from Mso Bay to the south and to an unadorned finger ring from Tumbe to the north (see Fig. 11), MG1 may demonstrate the movement of copper from a common source between Swahili sites at their earliest phases. Maganbani was contemporary with Tumbe, Mso Bay, and Unguja Ukuu's Period I. These sites all appear to have been settled sometime in the 6^{th}-7^{th} century and all show evidence of participation in maritime trade networks before the 10^{th} century. Unguja Ukuu and Tumbe were perhaps the most active in Indian Ocean trade during this early period, as the highest densities of imported ceramics and glass beads have been recovered from these two sites compared to Maganbani and Mso Bay. Given that Kilwa was not yet a central Swahili trade hub during this early period, it is possible that goods from across the Indian Ocean were brought into the ports at Tumbe and Unguja Ukuu and diffused south along the Tanzanian coast towards the Kilwa Archipelago.

Alternately, Mso Bay's collection of isotopically diverse copper beads indicates that this early settlement was importing copper from multiple sources and remaking it into beads and bangles for local consumption. Since the isotopic signatures and relatively high concentrations of lead in these objects don't match copper sources in central and southern Africa, this provides evidence for early Indian Ocean connections in the Kilwa area, particularly with the Arabian Peninsula as indicated by MB3B's unique isotopic signature as well as somewhere within the Tethyan metallogenic belt. Instead of trade between Swahili Coast settlements, the similarities in composition of P738 and MG1 with MB4 may suggest that one merchant vessel bearing a shipment of copper metal made multiple stops along the Tanzanian coast on its way south, trading copper to local merchants at each stop, or that several shipments of copper from the same source traded with several Swahili towns during this early time period. Given the lack of evidence for diffusion of imported trade items out of sites like Tumbe into neighboring settlements on Pemba Island (Fleisher & LaViolette 2013), these scenarios of multiple points of contact with merchant vessels that bore copper may be more likely than secondary regional trade of imported goods between Swahili sites.

Tumbe. Evidence for copper working and remaking practices is also strong at Tumbe. Four of the five objects from this site are decorative in nature, three of which are probably Swahili in design. The incised geometric patterns on two of the finger rings, P571 and P842, echo those typical of the triangular incised ware (TIW) ceramic tradition that is characteristic of East African coastal and hinterland settlements between the 6^{th}-10^{th} centuries CE (Fleisher & LaViolette 2013). The penannular earring morphology of P844 is also probably a local style, as similar earrings have also been recovered from other Swahili sites such as Shanga (Horton 1996, p. 361). These regional stylistic similarities suggest that these objects were made into their final forms after the copper material arrived on the Swahili Coast and was thus reworked by local artisans.

Chemically, this collection demonstrates that a variety of copper-based metals were utilized for local making practices. Pure copper, recycled brass, leaded brass, and high tin bronze are all represented here. The low zinc concentrations in the two brass finger rings indicate multiple iterations of remelting and reworking, as some of the original zinc content would evaporate off each time. While metal recycling has been documented as a common practice within the medieval Islamic world, it seems likely that the last iteration of recycling occurred after the brass arrived at Tumbe to create objects that catered to local preferences. The earring, P844, has a high enough zinc concentration at 17.85 wt% that it is potentially a primary brass. Typically, fresh brass made via the cementation process in the Islamic world would contain 20-28% zinc depending on the smelting temperatures reached and the other impurities present. Since

P844 has some added lead, which would have reduced to maximum zinc content that could be absorbed into the copper somewhat. Therefore, this may have been a primary brass object that was reworked upon arrival at Tumbe, accounting for a small loss in zinc. Although P464 is only a thin, flat bronze fragment, the high tin composition suggests that it was once part of a mirror, which was a common product to make from high tin bronze in the Middle East and China due to its reflective properties, although Chinese mirrors from this period usually contained several percent of added lead; binary high tin bronzes such as P464 were more typical in southern India and the Middle East. Furthermore, its higher cobalt concentration is a regular phenomenon found in Islamic high tin bronzes. P738 is a pure copper with very similar trace element composition and lead isotope signatures to MG1 and MB4, indicating the same copper source for these three objects.

Isotopically these objects lie comfortably within the expected range for Tethyan metallogenic belt ores, and there seems to be a relationship between the lead isotope ratios and zinc concentrations in brasses P571, P842, and P844, along with brasses from other sites UU8, UU10, and SM5 (Fig. 34). As seen in Figure 34, all six of these brass objects' isotopic signatures become consistently less radiogenic as the zinc content increases. This may indicate that radiogenic copper was being combined with zinc and/or lead from less radiogenic ore deposits, or that brasses that were recycled were remixed with more highly radiogenic copper as the zinc was increasingly diluted. P571 and P842, the two TIW incised finger rings, lie at the high radiogenic and low zinc end of this trend, while P844 lies at the low radiogenic and high zinc end. The lead concentrations do not fall on such a linear trend in relation to the zinc concentrations in these objects, but in general the objects with lower lead (P842, P571, and UU8) are more radiogenic than the objects with more lead, supporting the above hypothesis.

As a group, these diverse copper-based metal objects from Tumbe indicate a variety of metals were imported from across the Indian Ocean and that local craftsmen were experimenting with reworking and remaking this imported copper material into objects of local significance. The fact that they are mainly decorative objects indicates that copper was valued for its aesthetic properties.

Unguja Ukuu. The largest number of objects analyzed were from Unguja Ukuu, which together paint the most complex picture of copper trade and consumption given the wide variety of object types, multiple chronological contexts, and chemical variability. The earlier phase from the Sealinks Project excavations at Unguja Ukuu encompasses the 7th-13th centuries CE, which includes Juma's Period Ia, Ib, IIa, and beyond (Juma 2004). The disturbed stratigraphy at the site makes it difficult to discern the chronological order of these finds within this range, but the fact that there was imported copper present during these centuries indicates that the Unguja Ukuu may not have been as completely abandoned between Period Ib and IIa or after Period IIa as previously thought. Copper from this time includes pure copper, high tin bronze, brass, leaded brass, and highly leaded recycled alloys. The object types include some utilitarian and some decorative in nature. The pure copper objects from this context are UU7, UU11, UU12A and UU12B. UU7 is noticeably purer than the other three, with less than 1ppm of lead and very low other chalcophile and siderophile impurities as well, suggesting a similar source as the "X" shaped ingots from the Central African Copperbelt, as extremely low impurity concentrations are characteristic of ore deposits in that region (Stephens et al. 2023a; Rademakers et al. 2019). In addition, UU7 is a flat wire twisted into a narrow spiral, similar in form to the wound wire bangles that are commonly found at sites in the southern third of the African continent (Stephens et al. 2023a). Although the lead isotope analysis has not yet been carried out for this object, we expect the isotopic signature will be consistent with a Copperbelt geological source.

On the other hand, UU11 and UU12A and B are made of pure copper with much higher impurity levels, which is more typical of copper sources in the greater Indian Ocean world. UU11 has the highest arsenic and antimony as minor concentrations (>0.1%) and about 1% lead. UU12A and 12B, a rivet and the plate it was holding together, have trace element signatures close enough to consider them from the same copper source, except that the rivet has 1.52% Pb while the plate only has 1.18%. Isotopically, these the three samples fall comfortably within the range typical of Tethyan metallogenic belt ores, making it impossible to determine their exact geographical provenance, but likely confirming an Indian Ocean copper import.

The binary high tin bronze object from this context is a fragment of a vessel rim, and although not isotopically analyzed yet probably came from Persia or southern India. Both of these regions are known for manufacturing binary high tin bronze vessels (goblets and bowls) during this time period. Furthermore, chemical analysis of glass beads from the earlier phases at Unguja Ukuu provide strong evidence for imports from southern India or Sri Lanka as well as the Middle East (Wood et al. 2017). We hope that future LI analysis will help distinguish between these two possible locations of origin for this high tin bronze vessel.

The brasses from this context, UU8 and UU10, a spoon and a decorated cylinder, are both made of recycled brass, evidenced by their low zinc concentrations at 7 and 9%, respectively. Trace and minor element impurities reflect a mixture of copper, zinc, and lead impurities in the case of UU10, which also contains over 4% added lead. Isotopically, these two brasses fall along a trendline with the brasses from Tumbe and Songo Mnara, which seems to relate lead isotopes to the zinc concentrations, suggesting that brasses may have been diluted with more radiogenic copper or less radiogenic lead as they were recycled.

UU9 and UU13, the two highly leaded objects, are a bracelet or bangle fragment and a flask cap. These high lead alloys are typical of metal recycling in the medieval Islamic world, with low concentrations of Sn and Zn that indicate very diluted scrap bronze and brass being melted down and remixed with more copper and lead. Their trace element and isotopic signatures reflect a complex mixture of multiple metallic components. Although this makes it difficult to understand anything about the provenance of the metals, it gives us important information about the recycling practices which may have partially taken place on the Swahili Coast, as well as the opportunism of Swahili merchants and metalworkers in using whatever copper-based metal they could import since they had no local copper resources available.

The later context from Unguja Ukuu contains only five objects, and dates between the 13th–15th centuries CE. Thus, we shift to a different timeframe in Swahili history, after the abandonment of some of the early successful trade towns such as Tumbe and Period I of Unguja Ukuu, and the rise of other major ports like Kilwa Kisiwani, which had an established Islamic sultanate and was an important port of trade in the Indian Ocean world. This timeframe at Unguja Ukuu encompasses the centuries between Juma's Period IIa and IIb and leading up to Portuguese contact. Originally thought to be a period of abandonment, these centuries are now understood to be a slight shift in site location due to the coins and rag-coral wall foundations discovered in Fitton's "Area D" (Fitton 2017). This near-surface context was likely disturbed, but four of the objects are coins, likely of Kilwa-type, which are known to have been minted at Kilwa during between the 13th-15th centuries CE. However, sustained minting of coinage began at Kilwa in the 11th century (Wynne-Jones & Fleisher 2016). Although their markings are quite worn and difficult to make out, two apparent stylistic features, namely an eight-pointed starburst and central dot, correspond with Kilwa coin designs. These similarities can be seen in several of the Kilwa-type coins currently housed at the British Museum. However, it has been suggested that coins were minted on Zanzibar Island as well, so it is possible that these coins were produced more locally (Perkins et al. 2014; Wynne-Jones & Fleisher 2016; Walker 1936).

Chemical analysis of the four coins from Unguja Ukuu shows a variety of copper types were being used to mint coins. UU1 and UU6 are both composed of very pure copper with lead values of 0.67 and 2.03ppm, respectively, potentially indicating a source in the Central African Copperbelt. Future LI analysis will help us determine if this is true. Both these coins are extremely thin and delicate, and UU6 is a warped fragment of a coin while UU1 is mostly complete with worn edges. UU4 is also very thin and warped and has almost no markings left. Chemically, it almost appears to be unalloyed copper from a less pure source but contains slightly too high lead and tin content to be considered true pure copper. This coin was likely made from copper with some recycled metal mixed in or perhaps was remelted at some point in a crucible that had been used to melt other metals previously, which would have contaminated the copper with more impurities (Powell et al. 2024). In size and weight, UU4 is quite similar to UU1 and UU6. UU3 on the other hand is a much more robust coin, is made of a highly leaded copper alloy, containing enough tin and zinc to be considered a recycled gunmetal with significant added lead.

As objects that were almost certainly manufactured on the Swahili Coast, likely at Kilwa, these coins again demonstrate the adaptability and opportunism of Swahili economies, using whatever copper-based metals were at their disposal to create objects for local consumption and trade. Kilwa is one of the few sites where significant evidence of copper metallurgy has been found, in the form of slag and copper-lined crucibles (Chittick 1974; Kusimba et al. 1994; Bauzyte et al. 2021). Kilwa is known to have minted many coins that have been discovered across the Swahili Coast, most commonly around the Kilwa Archipelago and Mafia Island with isolated instances as far north as Shanga (Wynne-Jones & Fleisher 2016). The presence of copper crucibles and slag at Kilwa may suggest that the town's inhabitants were smelting copper ore, although both of these products could also be generated through reforging. In the case of local smelting, the copper ore must have been brought to the Swahili Coast from the African interior (Bauzyte et al. 2021), as it is quite inefficient to transport raw metallic ores over long distances, especially overseas. The use of locally smelted copper to produce some coins would explain the extremely chemically pure copper used for the manufacture of UU1 and UU6. However, due to the inefficiency of transporting ores, it is more likely that this metallurgical debris was produced by remelting imported copper metal, which could have come from Indian Ocean or interior African sources, in the manufacture of coins and other objects.

In contrast, copper imported via Indian Ocean trade was probably used in the creation of the other two coins, UU3 and UU4. The evidence of local copper metallurgy also suggests that these two coins could have been recycled (and intentionally mixed with lead metal in the case of UU3) on site. The isotopic ratios for UU3 and UU4 fall right in the center of our Swahili isotopes cluster (Fig. 37) which is to be expected for mixed, recycled metals. However, in UU3 this isotope signature should be representative of the lead source since 11% Pb would overwhelm any lead component contributed by the copper or other alloy components. However, given that the isotopic signature for UU3 falls comfortably within the range for Tethyan metallogenic belt ores, we cannot ascertain its provenance. Furthermore, given that this is already a mixed metal, we cannot rule out the possibility that the lead component of the alloy was also comprised of a mixture of lead from different sources.

The fifth object from late Unguja Ukuu and only non-coin object is a bronze mirror fragment, UU2. This mirror was made from a binary high tin bronze with 19% tin, a typical composition for mirrors throughout antiquity and the Middle Ages in the Middle East, India, and China due to the highly reflective property of this material. This mirror fragment is plain and smooth on one side and exhibits a simple geometric incised border decoration on the other, which may be Swahili in origin. High tin bronze, especially the binary alloy which would not be conducive for casting, requires specialized technological knowledge to produce due to its propensity for becoming very brittle. Although there is no evidence for high tin bronze production on the Swahili Coast, it is likely that this mirror was at least completed after arriving there, further suggesting local modification of imported copper material. Future LI analysis will be used to help distinguish between potential Middle Eastern and South Indian ore sources.

The presence of Kilwa-type coins at Unguja Ukuu demonstrates the interconnectedness of regional Swahili economies and may provide evidence for affiliation between late-phase Unguja Ukuu and the Kilwa sultanate at the height of its prosperity. Although this period in Unguja Ukuu's history is less well understood than its earlier phase, this apparent connection to Kilwa hints at more economic activity during its later phases than previously thought. Consideration of the analysis of copper objects from both early and late phases at Unguja Ukuu demonstrates a prevalent use of copper and copper alloys sourced from diverse long-distance trade networks for a wide variety of objects throughout the site's history. The three pure copper objects with noticeably lower than normal impurities, spanning both early and late phases, indicate enduring connections with copper sources in the African interior. Although there is no evidence of direct trade between the Swahili Coast and the Central African Copperbelt region, it is possible that triangular terrestrial trade networks were articulated between these two regions by communities in southern Africa. Indian Ocean trade goods have been recovered from several sites in Zimbabwe, Zambia, and northern Botswana, attesting to their trade connections with the Swahili Coast, and these sites have been shown to have sourced some of their copper from the Copperbelt (Stephens et al. 2020; Stephens et al. 2023a; Rademakers et al. 2019), which could have then made its way to Unguja Ukuu along the established trade routes. The other less pure copper, copper alloys, and recycled metals from Unguja Ukuu illustrate a thriving scene of maritime imports of copper and copper alloys, potential local reworking practices, and regional economic ties to Kilwa Kisiwani during its height.

Songo Mnara. Another site with close ties to Kilwa during its later phase was Songo Mnara. Although only four objects from this town were analyzed in this study, they help flesh out a better understanding of local economies in the Kilwa Archipelago. Songo Mnara notably had a lower density of copper objects compared to copper coins and glass beads. The four objects analyzed in this study are varied in style and chemistry. SM1 is a small, pure copper rod which may have been a kohl stick, a common object found in high frequencies at many contemporary Swahili Coast sites (Mapunda 2017). SM2 is a high tin bronze with low lead content. It is a small, flat fragment, and may have been part of a mirror based on its composition, which was estimated by the SEM-EDS, but severe heterogeneity of the metal prevented more accurate bulk elemental analysis via ICP-MS. It is not clear whether this fragment's heterogeneity is a result of diffusion during corrosion processes or whether the ~28% tin was never fully dissolved in the copper during production, in which case SM2 could be scrap metal from a mixing process. SM3 is also a high tin bronze, a thoroughly corroded rim fragment from a thinly walled bowl or other vessel. SM5 is a stylized cylindrical cuff that was likely cast and is made of a highly leaded recycled brass containing some tin as well.

SM3 has not yet been analyzed for lead isotopes, but the other three objects all fall towards the middle of our range and notably form a linear trend with SM5 in the middle (see Fig. 37). SM1, the only pure copper from Songo Mnara, has rather similar isotopic ratios to the cluster of MB4, MG1, and P738, although not close enough to be likely from the same ore source, and considering that this small rod is from several centuries later this similarity is almost certainly coincidental. However, if future studies analyze more copper objects from Songo Mnara it will be interesting to see if the linear trend in isotope signatures holds, which could provide insights into local mixing practices.

Chapter 6: Conclusions

The elemental and isotopic data collected from copper-based objects from these five archaeological sites reveal an intriguing narrative of the complexity of copper exchange at the global, regional, and local scales along the medieval Tanzanian coastline. An integrated analysis of this new geochemical dataset within the archaeological site contexts and positioned through theoretical frameworks of disjunctive global flows, object itineraries, and materiality work together to shed light on the diverse, far reaching economic avenues through which copper arrived on the Swahili Coast, how it may have moved between Swahili towns regionally, and local copper working practices that were used to modify and remake this imported material upon arrival.

Lead isotopic and trace element signatures demonstrate a variety of long-distance trade connections that brought copper and copper alloy metals to the Swahili Coast. A strong lead isotopic match between a pure copper object and Proterozoic ore sources in the Arabian Shield provide strong evidence for the importation of copper metal from Arabia. Isotopic signatures correlating with the Tethyan metallogenic belt ores point towards other copper and lead sources in Persia and India. Elemental compositions of binary high tin bronze objects support these as likely copper and copper alloy sources. Conversely, three extremely pure copper compositions with remarkably low chalcophile and siderophile element impurities strongly suggest a copper source within the Central African Copperbelt, and future isotopic analysis of these objects will confirm or deny this hypothesis. Through this combination of lead isotope and compositional analyses, this thesis demonstrates the diversity and extensivity of copper trade networks and shows that the Swahili took advantage of global Indian Ocean and African trade routes to source this locally extinct material throughout the Global Middle Ages.

On the regional scale, closely matched trace element and isotopic signatures between objects from three different sites in 7^{th} -10^{th} century Tanzania indicates either the regional distribution of copper imported from a common source or shared maritime trade connections between early Swahili settlements. Although it is impossible to determine which of these scenarios is more likely at this point, this chemical and isotopic comparison of pure copper objects from different sites begins to shed light on the regional economic relationships between Swahili towns in the Zanzibar and Kilwa Archipelagos.

Finally, this data set establishes evidence for local non-ferrous metal working practices. Comparing zinc concentrations to lead isotope signatures reveals probable mixing and recycling of brass alloys at Tumbe. In addition, lead isotopes confirm foreign Indian Ocean origins for the copper used to make objects of distinctly African design such as the conical beads from Mso Bay and Maganbani, TIW incised finger rings from Tumbe, and Kilwa-type coins from Unguja Ukuu. This evidence of the local remaking of imported materials demonstrates the disjunctive flows of material goods and systems of value. It indicates that the material properties of copper and copper alloys were valued and utilized differently by the Swahili people. This evidence shows Swahili agency in action as they transformed nonlocal materials into objects of local significance within their East African context.

The chemical and isotopic data presented in this thesis help improve understanding of the multi-scalar nature of economic systems through which copper-based metals were translated from their foreign geological origins and became valued objects within medieval Swahili Coast communities. Furthermore, this study demonstrates the potential of the geochemical analysis of semi-precious materials such as copper to help understand the Swahili Coast's relationship and role in long-distance maritime and terrestrial economic world systems, and to reveal how the Swahili articulated their unique identities through the interplay of commodities from global exchange networks with regional and local technological practices and systems of value.

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Figures

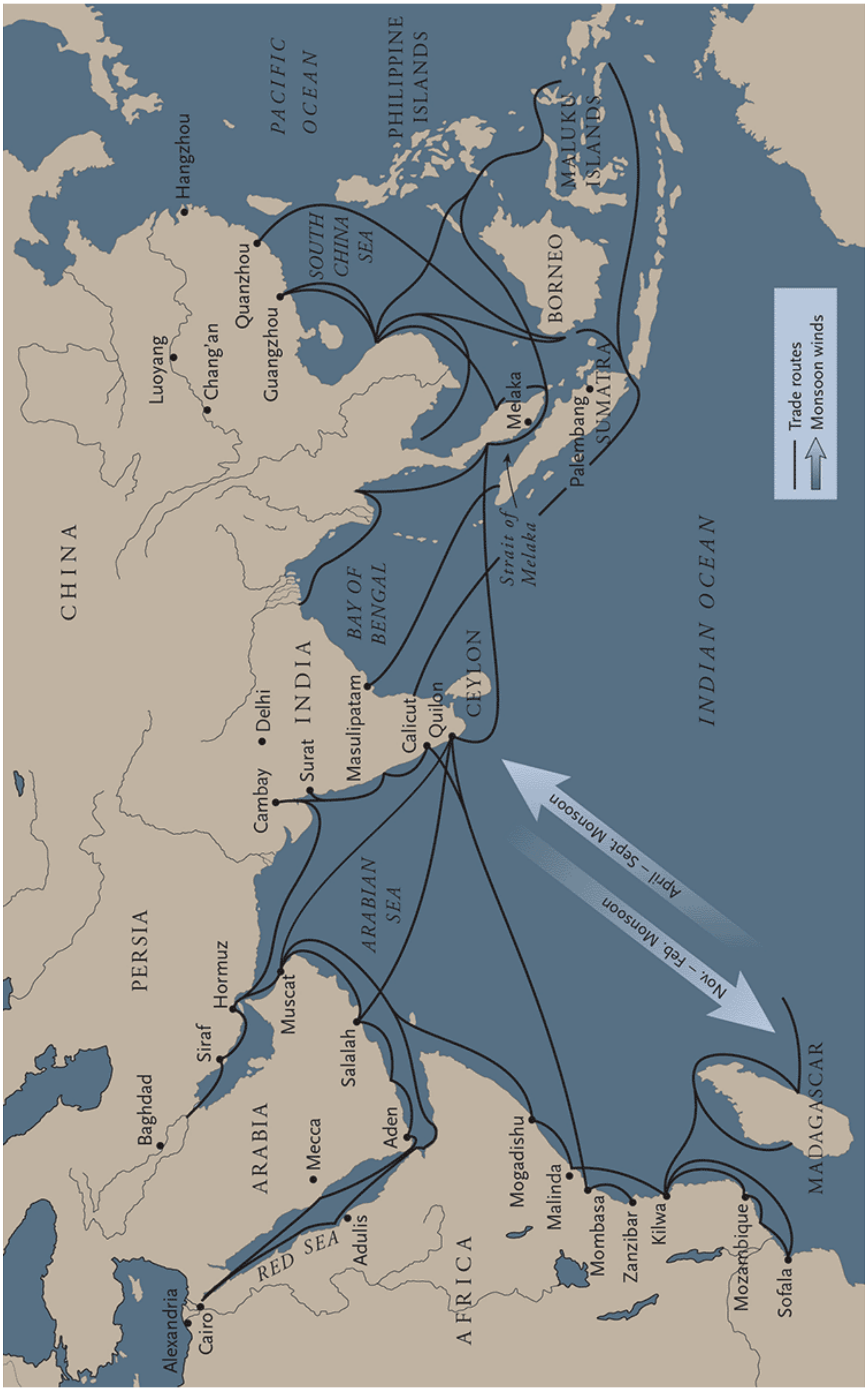


Figure 1: Monsoon winds and trade routes around the Indian Ocean during the Global Middle Ages

(500-1500 CE) (Smithsonian National Museum of African Art 2015)

Figure 2: The Swahili Coast (Fleisher 2010; Fleisher 2014) – Sites for this thesis marked in red

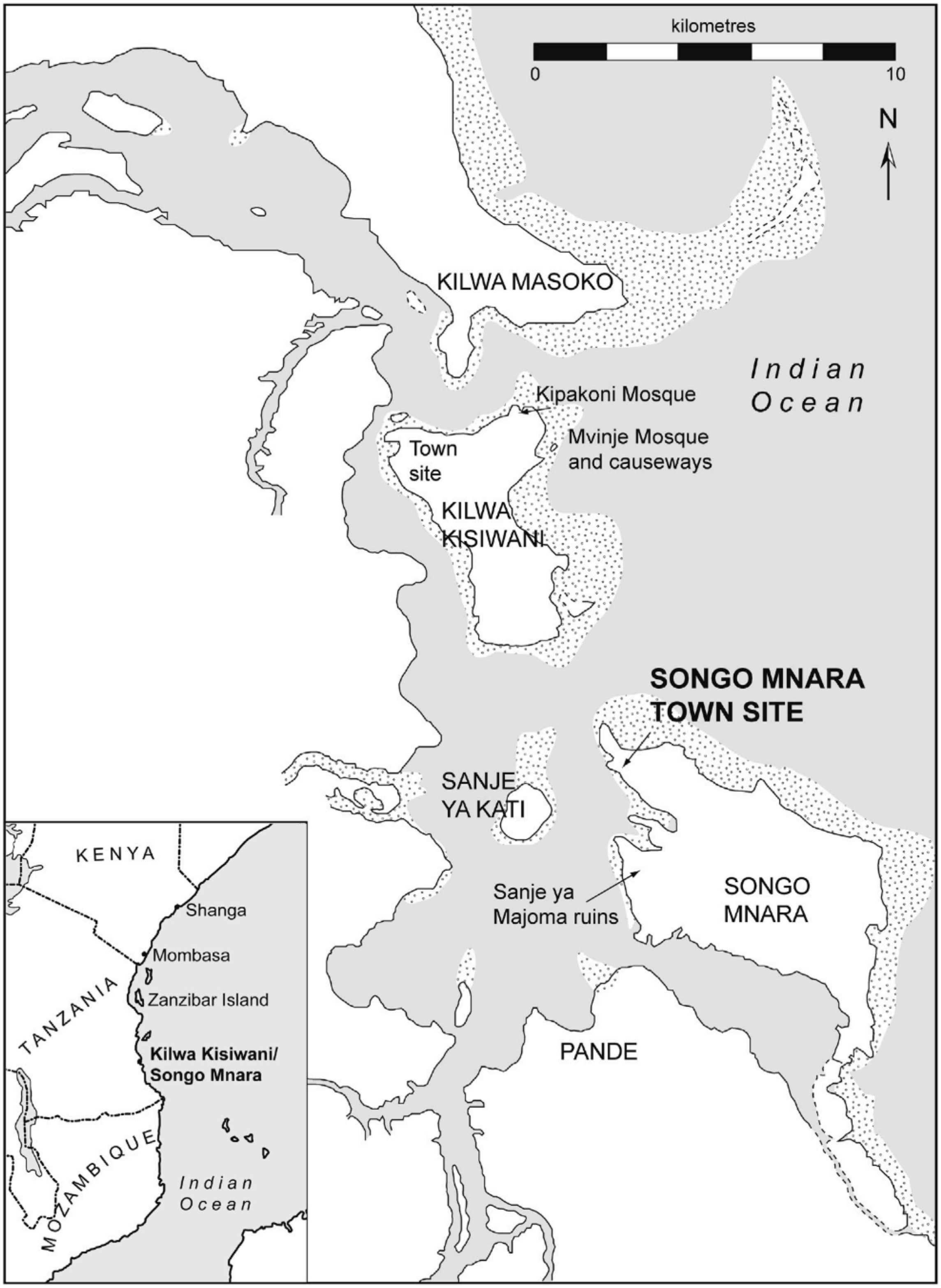


Figure 3: The Kilwa Archipelago (Fleisher & Sulas 2015)

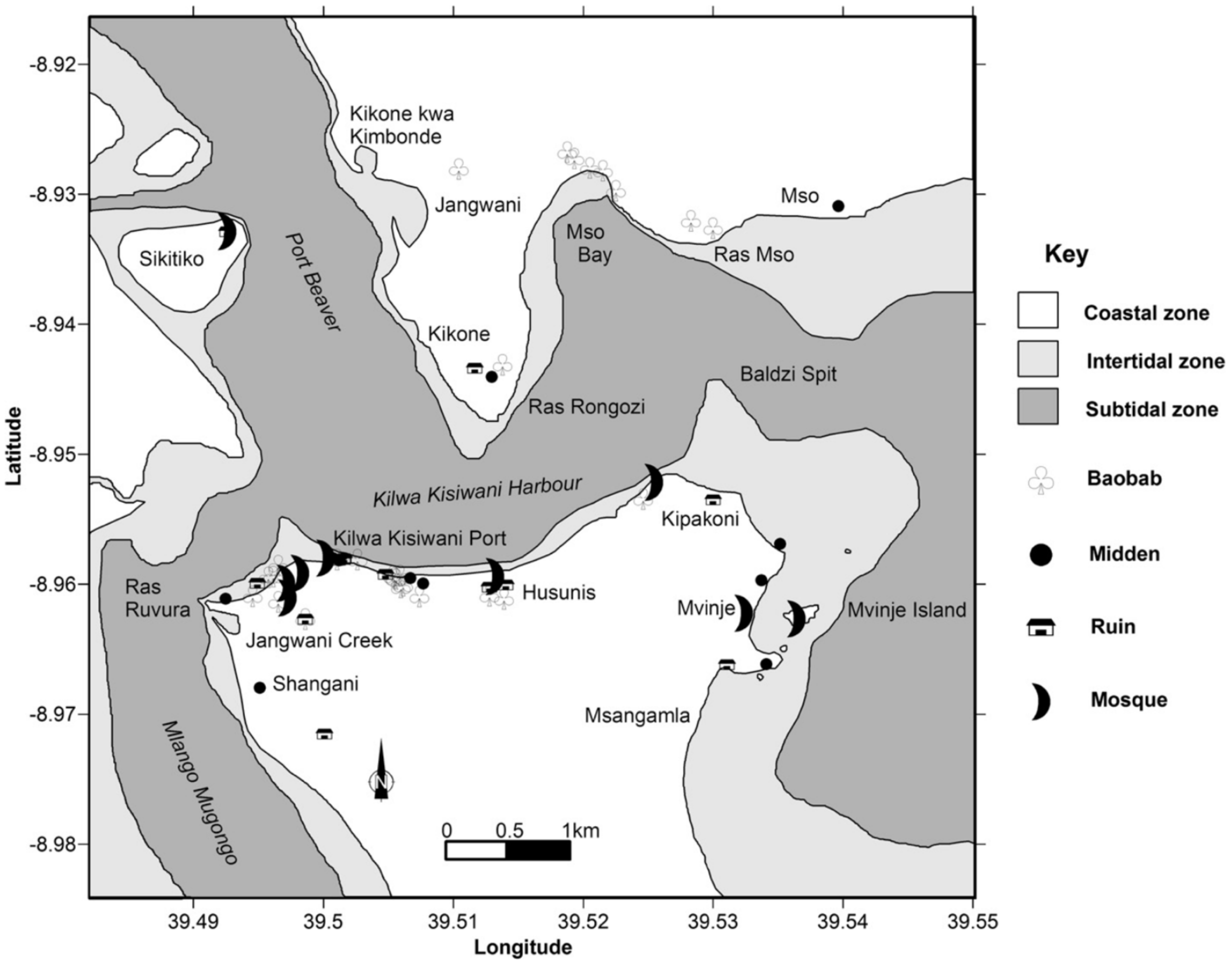


Figure 4: Mso Bay location in relation to Kilwa Kisiwani (Pollard 2008b)

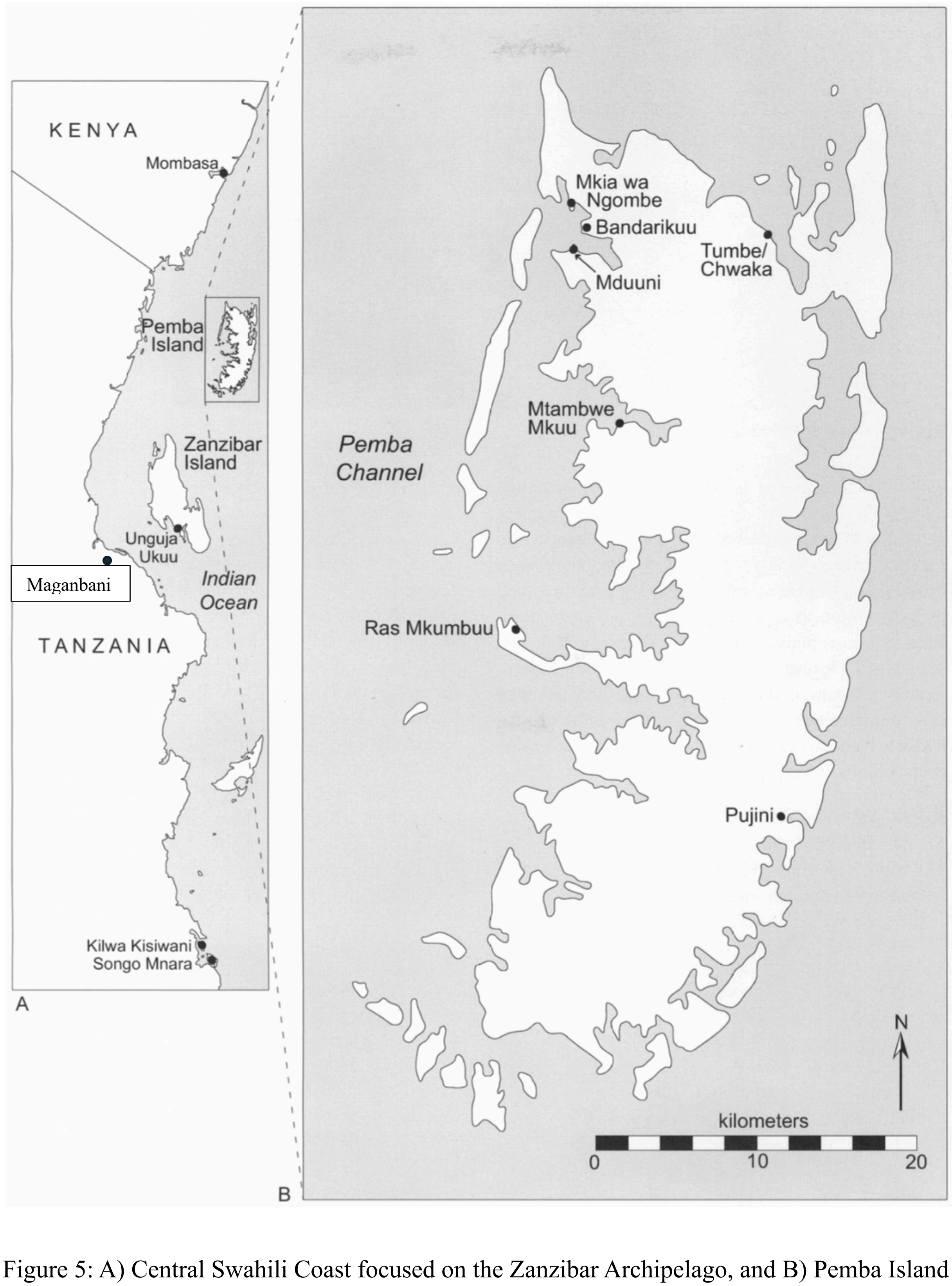


Figure 5: A) Central Swahili Coast focused on the Zanzibar Archipelago, and B) Pemba Island

(Fleisher 2010)

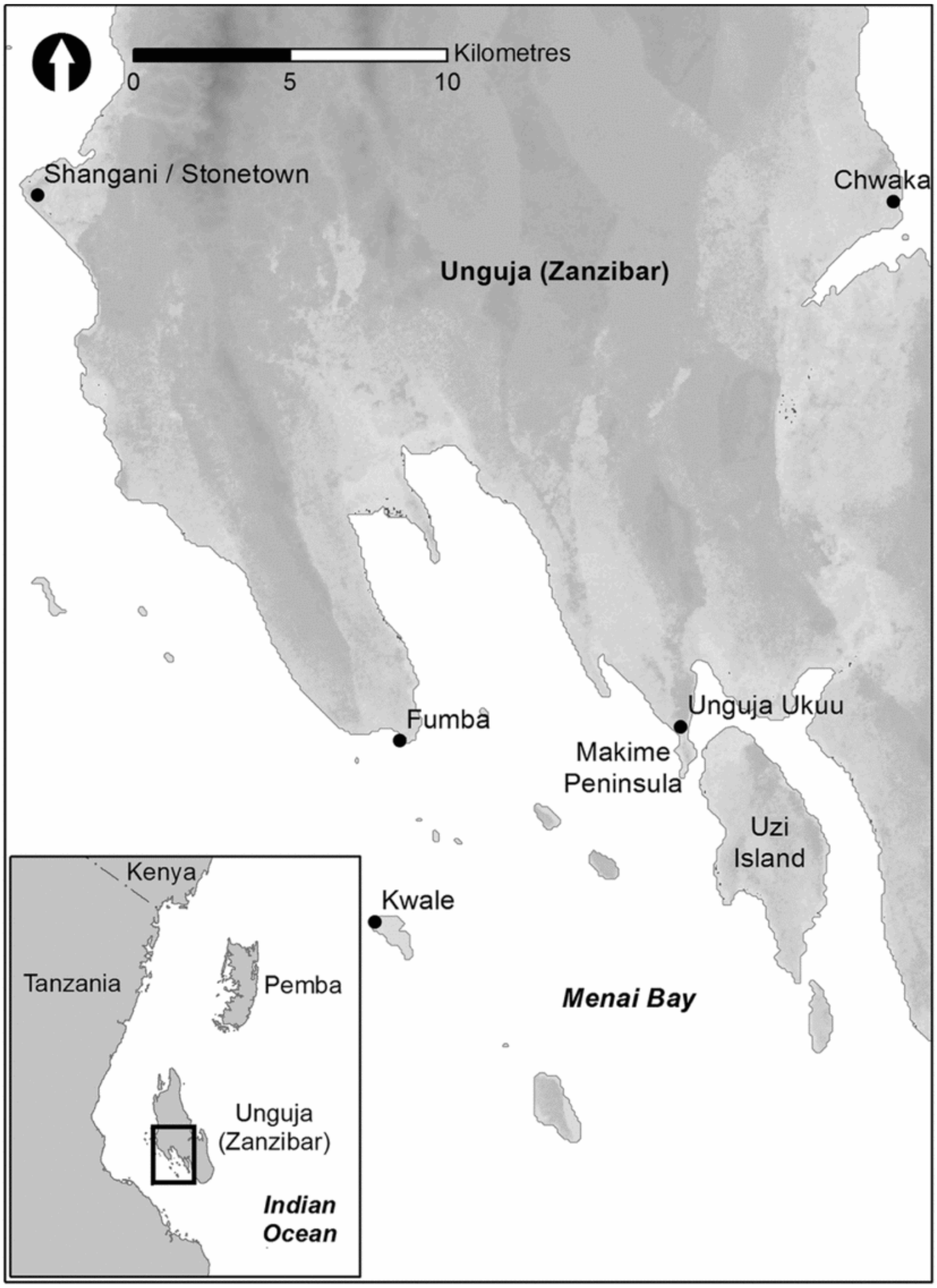


Figure 6: The Zanzibar Archipelago and Unguja Ukuu (Fitton & Wynne-Jones 2017)

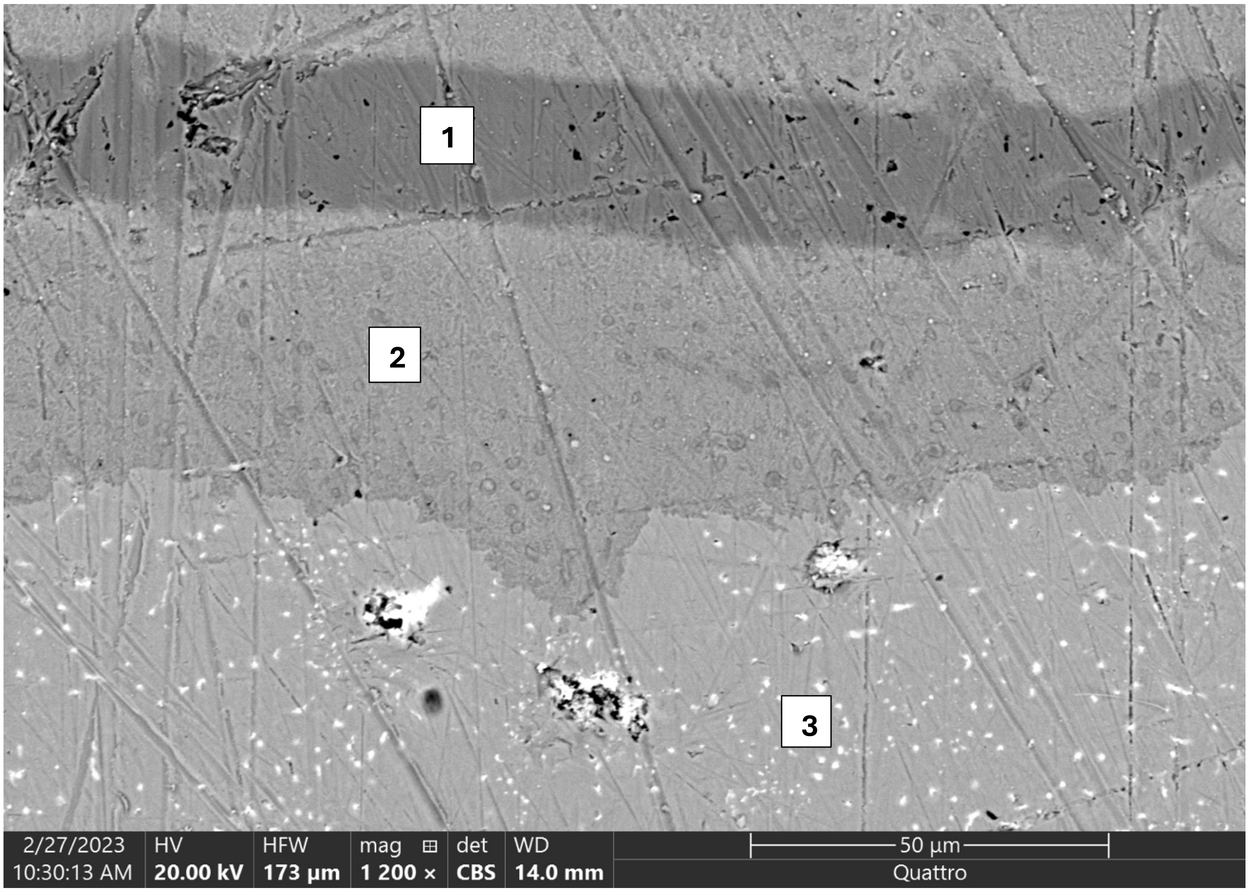


Figure 7: SM2 microstructure under the SEM electron backscatter detector at 1200x magnification, showing three phases: 1) Copper-rich, 2) Tin-rich, and 3) Bronze alloy composition of ~68% Cu, 28% Sn, 2% Zn, and 1.5% Pb. White dots are lead-rich regions.

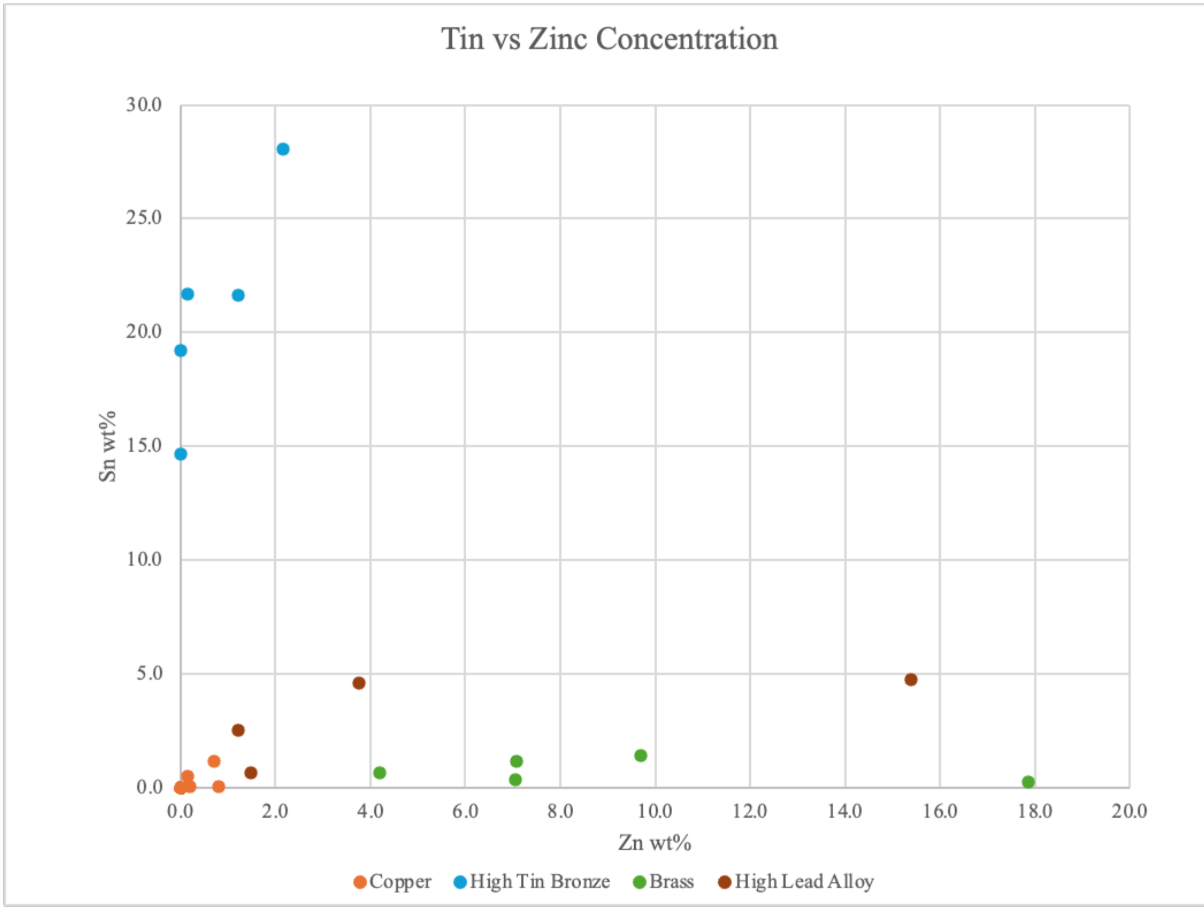


Figure 8: Tin concentrations plotted against zinc concentrations

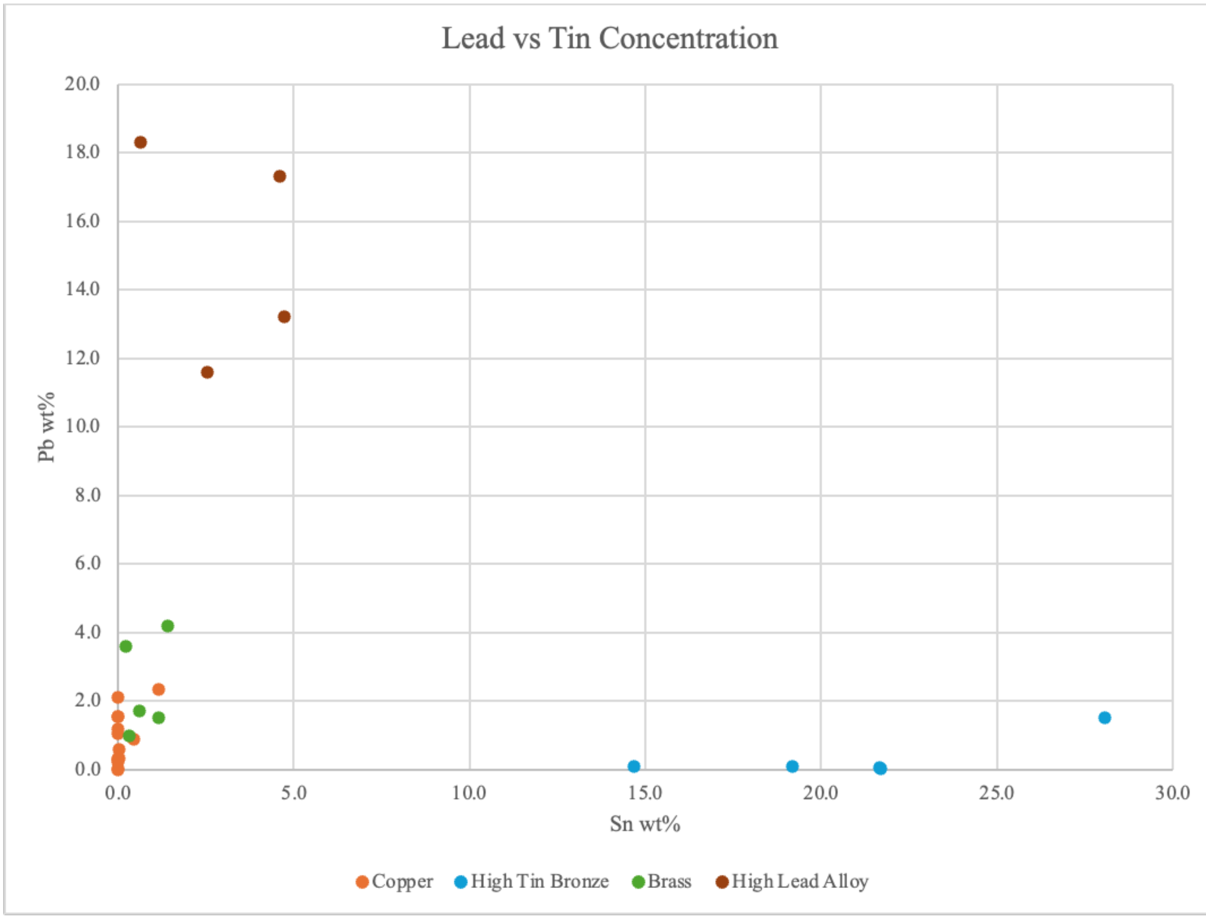


Figure 9: Lead concentrations plotted against tin concentrations

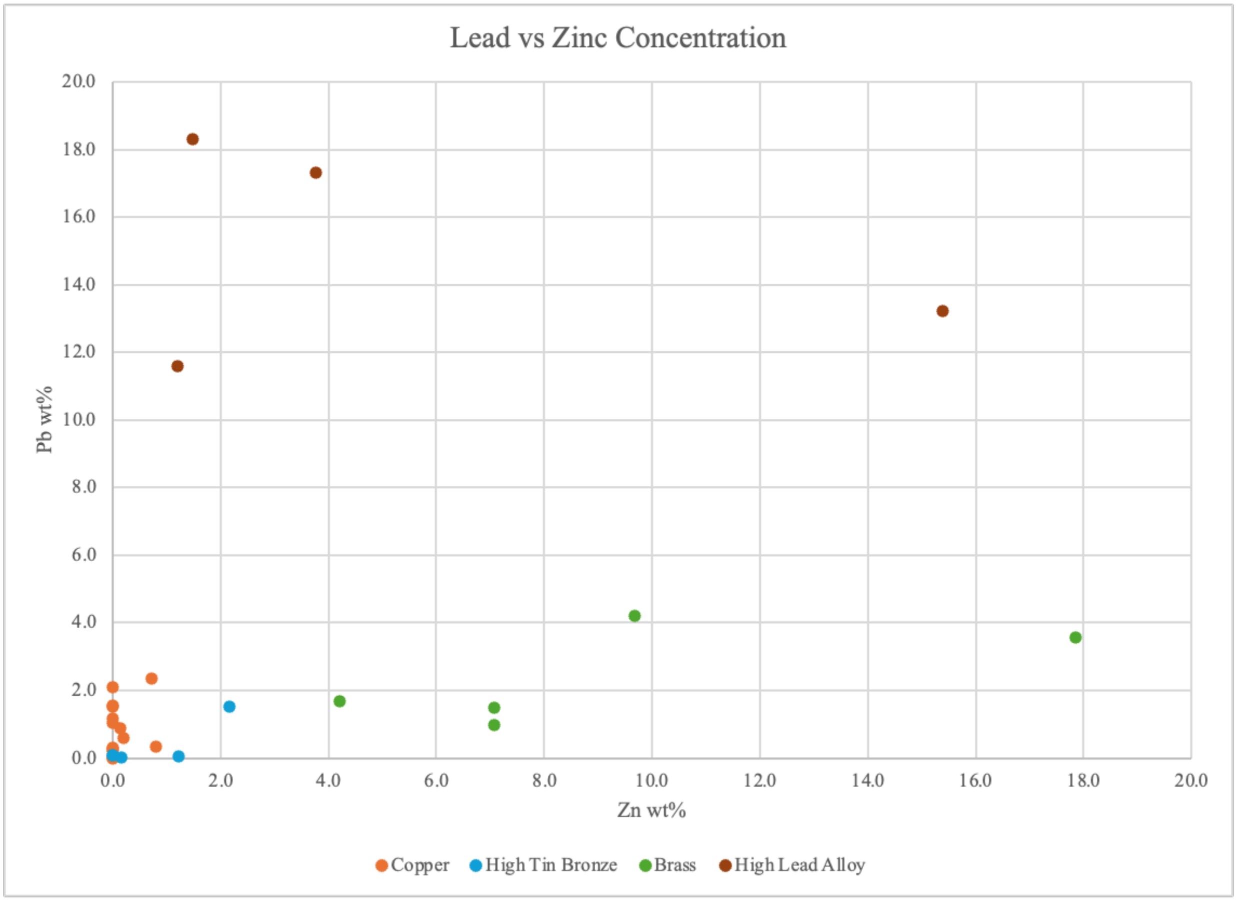


Figure 10: Lead concentrations plotted against zinc concentrations

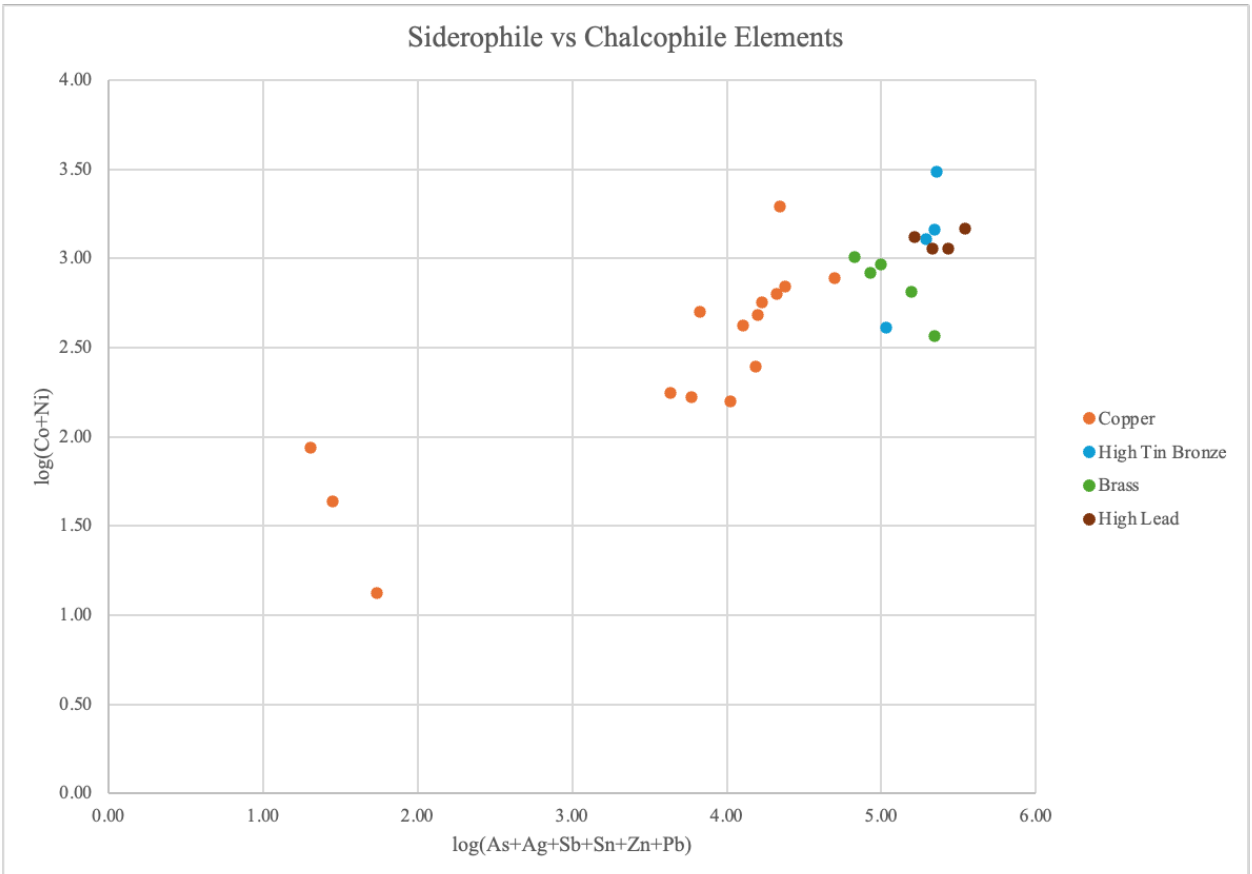


Figure 11: Siderophile vs. Chalcophile elements

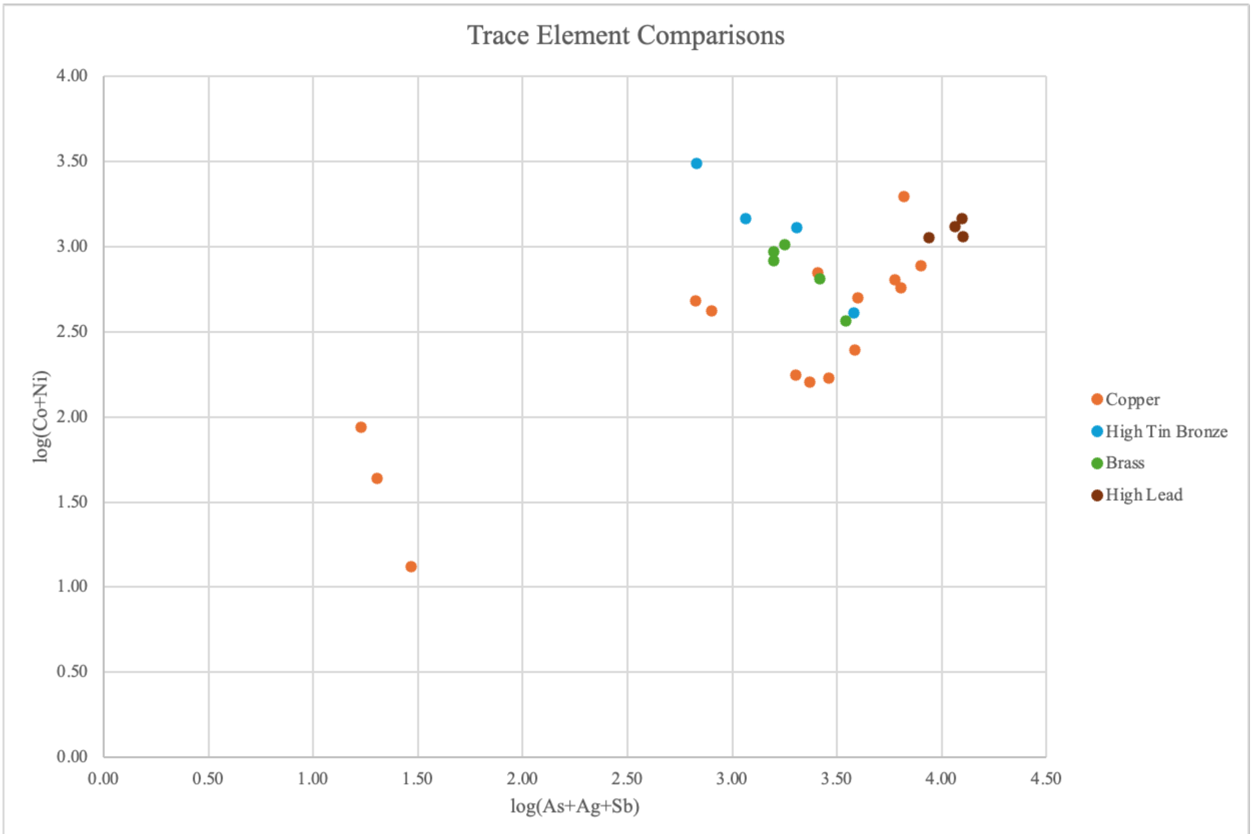


Figure 12: Siderophile vs. Chalcophile (minor & trace elements only)

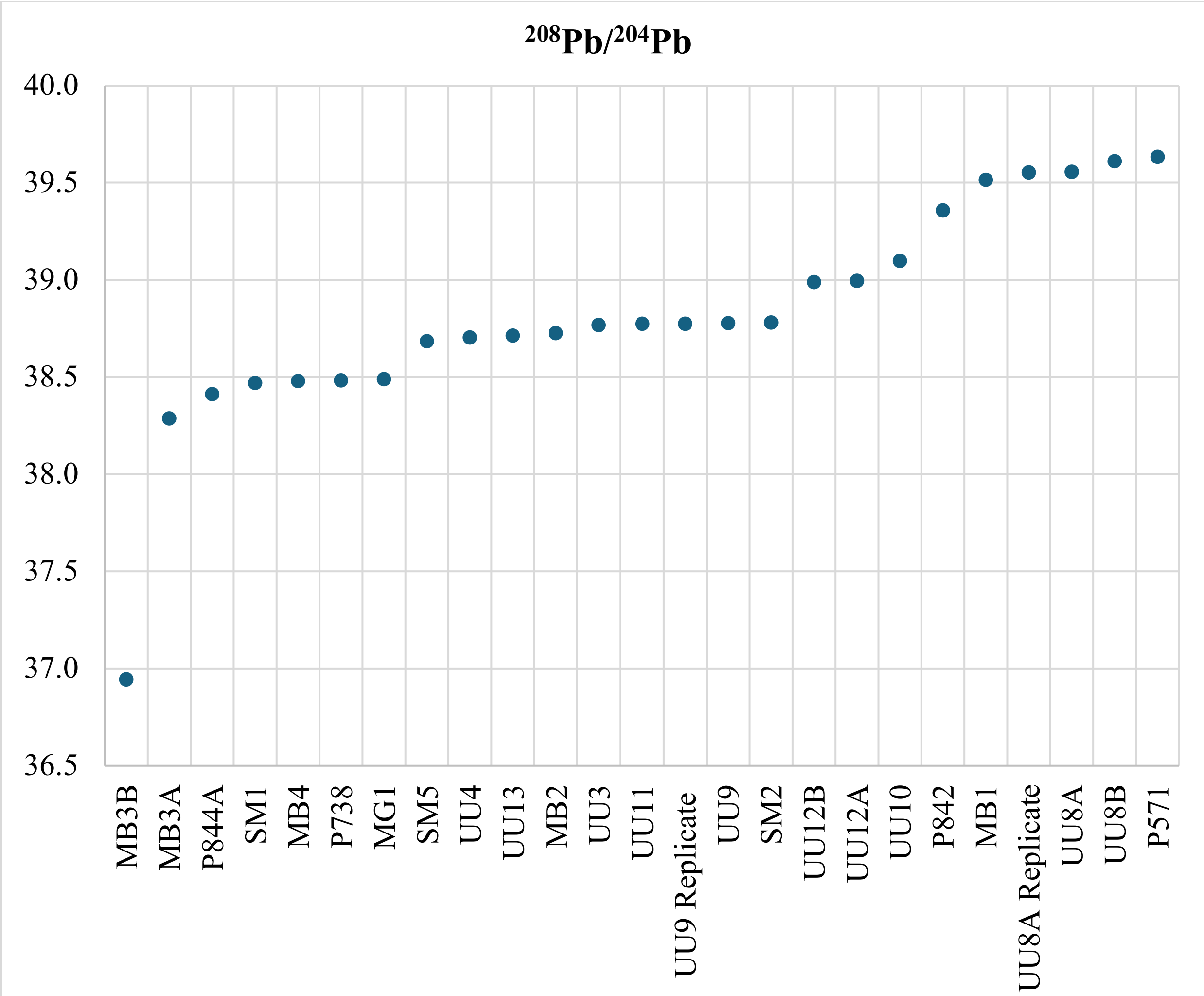


Figure 13: Plot of $^{208}Pb/^{204}Pb$ ratios for the 25 analyses produced in this research. NOTE: The 2se error is individually plotted on each data point, but the error margin is smaller than the size of the symbol used to plot the data point.

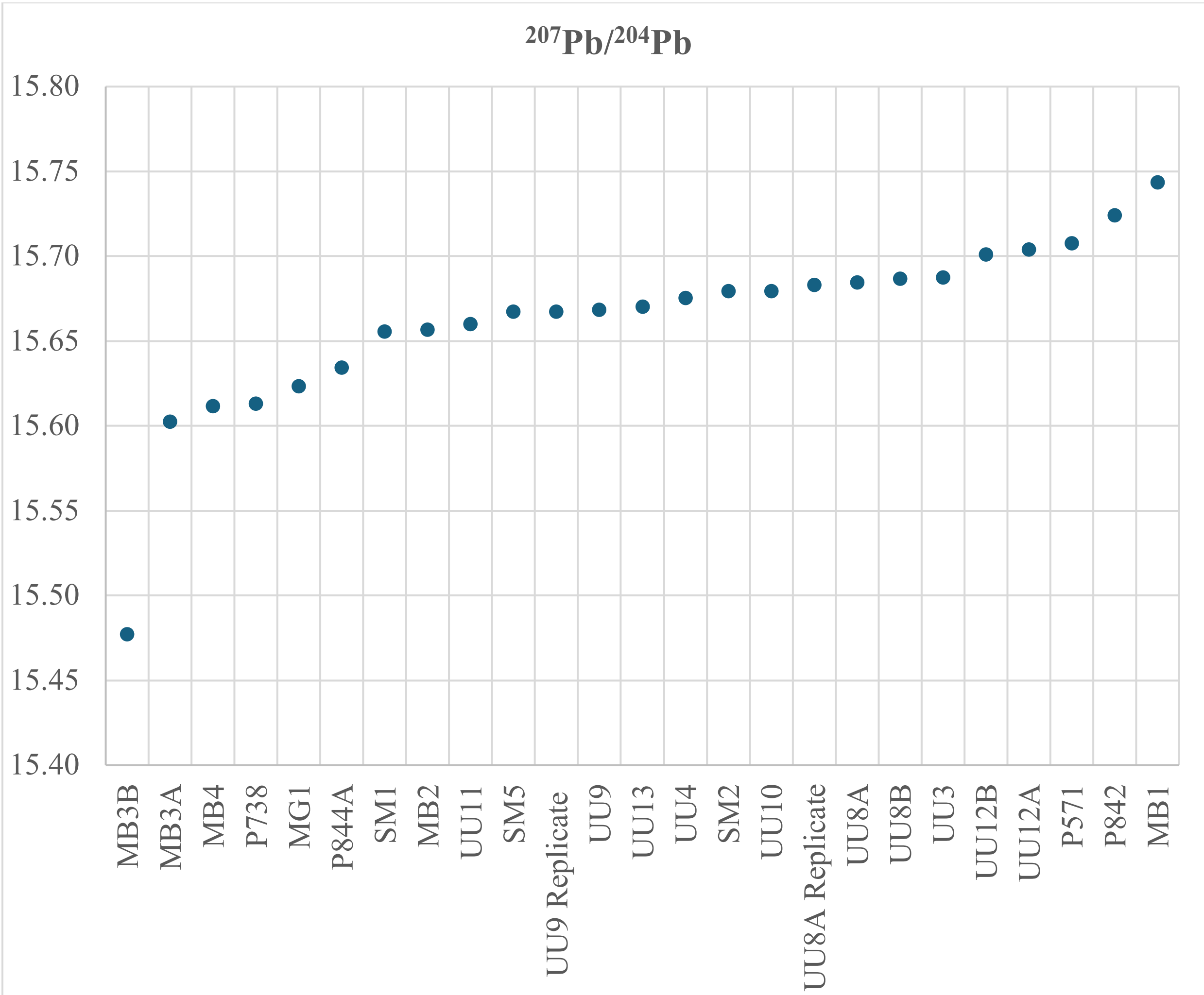


Figure 14: Plot of $^{207}Pb/^{204}Pb$ ratios for the 25 analyses produced in this research. NOTE: The 2se error is individually plotted on each data point, but the error margin is smaller than the size of the symbol used to plot the data point.

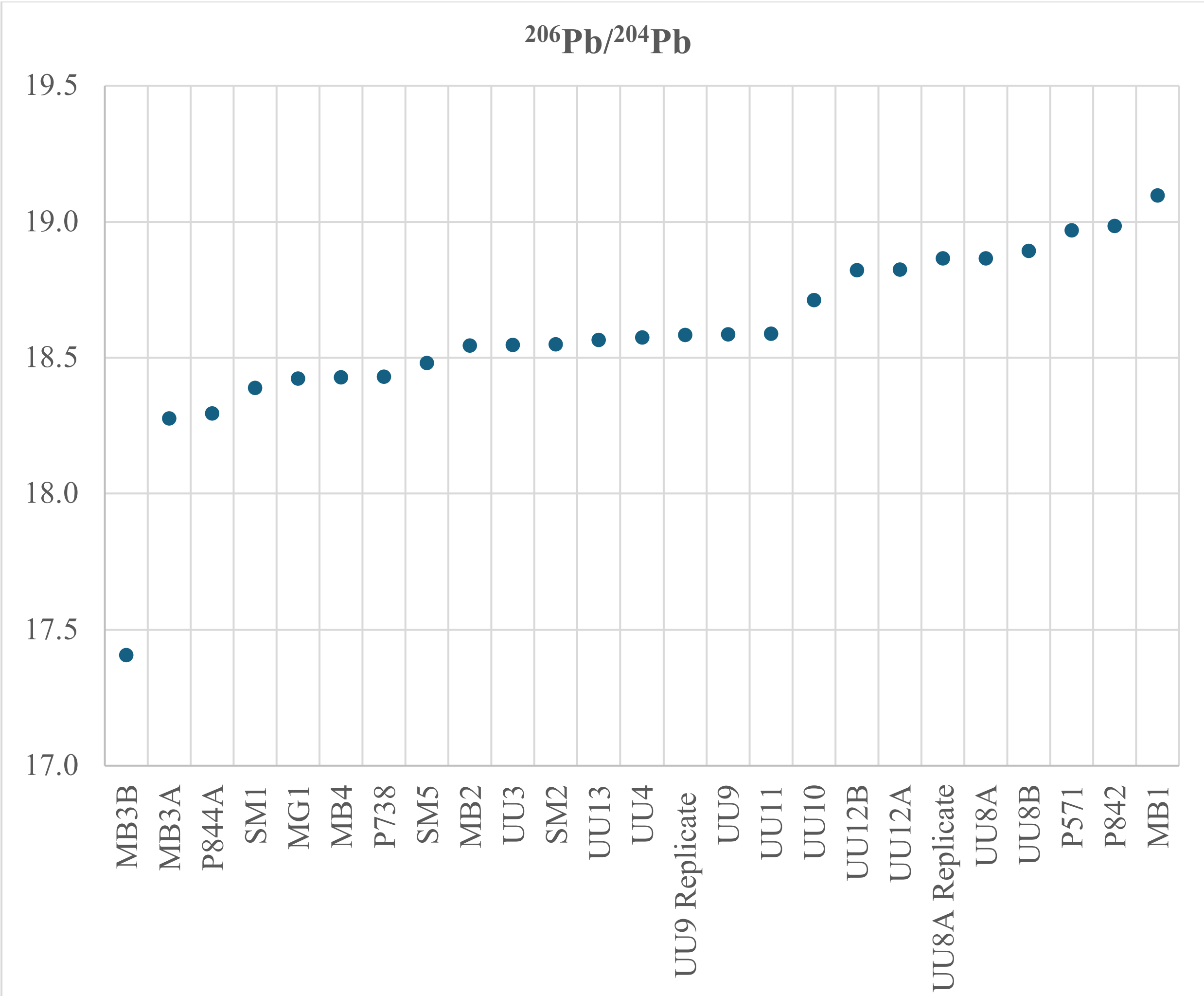


Figure 15. Plot of $^{206}Pb/^{204}Pb$ ratios for the 25 analyses produced in this research. NOTE: The 2se error is individually plotted on each data point, but the error margin is smaller than the size of the symbol used to plot the data point.

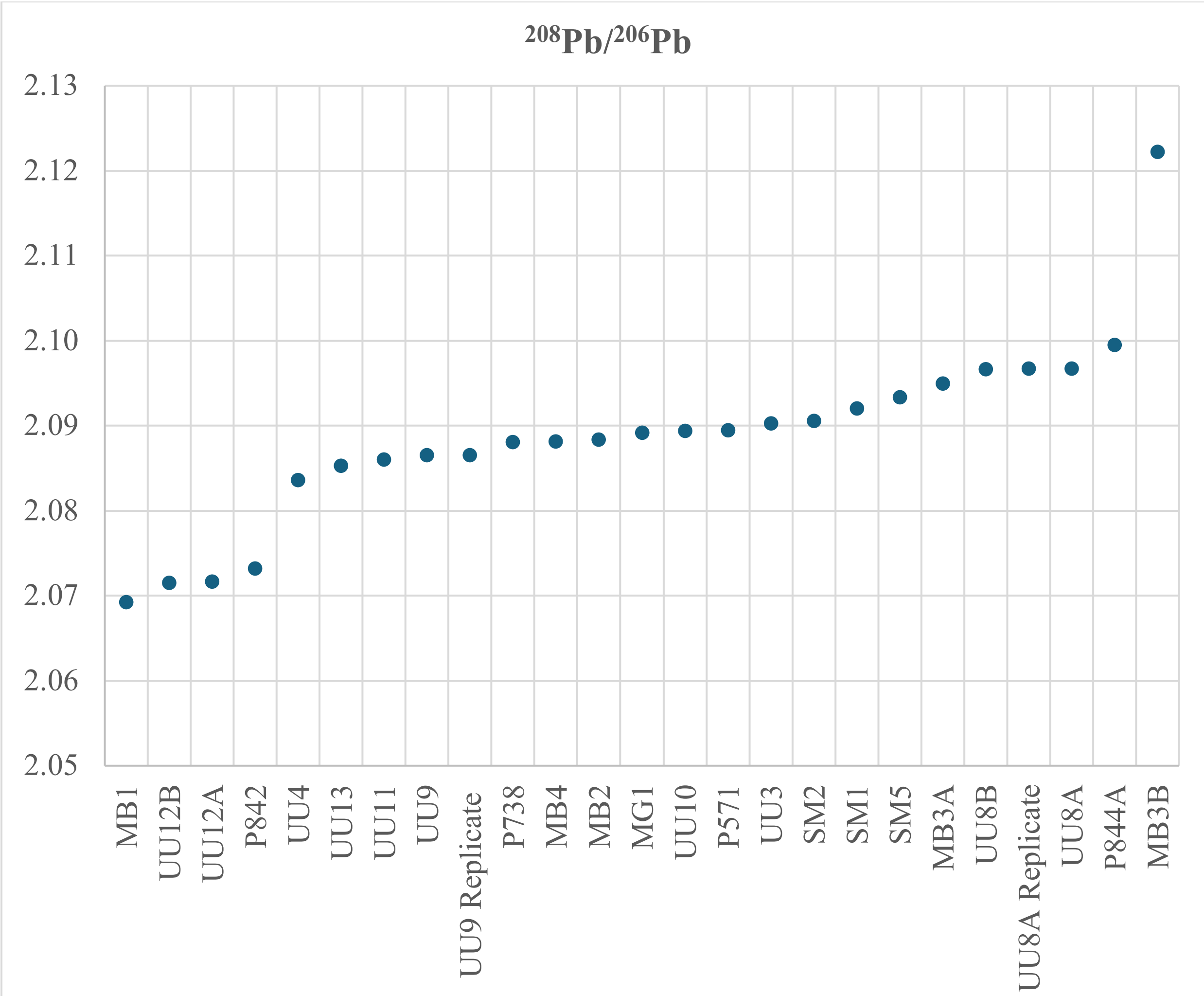


Figure 16: Plot of $^{208}Pb/^{206}Pb$ ratios for the 25 analyses produced in this research. NOTE: The 2se error is individually plotted on each data point, but the error margin is smaller than the size of the symbol used to plot the data point.

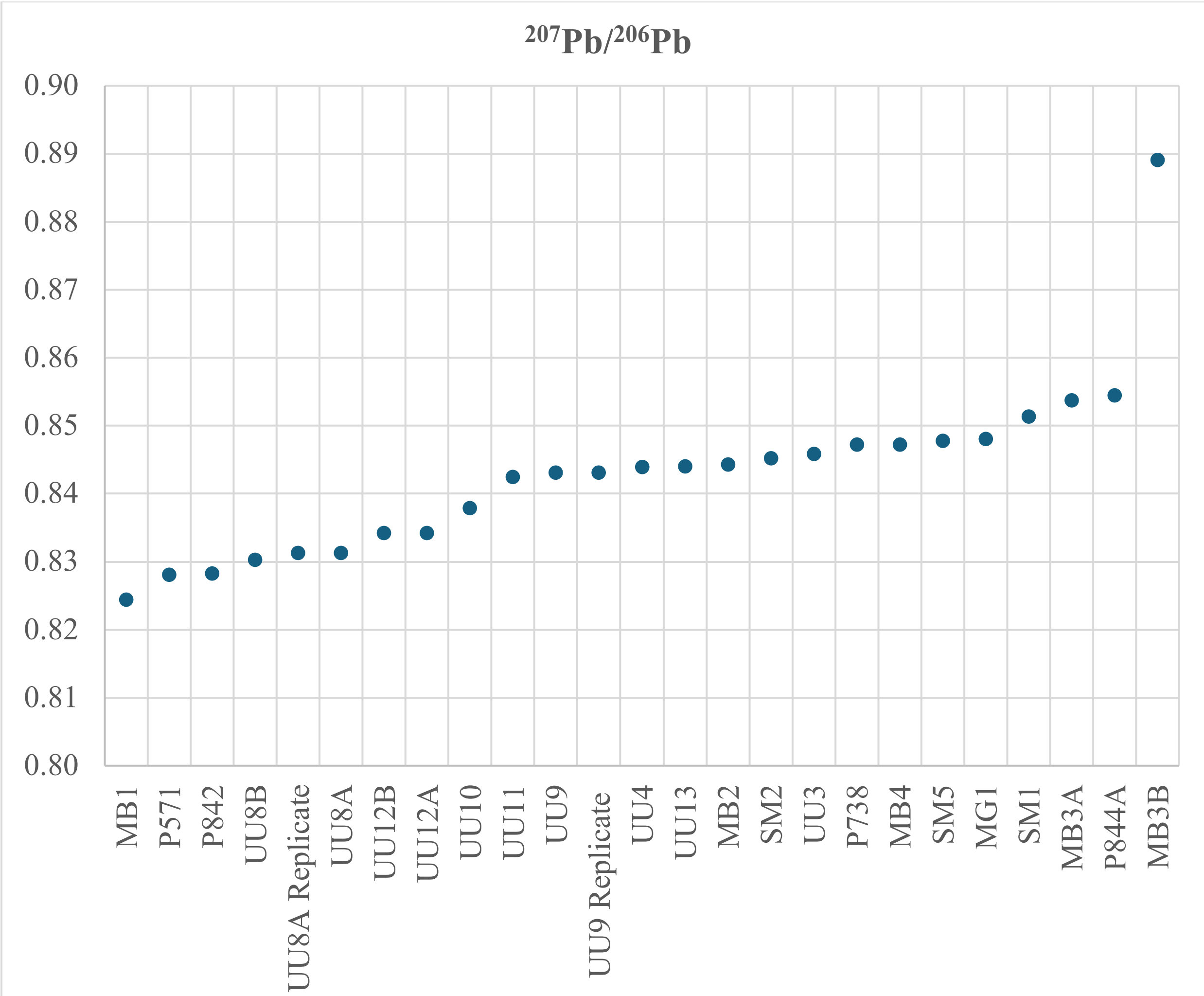


Figure 17: Plot of $^{207}Pb/^{206}Pb$ ratios for the 25 analyses produced in this research. NOTE: The 2se error is individually plotted on each data point, but the error margin is smaller than the size of the symbol used to plot the data point.

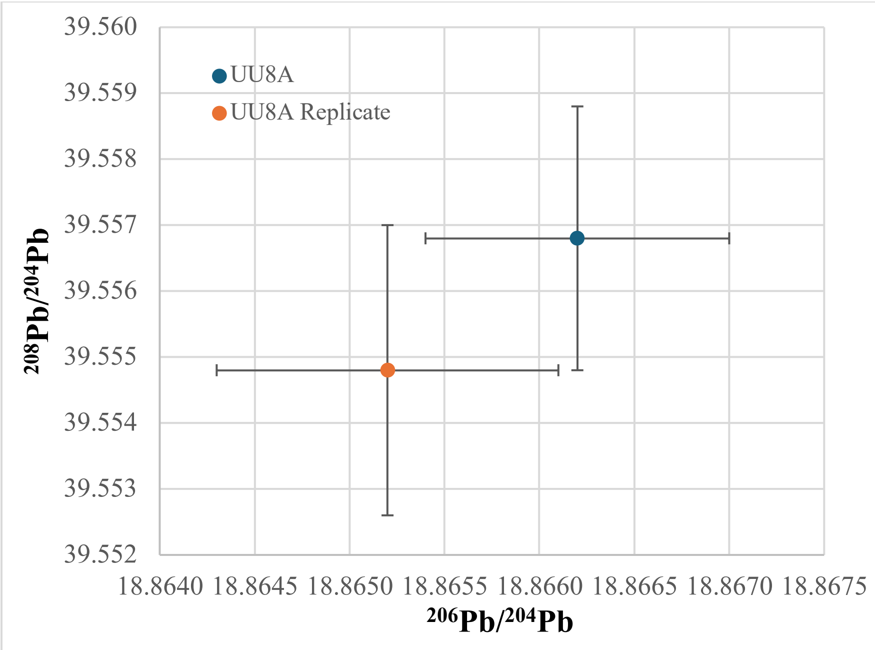


Figure 18: Bivariate plot of $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ ratios for sample UU8A and the replicate analysis of UU8A. NOTE: The 2se errors for each ratio are plotted for each data point.

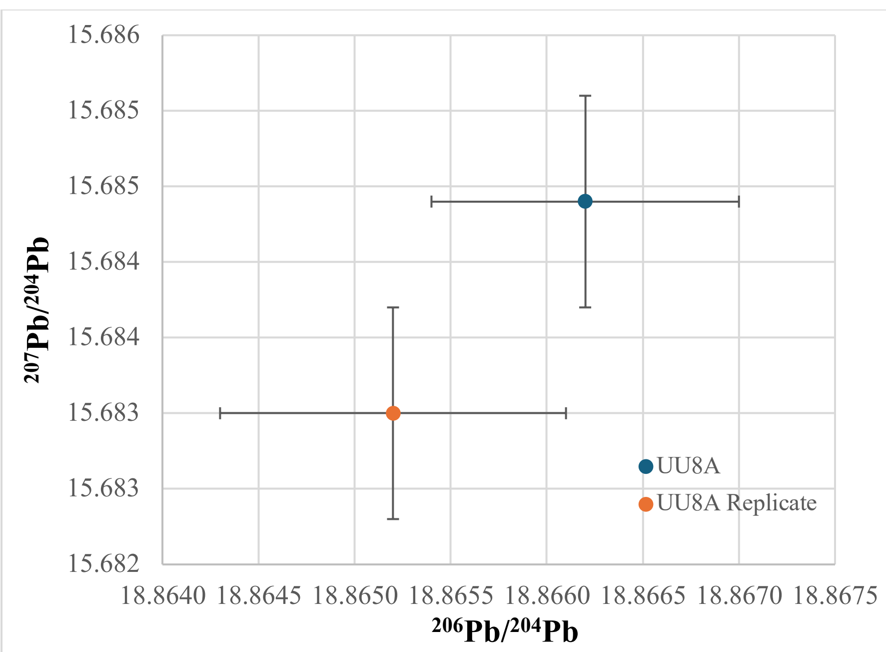


Figure 19: Bivariate plot of $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ ratios for sample UU8A and the replicate analysis of UU8A. NOTE: The 2se errors for each ratio are plotted for each data point.

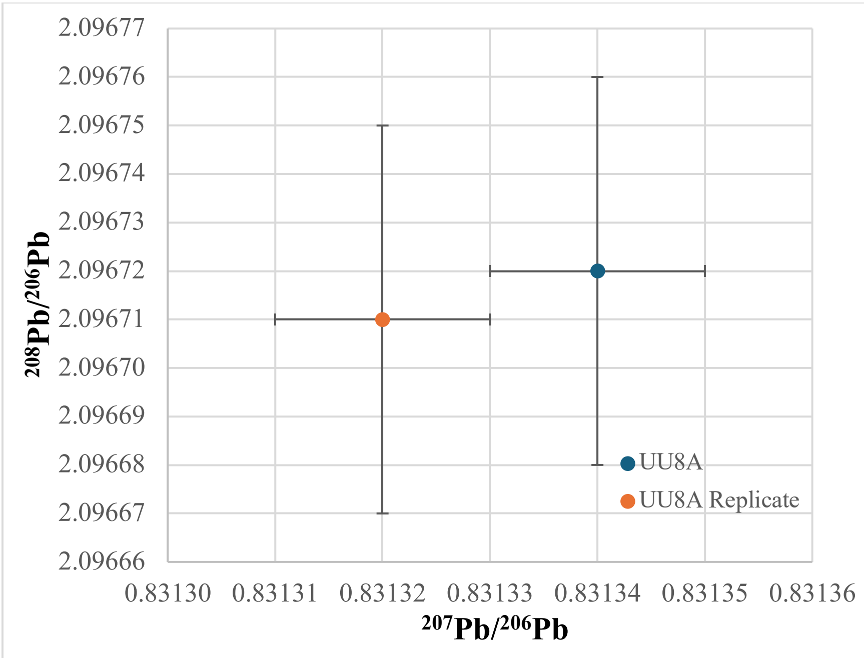


Figure 20: Bivariate plot of $^{208}Pb/^{206}Pb$ vs. $^{207}Pb/^{206}Pb$ ratios for sample UU8A and the replicate analysis of UU8A. NOTE: The 2se errors for each ratio are plotted for each data point.

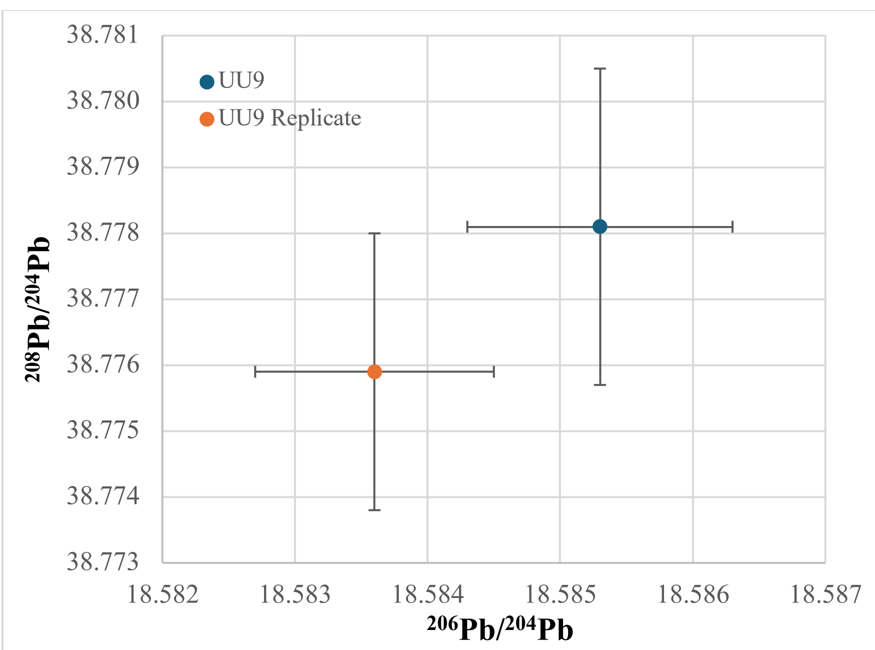


Figure 21: Bivariate plot of $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ ratios for sample UU9 and the replicate analysis of UU9. NOTE: The 2se errors for each ratio are plotted for each data point.

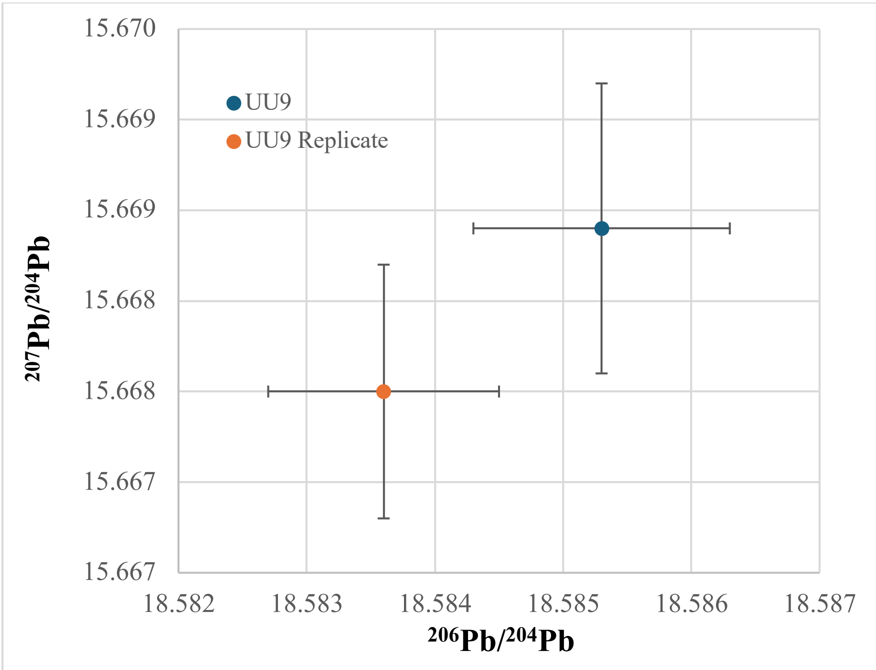


Figure 22: Bivariate plot of $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ ratios for sample UU9 and the replicate analysis of UU9. NOTE: The 2se errors for each ratio are plotted for each data point.

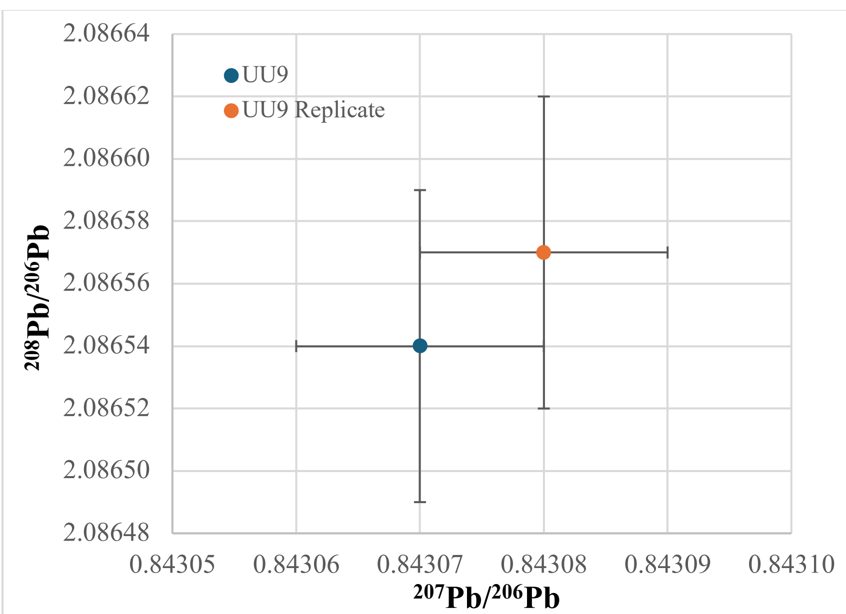


Figure 23: Bivariate plot of $^{207}Pb/^{206}Pb$ vs. $^{208}Pb/^{206}Pb$ ratios for sample UU9 and the replicate analysis of UU9. NOTE: The 2se errors for each ratio are plotted for each data point.

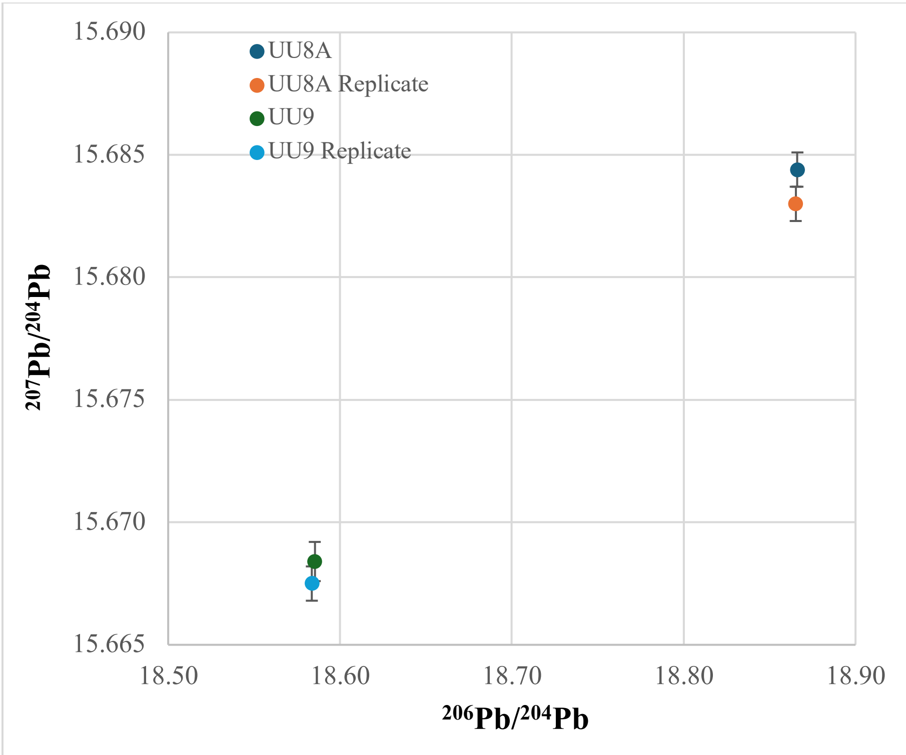


Figure 24: Bivariate plot of $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ ratios for samples UU8A and UU9 and their replicate analyses. NOTE: The 2se errors for each ratio are plotted for each data point.

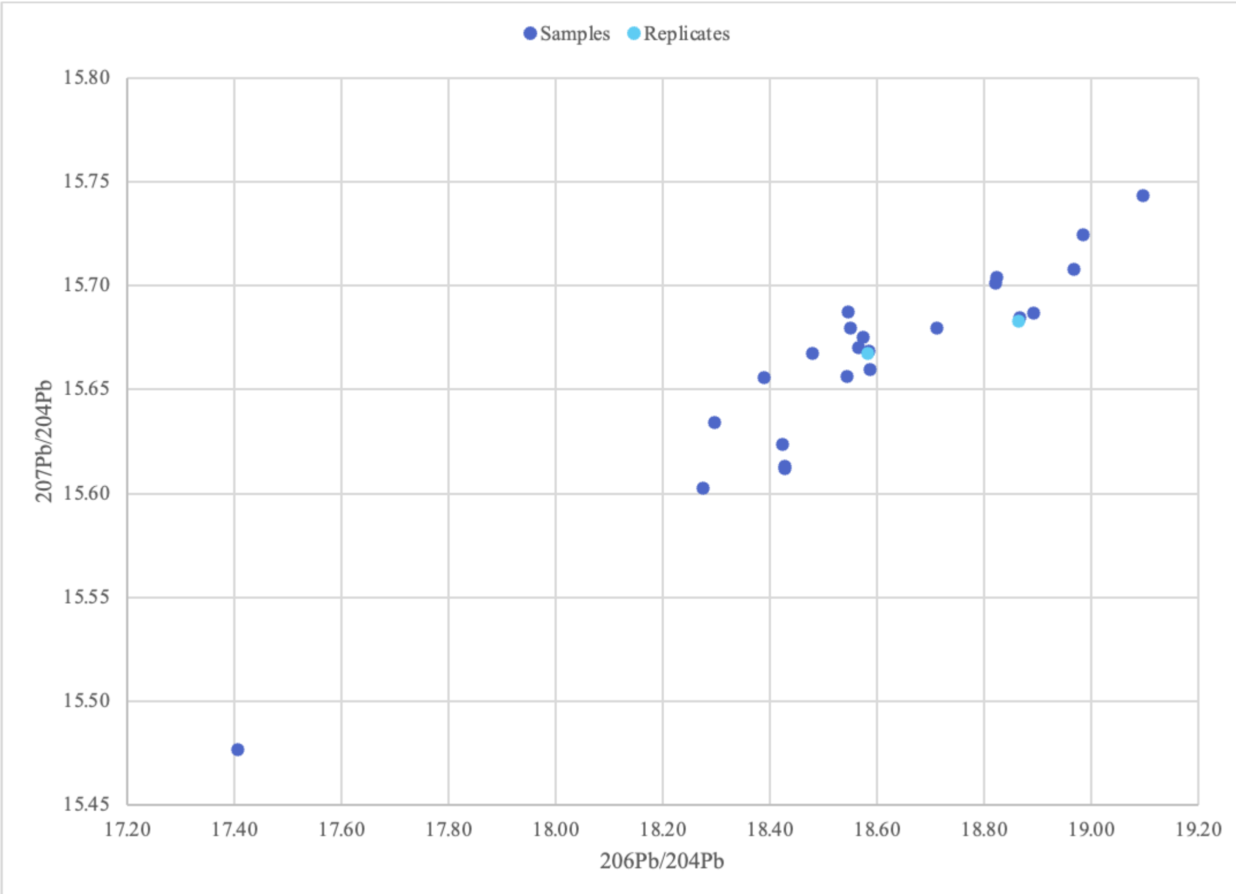


Figure 25: Bivariate plot of $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ for samples and replicates

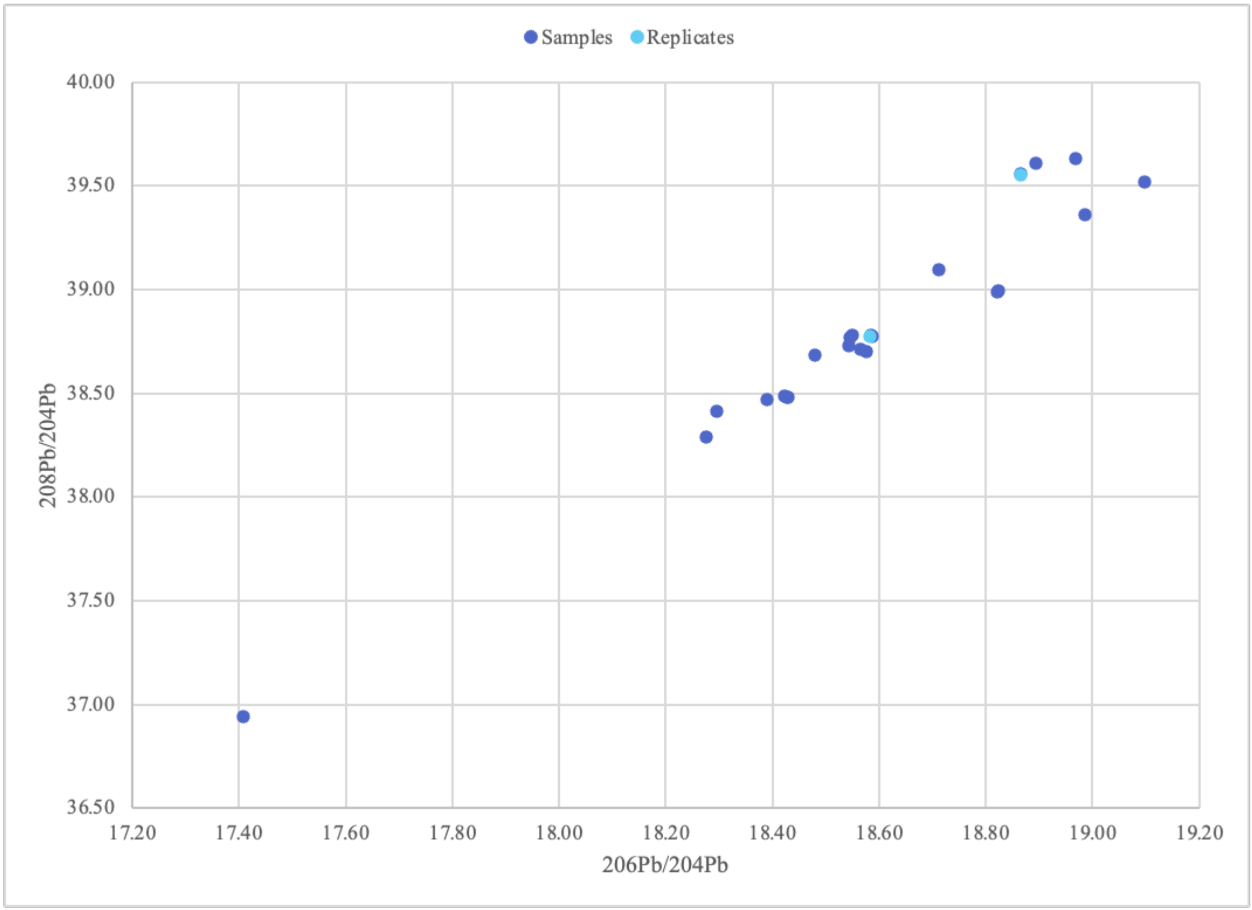


Figure 26: Bivariate plot of $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ for samples and replicates

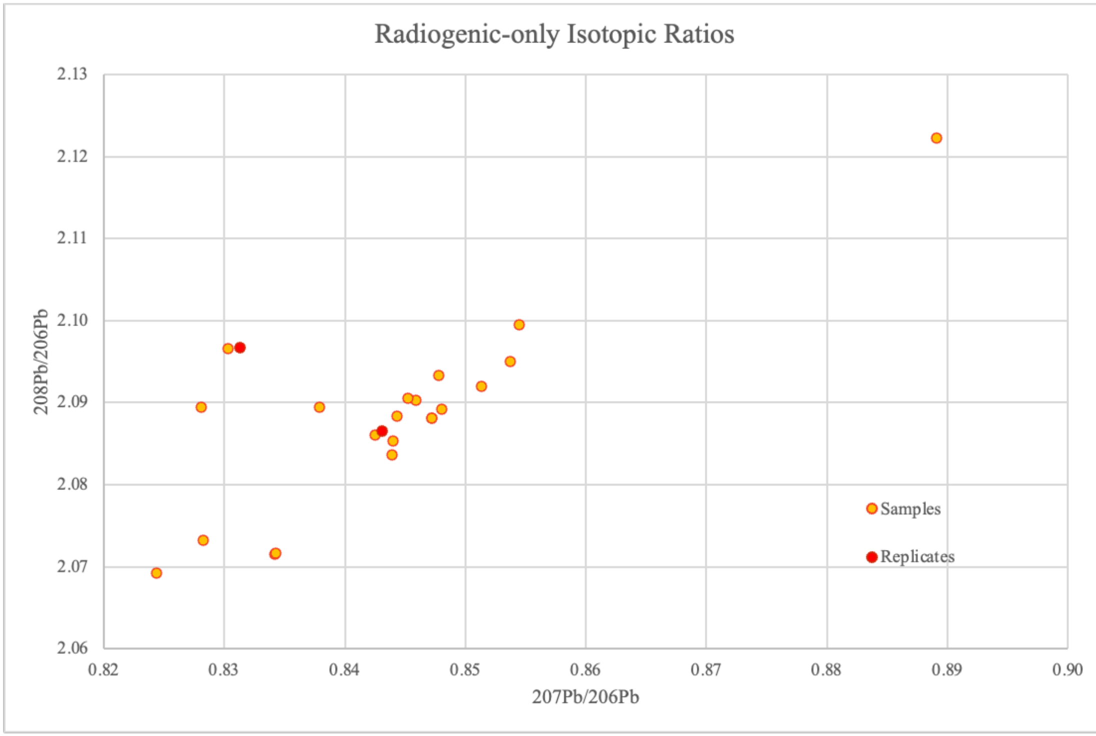


Figure 27: Bivariate plot of $^{208}Pb/^{206}Pb$ vs $^{207}Pb/^{206}Pb$ for samples and replicates

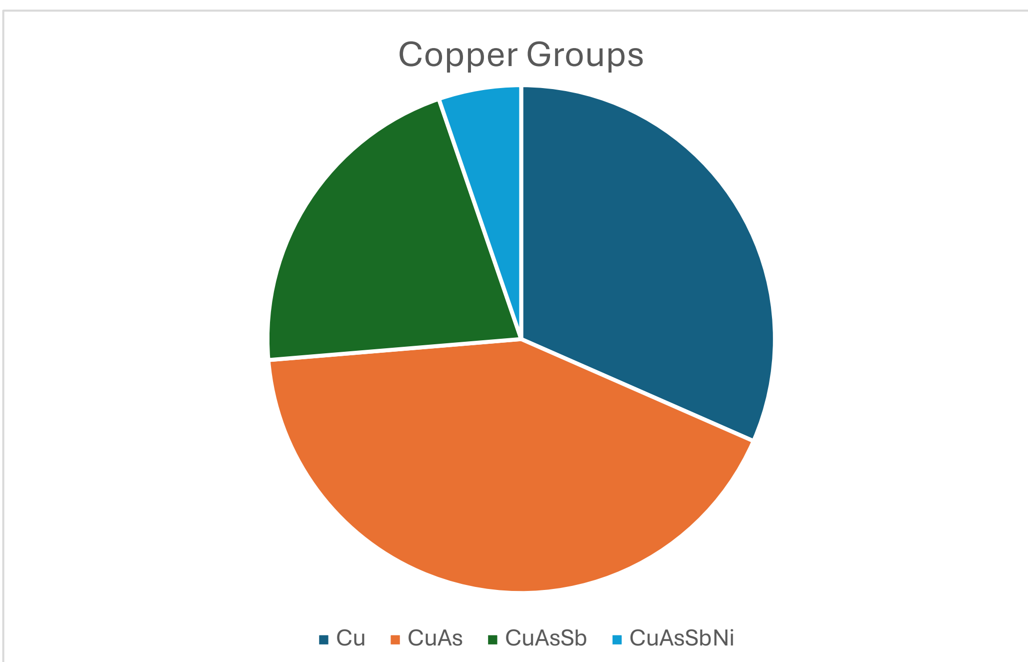


Figure 28: Swahili pure coppers and copper component of bronzes grouped based on As, Sb, Ag, and Ni presence/absence method defined by Pollard 2018.

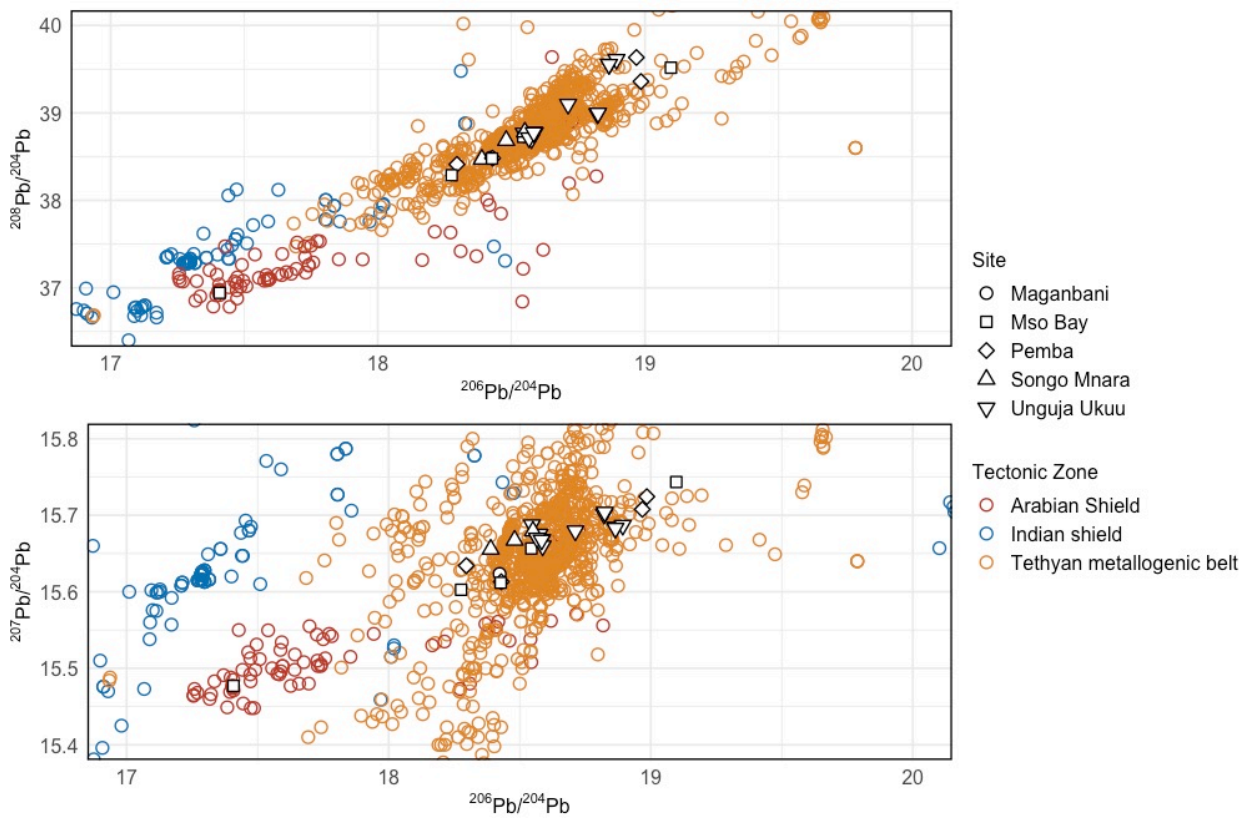


Figure 29: LI ratios from Swahili copper objects from analyzed in this study compared to reference ores in three different tectonic zones around the Indian Ocean.

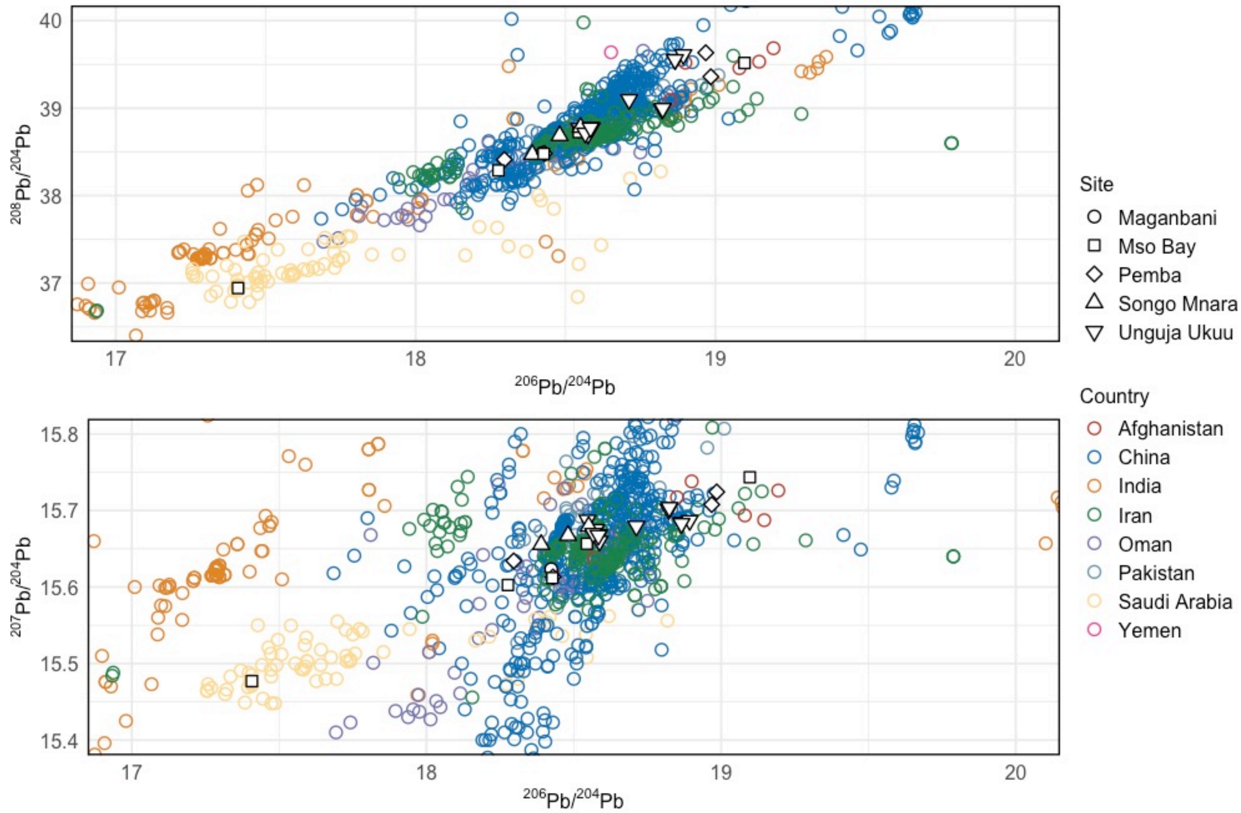
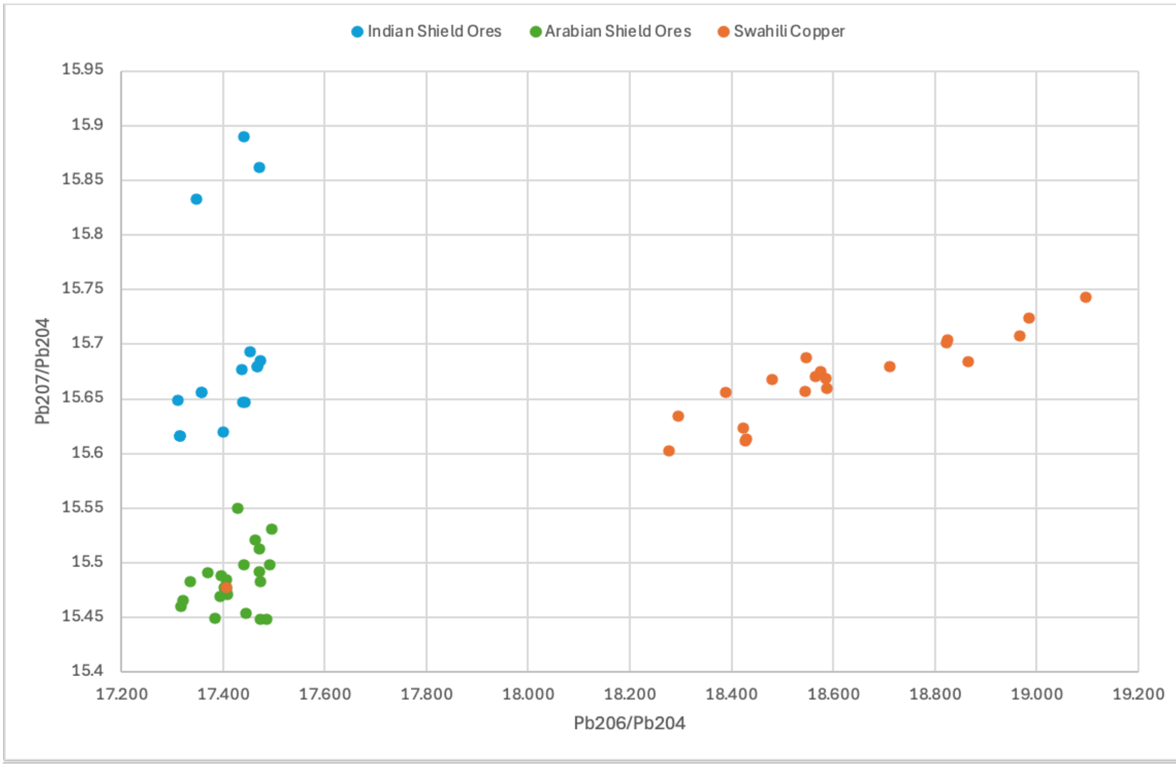


Figure 30: LI rations from Swahili copper objects from analyzed in this study compared to reference ores in different regions around the Indian Ocean.



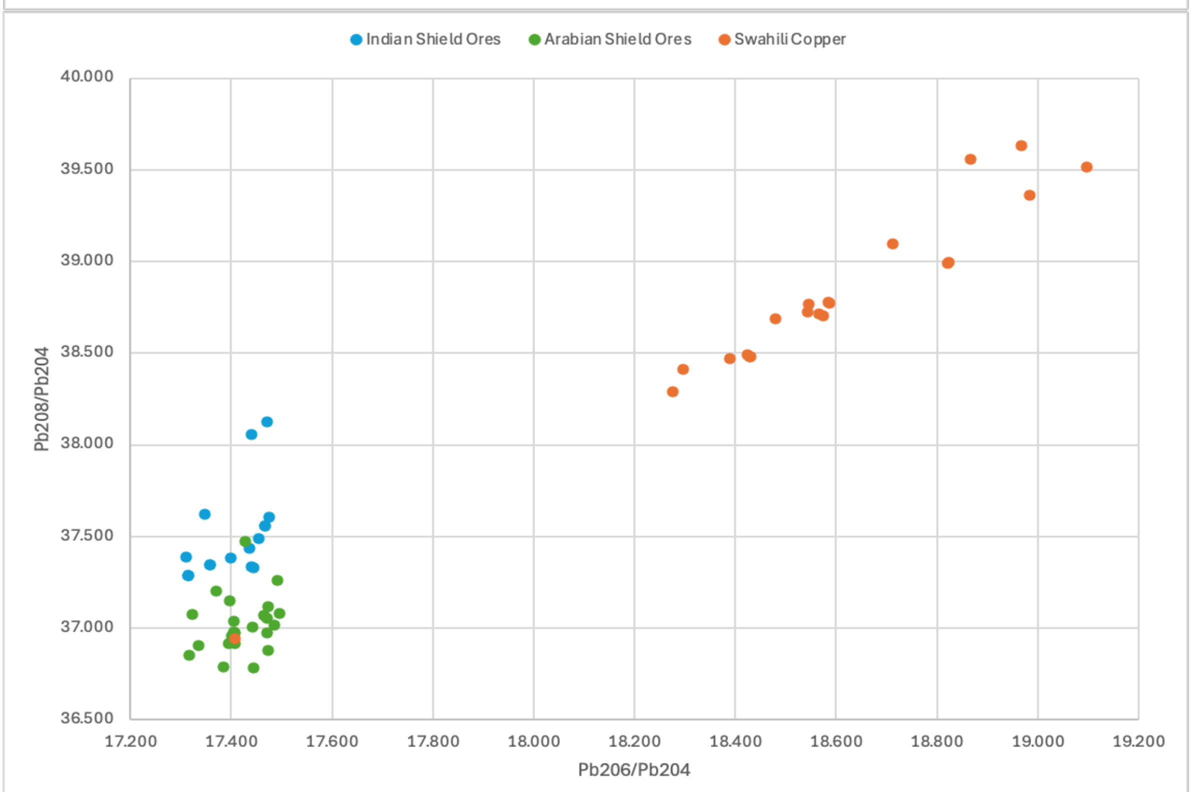


Figure 31: Lead isotope ratios for Swahili Copper artifacts plotted against late Precambrian lead ores (galena) from the Arabian Shield and Indian Shield for comparison.

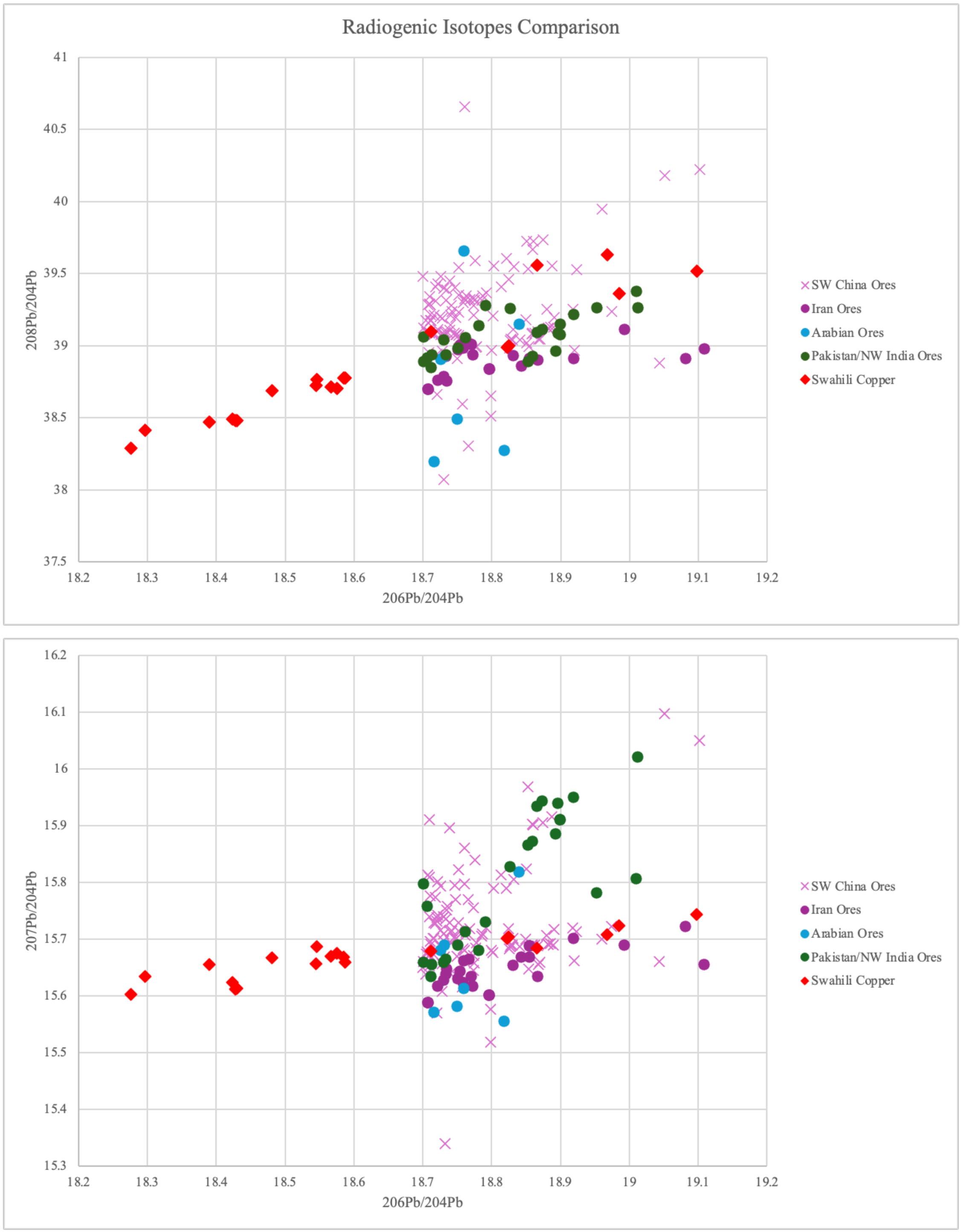


Figure 32A & 32B: Swahili copper lead isotope data compared with other slightly radiogenic ore sources with $^{206}Pb/^{204}Pb$ ratios between 18.7-19.2 around the Indian Ocean sphere, demonstrating considerable overlap between regions

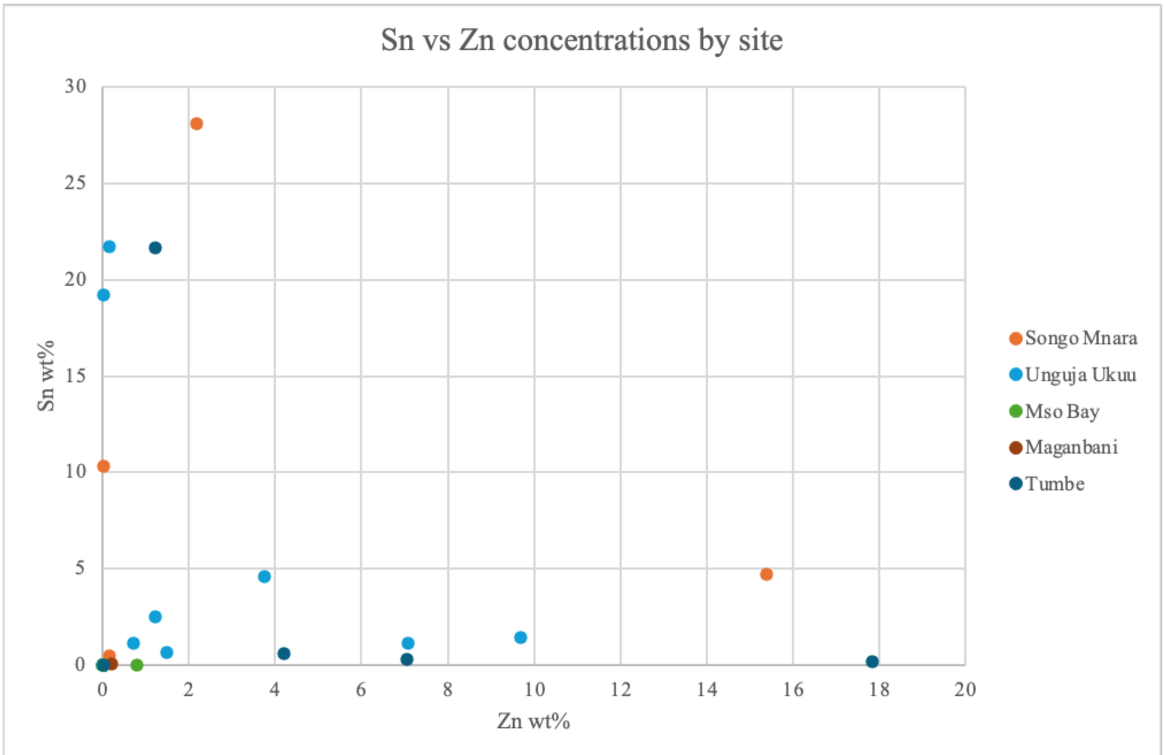


Figure 33A: Distribution of alloy compositions by site: tin vs zinc concentrations

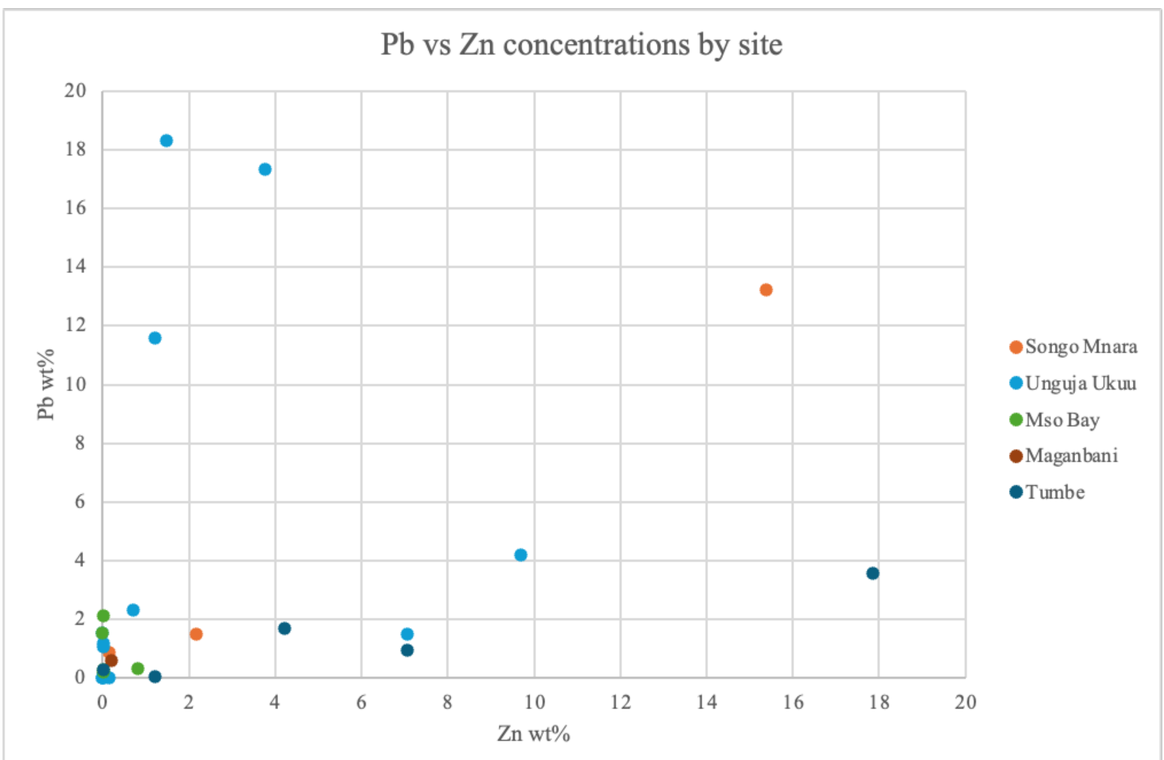


Figure 33B: Distribution of alloy compositions by site: lead vs zinc concentrations

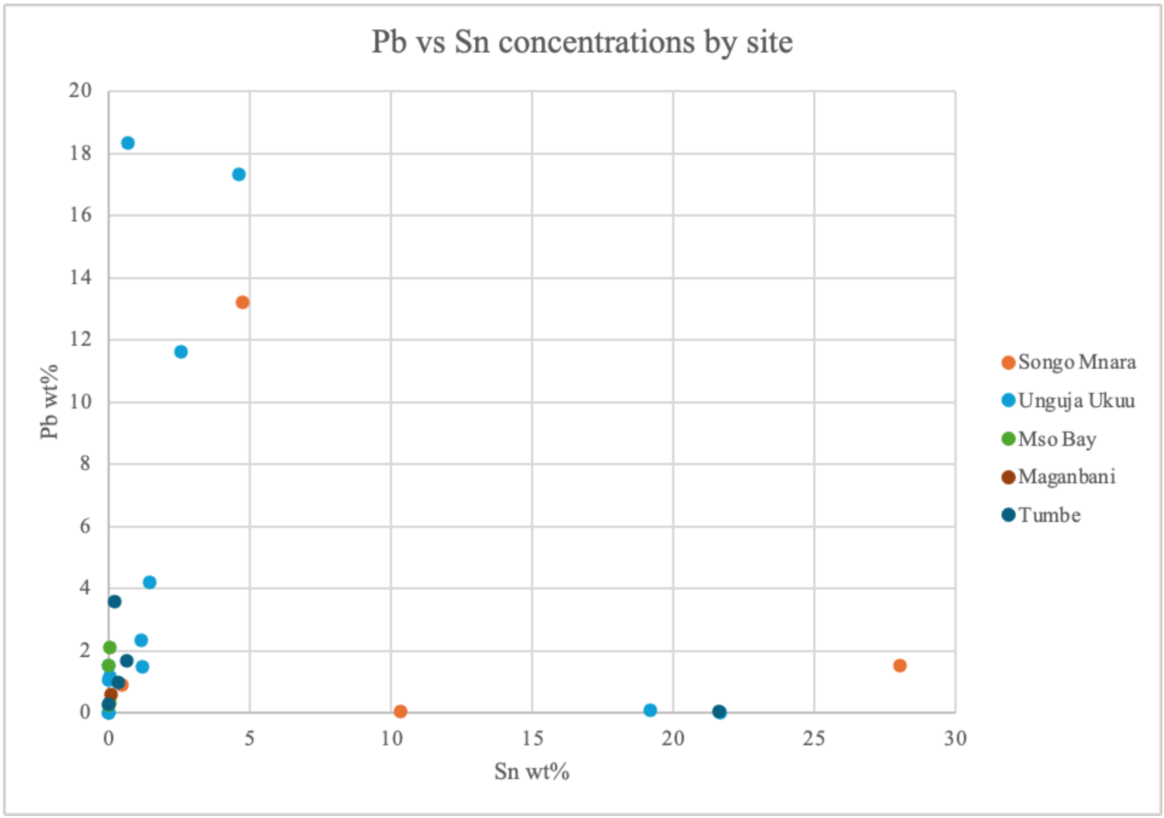
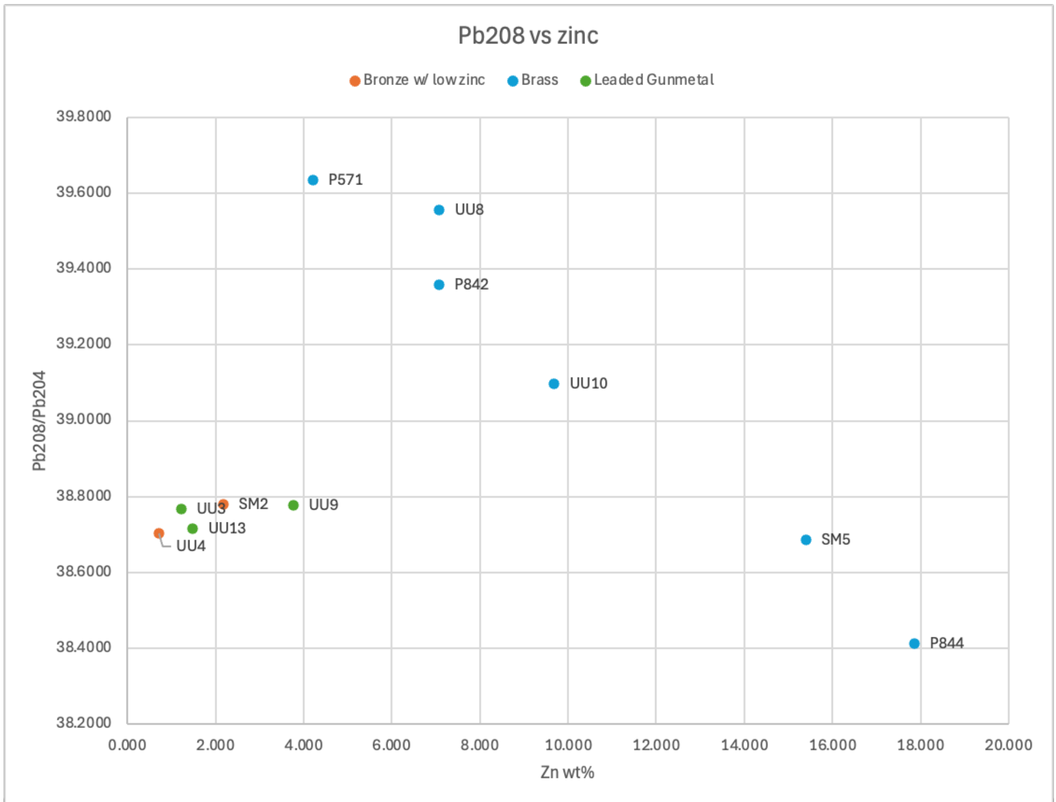


Figure 33C: Distribution of alloy compositions by site: lead vs tin concentrations



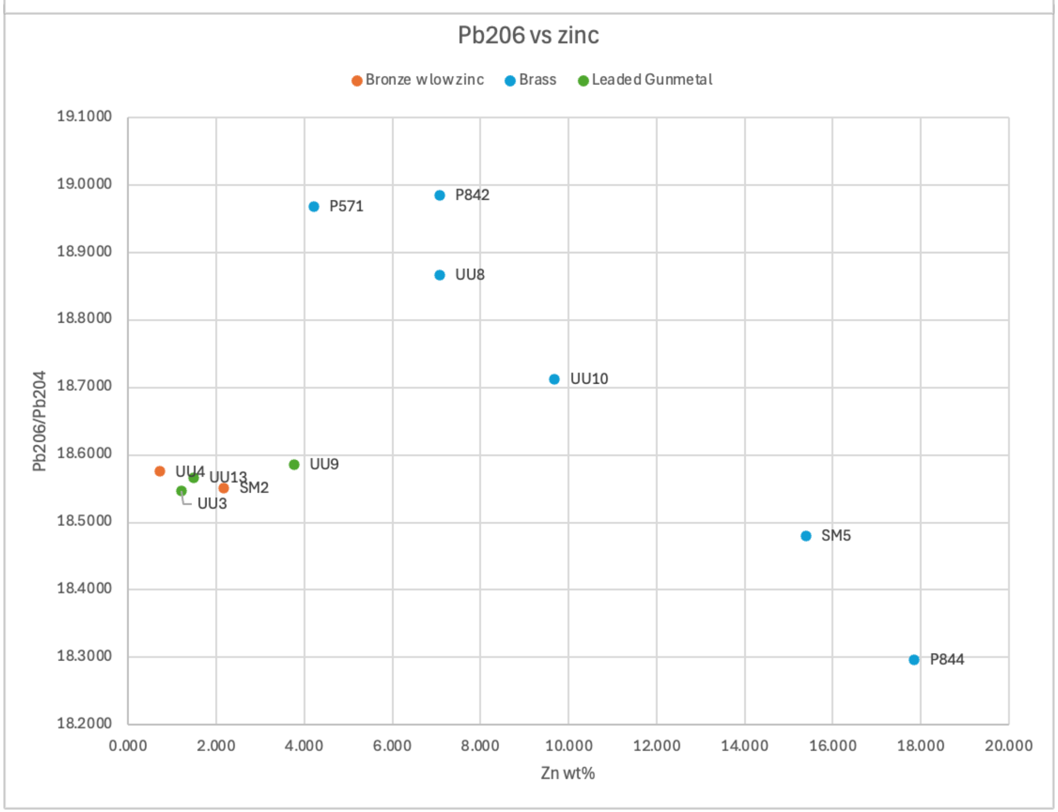


Figure 34: Relationship between lead isotopes and zinc concentrations among the alloys

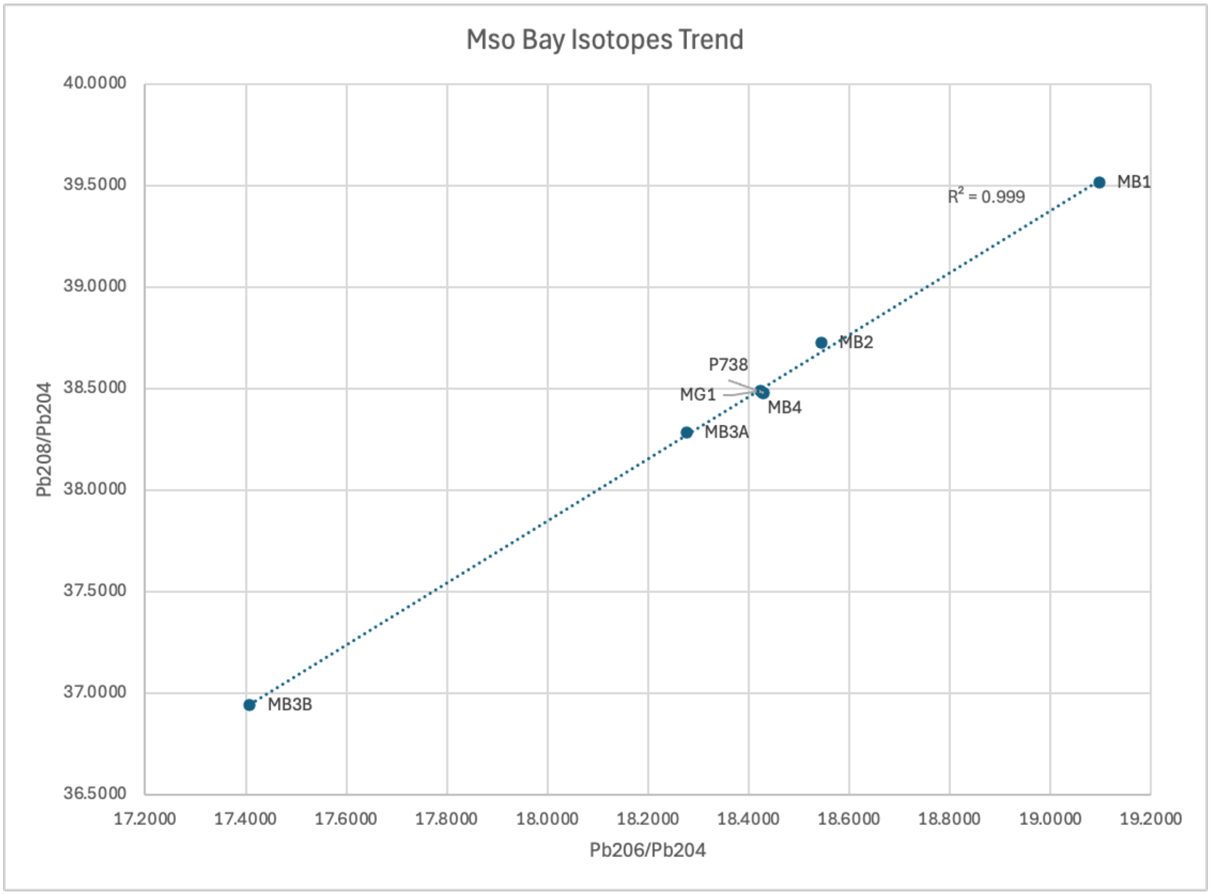


Figure 35: Isotopic trendline for Mso Bay objects

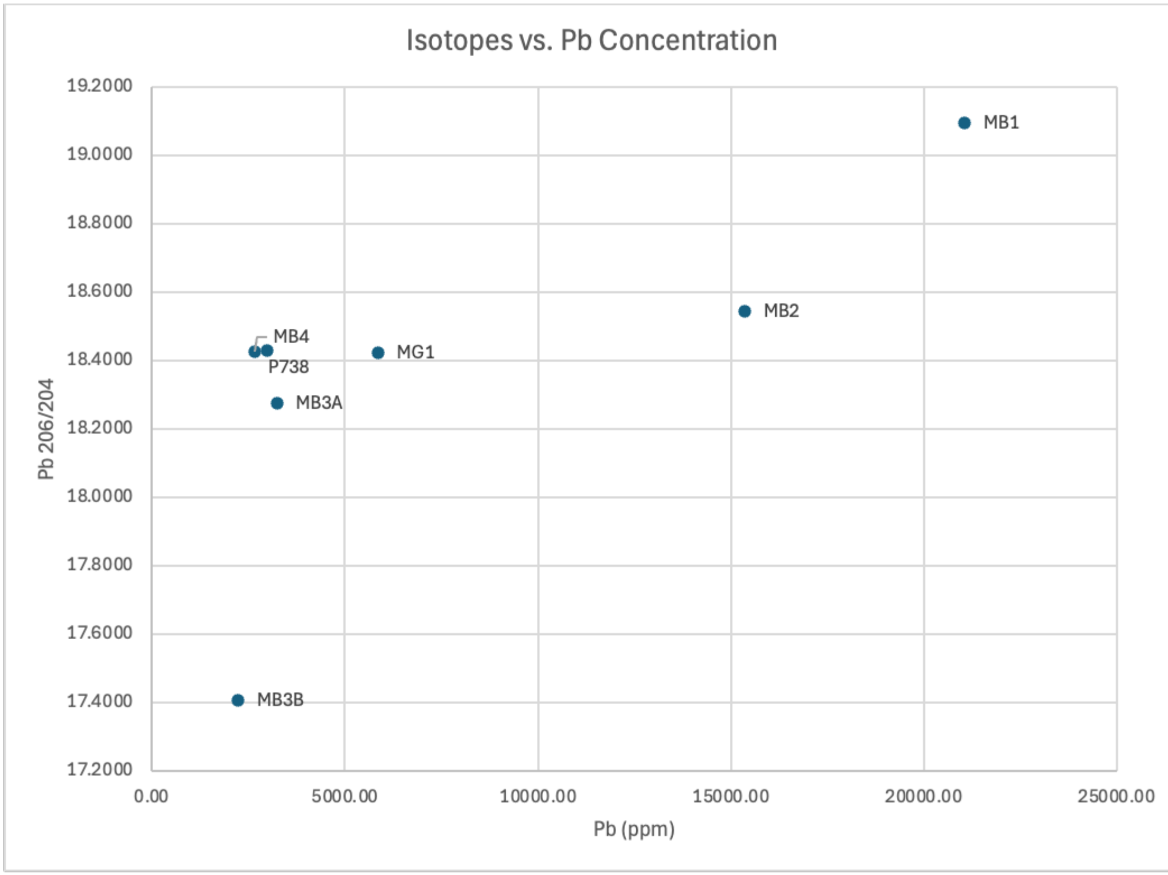


Figure 36: Plot of lead isotope ratios vs lead concentration for Mso Bay samples

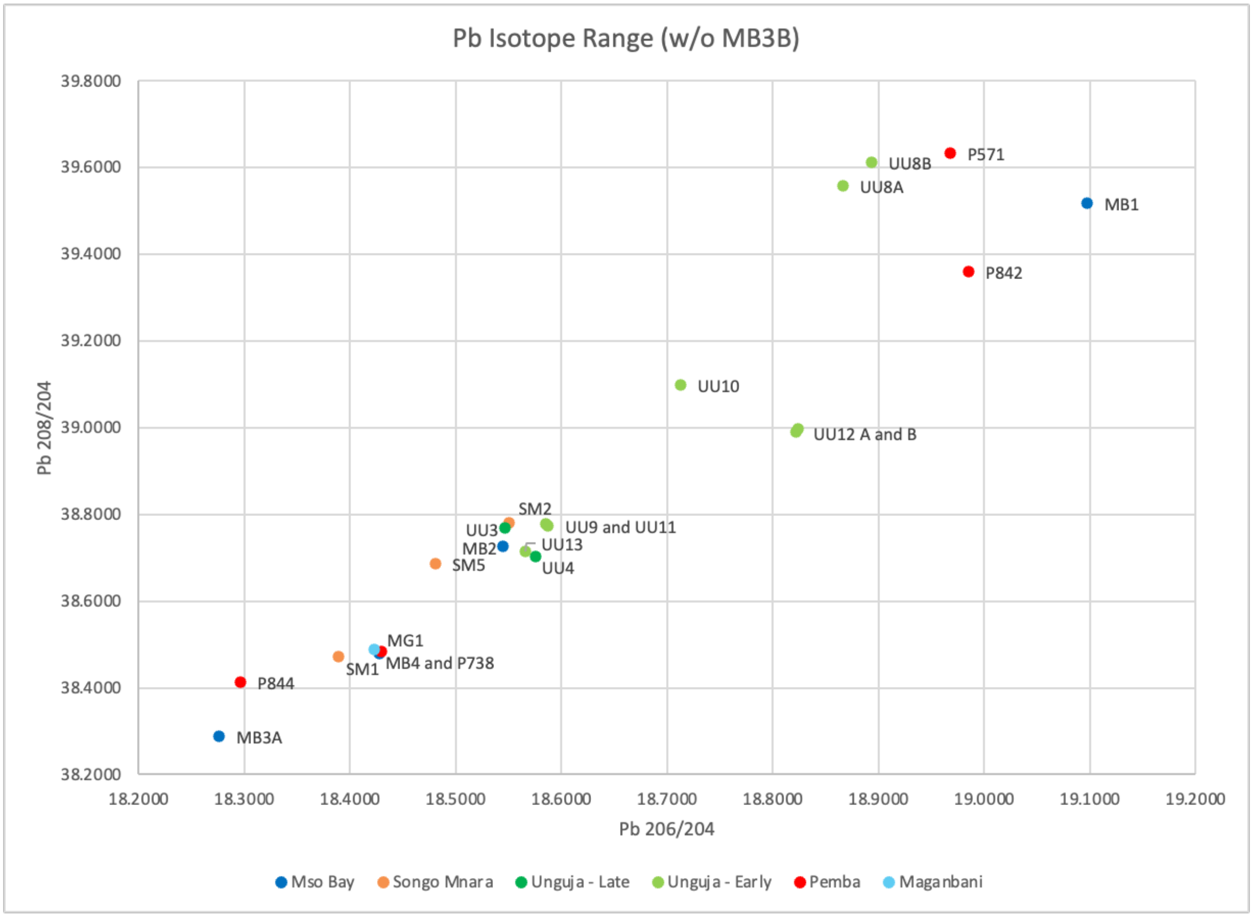


Figure 37: Isotopic distribution of Swahili copper objects categorized by archaeological context (not including outlier MB3B for better resolution in the tightly clustered signatures).

Tables

Site Name	Sample ID	Approx. Context Date	Description
Songo Mnara	SM1	Late 14th-15th Centuries	Rod, small
	SM2	Late 14th-15th Centuries	Sheet, thin flat, fragment
	SM3	Late 14th-15th Centuries	Bowl, rim fragment
	SM5	Late 14th-15th Centuries	Cylinder, stylized, hollow
Unguja Ukuu	UU1	13th-15th Centuries	Coin (Kilwa type?)
	UU2	13th-15th Centuries	Mirror, fragment
	UU3	13th-15th Centuries	Coin (Kilwa type?)
	UU4	13th-15th Centuries	Coin (Kilwa type? -modified)
	UU6	13th-15th Centuries	Coin, clipped (Kilwa type?)
	UU7	7th-13th Centuries	Wire, twisted
	UU8A	7th-13th Centuries	Spoon, blade fragment
	UU8B	7th-13th Centuries	Spoon, handle fragment
	UU9	7th-13th Centuries	Cap, to flask
	UU10	7th-13th Centuries	Cylinder, decorated, solid
	UU11	7th-13th Centuries	Strip, pierced
	UU12A	7th-13th Centuries	Plate, riveted, fragment (plate)
	UU12B	7th-13th Centuries	Plate, riveted (rivet)
	UU13	7th-13th Centuries	Bracelet
	UU14	7th-13th Centuries	Vessel, rim fragment
Mso Bay	MB1	7th-10th Centuries	Bangle
	MB2	7th-10th Centuries	Bead, short conical
	MB3A	7th-10th Centuries	Bead, short conical
	MB3B	7th-10th Centuries	Bead, long conical
	MB4	7th-10th Centuries	Bead, short conical
Maganbani	MG1	7th-10th Centuries	Bead, short conical
Tumbe	P464	770-980 CE	Sheet, fragment
	P571	770-980 CE	Ring, finger, incised
	P738	770-980 CE	Ring
	P842	770-980 CE	Ring, finger, incised
	P844A	770-980 CE	Earrings (only 1 sampled)

Table 1: Copper-based metal artifacts selected for this study

Analyte	Limit of Detection (ppb)	Analyte	Limit of Detection (ppb)
P-31	3.539669	Sn-119	0.012966
Cr-52	0.014312	Sn-120	0.005778
Fe-56	0.266393	Sb-121	0.002584
Co-59	0.001232	Sb-123	0.006196
Ni-60	0.009482	Te-125	0.035732
Ni-61	0.398147	Te-126	0.019386
Ni-62	0.029527	W-182	0.001959
Cu-63	0.018358	W-184	0.002034
Cu-65	0.035960	Pb-204	0.075116
Zn-66	0.031161	Pb-206	0.000893
Zn-68	0.045353	Pb-207	0.000825
As-75	0.026345	Pb-208	0.001308
Se-77	0.285320	Bi-209	0.001427
Mo-95	0.003187	P-1-31	0.026861
Mo-98	0.002625	Cr-1-52	0.028828
Ag-107	0.004591	Fe-1-56	0.142459
Ag-109	0.001947	As-1-75	0.140105
Cd-111	0.006067	Se-1-77	7.963167
Cd-113	0.014084	Total Pb	0.001252
Sn-118	0.004895	Total Pb (206, 207, 208)	0.000474

Table 2: Analytes and their limits of detection in ppb on the PerkinElmer NexION 300x quadrupole ICP-MS.

	Wet Plasma Analysis
RF Power	1300 W
Acceleration Voltage	6000 V
Mass Analyzer Pressure	~2-3 x 10^{-8} mbar
Nebulizer	Glass expansion
Sample Uptake Rate	120-140 μL/min
Spray Chamber Temperature	~5^{o}C

Table 3: Operating conditions for the Nu Plasma II (Nu Instruments) MC-ICP-MS.

	P	Cr	Fe	Co	Ni	Cu	Zn	As	Se	Mo	Ag	Cd	Sn	Sb	Te	W	Pb	Bi
EBM-SM1	<D.L.	2.38	2822.78	68.45	566.01	969515.16	1483.78	2940.77	<D.L.	0.28	888.63	5.22	4664.06	2160.01	1.52	0.20	8890.15	337.98
EBM-MB1	<D.L.	<D.L.	7.92	70.56	626.39	957880.07	19.04	1838.98	<D.L.	<D.L.	270.84	1.59	39.97	444.59	5.03	<D.L.	21069.95	5.47
EBM-MB2	<D.L.	<D.L.	16.50	0.07	1961.25	956363.78	3.26	3077.81	<D.L.	<D.L.	253.47	<D.L.	0.72	3296.53	7.51	<D.L.	15359.87	3.03
EBM-MB3B	<D.L.	<D.L.	33.78	4.54	171.02	975979.33	61.67	1896.51	<D.L.	0.06	84.69	2.27	10.37	30.87	13.64	0.04	2229.33	28.29
EBM-MB4	<D.L.	<D.L.	17.99	29.63	472.44	965589.66	43.11	3171.03	<D.L.	<D.L.	110.05	0.82	9.30	695.08	33.89	<D.L.	2655.51	74.91
EBM-MG1	<D.L.	<D.L.	315.24	7.14	151.74	964212.40	1960.33	1558.87	<D.L.	<D.L.	346.48	1.10	450.87	429.96	35.79	<D.L.	5854.55	220.78
EBM-P738	<D.L.	<D.L.	10.46	3.19	164.56	972426.02	31.50	2140.35	<D.L.	<D.L.	356.10	<D.L.	2.84	399.45	24.93	<D.L.	2983.54	50.39
EBM-UU1	<D.L.	<D.L.	10.68	20.47	22.74	975895.97	7.02	18.98	<D.L.	<D.L.	0.77	<D.L.	0.34	0.36	<D.L.	<D.L.	0.67	3.22
EBM-UU11	<D.L.	<D.L.	4.17	0.07	570.09	958605.64	13.77	4666.92	<D.L.	<D.L.	512.97	<D.L.	0.61	1233.99	26.05	0.05	10483.15	140.57
EBM-UU12A	<D.L.	<D.L.	83.68	28.57	390.20	946147.69	61.87	571.21	<D.L.	<D.L.	158.25	3.02	75.47	65.81	3.70	<D.L.	11821.44	4.06
EBM-UU12B	<D.L.	<D.L.	16.19	18.28	462.53	946867.04	7.07	363.77	<D.L.	<D.L.	256.38	<D.L.	11.08	46.38	3.92	<D.L.	15294.04	3.86
EBM-MB3A	<D.L.	<D.L.	1180.36	22.38	225.17	958611.70	8011.46	2540.02	<D.L.	0.09	584.11	1.33	394.32	715.84	29.80	<D.L.	3236.36	72.07
EBM-UU6	<D.L.	<D.L.	<D.L.	3.49	9.73	959320.02	22.92	28.44	<D.L.	<D.L.	0.82	<D.L.	0.64	<D.L.	<D.L.	<D.L.	2.03	0.25
EBM-UU7	<D.L.	<D.L.	38.35	75.77	11.48	983307.82	2.67	16.85	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	0.85	0.35
EBM-UU2	<D.L.	<D.L.	493.68	568.53	718.48	746977.23	73.12	1318.66	<D.L.	<D.L.	369.01	1.98	191895.75	343.07	10.51	0.14	796.42	30.33
EBM-UU14	<D.L.	<D.L.	8254.57	813.96	634.99	692519.22	1527.99	996.29	<D.L.	0.40	130.78	8.21	216870.69	28.16	14.95	<D.L.	229.44	18.77
EBM UU4	<D.L.	0.67	5375.97	131.37	642.63	868172.18	7152.92	5406.39	<D.L.	<D.L.	261.94	7.21	11472.47	2270.53	4.56	<D.L.	23344.56	158.46
EBM UU3	<D.L.	<D.L.	1928.83	89.31	1225.67	749903.79	12110.08	5060.33	<D.L.	<D.L.	531.50	2.08	25331.97	6042.23	8.09	0.06	116006.22	277.61
EBM UU13	<D.L.	<D.L.	5703.96	103.52	1030.91	681926.24	14758.73	1795.67	<D.L.	0.39	165.42	9.52	6551.74	6749.61	61.01	<D.L.	183155.19	351.11
EBM UU9	<D.L.	<D.L.	6727.88	176.95	964.55	651347.52	37587.79	6306.85	<D.L.	0.67	82.64	2.89	45885.51	6196.61	22.72	<D.L.	173219.27	303.58
EBM P571	<D.L.	<D.L.	607.21	483.26	539.46	860926.83	42065.52	1381.82	<D.L.	<D.L.	194.79	10.64	6207.52	197.81	9.50	<D.L.	16944.65	18.68
EBM P842	<D.L.	<D.L.	1665.25	343.49	486.97	851953.31	70642.80	1035.53	<D.L.	0.25	283.63	3.23	3295.46	262.52	6.79	0.05	9611.18	36.39
EBM UU8	<D.L.	<D.L.	2174.95	426.18	500.86	805573.53	70735.45	1140.15	<D.L.	0.22	243.50	4.05	11601.66	199.88	6.87	<D.L.	14929.86	44.90
EBM UU10	<D.L.	<D.L.	5632.14	202.72	445.21	756209.74	96858.38	1910.04	<D.L.	0.19	98.81	3.41	14232.95	600.03	9.88	<D.L.	41928.29	71.45
EBM SM5	<D.L.	<D.L.	1577.97	6.30	1457.40	596730.27	153941.91	3652.62	<D.L.	0.20	805.29	2.32	47206.93	8002.86	<D.L.	<D.L.	132200.01	138.68
EBM P844	<D.L.	<D.L.	3674.39	36.95	330.28	695212.24	178513.91	2919.72	<D.L.	0.86	88.73	2.19	2154.90	463.33	36.41	<D.L.	35797.59	194.48
EBM P464	1.56	0.74	10990.09	2602.03	457.83	686109.07	12155.19	414.63	<D.L.	2.92	212.84	13.09	216416.39	47.81	10.90	<D.L.	420.64	14.76
EBM SM3	<D.L.	<D.L.	566.81	89.34	318.59	594452.07	18.98	2366.33	<D.L.	<D.L.	373.61	0.63	103161.46	1080.08	6.06	<D.L.	613.40	13.51

Table 4: Sample compositions with elemental concentrations of all analytes reported in parts per million (ppm), as measured by ICP-MS

	P	Cr	Fe	Co	Ni	Cu	Zn	As	Se	Mo	Ag	Cd	Sn	Sb	Te	W	Pb	Bi		SUM
SM1	<D.L.	0.0002	0.2823	0.0068	0.0566	96.9515	0.1484	0.2941	<D.L.	0.0000	0.0889	0.0005	0.4664	0.2160	0.0002	0.0000	0.8890	0.0338		99.4347
MB1	<D.L.	<D.L.	0.0008	0.0071	0.0626	95.7880	0.0019	0.1839	<D.L.	<D.L.	0.0271	0.0002	0.0040	0.0445	0.0005	<D.L.	2.1070	0.0005		98.2280
MB2	<D.L.	<D.L.	0.0016	0.0000	0.1961	95.6364	0.0003	0.3078	<D.L.	<D.L.	0.0253	<D.L.	0.0001	0.3297	0.0008	<D.L.	1.5360	0.0003		98.0344
MB3B	<D.L.	<D.L.	0.0034	0.0005	0.0171	97.5979	0.0062	0.1897	<D.L.	0.0000	0.0085	0.0002	0.0010	0.0031	0.0014	0.0000	0.2229	0.0028		98.0546
MB4	<D.L.	<D.L.	0.0018	0.0030	0.0472	96.5590	0.0043	0.3171	<D.L.	<D.L.	0.0110	0.0001	0.0009	0.0695	0.0034	<D.L.	0.2656	0.0075		97.2903
MG1	<D.L.	<D.L.	0.0315	0.0007	0.0152	96.4212	0.1960	0.1559	<D.L.	<D.L.	0.0346	0.0001	0.0451	0.0430	0.0036	<D.L.	0.5855	0.0221		97.5545
P738	<D.L.	<D.L.	0.0010	0.0003	0.0165	97.2426	0.0031	0.2140	<D.L.	<D.L.	0.0356	<D.L.	0.0003	0.0399	0.0025	<D.L.	0.2984	0.0050		97.8593
UU1	<D.L.	<D.L.	0.0011	0.0020	0.0023	97.5896	0.0007	0.0019	<D.L.	<D.L.	0.0001	<D.L.	0.0000	0.0000	<D.L.	<D.L.	0.0001	0.0003		97.5981
UU11	<D.L.	<D.L.	0.0004	0.0000	0.0570	95.8606	0.0014	0.4667	<D.L.	<D.L.	0.0513	<D.L.	0.0001	0.1234	0.0026	0.0000	1.0483	0.0141		97.6258
UU12A	<D.L.	<D.L.	0.0084	0.0029	0.0390	94.6148	0.0062	0.0571	<D.L.	<D.L.	0.0158	0.0003	0.0075	0.0066	0.0004	<D.L.	1.1821	0.0004		95.9415
UU12B	<D.L.	<D.L.	0.0016	0.0018	0.0463	94.6867	0.0007	0.0364	<D.L.	<D.L.	0.0256	<D.L.	0.0011	0.0046	0.0004	<D.L.	1.5294	0.0004		96.3351
MB3A	<D.L.	<D.L.	0.1180	0.0022	0.0225	95.8612	0.8011	0.2540	<D.L.	0.0000	0.0584	0.0001	0.0394	0.0716	0.0030	<D.L.	0.3236	0.0072		97.5625
UU6	<D.L.	<D.L.	<D.L.	0.0003	0.0010	95.9320	0.0023	0.0028	<D.L.	<D.L.	0.0001	<D.L.	0.0001	<D.L.	<D.L.	<D.L.	0.0002	0.0000		95.9388
UU7	<D.L.	<D.L.	0.0038	0.0076	0.0011	98.3308	0.0003	0.0017	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	<D.L.	0.0001	0.0000		98.3454
UU2	<D.L.	<D.L.	0.0494	0.0569	0.0718	74.6977	0.0073	0.1319	<D.L.	<D.L.	0.0369	0.0002	19.1896	0.0343	0.0011	0.0000	0.0796	0.0030		94.3597
UU14	<D.L.	<D.L.	0.8255	0.0814	0.0635	69.2519	0.1528	0.0996	<D.L.	0.0000	0.0131	0.0008	21.6871	0.0028	0.0015	<D.L.	0.0229	0.0019		92.2048
UU4	<D.L.	0.0001	0.5376	0.0131	0.0643	86.8172	0.7153	0.5406	<D.L.	<D.L.	0.0262	0.0007	1.1472	0.2271	0.0005	<D.L.	2.3345	0.0158		92.4402
UU3	<D.L.	<D.L.	0.1929	0.0089	0.1226	74.9904	1.2110	0.5060	<D.L.	<D.L.	0.0531	0.0002	2.5332	0.6042	0.0008	0.0000	11.6006	0.0278		91.8518
UU13	<D.L.	<D.L.	0.5704	0.0104	0.1031	68.1926	1.4759	0.1796	<D.L.	0.0000	0.0165	0.0010	0.6552	0.6750	0.0061	<D.L.	18.3155	0.0351		90.2363
UU9	<D.L.	<D.L.	0.6728	0.0177	0.0965	65.1348	3.7588	0.6307	<D.L.	0.0001	0.0083	0.0003	4.5886	0.6197	0.0023	<D.L.	17.3219	0.0304		92.8825
P571	<D.L.	<D.L.	0.0607	0.0483	0.0539	86.0927	4.2066	0.1382	<D.L.	<D.L.	0.0195	0.0011	0.6208	0.0198	0.0009	<D.L.	1.6945	0.0019		92.9588
P842	<D.L.	<D.L.	0.1665	0.0343	0.0487	85.1953	7.0643	0.1036	<D.L.	0.0000	0.0284	0.0003	0.3295	0.0263	0.0007	0.0000	0.9611	0.0036		93.9627
UU8	<D.L.	<D.L.	0.2175	0.0426	0.0501	80.5574	7.0735	0.1140	<D.L.	0.0000	0.0243	0.0004	1.1602	0.0200	0.0007	<D.L.	1.4930	0.0045		90.7582
UU10	<D.L.	<D.L.	0.5632	0.0203	0.0445	75.6210	9.6858	0.1910	<D.L.	0.0000	0.0099	0.0003	1.4233	0.0600	0.0010	<D.L.	4.1928	0.0071		91.8203
SM5	<D.L.	<D.L.	0.1578	0.0006	0.1457	59.6730	15.3942	0.3653	<D.L.	0.0000	0.0805	0.0002	4.7207	0.8003	<D.L.	<D.L.	13.2200	0.0139		94.5723
P844	<D.L.	<D.L.	0.3674	0.0037	0.0330	69.5212	17.8514	0.2920	<D.L.	0.0001	0.0089	0.0002	0.2155	0.0463	0.0036	<D.L.	3.5798	0.0194		91.9426
P464	0.0002	0.0001	1.0990	0.2602	0.0458	68.6109	1.2155	0.0415	<D.L.	0.0003	0.0213	0.0013	21.6416	0.0048	0.0011	<D.L.	0.0421	0.0015		92.9871
SM3	<D.L.	<D.L.	0.0567	0.0089	0.0319	59.4452	0.0019	0.2366	<D.L.	<D.L.	0.0374	0.0001	10.3161	0.1080	0.0006	<D.L.	0.0613	0.0014		70.3061

Table 5: Sample compositions with element concentrations of all analytes reported in weight percent concentration, as measured by ICP-MS. Total percent measured is shown in SUM column.

Sample ID	$^{208}Pb/^{204}Pb$	2se	$^{207}Pb/^{204}Pb$	2se	$^{206}Pb/^{204}Pb$	2se	$^{208}Pb/^{206}Pb$	2se	$^{207}Pb/^{206}Pb$	2se
SM1	38.4709	0.0020	15.6556	0.0007	18.3893	0.0008	2.09201	0.00005	0.85135	0.00001
SM2	38.7807	0.0019	15.6793	0.0007	18.5505	0.0008	2.09058	0.00004	0.84524	0.00001
SM5	38.6857	0.0018	15.6674	0.0007	18.4805	0.0008	2.09332	0.00004	0.84777	0.00001
UU3	38.7677	0.0024	15.6875	0.0009	18.5463	0.0010	2.09031	0.00004	0.84586	0.00001
UU4	38.7034	0.0022	15.6753	0.0008	18.5751	0.0009	2.08362	0.00004	0.84389	0.00001
UU8A	39.5568	0.0020	15.6844	0.0007	18.8662	0.0008	2.09672	0.00004	0.83134	0.00001
UU8A Replicate	39.5548	0.0022	15.6830	0.0007	18.8652	0.0009	2.09671	0.00004	0.83132	0.00001
UU8B	39.6113	0.0020	15.6868	0.0008	18.8932	0.0008	2.09664	0.00004	0.83031	0.00001
UU9	38.7781	0.0024	15.6684	0.0008	18.5853	0.0010	2.08654	0.00005	0.84307	0.00001
UU9 Replicate	38.7759	0.0021	15.6675	0.0007	18.5836	0.0009	2.08657	0.00005	0.84308	0.00001
UU10	39.0985	0.0020	15.6795	0.0007	18.7123	0.0008	2.08943	0.00004	0.83793	0.00001
UU11	38.7745	0.0019	15.6599	0.0007	18.5874	0.0008	2.08604	0.00005	0.84250	0.00001
UU12A	38.9972	0.0019	15.7039	0.0008	18.8243	0.0008	2.07163	0.00003	0.83424	0.00001
UU12B	38.9890	0.0024	15.7012	0.0008	18.8221	0.0010	2.07150	0.00004	0.83421	0.00001
UU13	38.7151	0.0019	15.6701	0.0007	18.5660	0.0007	2.08529	0.00005	0.84403	0.00001
MB1	39.5170	0.0025	15.7434	0.0009	19.0973	0.0010	2.06924	0.00005	0.82438	0.00001
MB2	38.7266	0.0022	15.6566	0.0008	18.5443	0.0008	2.08837	0.00005	0.84429	0.00001
MB3A	38.2875	0.0018	15.6026	0.0007	18.2763	0.0008	2.09497	0.00004	0.85372	0.00001
MB3B	36.9431	0.0014	15.4770	0.0005	17.4076	0.0006	2.12224	0.00004	0.88908	0.00001
MB4	38.4787	0.0022	15.6117	0.0008	18.4273	0.0009	2.08812	0.00004	0.84721	0.00001
MG1	38.4891	0.0021	15.6234	0.0008	18.4233	0.0008	2.08916	0.00005	0.84803	0.00001
P571	39.6339	0.0017	15.7078	0.0007	18.9680	0.0008	2.08949	0.00003	0.82811	0.00001
P738	38.4827	0.0019	15.6131	0.0007	18.4294	0.0007	2.08811	0.00004	0.84719	0.00001
P842	39.3597	0.0023	15.7243	0.0008	18.9849	0.0009	2.07323	0.00005	0.82826	0.00001
P844A	38.4122	0.0022	15.6342	0.0007	18.2961	0.0008	2.09948	0.00005	0.85450	0.00001

Table 6: Lead isotopic ratios for 23 samples with associated standard errors, and two replicate measurements.

Sample ID	Fe	Co	Ni	Cu	Zn	As	Ag	Sn	Sb	Pb	Bi	SUM	Metal Type
UU7	0.0038	0.0076	0.0011	98.3308	0.0003	0.0017	<D.L.	<D.L.	<D.L.	0.0001	0.0000	98.3454	Pure Copper
MB3B	0.0034	0.0005	0.0171	97.5979	0.0062	0.1897	0.0085	0.0010	0.0031	0.2229	0.0028	98.0546	Pure Copper
UU1	0.0011	0.0020	0.0023	97.5896	0.0007	0.0019	0.0001	0.0000	0.0000	0.0001	0.0003	97.5981	Pure Copper
P738	0.0010	0.0003	0.0165	97.2426	0.0031	0.2140	0.0356	0.0003	0.0399	0.2984	0.0050	97.8593	Pure Copper
SM1	0.2823	0.0068	0.0566	96.9515	0.1484	0.2941	0.0889	0.4664	0.2160	0.8890	0.0338	99.4347	Pure Copper
MB4	0.0018	0.0030	0.0472	96.5590	0.0043	0.3171	0.0110	0.0009	0.0695	0.2656	0.0075	97.2903	Pure Copper
MG1	0.0315	0.0007	0.0152	96.4212	0.1960	0.1559	0.0346	0.0451	0.0430	0.5855	0.0221	97.5545	Pure Copper
UU6	<D.L.	0.0003	0.0010	95.9320	0.0023	0.0028	0.0001	0.0001	<D.L.	0.0002	0.0000	95.9388	Pure Copper
MB3A	0.1180	0.0022	0.0225	95.8612	0.8011	0.2540	0.0584	0.0394	0.0716	0.3236	0.0072	97.5625	Pure Copper
UU11	0.0004	0.0000	0.0570	95.8606	0.0014	0.4667	0.0513	0.0001	0.1234	1.0483	0.0141	97.6258	Pure Copper
MB1	0.0008	0.0071	0.0626	95.7880	0.0019	0.1839	0.0271	0.0040	0.0445	2.1070	0.0005	98.2280	Pure Copper
MB2	0.0016	0.0000	0.1961	95.6364	0.0003	0.3078	0.0253	0.0001	0.3297	1.5360	0.0003	98.0344	Pure Copper
UU12B	0.0016	0.0018	0.0463	94.6867	0.0007	0.0364	0.0256	0.0011	0.0046	1.5294	0.0004	96.3351	Pure Copper
UU12A	0.0084	0.0029	0.0390	94.6148	0.0062	0.0571	0.0158	0.0075	0.0066	1.1821	0.0004	95.9415	Pure Copper
UU4	0.5376	0.0131	0.0643	86.8172	0.7153	0.5406	0.0262	1.1472	0.2271	2.3345	0.0158	92.4402	Copper, likely recycled
SM3 (norm.)	0.0806	0.0127	0.0453	84.5311	0.0027	0.3365	0.0531	14.6696	0.1536	0.0872	0.0019	99.9753	High Tin Bronze
UU2	0.0494	0.0569	0.0718	74.6977	0.0073	0.1319	0.0369	19.1896	0.0343	0.0796	0.0030	94.3597	High Tin Bronze
UU14	0.8255	0.0814	0.0635	69.2519	0.1528	0.0996	0.0131	21.6871	0.0028	0.0229	0.0019	92.2048	High Tin Bronze
P464	1.0990	0.2602	0.0458	68.6109	1.2155	0.0415	0.0213	21.6416	0.0048	0.0421	0.0015	92.9871	High Tin Bronze
P571	0.0607	0.0483	0.0539	86.0927	4.2066	0.1382	0.0195	0.6208	0.0198	1.6945	0.0019	92.9588	Brass
P842	0.1665	0.0343	0.0487	85.1953	7.0643	0.1036	0.0284	0.3295	0.0263	0.9611	0.0036	93.9627	Brass
UU8	0.2175	0.0426	0.0501	80.5574	7.0735	0.1140	0.0243	1.1602	0.0200	1.4930	0.0045	90.7582	Brass
UU10	0.5632	0.0203	0.0445	75.6210	9.6858	0.1910	0.0099	1.4233	0.0600	4.1928	0.0071	91.8203	Leaded Brass
P844	0.3674	0.0037	0.0330	69.5212	17.8514	0.2920	0.0089	0.2155	0.0463	3.5798	0.0194	91.9426	Leaded Brass
UU13	0.5704	0.0104	0.1031	68.1926	1.4759	0.1796	0.0165	0.6552	0.6750	18.3155	0.0351	90.2363	Leaded Brass
UU3	0.1929	0.0089	0.1226	74.9904	1.2110	0.5060	0.0531	2.5332	0.6042	11.6006	0.0278	91.8518	Quaternary Alloy
UU9	0.6728	0.0177	0.0965	65.1348	3.7588	0.6307	0.0083	4.5886	0.6197	17.3219	0.0304	92.8825	Quaternary Alloy
SM5	0.1578	0.0006	0.1457	59.6730	15.3942	0.3653	0.0805	4.7207	0.8003	13.2200	0.0139	94.5723	Quaternary Alloy

Table 7: Summarized table of element concentrations in wt% including major minor and trace elements of the most significance and the corresponding alloy category

Sample ID	Fe	Co	Ni	Cu	Zn	As	Ag	Sb	Pb	Bi	SUM
SM3	0.0898	0.0141	0.0505	94.1374	0.0030	0.3747	0.0592	0.1710	0.0971	0.0021	94.9989
UU2	0.0624	0.0719	0.0908	94.4030	0.0092	0.1667	0.0466	0.0434	0.1007	0.0038	94.9984
UU14	1.1120	0.1097	0.0855	93.2947	0.2058	0.1342	0.0176	0.0038	0.0309	0.0025	94.9968
P464	1.4634	0.3465	0.0610	91.3589	1.6185	0.0552	0.0283	0.0064	0.0560	0.0020	94.9961

Table 8: Composition estimates (given in wt% concentration) of copper metal used to make bronze (renormalized after subtracting tin percentage).

Sample ID	As	Sb	Ag	Ni	Code	Description
UU7	0.0017	<D.L.	<D.L.	0.0011	NNNN	Cu
MB3B	0.1897	0.0031	0.0085	0.0171	YNNN	CuAs
UU1	0.0019	0.0000	0.0001	0.0023	NNNN	Cu
P738	0.2140	0.0399	0.0356	0.0165	YNNN	CuAs
SM1	0.2941	0.2160	0.0889	0.0566	YYNN	CuAsSb
MB4	0.3171	0.0695	0.0110	0.0472	YNNN	CuAs
MG1	0.1559	0.0430	0.0346	0.0152	YNNN	CuAs
UU6	0.0028	<D.L.	0.0001	0.0010	NNNN	Cu
MB3A	0.2540	0.0716	0.0584	0.0225	YNNN	CuAs
UU11	0.4667	0.1234	0.0513	0.0570	YYNN	CuAsSb
MB1	0.1839	0.0445	0.0271	0.0626	YNNN	CuAs
MB2	0.3078	0.3297	0.0253	0.1961	YYNY	CuAsSbNi
UU12B	0.0364	0.0046	0.0256	0.0463	NNNN	Cu
UU12A	0.0571	0.0066	0.0158	0.0390	NNNN	Cu
UU4	0.5406	0.2271	0.0262	0.0643	YYNN	CuAsSb
SM3	0.3747	0.1710	0.0592	0.0505	YYNN	CuAsSb
UU2	0.1667	0.0434	0.0466	0.0908	YNNN	CuAs
UU14	0.1342	0.0038	0.0176	0.0855	YNNN	CuAs
P464	0.0552	0.0064	0.0283	0.0610	NNNN	Cu

Table 9: Swahili pure coppers and copper component of bronzes grouped based on As, Sb, Ag, and Ni presence/absence method defined by Pollard 2018.