Early Iron Age iron-smelting debris from Rwanda and Burundi, East Africa

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ABSTRACT: Iron smelting is attested from at least the first part of the 1st millennium BC in both West and East Africa. In both regions the earliest furnaces seem to have been the slag-pit type. In this study the slags and furnace remains from such a furnace have been studied. The clays used for the furnace structures and for the tuyères were not especially refractory. Fayalite and hercynite with some wüstite were the main phases present in the slags, with compositions suggesting either the deliberate addition of clay as a flux or a significant clay contribution from the refractories. Such slags are known from contemporary and more recent African smelting practice. The significant differences in the slag mineralogy were found to be due to quite minor differences in composition rather than real variations in the processes carried on at the various sites studied.

Introduction

This article continues the archaeological research into the Early Iron Age Urewe culture in Rwanda and Burundi (Figs 1a and 1b), in which one of us (M C Van G) has for a number of years proposed new insights regarding the chronology (Van Grunderbeek 1992), ceramics (Van Grunderbeek 1988), environment (Van Grunderbeek and Doutrelepont 1989), agriculture (Van Grunderbeek and Roche forthcoming), way of life, society, degradation of the environment as a consequence of human activity, and iron-smelting technology (Van Grunderbeek *et al* 1983 and 2001). The study of early iron smelting in the region continues with the survey etc of Jane Humphris, Institute of Archaeology, UCL, London. The subject of this paper is the iron-smelting technology, concentrating on scientific analysis and interpretation of the ores, slags and refractory materials from the furnaces.

The development of iron smelting south of the Sahara embodies some of the most significant questions in the whole of archaeometallurgy. The possibilities of an independent invention of iron smelting cannot be easily dismissed, and the range of smelting methods employed, many apparently unique to Africa, are of continuing interest (Descœudres *et al* 2001). The study is further enhanced by the strong ethnographic contribution. Traditional iron-smelting operations were still conducted in many parts of Africa until the recent past; some were recorded whilst still working and in others the former operatives have taken part in smelting replications, thereby adding another dimension to the interpretation of the archaeological remains of smelting generally (Herbert 1993; Schmidt 1997). There is a wealth of information concerning the more social and ritual aspects of the processes and on the gender, role and status of the smelters and smiths. These more ritualistic aspects are hinted at in some of the surviving early records from other parts of the world, but surprisingly little has been recorded from traditional smelting and other metallurgical operations outside Africa. This is especially true of South Asia where the many 19th- and early 20th-century descriptions of mining and smelting activities, mainly made by geologists, almost totally ignore the social and ritual aspects. Knowledge of the often elaborate symbolism and complex ritual recorded in Africa must give pause when interpreting prehistoric remains in a purely functional manner. Turning specifically to the iron-smelting remains of the Urewe culture in Rwanda and Burundi, it has to be stated that no

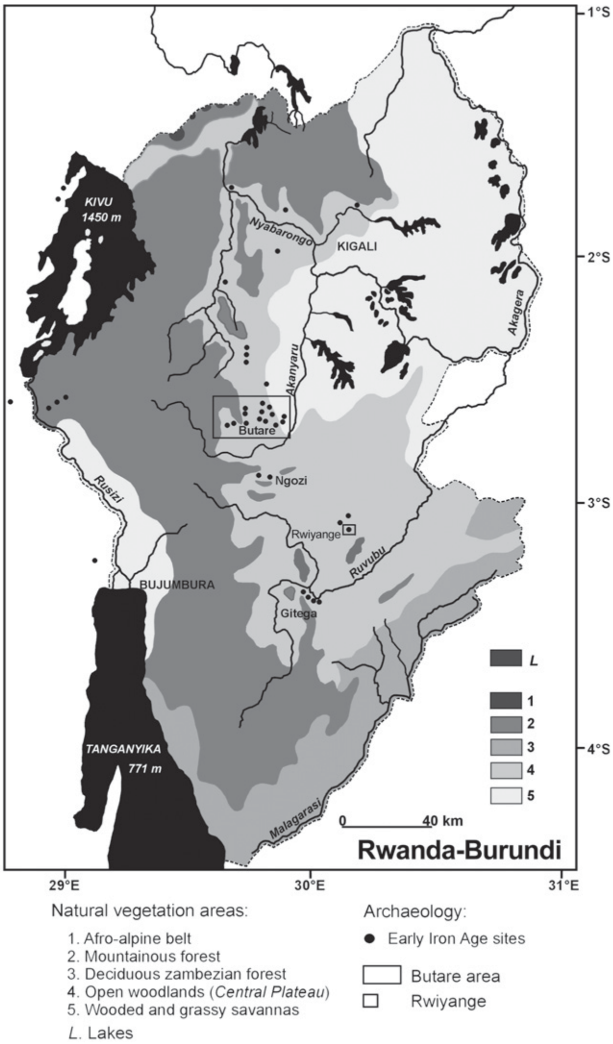

Figure 1a Location of the Early Iron Age Urewe sites in Burundi and Rwanda. They are concentrated on the Central Plateau with good agricultural soils and easy access to iron ore and to wood.

non-functional or ritualistic elements have been found. There is only the decoration on some of the clay rolls of the furnace wall, somewhat complementing the spirit of the decoration of the neck and rims on some Urewe pots (Van Grunderbeek *et al* 2001). However, at Buhaya in north-western Tanzania, adjacent to Burundi, small holes were found in the centre of some of the Urewe slag-pit furnaces dated to the first part of the 1st millennium AD (Schmidt 1997, 253). The holes were no more than about 100mm in diameter and about as deep in the floor of the pit itself; most were empty, but a few contained pieces of slag. These could, as Schmidt suggested, have originally contained a 'medicine', but equally they could originally have held a central post to support the furnace during its construction, that was removed prior to the smelt. A pot was found beneath the slag pit of the Early Iron Age (but non-Urewe) iron-smelting furnaces at Kabuye II and Mutwarubona II, dated to about the 6th century AD (Van Grunderbeek *et al* 2001).

This paper concerns the scientific examination of material excavated from iron-smelting sites associated with Urewe culture material. The study was undertaken to learn something of the operating parameters and chemistry of the processes at the beginning of iron smelting in Africa. Iron smelting seems to have commenced in this region early in the 1st millennium BC at the latest, and flourished in the early 1st millennium AD up to about the 7th century AD (Van Grunderbeek 1992; Van Grunderbeek *et al* 1983 and 2001). This is

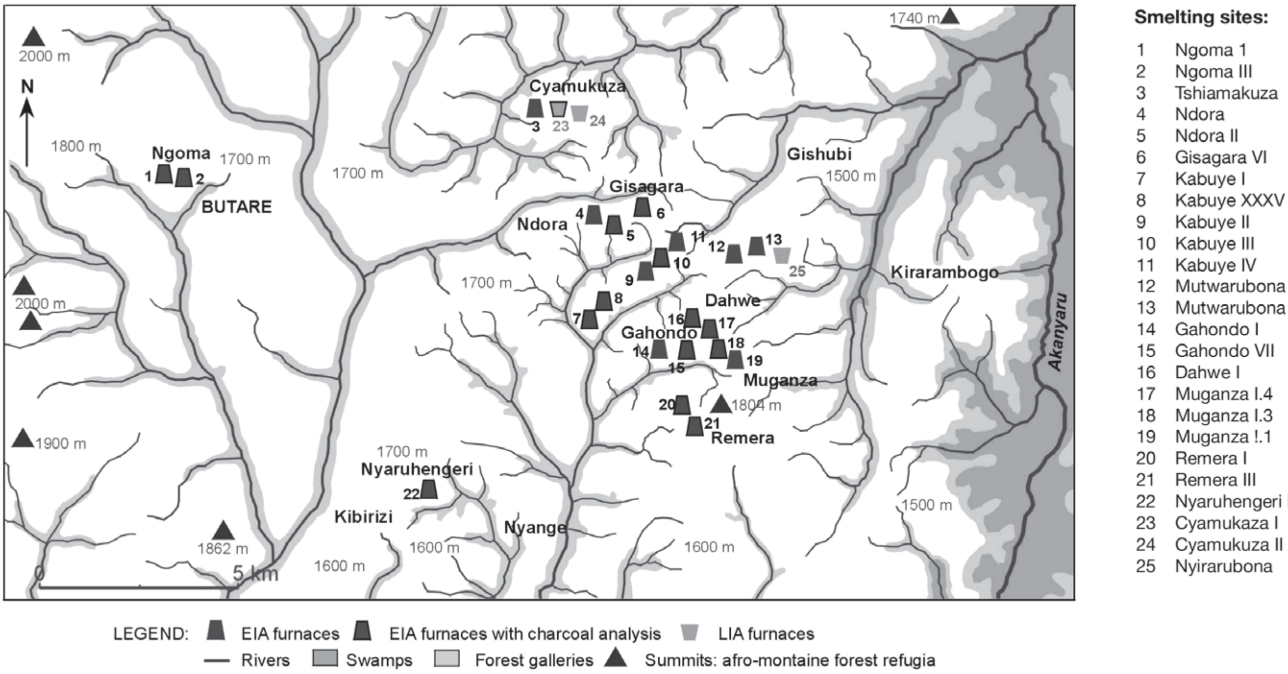

Figure 1b: The Butare area of Rwanda. The samples examined come from Nyaruhengeri I (no 22) and Muganza I.1 (no 19).

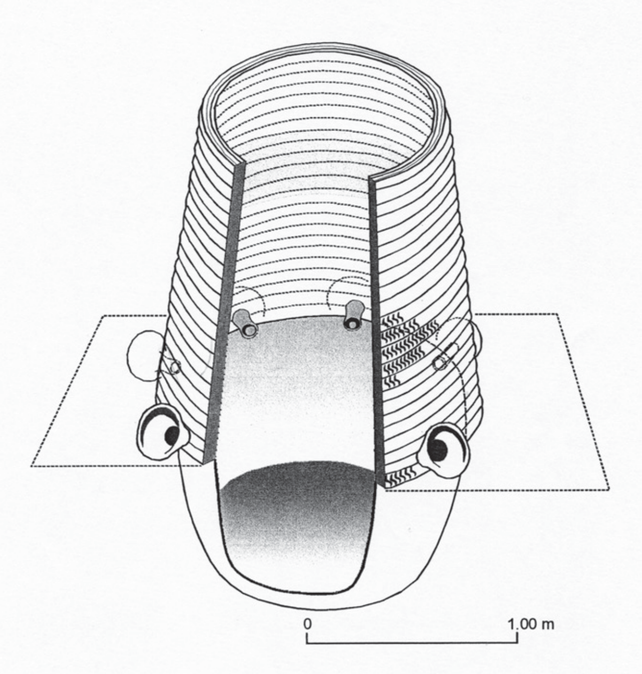

Figure 2: Reconstruction of a typical large Urewe furnace built of large rolls or coils of clay, based on the excavated slag pits and the material within them. (Updated from Van Grunderbreek et al 1983, fig 2).

based on radiocarbon dating of charcoal associated with the furnaces. There have been problems with the radiocarbon dating of early smelting installations in parts of Africa (Killick *et al* 1988). In the arid regions of the Sahel, dead trees can survive for many years, leading to dates that could be centuries too early for the features in which the charcoal had been found. However, in the much wetter conditions prevalent in Rwanda and Burundi such survival of dead wood is very unlikely. Moreover, green wood has always been favoured for charcoal making, and the charcoal examined from the furnaces suggested that it came from trees no more than 300mm in diameter.

The very origins of iron smelting south of the Sahara remain uncertain (*eg* Childs and Killick 1993; Craddock 1995, 261–5; Holl 2000; Alpern 2005) with many potentially important areas unsurveyed and problems with the interpretation and physical dating of some sites that have been investigated (Killick *et al* 1988). Another major problem has been the absence of contemporary early smelting evidence from the Mediterranean, Near and Middle East. There, iron artefacts abound but very little smelting evidence has been identified to date. In both West and East Africa there are smelting sites which should date from the first half of the 1st millennium BC at the latest (Van Grunderbeek 1992).

Figure 3: Typical slag pit filled with slag and the ceramic clay rolls and tuyère fragments from the upper parts of the furnace. Ngoma 1, Rwanda. Scale bar 0.3m. (Photo: M-C Van Grunderbeek)

Some of these early African smelting sites have furnaces which are of the distinctive slag-pit type (Fig 2). Specifically, the shafts of the furnaces were built over a pit dug into the ground filled with plant matter such as grasses or reeds into which the slag sank (see below). The smelting pits are often found still containing the plug of slag together with remains of the upper parts of the furnace that had fallen in (Fig 3). Thus, they are archaeologically very distinctive and, unlike many other smelting operations, evidence for them should survive and be easily recognised, but there is no record of them north of the Sahara. Very recently an iron-smelting site dating to the 10th century BC has been excavated at Tell Hammeh (az-Zarqa) in Jordan but it was not of a slag-pit furnace (Veldhuijzen and Rehren forthcoming), although there were similarities in the fluxing of the slag (see below). Slag-pit furnaces are known from the Iron Age of Central Europe at approximately the same date as in Africa (Tylecote 1987, 154–6; Pleiner 2000). Tylecote made the ingenious suggestion that ‘It is possible that these furnaces represent the sole remains of a type which spread out from Anatolia around 1000 BC westwards and both northwards and southwards as far as Sweden and Nigeria’. However, the absence of anything like a slag-pit furnace from the Mediterranean, Near or Middle East would seem to preclude this idea. It really would seem that in both Africa and central Europe the slag-pit furnace represents a purely local innovation.

A problem with ascribing an independent discovery of iron smelting to Africa may be in the physical chemistry of the solid-state iron, or bloomery, smelting process. In this the tiny particles of iron metal form and coalesce within the slag which protects them from re-oxidation. Thus a liquid slag is necessary for the process and, no matter how indirectly, it seems that iron smelting arose out of the fully-slagging processes that were being used to smelt copper from the third millennium BC in the Near and Middle East (Craddock 1995). As yet there is no evidence for such processes operating south of the Sahara at such an early date. The precocious production of copper in the Agadez region of Niger seems to have mainly involved the melting of native copper and apparently very little slag was produced (Bernus and Echard 1985; Killick *et al* 1988). In fact, it is possible that the development of the true slagging processes for smelting copper ores that seem to have evolved from the end of the 1st millennium BC in Africa (Herbert 1984; Miller and van der Merwe 1994) may be derived from the iron-smelting furnaces.

Claims for the unique nature of African iron smelting have focused on some of the East African processes, sometimes with rather controversial interpretations of the process mechanisms. It has been postulated that the function of the grasses in the pit below the slag was vital to the formation of the metal, actually reducing some of the iron oxides and iron silicates of the slag to iron to form the bloom, as well as to carburize the iron to form steel (Avery and Schmidt 1979; Avery *et al* 1987). On a purely common sense basis it seems inherently unlikely that the grasses can have contained enough carbon to sustain such activity for the many hours duration of a smelt. The likely nature of the bloomery process has been described by Killick and Gordon (1988) and the function of the slag pit just to contain the slag, as understood in Europe, is described by Pleiner (2000, 149–50).

Another contentious issue has concerned the pre-heated blast. The various arguments whether any significant warming could take place whilst the air was in the tuyère, thus delivering a hot blast, are discussed in various papers (Schmidt 1996). In most simple smelting operations the air was delivered from the bellows straight into the furnace through the clay tube known as the tuyère, which protruded a short distance, if at all, through the furnace wall. Thus the air was delivered cold into the fire. Many ancient and more recent tuyères from African iron smelting operations are notably longer than usual, and are vitrified on their outside for part of their length, showing that they must have protruded a considerable way into the furnace. This led to the suggestion that the air would have been significantly heated during its passage through the tuyère and thus a hot blast would be delivered to the fire, notably improving the efficiency and maximum temperature. Hot-blast iron smelting is redolent of the Industrial Revolution and the comparison was made with the Cowper stoves of the early-19th century (Gale 1966, 69–75). These took the hot flue gases escaping from the furnace and used them to heat the air entering the furnace, but the heat exchange proposed in the hot tuyères is of course very different. There, any heat absorbed by the tuyères to heat the blast was being taken from the fire around them, not from heat that had left the system; at best the tuyères were robbing Peter to pay Paul. The unusual iron-smelting furnaces at Mafa in North Cameroon are an exception to this. The long tuyère penetrated down into the furnace from its top and so would have been heated by the rising flue gases that were otherwise going to waste. Whether any heat exchange took place is not known (David *et al* 1989). Overall, it does seem unlikely that there was significant heating of the blast (Killick 1996). The probable reason for the tuyères protruding into the furnace was the size of the furnace. At over a metre in diameter and using the relatively low-powered pot bellows, the only way to ensure that the blast penetrated to the middle of the fire was by laying the tuyères almost to the centre.

The Urewe furnaces

The Urewe furnaces from Rwanda and the slags from Burundi studied here are of the slag-pit variety with typically only the pit surviving, but which often contains substantial fragments of the upper parts of the furnace, including fragments of the clay rolls or coils from which they were built (Fig 4a) and tuyères (Fig 4b), as well as the slag that had settled in the pit (Fig 3). At the Muganza site 1, 3rd furnace, fragments with flat bases from the lowest layer of the shaft were found, some of which showed the imprint of the tuyère where it changed from conical to cylindrical shape. The tuyère fragments fitted into these negatives perfectly (Figs 4b and 5). The pits are circular and vary in diameter from 0.8–1.2m at the surface and are 0.4–0.7m deep (Fig 7). It is possible that some of the shallower pits could have been hearths to anneal the smelted iron bloom during the bloom-smithing operations which followed the smelting.

The conical clay superstructures were built up of rolls of clay that are approximately 50mm thick (Fig 4a). They are sometimes decorated on their outer surfaces with simple designs impressed into the unfired clay, possibly produced during the pressing of the clay in order to strengthen the junction. Somewhat similar patterns were found on the clay rolls used to form the shaft of the Romano-British furnaces at Laxton in Nottinghamshire (Crew 1998). The top layer was finished with longitudinal parallel flutes on the upper surface, sometimes running down on to the convex outer side.

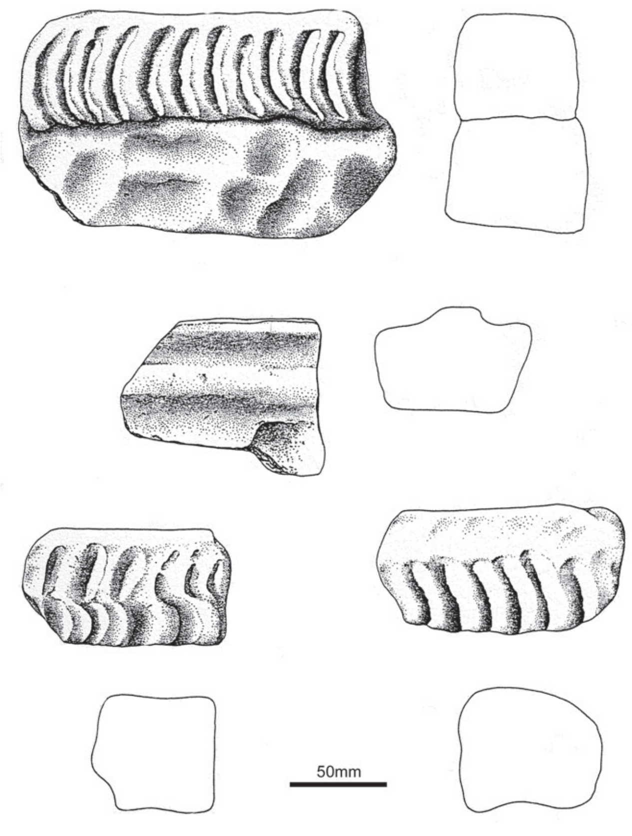

Figure 4a: Typical roll pieces from the slag-pit fillings.

It is calculated that the inclination of the cone walls was on average approximately 84° to the vertical. This figure is based on the inclination measured on three roll fragments which were still joined and placed upright onto the bottom roll with its flat base. Where sufficient of the distinctive rolls forming the rim survived, it was possible to calculate the diameter, and assuming the 84° angle was constant through the height of the shaft, the height could calculated; for the larger furnaces it was up to approximately 1.35m. Depending on their size it is estimated that the furnaces had between three and eight tuyères arranged radially. Those in the smaller furnaces were at ground level at the junction of the pit and the furnace shaft (see Figs 2, 5 and 6, and also Van Noten 1983, fig 33) and were horizontal, but in the larger furnaces it is believed that they were set between the basal and second circuit of rolls of the furnace wall at an angle of 30° to the horizontal (Van Grunderbeek *et al* 2001, fig 12). The surviving tuyères are all very eroded by the process, but based on some of the more recent furnaces and the smelting replications, it is believed that originally the tuyères would have protruded into the furnace for at least 300mm (Devisse and Vansima 1988). The form of the bellows is not known; pot bellows

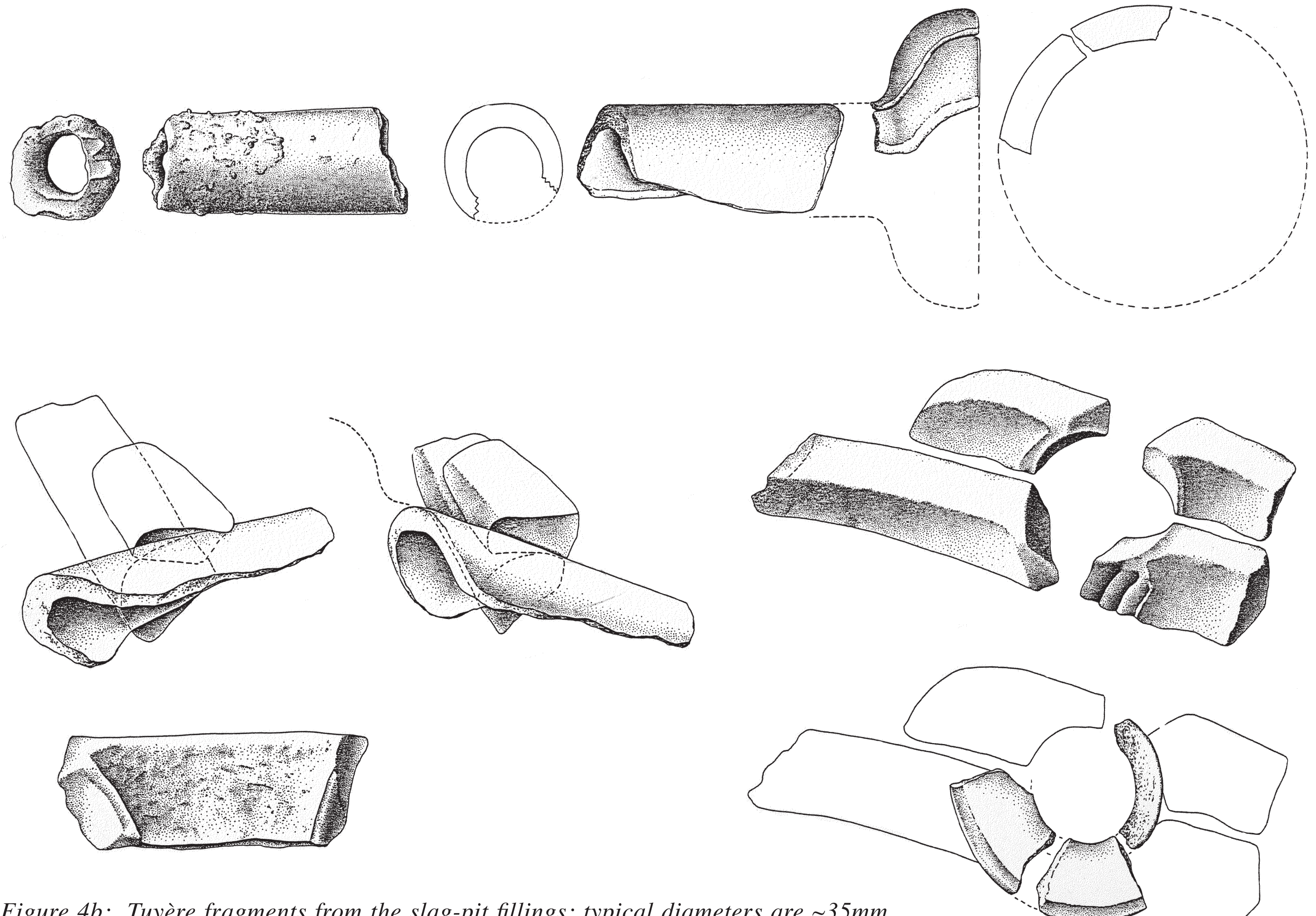

Figure 4b: Tuyère fragments from the slag-pit fillings; typical diameters are ~35mm internally and 50–60mm externally. The roll pieces fit round them, holding them in place.

Figure 5: Slag pit furnace with lower part of the furnace wall surviving and one tuyère still in situ. Gisagara VI, Rwanda. Scale bar 0.3m. (Photo: M-C Van Grunderbeek)

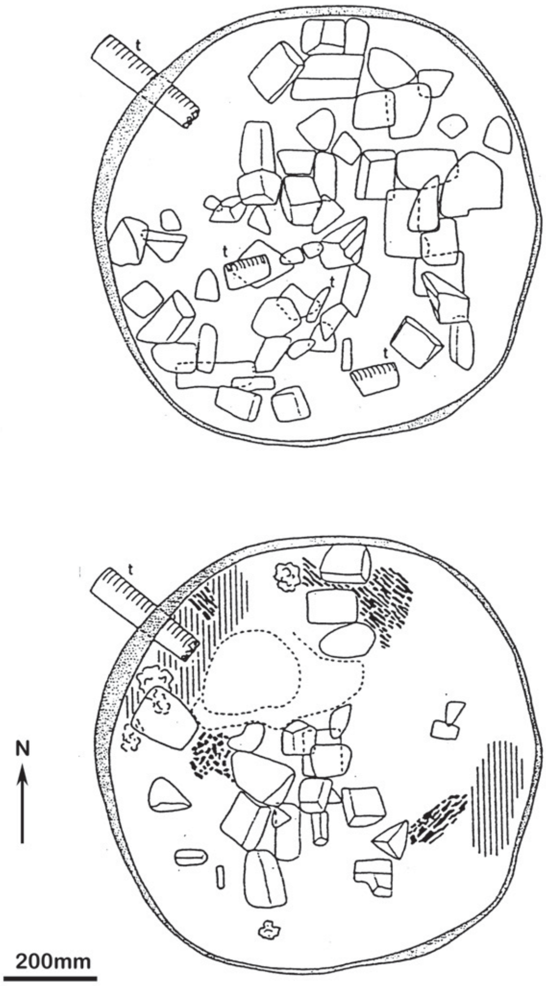

Figure 6: Plan at two levels of the furnace at Gisagara VI, Rwanda, with a tuyère still in situ.

were common in the recent past for smelting in Africa and are still used by traditional blacksmiths.

Prior to smelting, the pits were filled with grasses and reeds; the charred impressions of papyrus have been identified in the slags (Van Grunderbeek and Doutrelepont 1989). During the smelt, the forming slag would settle on top of the grass packing. The heat of the slag would not be lost as it would be in a slag-tapping furnace. In the absence of air the packing would slowly char rather than burn and thus allow the slag to sink at a uniform rate into the pit. If correctly judged, this would ensure that slag levels within the furnace proper, so vital for the formation of the iron bloom, were maintained at a constant height.

A small pit at Remera I and II was excavated that had contained logs of wood (Van Noten 1983). This could be the remains of roasting operations where the iron ore was roasted prior to smelting or, just possibly, it could be the remains of charcoal burning which in Africa was often conducted in pits (Herbert 1984, 53; Avery *et al* 1987).

Scientific examination

The material

Examples of the clay rolls used to construct the furnace shafts, fragments of tuyères and samples of slag were available from three sites, Muganza (MUG I.1) and Nyaruhengeri (NYG I) in Rwanda (Fig 1b) and Rwiyange (RWI I) in Burundi (Fig 1a). In addition, examples of local pottery from Nyaruhengeri and Rwiyange, and samples of 'good' and 'bad' iron ore from Butare region, Rwanda (about 10km from Nyaruhengeri) were also analysed. A summary of the samples examined is given as Table 1.

Techniques

Samples of the ceramic materials (in general, fragments showing evidence of the most advanced degree of firing were selected) were prepared as thin sections and/or polished sections for examination by optical microscopy and in a scanning electron microscope (SEM; JEOL JSM840) equipped with an energy-dispersive X-ray analyser (EDXA; Oxford Instruments). The samples of slag and iron ore were similarly prepared for phase analysis using transmitted and reflected polarised light microscopy and elemental analysis in the SEM using EDXA. Bulk chemical analyses were obtained by rastering the electron beam over areas of about 20 mm^2.

Observation of the degree of vitrification of ceramic material in the SEM, coupled with a knowledge of its chemical composition (which can be obtained by EDXA) can provide an indication of the maximum temperature to which the ceramic has been exposed during firing or subsequent use (Maniatis and Tite

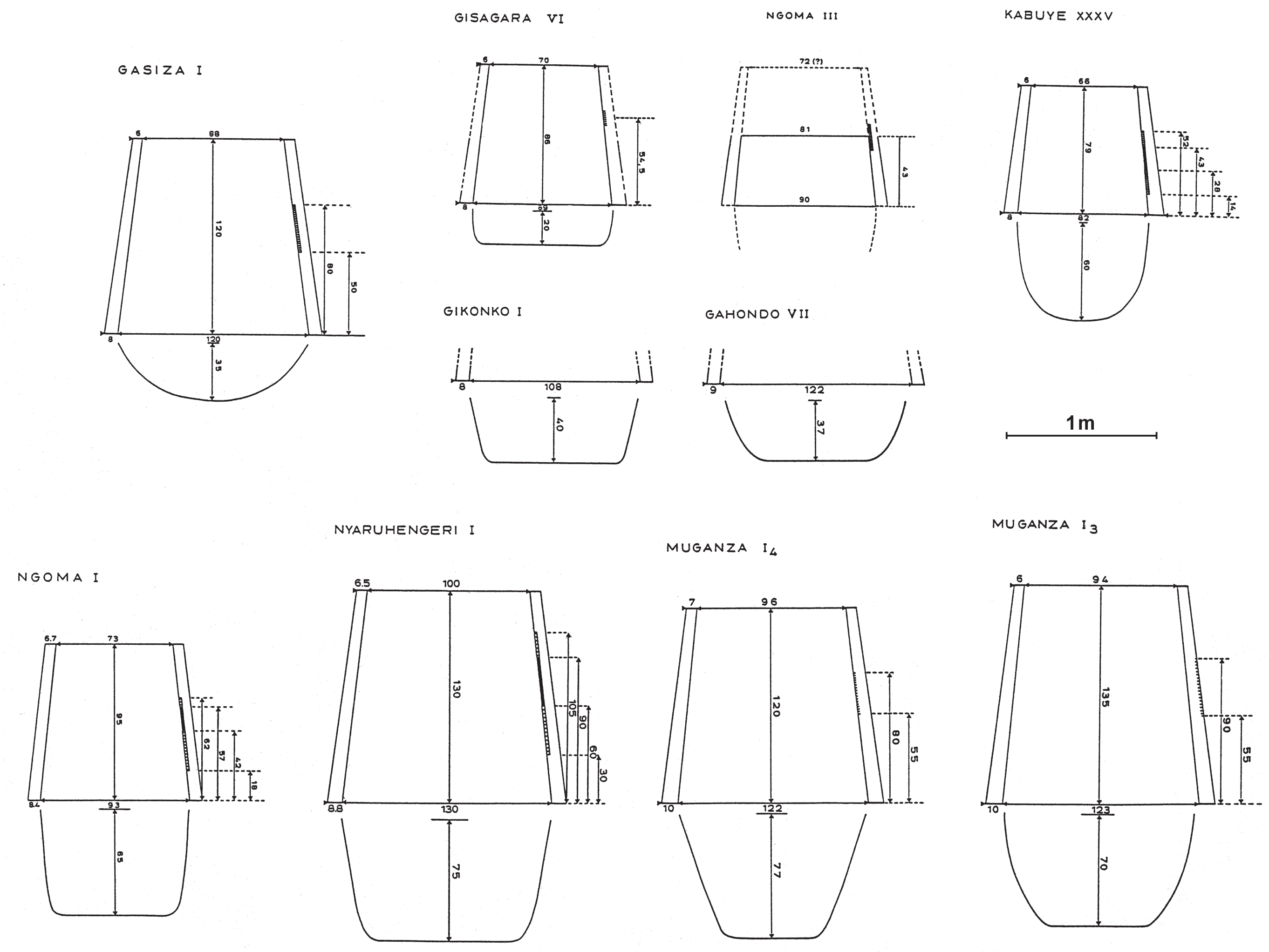

Figure 7: Sections of a series of excavated slag pits, with reconstructed superstructures.

Table 1: Samples analysed

Site	Sample no	Laboratory no		Nature of sample
Nyaruhengeri	NYG 1	22278	V	shaft roll
	80 NYG NV4	22279	T	tuyere
	79 NYG NV3	22280	W	potsherd
		22281	U	iron ore ‘good’ *
		22282	S	iron ore ‘bad’ *
		22283	Q	slag (ropey)
		22284	Z	slag (platey)
		22285	X	slag (scoriaceous)
Muganza	MUG I.1	27089	Y	shaft roll
	MUG I.1	27090	Q	slag
	MUG I.1	27091	Z	tuyere
Rwiyange	RWI.1	27092	X	shaft roll
	RWI.1	27093	V	tuyere
	RWI.1	27094	T	slag
		27095	R	potsherd

Note: * The ore samples are from Butare region, about 10km from Nyaruhengeri

1981; Tite *et al* 1982 for details).

The ceramic materials

Petrographic examination of the furnace materials indicated that they had been made from unrefined clays, heavily tempered with coarse quartz sand. The clay used to produce the shaft roll from RWI is unusual in being highly micaceous. The fabrics of the tuyère fragment and potsherd from this site are similar to each other and are distinctive in containing common fragments (up to several millimetres across), thought to be a ‘ferruginous laterite’, probably added deliberately as temper.

The examples of rolls from the furnace shafts at NYG and MUG were made from non-calcareous, fairly refractory (*ie* low-alkali) clays and show no evidence of any vitrification. However, the RWI shaft roll made from highly-micaceous (and hence low-refractory) clays has a continuously vitrified texture with fine bloating pores (up to 10µm diameter) at its ‘hot’ surface.

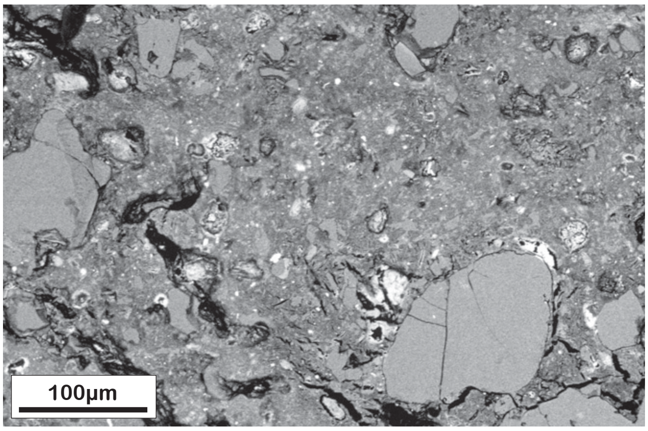

Figure 8: Back-scattered electron (BSE) image of tuyère from Rwiyange (27093) showing inclusions of quartz (mid grey) in an unvitrified clay matrix .

The tuyères from the three sites (Tables 1 and 3) are also of variable refractoriness and exhibited textures ranging from no vitrification (RWI, Fig 8) to continuous vitrification with coarse bloating pores (40–100μm in diameter) in the NYG sample (Fig 9).

Table 2: EDX analyses of slags (wt%)

Site	NYG	NYG	NYG	MUG	RWI
Laboratory No	22283	22284	22285	27090	27094
SiO_2	17.4	21.5	17.7	28.9	13.5
TiO_2	0.9	0.6	0.4	0.5	<0.3
Al_2O_3	9.0	9.9	10.4	10.1	10.3
FeO	66.2	62.4	66.3	57.5	71.5
MnO	2.9	0.4	<0.3	<0.3	<0.3
MgO	0.3	0.3	0.5	0.2	0.2
CaO	1.0	1.9	1.8	1.6	2.6
K_2O	0.4	0.7	0.7	0.4	0.8
Na_2O	0.5	<0.4	<0.4	<0.4	< 0.4
P_2O_5	1.3	1.8	1.5	<0.3	0.4

Table 3: Compositions of ceramic tuyères from each of the smelting sites (wt%)

Site	NYG	MUG	RWI
Laboratory No	22279	27091	27093
SiO_2	71.8	60.9	52.6
TiO_2	0.7	0.9	2.0
Al_2O_3	19.8	26.5	35.3
FeO	3.9	8.6	8.1
MnO	<0.3	<0.3	<0.3
MgO	0.4	0.5	0.2
CaO	0.3	0.4	0.5
K_2O	2.6	0.9	0.3
Na_2O	<0.4	0.7	<0.4
P_2O_5	<0.3	<0.3	<0.3

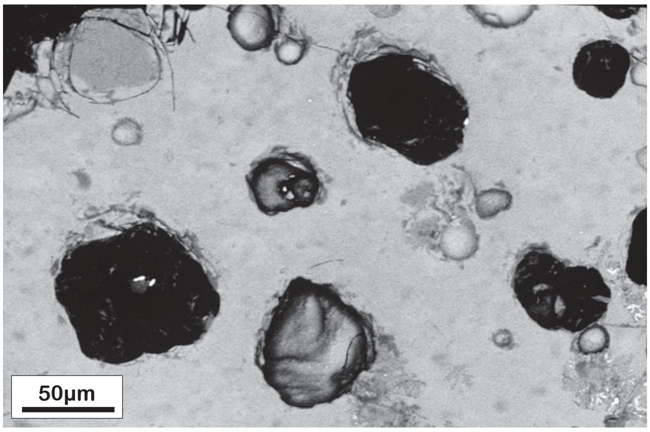

Figure 9: BSE image of tuyère from Nyaruhengeri (22279) showing continuously vitrified texture with coarse bloating pores.

Comparison of these observations with existing data on clays of comparable compositions suggest that the furnace rolls achieved temperatures up to about 1000°C, whilst the tuyères were exposed to higher maximum temperatures in the region of 1150–1200°C.

The chemistries of the clays used to make the refractories suggest that their refractory properties were relatively variable, but on this admittedly small sample there is no evidence for the deliberate selection of raw materials for their refractory properties. For instance, it might be expected that the shaft rolls, which appear to have been well removed from the hottest part of the furnace, would be of consistently lower refractoriness than the tuyères, which would have been closer to the seat of the reaction. However, this is not the case, and it seems probable that clays which were locally available in suitable quantities were used indiscriminately for making the rolls used to build the furnace shafts. The similarity between the fabrics of the tuyère and the potsherd from RWI perhaps indicates that (at this site at least) the selection of clays for making tuyères depended on their suitability as potting clays (which could be successfully used to make the relatively thin-walled tuyères) and upon properties such as plasticity and green strength.

The slags

Mineralogy

The following minerals are present in the slags:

- Fayalite (Fe_2SiO_4) is a major phase in all of the slags examined. In addition to the FeO and SiO_2, it contains most of the MnO and MgO and some of the CaO in the slags.
- Hercynite ($FeAl_2O_4$) is present in all samples but subordinate to the fayalite. It has iron in excess of the stoichiometric value, indicating the presence of some magnetite Fe_3O_4 in solid solution with the $FeAl_2O_4$

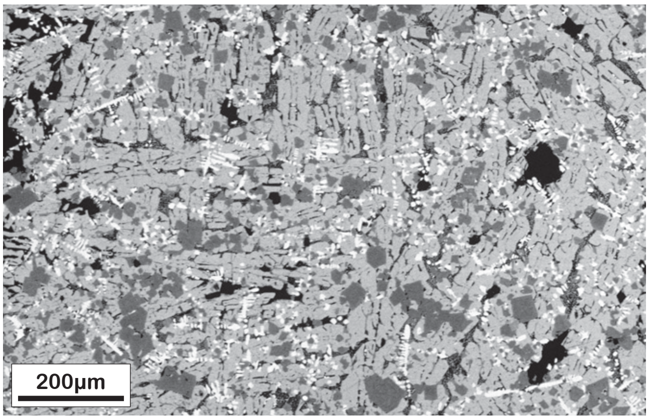

Figure 10: BSE image of slag from Nyaruhengeri (22284) showing dendritic wüstite (white), abundant fayalite (light grey), hercynite (dark grey, flat faces) with some interstitial glass (black).

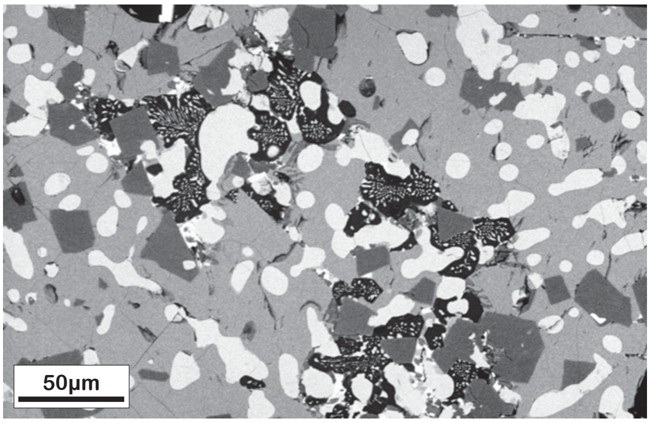

Figure 11: BSE image of slag from Nyaruhengeri (22283) showing wüstite (light grey), fayalite (mid grey), hercynite (dark grey) and leucite (black) with symplectitic inclusions of wüstite.

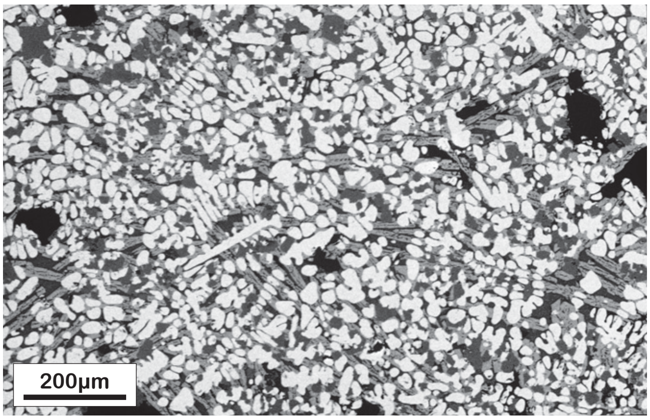

Figure 12: BSE image of slag from Rwiyange (27094) showing abundant wüstite (light grey), skeletal fayalite (mid grey), hercynite (dark grey) and glass (black).

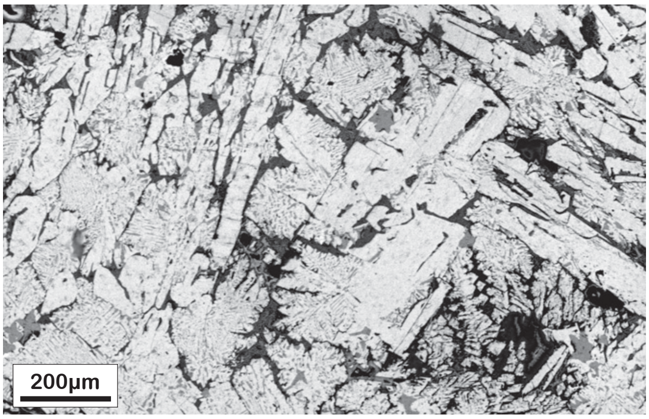

Figure 13: BSE image of slag from Muganza (27090) showing complex intergrowth of fayalite (light grey) and hercynite (dark grey) in a matrix of devitrified glass (black).

component. This phase contains most of the Al_2O_3 and TiO_2 in the slags, as well as a little MgO and MnO.

- Wüstite (FeO) is a reduced oxide of iron and varies considerably in concentration between slags. Essentially there are no other chemical constituents.
- Interstitial (silicate) glass is present in most of the slags in minor quantities and contains those elements which are not present in crystalline phases. Typically it contains 30–40% SiO_2, 20–30% FeO, 10% CaO and 10% Al_2O_3 along with most of the K_2O and P_2O_5. The glass is commonly devitrified but the crystals are too fine to identify in the SEM.
- In addition, fine grains of metallic iron were present in every slag examined. These are possibly the residuum of the iron platelets that were not incorporated into a forming bloom, or formed as the slag cooled in the pit beneath the furnace.
- Minor phases identified in individual slags include leucite ($KAlSi_2O_6$), an apatite-like phase ($\sim Ca_{10}P_6O_{25}$) and pyrrhotite (FeS).

Petrography

The inter-relationships and distribution of minerals within the slags were shown by petrography.

The three slags from Nyaruhengeri (NYG) showed similar features with common dendritic wüstite and equant anhedral hercynite poikilitically enclosed in abundant fayalite with minor interstitial material (Fig 10). Interstitial glass or leucite occurs with the fayalite, and the leucite shows a symplectitic structure with included wüstite (Fig 11). One example (22785X), which was of a more cindery or scoriaceous appearance in a hand specimen, contained large areas poorer in wüstite and hercynite and richer in leucite and glass (Note that these areas were avoided when obtaining a chemical analysis of the slag).

The slag from Rwiyange contains much more abundant wüstite than any of the NYG samples. Fayalite and hercynite are common, with an interstitial glass, but wüstite is the dominant phase (Fig 12).

The sample from Muganza differs from the other slags in that it contains no wüstite. Instead there is a complex intergrowth of fayalite and hercynite with a devitrified glass phase in the interstices (Fig 13).

Considerable evidence of alteration (leaching) of the slags was observed. This took the form of linings of goethite (hydrated iron oxide) in vesicles and voids, and the depletion of alkalis in the interstitial glass in some areas of the samples. While the magnitude of this effect is unlikely to have affected the phase analysis, it may have resulted in the depression of the K_2O contents of the slags (see below).

Chemistry

The chemistry (major element composition) of the slags is given in Table 2. FeO (total iron given as FeO), SiO_2 and Al_2O_3 account for 92–97% of the total. FeO is dominant, as is typical for iron-smelting slags from all regions before the introduction of the blast furnace. It should be noted that a little Fe_2O_3 is present in the slags as inferred from the compositions of the hercynite (see above) but that this is not differentiated from FeO by EDXA. While Al_2O_3 is constantly high at about 10%, FeO and SiO_2 vary inversely with one another. Of the other components, CaO is consistently present at levels in excess of 1% while P_2O_5 and MnO may exceed 1% in the Nyaruhengeri slags (Table 2). MgO, TiO_2, K_2O and Na_2O are invariably present in concentrations below 1%, although in the case of K_2O this may be in part due to weathering; however, the small amount of glass in the samples suggests that the K_2O at no time greatly exceeded this level.

Discussion

The marked differences in mineralogy—notably in the wüstite content—of slags from different sites could be a reflection of differences in smelting technology or the furnace conditions attained. To investigate this possibility, the compositions of the slags have been recalculated to 100% FeO + Al_2O_3 + SiO_2 and plotted in the appropriate phase diagram (Fig 14, after Muan and Osborn 1965). The few per cent minor oxides neglected will not dramatically affect the phase relationships, but will lower the temperatures shown and probably suppress the narrow field of crystallisation of iron cordierite (Roedder 1978). The positions of the slags in the phase diagram readily account for their contrasting mineralogy. All plot in the hercynite field. Thus on cooling, hercynite is the first phase to crystallize from the slag (neglecting metallic iron), and as they are cooled further the compositions of the remaining liquids move away from the hercynite composition on the base line of the diagram. The slag from Rwiyange moves to the phase boundary between the wüstite and hercynite fields (below point S), crystallizes wüstite while moving to point S where fayalite crystallizes as the third phase. In this slag wüstite is dominant, as expected from this behaviour (Fig 12). The slags from Nyaruhengeri move to the fayalite-hercynite phase boundary above point S and move down the boundary crystallizing fayalite and hercynite until at S they begin to crystallize wüstite as a third phase. In these slags wüstite is present but fayalite is dominant (Fig 10). The slag from Muganza is separated from the others by the line joining the fayalite and hercynite compositions which means that no wüstite should crystallize from this sample. Instead it crystallizes along the fayalite-hercynite phase boundary, moving up the diagram away from point S where wüstite would crystallize. This sample in fact contains no wüstite (Fig 13) as predicted from the phase diagram. Thus although the bulk elemental compositions of the slags from the three sites are relatively similar, the chemical differences are sufficient to cause major differences in the mineralogy. The mineralogical differences do not reflect differences in smelting technology.

The materials which contributed to the slag compositions may be inferred from our understanding of smelting processes and materials in general. Most of the iron oxide represents partly-reduced ore. Two ore samples from a locality about 10km from Nyaruhengeri were analysed and found to be hematite with only 1–2% impurites of SiO_2, Al_2O_3 and TiO_2. Thus minor components in the slags such as K_2O, Na_2O, MgO and CaO were introduced in some other form, the most probable being from the charcoal used to smelt the iron (*eg* Tylecote *et al* 1977). David *et al* (1989) found that the CaO content of many African charcoals was much higher than in their European counterparts. While elevated P_2O_5, and MnO may occur in wood ashes (*eg* Sanderson and Hunter 1981) these components commonly occur in iron ores, and their relatively high concentrations in the Nyaruhengeri slags (Table 2) might reflect such a source if our ore samples are not representative, especially as the P_2O_5:CaO ratios in the Nyaruhengeri slags seem too high for wood ash. Also it is possible that the charring grasses in the slag pit introduced some material, especially SiO_2, into the slag. Although this would have played no part in the actual reduction of the iron and formation of the bloom, it would have promoted the solidification of the slag.

Silica was often added as a flux to promote the formation of smelting slags, probably as sand or crushed vein quartz. However, the Al_2O_3 concentrations of these

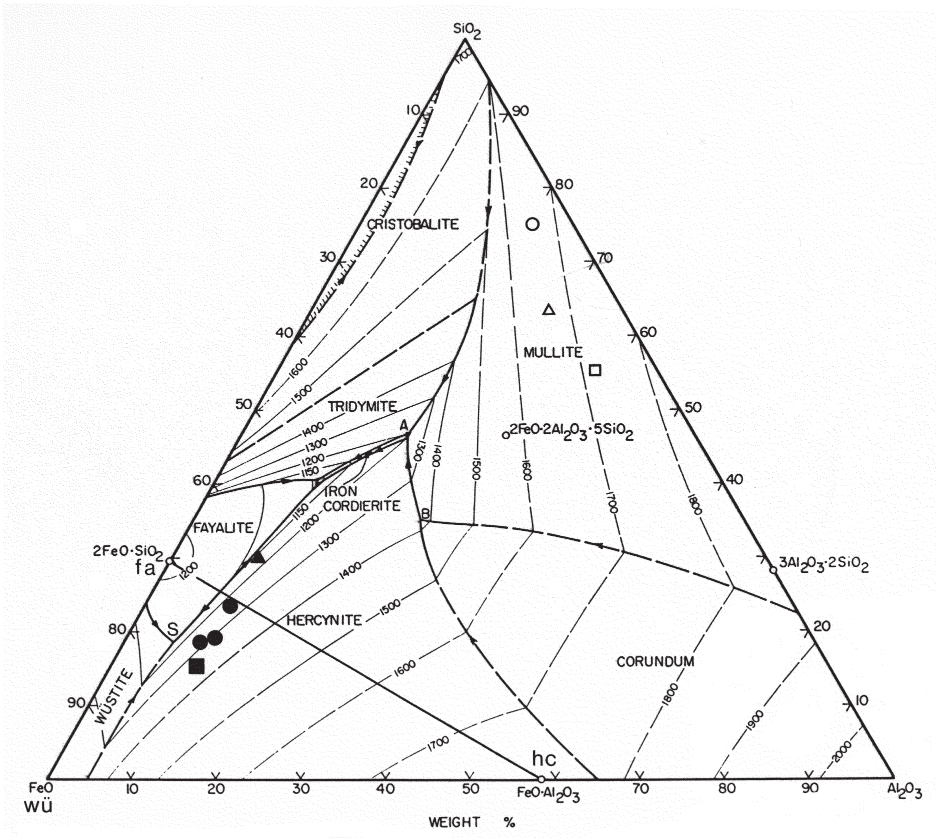

Figure 14: Phase diagram for the system FeO-Al$_2$O$_3$-SiO$_2$ (after Muan and Osborn 1965) showing the compositions of slags (filled symbols) and ceramics (open symbols) from: Rwiyange (squares), Nyarahengeri (circles) and Muganza (triangles). fa = fayalite, wü = wüstite, hc = hercynite.

slags, at around 10% are high relative to many bloomery slags, although similarly high Al$_2$O$_3$ contents do occur in certain medieval bloomery slags from Britain, produced by smelting ores with a clay-rich gangue (Morton and Wingrove 1972). Alumina contents of this magnitude do seem more prevalent in Africa. Slags analysed from iron-smelting sites in the Nsukka region of southern Nigeria spanning two millennia regularly contained similar quantities of Al$_2$O$_3$ to that in the Urewe slags, but the Nsukka iron ores used also contained aluminium and this was judged to be the source of the Al$_2$O$_3$ in the slags (Whiteman and Okafor 2003). The slag produced by traditional iron smelters, the Dimi in the south-west of Ethiopia, regularly contains substantial quantities of aluminium which again originates from the ore (Todd 1985). However, slag from the early slag-pit iron smelting site of Taruga in central Nigeria had similar quantities of Al$_2$O$_3$, but the ore contained only traces (Tylecote 1975), very similar to the situation here. It is likely that the Al$_2$O$_3$ in the slags examined here was obtained from clay, in which case most of the SiO$_2$ will have come from the same source. To test this possibility the compositions of ceramic tuyères from each of the smelting sites (Table 3) have been plotted on Figure 14. Mixtures of the corresponding clays and iron ore will lie on lines joining the FeO apex of the triangle with the tuyère compositions. It is observed that the slags lie in the appropriate part of the diagram to be mixtures of iron ore and ceramic clay and that the SiO$_2$:Al$_2$O$_3$ ratios are similar in slags and tuyères. Furthermore, the slag from Rwiyange lies precisely on the line joining its tuyère to FeO. Thus, the SiO$_2$ and Al$_2$O$_3$ components of the slags are best explained by a clay component. A pure quartz flux does not seem to have been added. The slags from Tell Hammeh (az-Zarqa) in Jordan are also believed to have been fluxed with clay (Veldhuijzen and Rehren forthcoming).

There are two possible paths by which clay became incorporated in the slag. Firstly, it could have been mixed deliberately as a flux with the charge in the form of raw clay or used furnace fragments. Alternatively, the slag could have been produced by reaction between a clay-free charge and the tuyères and walls of the furnace. The recent Mafa furnaces, described by David *et al* (1989), provide a good example of the latter. The huge tuyère weighing 20.5kg entered the furnace from the top of the shaft and initially hung all the way down. It was consumed during the course of the smelt as it acted as the flux for the forming slag. This hypothesis appears to be feasible in principle at least for the slags studied here. The purity of the iron ore analysed suggests that little slag would have been required to remove gangue, but a sufficient quantity has to be created for the bloom to form. Therefore it would have been possible to flux the slag with furnace ceramics without fatally eroding the furnace. However, arguing against this possibility is the very limited extent of slagging observed on the furnace remains (slagged layers are generally only of the order of a millimetre or so in thickness and show no signs of free running). Also only the tuyères would have been in the immediate proximity of the centre of the furnace where the slag was forming and even if they were totally consumed it is unclear if they contained enough clay to provide the total Al_2O_3 and SiO_2 for all the slag produced. Furthermore, although the Rwiyange slag is clearly a mixture of clay of composition equivalent to its tuyère and iron oxide, the slags from Nyaruhengeri and Rwiyange do not match their ceramic compositions precisely, suggesting the incorporation of additional material. This may have been gangue, or charcoal ash, or some clay similar but not identical to the tuyères. Therefore we cannot rule out a deliberate addition of clay to the charge, albeit in some cases the same clay as that used to build the furnace.

Estimation of smelting temperature from slag composition is problematic. However, the minimum temperature required to smelt a metal is indicated by the temperature required to melt the slag. In the present case, it is found that all of the slags lie below the 1350°C isotherm in the system $FeO-Al_2O_3-SiO_2$. The additional elements within the slag will lower the melting temperature further, probably by around 100°C or so. Therefore, the minimum temperatures required to melt the slag, and so allow it to flow, were of the order of 1200°C. Higher temperatures would have improved the reaction rate and lowered the viscosity of the slag and may well have been attained. Estimates of smelting temperatures based upon the degree of vitrification of furnace ceramics in general are typically of the order of 1200–1250°C (Freestone and Tite 1986). However it is unlikely that these record the temperature in the furnace hot spot immediately in front of the tuyères. Furthermore, the efficacy of ceramics as archaeothermometers fails once the temperature in the furnace exceeds that where the ceramics fail. For moderately refractory ceramics used in many archaeometallurgical installations, this limit is around 1250°C.

Some indication of the relative extraction efficiency of a process is given by the quantity of metal which is retained in the slag. On this basis the Muganza slag, with lower iron, represents a more efficient process than Nyaruhengeri which in turn was more efficient than Rwiyange. However, along with the increasing iron contents of the slags, there is an increasing $Al_2O_3:SiO_2$ ratio (Table 2, Fig 14). It is quite possible that the varying iron contents of the slags (and inferred varying efficiency of the smelts) are due to a chemical control exercised by the $Al_2O_3:SiO_2$ ratio over the FeO content of the slag, rather than due to any variations in furnace operating conditions. Furthermore, whether such differences in the yield of iron metal (that would result from such differences in slag compositions) would be significant in practice depends critically on the amount of slag produced per smelt, for which we have no data. If the weight of slag was less than that of metallic iron then the differences in efficiency are less than 10%, and may be considered negligible.

Conclusions

Examination of the ceramic materials from these iron-smelting sites suggests that locally-available, unrefined clays were used in the construction of the furnaces. The various clays used to produce furnace rolls and tuyères at the different sites were of variable refractoriness but the evidence suggests that there was no deliberate selection of raw materials for their refractory properties. The shaft rolls were apparently exposed to temperatures in the region of 1000°C and were probably well removed from the main reaction zone in the centre of the furnace. The tuyères were, as expected, closer to the hot, active region of the furnace and were exposed to temperatures at least as high as 1150–1200°C. This temperature seems rather lower than expected for an iron-smelting furnace and may be a function of the particular examples studied and their positions in the furnace, coupled with the inherent limitations of estimating smelting temperatures from ceramics that fully melt at or below the maximum temperatures attained in the furnace. Temperature estimates based on the slag compositions suggest a minimum of 1250°C, and higher temperatures are likely to have been attained in the reaction zone.

Few analyses have yet been reported of iron-smelting slags from the Early Iron Age of East Africa. The slags studied here are fayalitic in character as is typical for bloomery slags. The slags were fluxed by a clay-bound material similar or, in some cases, identical to the clay used to make the furnace walls and tuyères. This material is likely to have been added deliberately in the form of raw clay or used furnace roll. There appear to have been minor differences in iron content between the slags from the three sites but these were probably controlled by the different clays which fluxed the slags, and in any case, are inferred from a very small sample. The differences in extraction efficiency implied were probably negligible in practice. The differences in chemistry and mineralogy between the slags reflect variations in raw materials; the smelting technology and practice appears to have been constant.

The distinctive slag-pit furnaces have long been recognized as characteristic of the earliest iron smelting in Africa. More recent studies including that presented here show that the slags from both West and East Africa often have rather similar and regular aluminium contents, indicative of the addition of clay to the charge. Along with the slag-pit furnaces, this also seems to be a distinctive feature of iron smelting in many parts of Africa. There are significant differences in mineralogy between the slags examined here which might have been attributed to differences in the smelting process. However, quantitative analysis showed these simply reflect relatively minor differences in bulk chemical composition. Although much attention has been paid to slag mineralogy, it can mislead without an accompanying chemical analysis.

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