Decisions set in slag: the human factor in African iron smelting

Thilo Rehren, Michael Charlton, Shadreck Chirikure, Jane Humphris, Akin Ige and Harald Alexander Veldhuijzen

ABSTRACT Slags are the most abundant and best-preserved product of traditional iron smelting and are thus a staple of archaeometallurgical research in this area. A wealth of technical information has been gleaned from these studies, identifying the bloomery process as the universal method of pre-industrial iron production across the Old World. Despite covering such a vast expanse of land and spanning more than two millennia, there is little fundamental variability in the resulting products – bloomery iron and fayalitic slag.

This is at odds with the numerous ethnohistorical studies of traditional iron smelting, particularly in Africa, that have documented a bewildering array of practices, both social and technical. This is most spectacularly obvious from the range of furnace designs, from a mere hole in the ground to elaborately decorated and substantial structures kept in semi-permanent use. The social status of smelters within their societies, or associated ritualised practices, are other examples of wide-ranging diversity in iron smelting. Such diversity is not restricted to Africa, but is matched by a similarly wide range of archaeologically documented furnace designs across prehistoric western Asia and Europe.

This paper attempts to chart some common ground among the extremes of technical engineering studies, ethnographic documentation and sociopolitical contextualisation in African iron smelting. First by exploring the inherent factors providing the envelope or constraints of technical possibilities, and then identifying degrees of freedom within this envelope which offer room for, or rather require, human decision-taking. Some of these decisions have left their traces in the slag, and teasing out these variables may eventually offer insights into social and cultural practices through technical studies.

Keywords: bloomery smelting, Africa, ternary diagram, slag composition, iron.

Introduction

The study of traditional iron-smelting practices stems from several important roots. The two most predominant are the earth science and engineering approach – investigating the chemical and mineralogical compositions of iron, slag and other physical residues (Bachmann 1982; Miller and Killick 2004; Morton and Wingrove 1969, 1972; Tylecote 1962), and the ethnohistorical and anthropological approach – examining the cultural meaning and relationships between iron-makers, their products, behaviour and the whole of their environment (Haaland 2004; Herbert 1993; Schmidt 1978, 1997). For a number of reasons, most of the former research is centred on European archaeological evidence, while the latter has its stronghold in 20th-century African contexts, sometimes relying on re-enactments and oral histories as main sources. This separation suggests a dichotomy which is purely artificial and not inherent in the object of study. Unfortunately, the data obtained through these two approaches are often fundamentally incompatible although they clearly concern the very same activities. Even where they overlap, most visibly in the determination of iron yields, they are typically deduced through comparison of slag and ore composition on the one hand, and through direct observation on the other (Childs and Schmidt 1985; Schmidt 1997). Direct observation in most cases reports the quantities of ore and charcoal used, and iron metal produced; reconstructed yield data are typically based on assumed ore qualities and slag quantities as the only archaeologically measurable parameters, the two parameters least often reported in experimental or documented smelts. Both approaches are very much complementary, and allow very different aspects of the same operation to be documented, interpreted and possibly even understood. A survey of the literature, however, reveals an astonishing level of an 'either/or' approach, as if they were mutually exclusive (see Miller and van der Merwe 1994 for detailed surveys). Only more recently, approaches which view technologies as simultaneously material and sociocultural have somewhat reoriented technological studies of African iron smelting (Childs 1994; Killick 2004a).

It is not the intention of this paper to offer a complete and balanced view of the literature (see Miller and Maggs 1998), and we are consciously ignoring for the moment several very valuable contributions in this field. Most of the technical literature, however, is wholly descriptive or restricted in its interpretative ambition to provide technical explanations of specific features of the slag (estimated furnace temperature, phase content or slag morphology). Variability in process execution or raw material supply, both within short and long timescales, are only rarely investigated and reasons for it typically not explored (see Cline 1937). This latter is true for much of the ethnographic literature as well, often taking the one or two recorded smelts as representative of unchanged, or even unchangeable, past practice. Thus, the effects of cultural change and adaptation to varying environmental and economical constraints, and the potential for evolution are frequently overlooked or denied altogether, further contributing to a rather static image of early iron-smelting practice (Chirikure 2005; Chirikure and Rehren 2006). At the same time, both ethnographic and archaeological evidence offers a bewildering array of differing practices and furnace designs. These cannot possibly be the result of a multitude of independent inventions, but have to be seen as direct and strong evidence for large scale and significant evolution and development. Indeed, diffusion of iron technology from just a few points of discovery or entry into Africa has been high on the agenda for much of the last century (e.g. Kense 1983; van der Merwe and Avery 1982: 150–52; and see Killick 2004b; Quenchon 2002). Surprisingly, this seems not to have resulted in much consideration of the likely adaptation of processes and practices to the changing ecological, economic and political conditions under which they were performed. The slags, in stark contrast, are often found to be frustratingly similar to each other, and seemingly offer little representation of the variability in furnace designs (Miller and Killick 2004).

Having thus argued the case for widespread, even inevitable and necessary, change in African iron-smelting practice over space and time it is now appropriate to look for traces of such evolution in the archaeological record. Even if the archaeological record seems less informative regarding sociocultural patterns than ethnohistorical studies, it offers a much deeper time-resolved view (Chirikure 2005). Studies of change and development clearly depend on a strong timeline, and it is our aim to suggest a few approaches for teasing out these historically accumulated configurations from the slags of past iron smelting. These methods allow us to discuss evolution as an observable phenomenon as well as something which has human causes (Charlton 2007).

Slag homogeneity and past decisions

A screening of iron slag studies reveals a strong, systematic and highly repetitive pattern in slag composition (Bachmann 1982; Buchwald 2005; Killick and Gordon 1988; Miller *et al.* 2001; Morton and Wingrove 1969; Tylecote 1975). Most smelting slags plot around the fayalitic region of the FeO-SiO_2-Al_2O_3 phase diagram, typically drawn out parallel to the FeO-SiO_2 side linking two areas of particularly low melting temperature (Fig. 1). These temperature minima are here labelled Optimum 1 and Optimum 2 to emphasise that these areas are not merely characterised by the neutral aspect of their temperature, but that they are also areas which maximise slag fluidity relative to energy inputs. They are optimal engineering solutions for bloomery smelting and may reflect iron-making behaviour within specific socioeconomic contexts. We feel that the term ‘optimum’ carries a stronger connotation of subjectively better behaviour, relevant to the ancient smelter, than the term ‘minimum’. Optimum 1 lies left of the centre of the diagram, at about 50 wt% FeO, 40 wt% SiO_2 and 10 wt% Al_2O_3; Optimum 2 is situated nearer towards the iron-

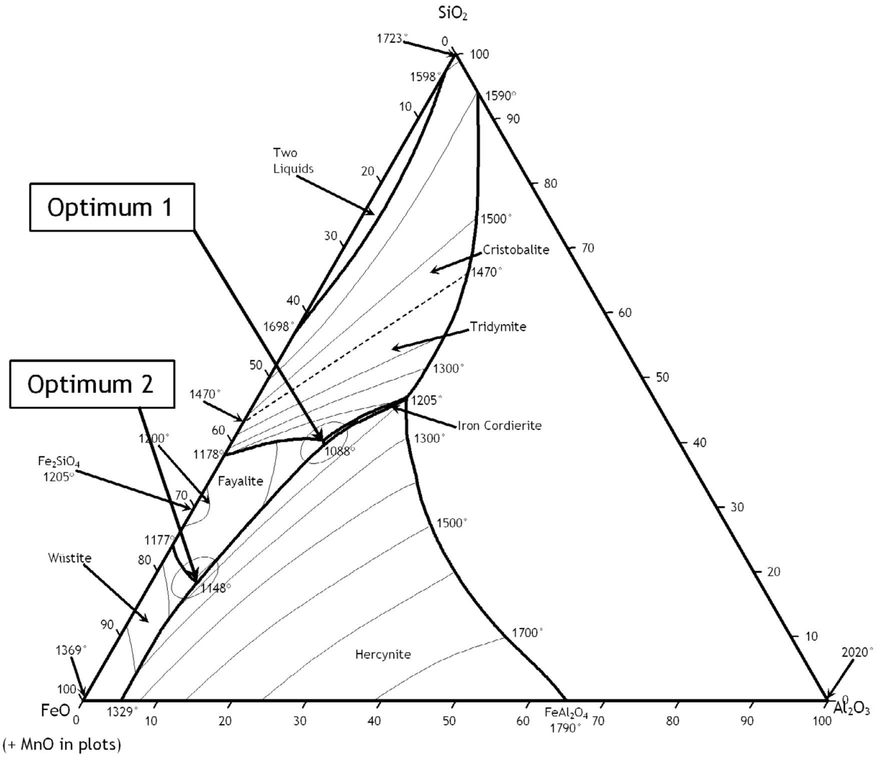

Figure 1 Ternary diagram presenting liquidus temperatures for the system FeO-SiO_2-Al_2O_3. The two areas most suitable for bloomery smelting are marked Optimum 1 and Optimum 2. They combine low-temperature melting with low-viscosity compositions.

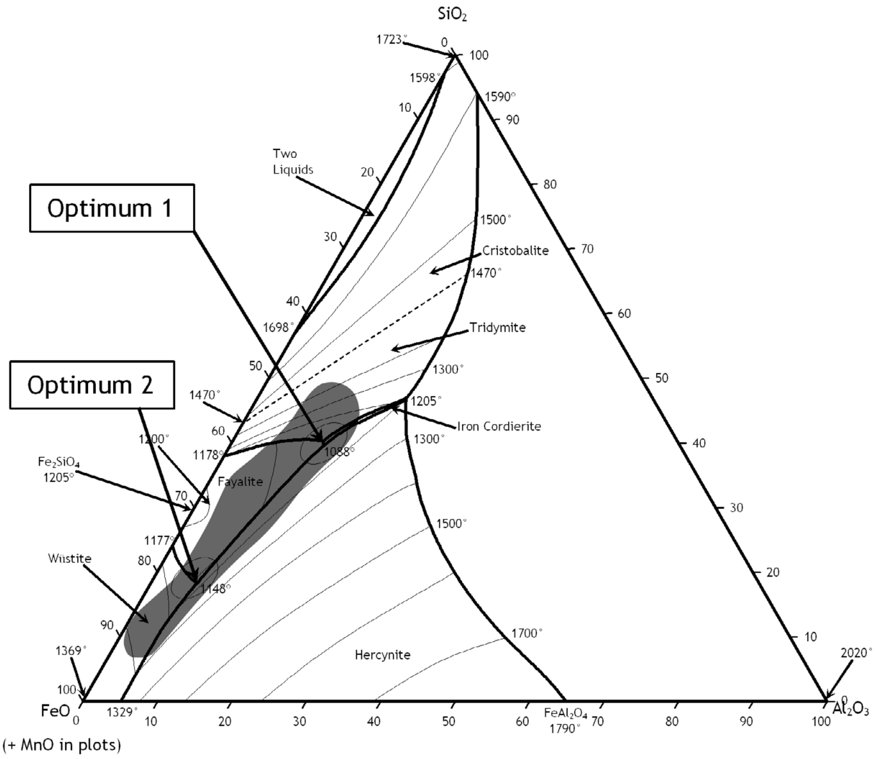

Figure 2a Distribution of pre-modern smithing and smelting slag compositions in the system FeO-SiO_2-Al_2O_3. Data reduced by combining suitable oxides (e.g. FeO and MnO) and omitting minor compounds (e.g. alkali oxides) to fit the ternary diagram. Smelting and smithing slag compositions overlap near the fayalite composition; smelting slags predominate around Optimum 1, smithing slags scatter around Optimum 2 and towards FeO-rich compositions (after Kronz 1998: fig. 6.1).

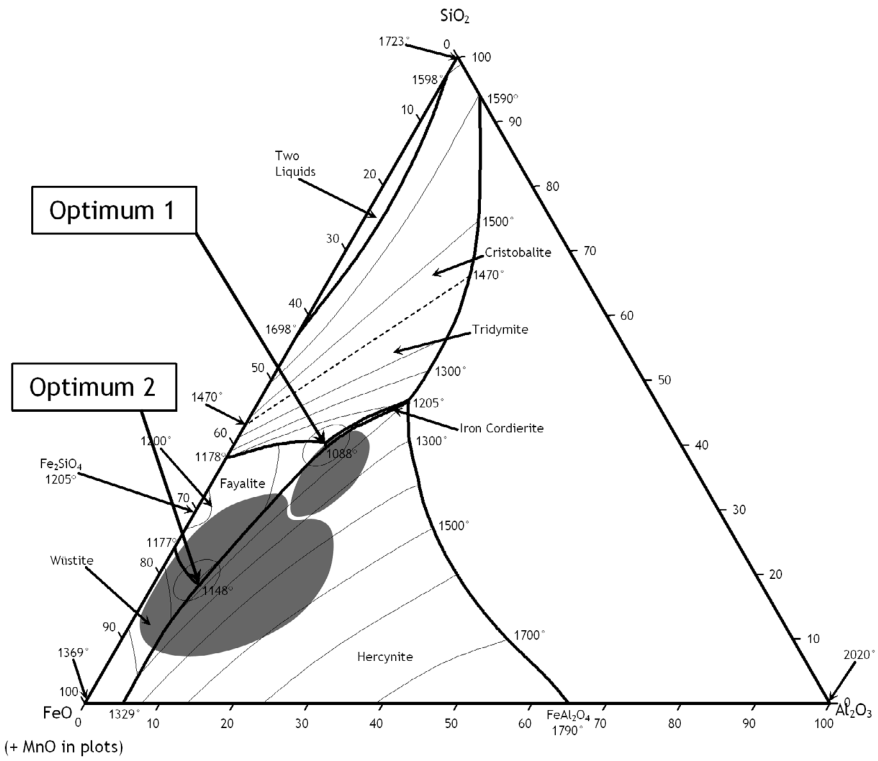

Figure 2b Distribution of early medieval smelting slag compositions in the system FeO-SiO_2-Al_2O_3. Data reduced by combining suitable oxides (e.g. FeO and MnO) and omitting minor compounds (e.g. alkali oxides) to fit the ternary diagram. Two different slag types cluster around the two optima and overlap near the fayalite composition (after Yalçin and Hauptmann 1995: fig. 11).

rich corner of the system, at about 75 wt% FeO, 20 wt% SiO_2 and 5 wt% Al_2O_3. It is between these two optima that most fayalitic iron slags form, and it appears almost as if the phase diagram dictates the composition that a slag can take at the given temperature frame of 1100–1250 °C. Indeed, it has been argued elsewhere in a different context that under certain conditions the behaviour and composition of a molten charge is closely governed, almost dictated, by the shape of the liquidus surface of the relevant diagram (Rehren 2000a, 2000b). These conditions – namely the availability of one or two solid phases which co-exist with the melt and can contribute more or less to the melt formation as the temperature changes – clearly took place in most prehistoric iron-smelting furnaces. One such solid material is the technical ceramic from which the furnace and any tuyeres are being built. It acts as a reservoir or 'buffer' from which the melt can draw additional material to develop its own composition in line with the particularities of the appropriate phase diagram. Another such buffer is the ore or any free iron oxide left in the slag. Increased ceramic absorption pulls the slag composition towards Optimum 1, excess free iron oxide towards Optimum 2. As a result, the typical slags plot along the line between technical ceramic and ore compositions (Fig. 2a,b). But is this really an unfettered tyranny of the phase diagram, leaving no choice and decision for the human actors? We don't believe so.

First of all, the melting temperature of Optimum 1 is not significantly different from Optimum 2; the system would not favour one over the other when a liquid slag is forming at around 1200 °C. Rather, reaching one or the other of these optima reflects the configurational parameters of the furnace and charge. These in turn are a direct consequence of human decisions regarding furnace design, raw material selection and charge recipe. The typical scenario for slag formation in a bloomery furnace is that an iron-rich charge (the ore) is heated under reducing conditions so that a part of the iron oxide is reduced to iron metal, while another part remains as iron oxide in the system, fluxing the more refractory gangue components silica and alumina. Under less strongly reducing conditions, relatively more iron oxide remains in the system, and the slag approaches Optimum 2, the iron-rich eutectic. There are two alternative ways in which Optimum 1, the iron-poor eutectic, can be reached. One is by operating the furnace under more strongly reducing conditions, removing more iron from the system as metal. The other is to add more alumina and silica to the charge, typically as melting furnace wall material. This can be achieved by using tuyeres protruding into the furnace, designed to melt away as the smelt progresses, to facilitate sufficient slag formation (David *et al.* 1989; Veldhuijzen 2005b; Veldhuijzen and Rehren 2006). The deliberate addition of sand as a flux to the furnace charge enabled the BaPhalaborwa people to reduce high-grade magnetite ores with relative ease (Miller *et al.* 2001). Thus, slag with a composition near Optimum 1 can either indicate a higher yield through more reducing conditions, or a larger contribution to the slag formation from the technical ceramic or intentionally added silica, depending on cultural context.

It is reasonable to assume that the relevant actions were based on human decisions rather than random acts of behaviour. There are different risks and costs associated with these decisions. The former, approaching Optimum 1 through increased removal of iron as metal, would typically include more strongly reducing conditions and hence the production of a carbon-rich steely bloom, carrying the risk of overcarburising and producing cast iron instead. Such a situation is not difficult to achieve as many recent experiments make clear (Crew 2004). Also, it requires much more fuel consumption, thus adding to initial costs. The latter, approaching a low-iron slag through increased sand or ceramic contribution, could reflect the need to add more siliceous flux in order to facilitate smelting of a calcareous (for example Veldhuijzen 2005a, 2005b; Veldhuijzen and Rehren 2006 and in this volume, pp. 189–201) or very rich ore (for example David *et al.* 1989; Miller *et al.* 2001). The costs involved include adding more ballast to the slag volume, increasing both the need for fuel and reducing the amount of iron oxide available to produce metal; due to the reaction of additional iron oxide with the added material, the yield decreases significantly, as demonstrated elsewhere (Joosten 2004; Joosten *et al.* 1998; Veldhuijzen and Rehren 2006). The ores in question, however, although nominally very rich, would otherwise not be smeltable with the available technology, thereby justifying the addition of a flux and accepting a lower yield.

Thus, within the low-temperature slag-forming region of the phase diagram, there are at least three fundamentally different scenarios which result in the clustering of slag compositions in one or the other optimum. These different scenarios are direct reflections of human choices. The degree of reduction is a function of fuel-to-ore ratios and air flow through the furnace; both parameters are directly controlled first by the furnace design, and then the head smelter during the smelt. The contribution of technical ceramic to slag formation is governed by the furnace and tuyere design and the selection of clay used for their production, parameters which have probably developed in response to the choice or availability of a particular ore type and which are enacted by the smelters when building their furnaces. Similarly, the addition of quartz sand as a flux in smelting extremely rich magnetite ore must have evolved in some way. Other cases of adjusting smelting practices to the particular ores include Phoka smelters (Malawi) semi-processing low-grade ores in natural draft furnaces and re-smelting the slag in bellows-driven furnaces. The process produced slags which were virtually wüstite free but contained more silicates and required increased amounts of fuel due to the repeated smelting of the charge (Killick 1990).

A further human-controlled factor influencing the slag composition is the choice of ore or ore blend; this determines – or at least influences – the chemical system within which the slag eventually has to form. Provided that a choice exists, as is often the case (for example Charlton 2007; Crew and Charlton, this volume, pp. 219–25; Gordon and Killick 1993; Ige and Rehren 2003; Miller *et al.* 2001; Rehren 2001), this is another powerful example of human supremacy over the 'tyranny' of the phase diagram.

The main challenge is to isolate and identify these human choices as drivers of evolution within the system-driven constraints (Charlton 2007), and to push the mineralogical slag studies beyond the immediately obvious engineering parameters (Chirikure and Rehren 2006). This not only requires a broad range of analysed materials, including technical ceramics, potential ore samples and even fuel ash material

(Veldhuijzen 2005a; Veldhuijzen and Rehren 2006), but also demands making full use of complementary evidence and information. This can involve, among other things, the assessment of relative costs and availabilities of labour, fuel, ore and metal, historical accounts of special practices, experimental reconstructions and the setting of the furnace sites within the wider sociocultural landscape (Chirikure 2005; Killick 1990). As a starting point, it is still necessary to understand the relevant phase diagrams and the behaviour of the melt as it evolves from ore to slag and metal, not least to identify those driving factors and constraints which have to be taken into account when isolating the variables available for human choice. In many cases, however, it appears that the smelter puts the immanent forces of the system to good use rather than being its powerless subject.

Current decisions affecting slag analyses

The previous section tried to sketch out a few areas of past human influence on slag formation and composition; here, we aim to look at some current human decisions which influence the part of the total initial slag assemblage we are actually analysing. 'Slag' is a rather general term, much like 'ceramic', and any given smelting site often comprises a multitude of subtypes of slag (Bayley *et al.* 1999; Craddock 1995; Veldhuijzen and Rehren, this volume, pp. 189–201). Most excavations have a clear system dealing with ceramic finds. Non-diagnostic body sherds are often discarded on site with only basic recording; diagnostic rim sherds are retained until fully documented, with some examples kept, while imports or exotic sherds are fully documented and kept in the archive (Orton *et al.* 1993). It is obvious that different types of ceramic finds have different significance, and give different types of information. The same is true for slags (Bachmann 1982); however, often no similarly well-developed system is used for recording and sampling slags for further study. Here lies a major challenge for the future of slag studies: to identify and understand the human factor in selecting slags for analysis. Depositional factors are impossible to control: humans in the past decided where to discard slags, and how. Some may have been recycled in the next smelt for further extraction of metal or to facilitate melt formation (Killick 1990). Some were discarded near the furnace site, others near the smithing hearth. Some formed dedicated slag heaps while others were mixed in with general waste. Similarly, the actions of humans intermediate between the smelters and us may have to be considered. Large slag heaps near suitable means of transport may in later periods have been removed preferentially for re-smelting using new (blast furnace) technology, or in the search for previously irrelevant metals, such as zinc in early lead slags. Slag blocks have been used in other activities such as building house foundations (Humphris 2004; Okafor 1993); some slags were used for ritual purposes etc. (Miller 2002). In contrast, small and scattered slag heaps were often considered unsuitable for reworking, and therefore survived in the archaeological record. Such human choices of the more recent past need to be considered when interpreting the nature and quantity of slag under study.

Our own sampling behaviour also has a potentially strong influence on the results (Fletcher and Locks 1996; Orton 2000). Sampling, of course, and the necessity for a rigorous sampling strategy, is not a new issue in archaeometallurgy (Bachmann 1982; Morton and Wingrove 1969), but we want to draw attention to some more recent observations in this respect. One example for future interesting work is related to the widespread pit furnaces and slag blocks preserved from some of these (Haaland 2004; Okafor 1993). Contrary to the average slag heap which contains jumbled-up waste from an unspecified and often unspecifiable number of smelts, these slag blocks should represent single-event records, or a small number of clearly sequential smelts (Okafor 1993). Thus, not only can the mass of each furnace charge be estimated with much better accuracy, but there is the potential to trace the development of the slag, and therefore the furnace conditions, over the lifetime of a single smelt (Humphris *et al.* 2006). It is reasonable to assume that the bottom of the slag heap represents the earliest slag flow from the charge; this may be richer in fuel ash components than the later material due to an initial pre-heating period which led to an initial accumulation of fuel ash in the furnace. Later, changes in air supply or drastic events such as the breaking open of the furnace to remove the hot bloom are probably reflected in changes of redox conditions in the slag. In essence, it not only matters where we sample slag blocks (top, centre or bottom), but that we are consistent in our sampling. Blocks that represent successive episodes would need different sampling strategy, and offer insight into the variability of ore compositions and consistency of furnace conditions.

We must also be aware that most tap slags (and we would argue that slag blocks are a type of tap slag) are not necessarily representative of the furnace charge overall; they represent by definition the low-melting and low-viscosity fraction of the furnace system which flows most easily. The less liquid, partly crystalline residual material, often rich in hercynitic spinel and/or other high-temperature phases, will remain in the furnace as furnace slag or attached to the bloom, often with a high degree of porosity and more or less intergrown with metallic iron bloom. Depending on the practicalities of bloom retrieval and further processing, this 'crown' or 'gromp' material may end up with the smithing waste rather than the tap slag near the smelting furnace, systematically distorting the chemical picture of the smelting operation based on slag analyses (Chirikure and Rehren 2004; Crew 1991). This is likely to have significant effects on compositional pattern including alumina, chromium, vanadium and other elements that partition strongly into spinels, as well as potash, manganese, lime and those elements that partition preferentially into the low-melting component. In addition, these porous slags are more likely to suffer from corrosion, which preferentially affects the glass phase and fayalite crystals, further concentrating those compounds of the more refractory phases. Furnace slags – here defined as only partly reacted ore with significant free iron oxide and remaining in the furnace – were possibly recycled in the next smelt and may be underrepresented in the archaeological record.

Costs, risks and efficiency

As briefly mentioned above, decisions carry different risks and costs, which need to be balanced against the potential gains. This is not the place to discuss the extent to which these decisions were made consciously or how much is due to serendipity; such discussions can only be of actual case studies. Factors such as ease of access to fuel and ore, costs of labour and transport, and the value of metal produced will be among the more directly relevant aspects which govern the practical details of iron smelting. It is to be expected that a community with unlimited access to iron ore but in a semi-arid environment will develop an optimum solution for their smelting practice which is different from that of a group with ample fuel supply but far from good quality ore. Similarly, the choice between natural draft and forced draft furnaces, or between different types of ore, is likely to be heavily dependent on both fuel and labour availability, provided the social context and constraints of tradition allow a choice (Gordon and Killick 1993; Killick 1990). As groups and knowledge move across space and time, however, it is to be expected that traditions develop and change, adapting earlier practice to meet current needs and constraints in an evolutionary process. This may be of (slightly) variable transmission, or indeed intentional problem-solving by experimentation, observation of different practice and exchange of ideas.

Evolutionary change implies a feedback loop between changing practice and variable results. The strongest feedback loop develops in an environment of observation of actions and judgement of results. The most likely measure brought to bear in such cumulative processes is probably the perceived efficiency of an individual smelt in relation to the experienced effort put into it. Much technical literature discusses the (lack of) efficiency of the bloomery process, often with some derogatory connotation. The most frequently used measure for efficiency is the remaining iron oxide content in the slag. In brief, much of the technical literature assumes that less iron oxide in the slag equates to a more efficient process. Our decision to select this one parameter, however, is only a very crude approximation of the reality within which past groups of smelters have operated. Their measures of efficiency may have involved all sorts of parameters, from ease of raw material procurement and furnace operation to quality and quantity of metal produced to the perceived effects of the smelt on culturally related events beyond our understanding (Chirikure and Rehren 2006). Residual iron oxide content in the slag will have been the one parameter they were certainly not considering, as it is firmly outside their reality. Our decision to select this one parameter is probably more based on convenience and tradition than comprehension of the reality of past societies; it is time to make the extra effort and improve this, by identifying and discussing parameters relevant to the subjects of our study.

Conclusions

This paper set out to identify some of the constraints which in the past have governed, or even limited, the study of iron smelting in pre-modern Africa. We noted a distinct lack of coherence and interaction between the two main branches of archaeometallurgy, namely engineering studies and ethnohistorical approaches. A common factor, however, in much of the earlier literature is an underlying assumption of constancy – or shall we say stagnation? – in early iron-smelting technology, despite glaring evidence of extreme diversity which can only be explained by a strong and sustained history of evolution, development and adaptation.

We argue furthermore that the superficially monotonous chemical compositions of many iron slags are technically necessary to obtain a suitably low-melting and fluid medium facilitating bloom formation, but still contain significant and identifiable information about a wide range of human actions and decisions. These human factors as recorded in the slags include both short-term individual decisions affecting only single smelts, and accumulated developments affecting more fundamental parameters such as furnace design and choice of raw materials. The interplay between technological constraints and experimentation, regulating traditions and taboos, and varying political and economic parameters thus results in a multifaceted record. Not every action and decision leaves its trace, and many traces remain undecipherable. However, modern archaeometallurgical research combining established and only seemingly incompatible approaches with awareness for parameters relevant to the subjects of our studies, namely the smelters operating in the past, and critical reflection on our own practices, can unravel details of past practice and contexts previously out of reach of archaeological enquiry.

Of course, none of this is restricted to African slags. European and Asian iron smelters will have operated in very similar networks of technical choices and constraints (Kronz and Keesmann 2005; Paynter 2006) with complex interacting and changing parameters (Pleiner 2000) and possibly with the same level of sophistication, skill and aptitude for change and development as their African counterparts so impressively show. The African record is much richer and therefore better suited to such a study.

References

Bachmann, H-G. 1982. *The Identification of Slags from Archaeological Sites*. Institute of Archaeology Occasional Paper 6. London: Institute of Archaeology.

Bayley, J., Dungworth, D. and Paynter, S. 1999. *Archaeometallurgy: English Heritage Guidelines for Projects*. English Heritage: London.

Buchwald, V.F. 2005. *Iron and Steel in Ancient Times, Copenhagen*. Det Kongelige: Danske Videnskabernes Selskab.

Charlton, M. 2007. *Ironworking in Northwest Wales: An Evolutionary Analysis*. Unpublished PhD thesis, University College London.

Childs, S.T. 1994. Society, culture and technology in Africa: an introduction. In *Society, Culture and Technology in Africa*, T. Childs (ed.). Philadelphia: MASCA Research Papers in Science and Archaeology 11 (supplement), 6–12.

Childs, S.T. and Schmidt, P. 1985. Experimental iron smelting: the genesis of a hypothesis with implications for African prehistory and history. In *African Iron Working: Ancient and Traditional*, R. Haaland and P. Shinnie (eds). Oslo: Norwegian University Press, 142–64.

Chirikure, S. 2005. *Iron Production in Iron Age Zimbabwe: Stagnation or Innovation?* Unpublished PhD thesis, University College London.

Chirikure, S. and Rehren, Th. 2004. Ores, slags and furnaces: aspects of iron working in the Nyanga complex. *African Archaeological Review* 21: 135–52.

Chirikure, S. and Rehren, Th. 2006. Iron smelting in pre-colonial Zimbabwe: evidence for diachronic change from Swart village and Baranda, northern Zimbabwe. *Journal of African Archaeology* 4(1): 37–54.

Cline, W. 1937. *Mining and Metallurgy in Negro Africa*. Menasha: George Banta.

Craddock, P.T. 1995. *Early Metal Mining and Production*. Edinburgh: Edinburgh University Press.

Crew, P. 1991. The iron and copper slags at Baratti, Populonia, Italy. *Historical Metallurgy* 21(2): 109–15.

Crew, P. 2004. Cast iron from a bloomery furnace. *Historical Metallurgy Society News* 57: 1–2.

David, N., Heiman, R., Killick, D. and Wayman, M. 1989. Between bloomery and blast furnace: Mafa iron smelting technology in northern Cameroon. *African Archaeological Review* 7: 183–207.

Fletcher, M. and Locks, G. 1996. *Digging up Numbers: Elementary Statistics for Archaeologists.* Oxford: Oxford Archaeology Committee.

Gordon, R. and Killick, D. 1993. Adaptation of technology to culture and environment: bloomery iron smelting in America and Africa. *Technology and Culture* 34: 243–70.

Haaland, R. 2004. Iron smelting – a vanishing tradition: ethnographic study of this craft in south western Ethiopia. *Journal of African Archaeology* 2: 65–81.

Herbert, E. 1993. *Iron, Gender and Power: Rituals of Transformations in African Iron Working*. Bloomington, IN: Indiana University Press.

Humphris, J. 2004. *Reconstructing Forgotten Technologies in Great Lakes, East Africa*. Unpublished MA dissertation, Institute of Archaeology, University College London.

Humphris, J., Martinon-Torres, M. and Rehren, Th. 2006. How representative is your slag sample? A pilot study using iron slag from Uganda. Presentation at the BUMA VI Conference, Beijing, September 2006.

Ige, A. and Rehren, Th. 2003. Black sand and iron stone: iron smelting in Modakeke, Ife, south-western Nigeria. *Institute of Archaeo-Metallurgical Studies* 23: 15–20.

Joosten, I. 2004. *Technology of Early Historical Iron Production in the Netherlands*. Amsterdam: Institute for Geo- and Bioarchaeology, Vrije Universiteit.

Joosten, I., Jansen, J.B.H. and Kars, H. 1998. Geochemistry and the past: estimation of the output of a Germanic iron production site in the Netherlands. *Journal of Geochemical Exploration* 62: 129–37.

Kense, J. 1983. *Traditional African Iron Working*. Calgary: Calgary University Press.

Killick, D. 1990. *Technology in its Social Setting: Bloomery Iron-workings at Kasungu, Malawi, 1860–1940*. PhD thesis, Yale University.

Killick, D. 2004a. Social constructionist approaches to the study of technology. *World Archaeology 36: Debates in World Archaeology*: 571–8.

Killick, D. 2004b. Review essay. What do we know about African iron working? *Journal of African Archaeology* 2: 97–113.

Killick, D. and Gordon, R. 1988. The mechanism of iron production in the furnace. In *Proceedings of the 26th International Archaeometry Symposium*, R.M. Farquhar, R.G.V. Hancock and L.A. Pavlish (eds). Toronto: University of Toronto, 120–23.

Kronz, A. 1998. *Phasenbeziehungen und Kristallisationsmechanismen in fayalitischen Schmelzsystemen – Untersuchungen an Eisen- und Buntmetallschlacken*. Friedland: Klaus Bielefeld Verlag.

Kronz, A. and Keesmann, I. 2005. Fayalitische Schmelzsysteme – ein Beitrage zur vorneuzeitlichen Eisen- und Buntmetalltechnologie im Dietzhölztal (Lahn-Dill-Gebiet, Hessen). In *Archäometallurgische Untersuchungen zur Geschichte und Struktur der mittelalterlichen Eisengewinnung im Lahn-Dill-Gebiet (Hessen) (Das Dietzhölztal-Projekt).* Rahden: Marie Leidorf, 403–98.

Miller, D. 2002. Smelter and smith: Iron Age metal fabrication technology in southern Africa. *Journal of Archaeological Science* 29: 1083–131.

Miller, D. and Killick, D. 2004. Slag identification at southern African archaeological sites. *Journal of African Archaeology* 2: 23–49.

Miller, D. and Maggs, T. O'C. 1998. *Pre-colonial Mining and Metallurgy in Africa: A Selected Bibliography*. Rondebosch: Department of Archaeology, University of Cape Town.

Miller, D. and van der Merwe, N.J. 1994. Early metalworking in sub-Saharan Africa: a review of recent research. *Journal of African History* 35: 1–36.

Miller, D., Killick, D. and van der Merwe, N. 2001. Metalworking in the northern Loveld, South Africa, AD 1000–1890. *Journal of Field Archaeology* 28: 401–17.

Morton, G. and Wingrove, J. 1969. Constitution of bloomery slag. Part 1: Roman. *Journal of the Iron and Steel Institute* 207: 1556–64.

Morton, G. and Wingrove, J. 1972. Constitution of bloomery slag. Part 2: Medieval. *Journal of the Iron and Steel Institute* 210: 478–88.

Okafor, E.E. 1993. New evidence on early iron-smelting from south-eastern Nigeria. In *The Archaeology of Africa: Food, Metals and Towns*, T. Shaw, P. Sinclair, B. Andah and A. Okpoko (eds). London: Routledge, 432–48.

Orton, C. 2000. *Sampling in Archaeology*. Cambridge: Cambridge University Press.

Orton, C., Vince, A. and Tyers, P. 1993. *Pottery in Archaeology*. Cambridge: Cambridge University Press.

Paynter, S. 2006. Regional variation in bloomery smelting slag of the Iron Age and Romano-British periods. *Archaeometry* 48: 271–92.

Pleiner, R. 2000. *Iron in Archaeology: The European Bloomery Smelters*. Praha: Archeologický Ústav Avčr.

Quenchon, G. 2002. Les Datations de la metallurgie du fer Termit (Niger): Leur fiabilite, leur signification. In *Aux origins de la metallurgie du fer en Afrique. Un anciente meconneeu. Afrique de l'Quest et afrique Centrale*, H. Bocoum (ed.). Paris: Publications UNESCO, 105–14.

Rehren, Th. 2000a. New aspects of ancient Egyptian glassmaking. *Journal of Glass Studies* 42: 13–24.

Rehren, Th. 2000b. Rationales in Old World glass making. *Journal of Archaeological Science* 27: 1225–34.

Rehren, Th. 2001. Meroe, iron and Africa. *Mitteilungen der Sudanarchäologischen Gesellschaft* 12: 102–9.

Schmidt, P.R. 1978. *Historical Archaeology: A Structural Approach in an African Culture*. Westpoort: Greenwood Press.

Schmidt, P.R. 1997. *Iron Technology in East Africa: Symbolism, Science and Archaeology*. Oxford: James Currey.

Tylecote, R.F. 1962. *The Prehistory of Metallurgy in the British Isles*. London: Edward Arnold.

Tylecote, R.F. 1975. The origin of iron smelting in Africa. *West African Journal of Archaeology* 5: 1–9.

van der Merwe, N.J. and Avery, D.H. 1982. Pathways to steel. *American Scientist* 70: 146–55.

Veldhuijzen, H.A. 2005a. *Early Iron Production in the Levant. Smelting and Smithing at Early 1st Millennium BC Tell Hammeh, Jordan, and Tel Beth-Shemesh, Israel*. Unpublished PhD thesis, University College London.

Veldhuijzen, H.A. 2005b. Technical ceramics in early iron smelting: the role of ceramics in the early first millennium BC iron production at Tell Hammeh (Az-Zarqa), Jordan. In *Understanding People through Their Pottery; Proceedings of the 7th European Meeting on Ancient Ceramics (EMAC '03)*, I. Prudêncio, I. Dias and J.C. Waerenborgh (eds). Lisbon: Instituto Português de Arqueologia (IPA), 295–302.

Veldhuijzen, H.A. and Rehren, Th. 2006. Iron smelting slag formation at Tell Hammeh (Az-Zarqa), Jordan. In *Proceedings of the 34th International Symposium on Archaeometry, 3–7 May 2004, Zaragoza, Spain*, J. Pérez-Arantegui (ed.). Zaragoza: Institución 'Fernando el Católico', 245–50.

Yalçin, Ü. and Hauptmann, A. 1995. Archäometallurgie des Eisens auf der Schwäbischen Alb. *Forschungen und Berichte zur Vor- und Frühgeschichte in Baden-Württemberg* 55 (= Beiträge zur Eisenverhüttung auf der Schwäbischen Alb), 269–309.

Authors' addresses

- Th. Rehren, Institute of Archaeology, 31–34 Gordon Square, London WC1H 0PY, UK (th.rehren@ucl.ac.uk)
- M. Charlton (michael.f.charlton@gmail.com)
- S. Chirikure, Department of Archaeology, University of Cape Town, Rondebosch 7701, South Africa (shadreck.chirikure@uct.ac.za)
- J. Humphris, Institute of Archaeology, 31–34 Gordon Square, London WC1H 0PY, UK (j.humphris@ucl.ac.uk)
- O.A. Ige, Natural History Museum, Obafemi Awolowo University Ile-Ife, Nigeria (Akin_ige2001@yahoo.com; oige@oauife.edu.ng)
- H.A. Veldhuijzen, Institute of Archaeology, 31–34 Gordon Square, London WC1H 0PY, UK (h.veldhuijzen@ucl.ac.uk)