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A Chemical Study of Archaeometallurgical Ceramics from Southwestern Tanzania

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ABSTRACT

Archaeometallurgical ceramics, including furnaces, tuyères, and potteries, were required for successful pre-industrial iron smelting and refining. However, there are limited chemical studies on archaeometallurgical ceramics in Tanzania. This paper examined the nature of clay source in terms of refractoriness, determined whether there were multiple clay sources, and verified the refractoriness of the archaeometallurgical ceramics. An x-ray fluorescence (XRF) analytical technique and experimental re-firing of the archaeometallurgical ceramics were employed. The chemical data clustered in the mullite region on the Al_2O_3 - SiO_2 - FeO ternary system indicate that iron smelters and refiners chose refractory clay sources for making archaeometallurgical ceramics. Small range and standard deviation suggest that the furnaces and tuyères were made from similar refractory clay source, while the relatively slight difference in range and standard deviation of the potteries indicate that they were made from another different clay source. The archaeometallurgical ceramics re-fired in the furnace lab did not bloat at 1300 °C, it verifies that they were indeed refractory.

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INTRODUCTION

Archaeometallurgical ceramics, including furnaces, tuyères and potteries, had varied technical functions. The furnaces contained the smelting and refining charge and provided the heat necessary for iron smelting and refining. The tuyères supplied air into furnaces, and in some cases, the smelting tuyères were also used to tap liquid slag outside the furnace (Lyaya, 2016; Mapunda, 2010; Killick, 1991; Tylecote *et al.*, 1971). Lyaya (2020, 2019, 2016) and Mapunda (2010) examined the evidence and mechanism related to the use

of tuyères to tap liquid slag with some of the smelting furnaces in Tanzania. The potteries were commonly used as containers of ritual, techno-medicine recipes, and carried food and water (Lyaya, 2012; Mapunda, 2010; van der Merwe and Avery, 1987). Smelters and refiners used rituals and medicines as psychological and moral boost (van der Merwe and Avery 1987). The African study of archaeometallurgical ceramics has mostly focused on establishing chronology, construction materials, air supply modes, morphology, type, size or diameter, decoration, and

colour. In terms of chronology, archaeometallurgical ceramics are commonly divided into two main groups, namely, the Early Iron Age (EIA) (Mapunda, 2002; Haaland, 1994; Mapunda and Burg, 1991; Chami, 1988; Schmidt, 1988; van Noten and Raymaekers, 1988; Schmidt and Childs, 1985; Schmidt and Avery, 1978; 1983) and Later Iron Age (LIA) (Mapunda, 1995, 2003; Maluma, 1979). The EIA date pre-1500 AD, while the LIA date post-1500 AD. The Mkumbi and Itaka iron smelting and refining sites considered for this study have broadly been dated to 1680-1950 AD (Mapunda 2010).

The majority of African EIA smelting furnaces were constructed through either bricks or clay rolls (Craddock *et al.*, 2007; Childs, 1996; Schmidt, 1988) and were mainly operated with a forced draft mechanism and - in many cases - had slag-pit provisions (Lyaya and Mapunda, 2014; Craddock *et al.*, 2007; Whiteman and Okafor, 2003; Schmidt, 1997). On the other hand, most LIA furnaces were morphologically variable and were mainly constructed using lumps of wet clay or slabs (Mapunda, 2010). It is possible that the change aimed at improving the efficiency of metal production. Some of African LIA furnaces were operated through natural draft mechanism (Mapunda, 2010), while others were forced draft furnaces (Lyaya, 2011, 2012, 2020; Schmidt, 1996; Sutton, 1985). Based on height, diameter, and shape, it is almost accepted that African furnaces altogether can be grouped into a bowl, short, and tall shaft furnaces (Chirikure and Rehren, 2006; Childs, 1991; Sutton, 1985), although there are intra-group variations. The variation was perhaps influenced by technical, geological and socio-economic factors (Childs, 1991). Some smelting furnaces were decorated with wood impressions (Mapunda, 2010), simple designs (Craddock *et al.*, 2007), or with anthropomorphic features (Lyaya, 2011; Chirikure, 2006; Chirikure and Rehren, 2004).

Tuyère physical attributes including morphology, length, diameter, and colour of tuyères have also received attention. There were two types of tuyères based on the shape of the proximal end – either flared proximal tuyères or unflared proximal tuyères with uniform diameter from tip to tip (Lyaya, 2016; Mapunda, 2010). Long tuyères have been identified (Schmidt and Avery, 1983, 1978) and short tuyères (Lyaya, 2012). There are small diameter tuyères – well below 6 cm (Mapunda, 2010) – and those called massive tuyères with diameters well above 6.5 cm (Lyaya, 2011; Haaland, 1993; Sutton, 1985). In terms of color, there are whitish tuyères made of kaolinitic clay (Lyaya, 2011) and brownish or blackish (Mapunda, 2010). It is noteworthy that most previous studies of archaeometallurgical ceramics in Tanzania have largely dwelt on physical attributes analysis. However, there are a few scholars who have worked on the chemical and mineralogical attributes, including Schmidt and Avery (1978), Schmidt and Childs (1985), Childs (1989a, 1989b, 1990, 1996), Chirikure and Rehren (2004, 2006), Chirikure (2006), Craddock *et al.*, (2007), and Iles and Martinon-Torres (2009). Mineralogical studies have been identified as an avenue to verify whether smelters and refiners use artificially or naturally tempered clays (Iles and Martinon-Torres, 2009; Chirikure, 2006; Chirikure and Rehren, 2006; Childs, 1989a, 1989b, 1990; Bishop *et al.*, 1982). Temper improves refractoriness (Hein *et al.*, 2007). Termite mounds have been reported naturally tempered clays (Lyaya *et al.*, 2012; Mapunda, 2010; Barndon, 2004), but such claims require scientific verification through mineralogical research, an avenue of research beyond the scope of this study. Archaeological science in Africa is engulfed with significant challenges (Thondhlana *et al.*, 2022), but similarly the over-concentration of on physical attributes has blindfolded archaeologists from developing archaeological science in Tanzania. There is need to endeavour

developing archaeological science in Tanzania of which this work forms part. This paper is a chemical study of the archaeometallurgical ceramics from southwestern Tanzania. It sets up three aims for discussion, namely, to examine nature of the clay sources in terms of geochemistry and refractoriness, to determine whether there were either single or multiple clay sources for making archaeometallurgical ceramics, and to verify the refractoriness of the archaeometallurgical ceramics through conducting three re-firing experiments in the furnace lab. These aims are examined based on the results of this study in the discussion.

MATERIALS AND METHODS

One hundred thirty-five archaeometallurgical ceramics were gathered through archaeological surface collections from smelting and refining sites.

The study area comprised of two archaeometallurgical sites from Mkumbi in Sumbawanga municipal and two archaeometallurgical sites from Itaka in Mbozi district (Figure 1). Mkumbi and Itaka were chosen because they were relatively best-preserved smelting and refining sites. Out of 135 archaeometallurgical ceramics, 27 samples were purposively selected from two smelting sites and two refining sites including 12 furnace pieces, 12 tuyères, and three potteries (Table 1). The samples were purposively selected based on physical attributes such as size, typology, morphology, texture, fabric, and colour. Purposive sampling strategy aimed at attaining representative sample size. The sample size considered was twenty percent of the total archaeometallurgical ceramics gathered from the study area as put above.

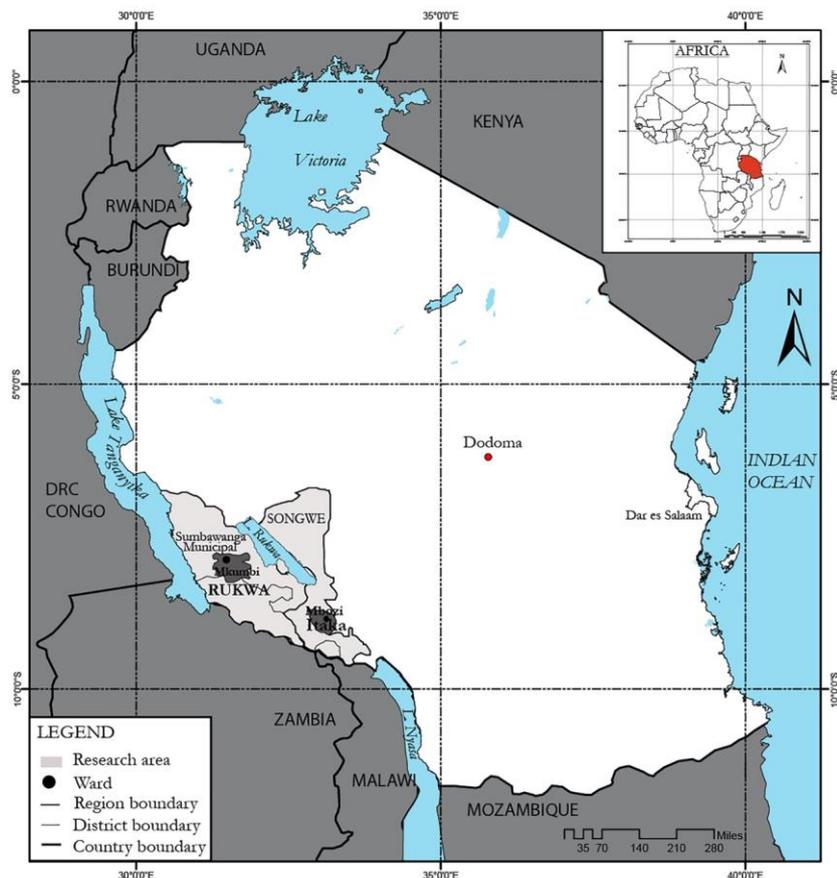


Figure 1: A map of the study area showing Mkumbi in Sumbawanga and Itaka in Mbozi. Source: National Bureau of Statistics (NBS) (with modifications).

Table 1: A list of archaeometallurgical sites for this study

No	Site name	GPS location	Furnaces	Tuyères	Potteries	Total
1	Mkumbi Smelting 3	S (8° 04.302'), E (31° 40.879')	3	3	-	6
2	Mkumbi Refining 2	S (8° 04.326'), E (31° 40.884')	3	3	-	6
3	Itaka Smelting 1	S (8° 52.594'), E (32° 45.964')	3	3	-	6
4	Itaka Refining 2	S (8° 52.621'), E (32° 46.168')	3	3	3	9
5	Total		12	12	3	27

Samples were prepared and re-fired in the UCL Wolfson Archaeological Science Laboratories (see Lyaya, 2013). Pellets preparation involved cutting a small specimen of about 10-20 g from each sample. Each specimen was resized into small pieces using an abrasive diamond tile cutter, with 0.704 ounces weight, 3.1x0.15x3.1 inches (LxWxH) dimensions, and 3.32 inches blade length. Next was drying and crushing the samples into smaller pieces through steel mortar and pestle. A Retsch PM 100 Planetary Ball milling machine was set up. The milling machine had five agate grinding balls. It was set up at 450 rpm speed with 2.60 kg counterweight to powder the samples to less than 50 µm grain size in six minutes. The powder was put into glass sample vials, covered with double clinical tissue elastic bands, and placed in a Lenton Binder main laboratory oven overnight at 105 °C. The analyte sample (5-8 g) and wax were mixed to a ratio of 9:1 in a dedicated balance and thoroughly mixed by a Walter Stern agate mortar and pestle set. Pellets were pressed in aluminium cups at 15 tonnes force in 2.5 minutes through the Specad pressing machine. They were finally labelled.

A batch of fifteen pellets and three reference materials (RMs) were loaded into a Spectro Lab XPro 2000 instrument. The reference materials were NBS 679 Brick Clay, SARM 69 Ceramic-1, and SO-1 Reference Soil. Each set of the pellets and RMs was analysed three times to assess the precision. A Turbo Quant (TQ-0261d)

method was used, because it is the precise method for archaeometallurgical ceramics analysis in UCL Wolfson Archaeological Science Laboratories (Schramm and Heckel, 1998). The analytical results were reported as stoichiometric oxides by an in-built XPro software. A re-conversion of Fe₂O₃ to FeO was done by multiplying Fe₂O₃ concentration with 0.8993. It is noteworthy that with smelting and refining temperature of around 1200 °C coupled with strongly reducing conditions, high iron oxides such as hematite (Fe₂O₃) must have been reduced to FeO. The analytical results were normalised to 100 wt%, but the analytical totals (AT) are reported for further reference.

The measured values (MVs) for the RMs were statistically compared to the certified values (CVs). To assess the precision of the data, the standard deviations (SDs) of the repeated measurements were calculated and compared to MVs to obtain the coefficient of variation (CoV) in percentage. To check the accuracy of the data, the difference between MVs and CVs (absolute accuracy abbreviated as Abs. δ) was compared to CVs to calculate the percentage relative errors (relative accuracy in % abbreviated as Rel. δ). The assessment technique of the precision and accuracy showed that major and minor oxides (except soda) were consistently precise, with acceptable precision errors below 10% with most cases errors being below 2%, while more than half of the oxides were surprisingly inaccurate, with relative errors above 10%. Because the machine was precise but

inaccurate, there was a need to re-calibrate the data through an empirical correction factors (CFs) technique. The correction factors (CFs) were statistically calculated and applied to MVs based on the following steps: (i) averaged ratios of MVs were compared to CVs of the RMs respectively to give the CFs, (ii) divided the MVs by CFs for all oxides, (iii) normalised the data to 100%, (iv) re-calculated the precision and accuracy of the MVs, and (v) compared the differences in the precision and accuracy of the data. The re-calibration of the data by the empirical CF technique significantly improved data accuracy to acceptable levels of relative accuracy errors of less than 10% with most cases errors being well below 5% for all RMs. Phosphorous and chromium oxides are exceptions for RMs, with unacceptable accuracy errors between 20% and 200% on average, and hence analytical data of the archaeometallurgical ceramics for these oxides are not reported or used.

Because the re-calibration technique via the CFs technique worked perfectly based on the acceptable precision and accuracy above for the RMs; it was then applied to the actual archaeometallurgical ceramics to re-calibrate and produce acceptable high-quality precision and accuracy. The results were presented as the average of three runs and were normalised to 100 wt%.

There were three experiments of re-firing 27 samples of the archaeometallurgical ceramics in the furnace lab. The order was to re-fire 12 furnace samples in the first place, then to re-fire 12 tuyère samples in the second place, while potteries were re-fired in the end. The methods of the three re-firing experiments involved cutting a piece from each of the archaeometallurgical ceramics and drying it in the central main furnace laboratory at 105 °C overnight. In round one, the dried specimens were re-fired up to 900 °C in the Lenton (oxidising)

furnace for three hours: the first hour up to 100 °C, the second hour up to 700 °C, and the 3rd hour up to 900 °C. For round two, they were re-fired for five hours up to 1200 °C and were left at this maximum temperature (1200 °C) for 2 hours. In the last round, the samples were re-fired for 7 hours up to 1300 °C and were left at this maximum temperature (1300 °C) for 3 hours. This routine was observed for all samples.

RESULTS AND DISCUSSIONS

Archaeometallurgical ceramics from Mkumbi

Table 2 presents concentration of major oxides namely alumina (Al_2O_3), silica (SiO_2), potash (K_2O), titania (TiO_2), and iron (II) oxide (FeO) and minor oxides namely soda (Na_2O), magnesia (MgO), sulfur trioxide (SO_3), lime (CaO), vanadia (V_2O_5), and manganese (II) oxide MnO . Note that SE represents smelting, RF = refining, FW = furnace walls, TYR = tuyères, and AT = analytical totals. Statistical range of major and minor oxides' concentration for smelting samples was 0.01-5.15 wt%, while for refining samples was 0.01-4.55 wt%. The SD was 0.01-2 wt% for furnace samples and 0.01-1.61 wt% for major and minor oxides. The small range and standard deviation in oxides' concentrations are suggestive of the use of clay sources with similar geochemical signatures. Once the major oxides' concentrations were plotted on an Al_2O_3 - SiO_2 - FeO ternary system, the similarity was more apparent – all clustered together in the mullite region – with estimated refractory temperatures of 1600-1700 °C (Figure 2). Note the open downward triangles represents furnace walls, open upward triangles = tuyères, and open circles = potteries.

Table 2: (P)XRF-EDS oxide concentrations of archaeometallurgical ceramics from Mkumbi smelting #3 and refining #2 sites.

S/No.	Sample	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	V ₂ O ₅	MnO	FeO	AT
1	MKUSE3FW1	0.2	0.92	23.57	64.94	0.03	1.54	0.19	1	0.02	0.11	7.47	99.37
2	MKUSE3FW2	0.19	0.87	22.19	66.59	0.03	1.51	0.2	0.96	0.02	0.13	7.31	99.75
3	MKUSE3FW3	0.15	0.92	22.67	65.8	0.03	1.55	0.19	1	0.02	0.11	7.57	99.85
4	MKURF2FW1	0.26	0.67	19.83	70.08	0.02	1.34	0.21	0.92	0.02	0.09	6.55	99.8
5	MKURF2FW2	0.18	0.66	20.97	69.1	0.03	1.32	0.21	0.91	0.02	0.1	6.51	99.78
6	MKURF2FW3	0.23	0.74	21.68	68.04	0.04	1.47	0.18	0.92	0.02	0.08	6.62	99.49
7	MKUSE3TYR1	0.17	0.72	24.51	64.5	0.02	1.1	0.23	1.08	0.02	0.12	7.55	99.41
8	MKUSE3TYR2	0.17	0.81	24.01	65.11	0.02	1.04	0.28	1.03	0.01	0.12	7.4	99.39
9	MKUSE3TYR3	0.2	0.79	23.45	65.39	0.02	1.1	0.3	1.06	0.01	0.12	7.55	99.56
10	MKURF2TYR1	0.18	0.93	24.14	63.77	0.03	1.33	0.48	1.05	0.02	0.13	7.96	99.59
11	MKURF2TYR2	0.2	0.99	21.1	68.3	0.01	1.35	0.41	0.96	0.01	0.12	6.54	99.65
12	MKURF2TYR3	0.2	0.92	24.25	64.35	0.03	1.31	0.46	1.03	0.02	0.13	7.31	99.22

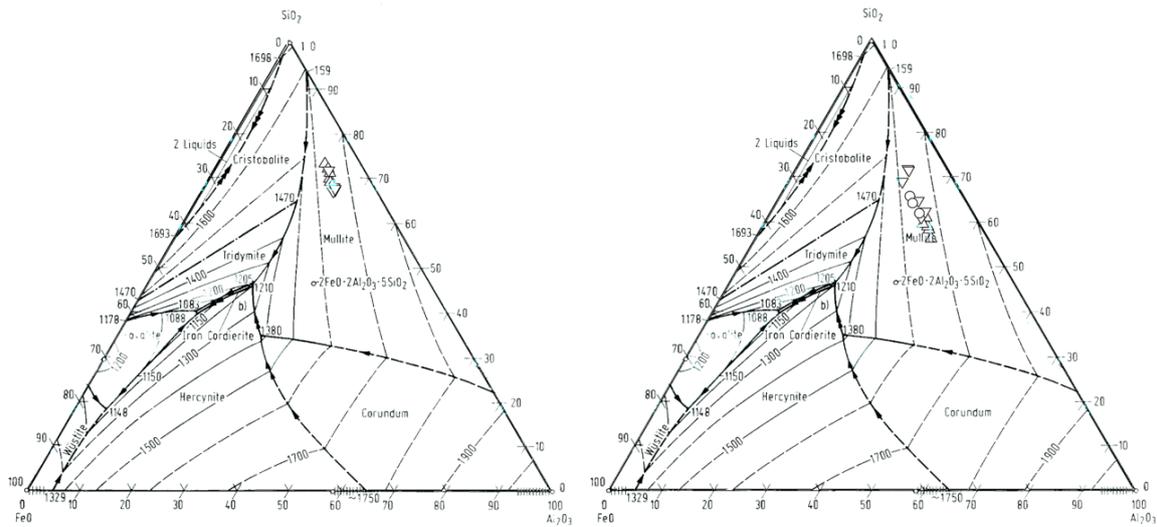


Figure 2: Al₂O₃-SiO₂-FeO ternary phase diagram illustrating the archaeometallurgical ceramics from Mkumbi smelting #3 and refining #2 (left) and from Itaka smelting #1 and refining #2 (right) sites.

Archaeometallurgical ceramics from Itaka

Table 3 presents concentration of major oxides including alumina, silica, potash, titania, and iron (II) oxide and minor oxides namely soda, magnesia, sulfur trioxide, lime, vanadia, and manganese (II) oxide. Note that PTR represents potteries. Statistical range of the oxides concentration in smelting samples was 0.01-4.30 wt%,

while for refining samples the range was 0.01-8.5 wt%, both with SD of 0.01-4.10 wt%. While most furnace and tuyère oxides' concentrations ranged below 1 wt%, it is noteworthy that a few smelting and refining tuyères had relatively high alumina and silica concentrations in the range between 7.5 wt% and 8.5 wt%, respectively. This slight difference was due to either variation in the local geochemistry

of clay sources, sampling, and differences in preparation methods of the furnaces and tuyères. Compared to furnace and tuyère samples, Itaka refining potteries had a range of 0.01-3.80 wt%, with a SD of 0.01-1.95 wt%. This relatively small range and SD point to the possibility of the use of another

different source of clay for the potteries, but when the major and minor oxides of smelting and refining furnace, tuyère, and pottery samples are plotted, the similarity and slight difference is evident (Figure 2, right). It appears that smelters and refiners selected refractory clays.

Table 3: (P)XRF-EDS major and minor oxide concentrations of archaeometallurgical ceramics from Itaka smelting #1 and refining #2 sites.

S/No.	Sample	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	V ₂ O ₅	MnO	FeO	AT
1	ITASE1FW1	0.29	0.28	29.29	56.71	0.03	1.37	0.21	1.7	0.02	0.25	9.85	92.32
2	ITASE1FW2	0.28	0.23	30.86	55.42	0.04	1.18	0.19	1.65	0.03	0.21	9.91	92
3	ITASE1FW3	0.29	0.24	32.11	53.37	0.07	1.34	0.19	1.72	0.03	0.22	10.43	91.94
4	ITARF2FW1	0.32	0.2	30.21	55.97	0.04	1.57	0.19	1.6	0.02	0.14	9.73	91.99
5	ITARF2FW2	0.4	0.21	28.91	57.66	0.05	1.7	0.21	1.59	0.02	0.22	9.04	91.8
6	ITARF2FW3	0.31	0.27	29.07	56.4	0.03	1.46	0.18	1.68	0.02	0.22	10.35	92.5
7	ITASE1TYR1	0.53	0.3	25.56	60.9	0.02	1.7	0.36	1.66	0.02	0.32	8.63	91.95
8	ITASE1TYR2	0.31	0.25	28.11	57.88	0.02	1.22	0.23	1.72	0.02	0.22	10	92.53
9	ITASE1TYR3	0.39	0.18	28.13	59.02	0.04	1.52	0.26	1.61	0.02	0.25	8.58	91.8
10	ITARF2TYR1	0.73	1.96	19.63	65.33	0.01	2.05	2.55	0.7	0.02	0.06	6.96	91.32
11	ITARF2TYR2	0.93	1.91	20.28	63.81	0.01	1.49	1.17	0.94	0.02	0.09	9.35	91.28
12	ITARF2TYR3	0.7	1.9	19.92	65.11	0.01	2.11	2.5	0.71	0.01	0.09	6.94	91.4
13	ITARF2PTR1	0.3	0.23	27.33	58.77	0.03	1.23	0.22	1.75	0.02	0.24	9.87	92.71
14	ITARF2PTR2	0.51	0.27	23.5	61.76	0.02	1.5	0.3	2.1	0.02	0.35	9.68	92.92
15	ITARF2PTR3	0.5	0.27	24.71	60.15	0.03	1.71	0.39	1.98	0.02	0.33	9.89	92.78

Re-firing experiments of the archaeometallurgical ceramics

Table 4 presents the vitrification observation of the re-fired archaeometallurgical ceramics. It was observed that none of the samples exhibited vitrification signs after being re-fired for three rounds between 900-

1300 °C, which is the maximum temperature for pre-industrial archaeometallurgical processes. The idea was to complement the chemical data of the archaeometallurgical ceramics to see if there was any coherence in the two methods.

Table 4: Results of the re-firing experiments of the archaeometallurgical ceramics

Round	Re-firing duration	Maximum temperature	Duration at maximum temperature in hours	Vitrification observation
Round 1	3	900 °C	1	Nil
Round 2	5	1200 °C	2	Nil
Round 3	7	1300 °C	3	Nil

DISCUSSION

The first aim of this study was to examine nature of the source of clay of the archaeometallurgical ceramics. The similarity in chemical composition of the iron smelting and refining furnaces and tuyères from Mkumbi strongly shows the raw materials were procured from a possibly termite mound clay source with similar geochemistry or geological formation. Earlier studies have also reported smelting furnaces were mostly located near termite mounds (Barndon, 2004). According to Mapunda (2010: 73), termite mounds were commonly used as sources of clay for furnace and tuyère making. Through repeated experience, the smelters and refiners were aware of the good refractory quality of the termite mounds clay (Hein *et al.*, 2007). One can argue that it is difficult to envisage why could have the smelters and refiners travelled long distances to procure clay for smelting furnaces and tuyères making other than using the available refractory termite mounds clay (Iles, 2011; MacDonald *et al.*, 2009). This thinking is strengthened by the fact that *malungu* furnaces were large in size - 3 m high and external diameters at the base averaging 1.5 meters whose construction was extremely labour intensive. Mkumbi smelters and refiners selected what Matson (1965) termed ceramic ecology – the availability of naturally functional clays for making ceramics. According to Killick (1990), in Malawi, which is relatively close to the study sites, termite mounds clay has been verified to have good refractory quality. Chen (2006) found out in Taiwan that clay from a similar source was indeed used to manufacture different ceramics (Montana *et al.*, 2011). It has been also reported smelters consistently selected the western location of termite mounds for smelting furnaces due to socio-cultural beliefs (Mapunda, 2010). The Fipa of Sumbawanga envisage their environment and culture as engendered bipolar world (Mapunda, 2010). Therefore,

the location of smelting and refining sites near termite mounds was due to both technical and socio-cultural reasons.

The question that there was a trivial contrast in chemical composition between Itaka smelting and refining furnaces and tuyères needs rigorous examination. One plausible explanation is that the refractory clays were not procured from a single source. Another possibility could be termite mounds used had slightly different geochemistry. There is, however, one inherent problem with this proposal; if the furnace termite mound was refractory, why the smelters did not use it to make refractory tuyères? The slight contrast in the chemical composition between the furnaces and tuyères was possibly due to either difference in clay sampling or preparation methods. This is posited as such because – as it was in Ufipa - the iron smelting and refining furnaces in Itaka in Unyiha were respectively referred to as *malungu* and *vintengwe* (Brock, 1966, 1968; Brock and Brock, 1965) and the smelting and refining sites were similarly located in very close proximity to termite mounds (Lyaya, 2010; Brock and Brock, 1965). So, it is difficult to propose that termite mounds were not used similarly to make tuyères.

The second aim was to determine whether there were multiple clay sources for making the archaeometallurgical ceramics. The slight difference in geochemistry between Itaka smelting and refining furnaces and tuyères when compared to potteries is essentially discussable. According to Jonas Elia Mwanakulya (77 years in 2012) – a son of a famous actual iron smelter in Itaka - iron smelters and refiners were not potters. They did not make potteries for smelting and refining purposes. Potteries were outsourced from specialised potters in Mbozi. Potteries in the *malungu* and *vintengwe* region were employed in metal production for ritual and personal uses. Even though the potteries plot in the mullite region on the ternary system, it is possible that the potteries were made from different sources other than termite mounds. This

finding is supported by the chemical compositions used to isolate chemical groups of ceramics, signifying the use of different sources of clay (Dikomitou-Eliadou *et al.*, 2016; Baria *et al.*, 2015; Frankel and Webb, 2012). In addition, it is important to strengthen this point based on a mineralogical study. Unfortunately, mineralogy was beyond the scope of this paper; it forms an avenue for a future research. However, the reader of this article is reminded that according to oral evidence, the making of smelting and refining furnaces and tuyères in Ufipa and Unyiha did not involve tempering of termite mounds clay with other materials; the termite mounds clay was self-refractory (Mapunda, 2010).

The third aim was to verify the refractoriness of the archaeometallurgical ceramics through three re-firing experiments in the furnace lab. Based on the estimated temperature for archaeometallurgical processes of 1200 – 1300 °C, it is logical to argue archaeometallurgical ceramics from this study had good refractory quality for iron production and hence their selection. They functioned effectively because the estimated temperature from the ternary diagrams ranged 1600 – 1700 °C (Figure 2). This proposition is strengthened by the experimental results of re-firing the samples in the furnace laboratory, none of the samples bloated, and none was inspected and found with any signs of vitrification at the three-round temperatures of 900 °C, 1200 °C, and 1300 °C (Table 4). According to Hein *et al.* (2007), re-firing of pottery bloated at 1200 °C. It means that the samples were resistant to conditions for bloating. It appears that the samples had good mechanical strength for the archaeometallurgical processes similar to studies by Müller *et al.* (2010), Tite *et al.* (2001) and Kilikoglou *et al.* (1998).

CONCLUSION AND RECOMMENDATION

AND

This study makes three conclusions. First, iron smelters and refiners selected refractory clays for making the archaeometallurgical ceramics. Second, the furnaces and tuyères were procured from a single clay source with a similar geochemistry, while potteries were procured from another geochemical clay source. Third, the archaeometallurgical ceramics were verified refractory through the re-firing experiments in the furnace lab; they did not bloat at maximum pre-industrial iron smelting and refining temperatures of 1300 °C. In terms of a future research avenue, this study recommends a mineralogical study of the archaeometallurgical ceramics.

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