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Iron Smelting in Sudan: Experimental Archaeology at The Royal City of Meroe

Jane Humphris [a], Michael F. Charlton [a], Jake Keen[b], Lee Sauder[c], and Fareed Alshishani[d]

[a]UCL Qatar, Doha, Qatar; [b]The Ancient Technology Centre, Cranborne, UK; [c]Germinal Ironworks, Lexington, Virginia; [d]The American Center of Oriental Research, Amman, Jordan

ABSTRACT
The Royal City of Meroe, ca. 200 km north of Khartoum in the modern-day Republic of the Sudan, was an ancient capital of the Kingdom of Kush. From the 3rd century B.C. to the 4th century A.D., Kushite rulers controlled significant territory from the banks of the Nile at Meroe, in part through their ability to ensure the production of significant quantities of iron. The extensive archaeological remains of Meroitic iron production have been investigated over decades, and recently a series of experimental iron smelts in a replica Meroitic furnace has shed new light on the archaeometallurgical evidence. The data generated during the smelting campaigns has provided an understanding of the type of iron ore used, the construction and operating parameters of the furnace, and the workshop space created by the ancient iron smelters during the later and post-Meroitic times.

KEYWORDS
Meroe; experimental iron smelting; archaeometallurgy; furnace; workshop

Introduction

Since 2012, intensive archaeometallurgical research has been conducted at the Royal City of Meroe, a site famed for its impressive ancient metallurgical remains. Situated on the east bank of the Nile about 200 km north of Khartoum in the Republic of Sudan, the UNESCO World Heritage site of Meroe was the main residence of the ruling family of the Kingdom of Kush from the 3rd century B.C. to the 4th century A.D. Kushite iron production created Meroe's most prominent non-architectural archaeological features, in the form of large heaps of metallurgical debris (slag, furnace materials, charcoal, ore, and other archaeological materials). First noted in the early 20th century (Garstang et al. 1911: 21; Sayce 1912: 55), the extent of Meroe's slag heaps has marked the city as one of the largest ironmaking centers in Africa (FIGURE 1). New radiocarbon dates (Humphris and Scheibner 2017) indicate that iron production on a significant scale took place from at least the 7th–6th century B.C. and was practiced at the site for over one thousand years. Meroe is therefore one of Africa's longest lived ancient ironmaking centers, and modelling its iron production is vital to understanding the city's role in the broader socioeconomy of the Nile Valley and beyond.

The first archaeometallurgical investigations at Meroe, led by Peter Shinnie, were conducted from the late 1960s to the early 1970s and involved the excavation of a number of furnaces found associated with two workshop spaces, underlying later metallurgical debris (FIGURE 1). These installations were in use during the first half of the 1st millennium A.D. (Shinnie and Anderson 2004: 73–79).

UCL Qatar's intensive archaeometallurgical research at Meroe led to the identification of another iron production workshop in 2014 (FIGURE 1), again underlying metallurgical debris. Radiocarbon dates of samples collected from the latest in situ contexts indicate that this workshop was in use during the first half of the 5th century CAL A.D., slightly later that those excavated previously (although slag deposits at this mound date to as early as the late 2nd century A.D.). Stylistic similarities between this and the earlier workshops demonstrate significant continuities in technological behavior despite the evolution of the social, political, and economic organization of the later and post-Kushite kingdom (Humphris and Carey 2016; Humphris and Scheibner 2017).

After decades of research at Meroe and a significant number of publications on the topic (see references noted above and Humphris and Rehren [2014]), a number of fundamental questions concerning the operating parameters and organization of the Meroitic ironmaking technology remained unanswered. Such questions include the type and quantity of ore and charcoal used, the use of the workshop space, slag management techniques, the design and operation of the bellows, the quantity of slag produced per smelt, and the quality and quantity of useable iron produced per smelt. Answers to such questions are essential if a comprehensive understanding of the role and impact of Meroitic iron production (and how this changed over time) is to be revealed.

This paper provides an overview of the experimental approaches applied at Meroe to test assumptions and reveal deeper understandings of the ancient ironmaking process (Charlton and Humphris in press, 2017a). We present some evolving hypotheses concerning iron smelting practices during the late and post-Kushite periods (ca. 2nd to 6th centuries A.D.).

Why Experimental Iron Smelting?

Meroe's iron producers made use of the direct, or bloomery, smelting technology. Unlike the blast furnace technologies of today, bloomery ironmaking involves the reduction of iron oxides to particles of iron metal in the solid state (Pleiner 2000: 141–142). All processes necessary for reduction occur within a reaction vessel, or furnace, that serves to concentrate heat and promote chemical interaction amongst key ingredients. A carbon-rich fuel, usually charcoal, is required for the

CONTACT Jane Humphris j.humphris@ucl.ac.uk UCL Qatar, Hamad Bin Khalifa University, Doha, Qatar, PO Box 25256

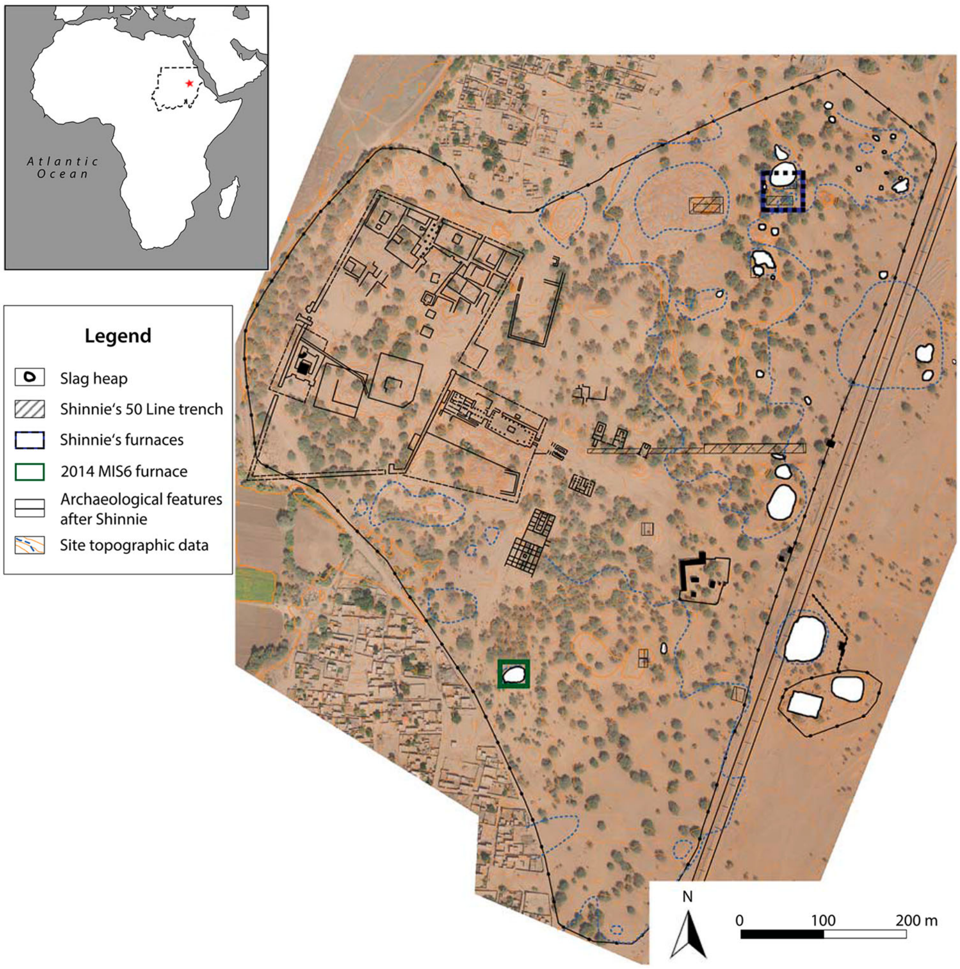

Figure 1. The Royal City of Meroe with all surface slag heaps (in white), the location of Shinnie's excavated workshops (blue dotted rectangle), the location of the workshop found in 2014 (green solid rectangle). Inset shows the location of Meroe in the Republic of the Sudan, marked with a star.

generation of heat (to a temperature of around 1200° C) and the production of carbon monoxide gas, necessary to reduce iron oxides to metal. Oxygen to facilitate the charcoal combustion is provided by air drawn in via a chimney effect (natural draft) or blown in via bellows (forced draft). Non-reduced compounds in the ore are removed as a liquid ferrosilicate slag that may incorporate quantities of furnace materials, fuel ash, and flux (a reactant for compounds that do not melt below the temperatures achieved by the furnace). Fluxing material can be deliberately added to a smelt or can occur as a natural part of the smelting process. For example, iron (II) oxide and/or manganese (II) oxide in the iron ore act as fluxes for silica, often a major component of an ore that has a higher melting temperature than a bloomery furnace can attain, to produce a fluid slag. Ores rich in iron oxide sometimes require additional silica to create a slag, while lean ores need efficient processing to prevent all of the iron oxide from entering the slag. The slag, however, is not just a waste material, but also a transport medium for iron particles, protecting these from re-oxidation as they move through the furnace. When successful, bloomery smelting yields a spongy mass of iron called a bloom that is then refined through successive cleaning and consolidating stages (smithing).

While the basic requirements for bloomery smelting are essential, there exists an enormous range of technical choice depending on the character and availability of resources, tradition, and knowledge (Killick 2004; Rehren et al. 2007). Experimental smelting therefore provides a means of exploring the possibilities created by the array of potential choices, to shed light on the practices wrought by metallurgists in the past (Killick 1991). Meaningful explorations of these possibilities are constrained by archaeological evidence, and often aided by ethnographic accounts.

The value of experimental smelting depends on its purpose (Birch et al. 2015; Juleff 1996, 1998; Killick 2001). Many experiments offer participants an experience that creates appreciation for past technological practices and the ability to ask more informed questions. Some experiments explore the feasibility of different modes of smelting behavior and the consequences of changing operating parameters (Tylecote et al. 1971; Sauder and Williams 2002). Others are used alongside archaeological findings to better understand production practices and the economy of single sites and regions in the past (Cleere 1971; Crew 2013). The experiments conducted at Meroe were designed with all of these purposes in mind, and an experienced international team was assembled to achieve these goals. This paper emphasizes the archaeological purpose of the experiments, specifically addressing fundamental questions about the ingredients added to the furnaces, the smelting techniques employed, and the quantities of waste and iron produced per smelt.

Iron Smelting at Meroe: The Archaeological Evidence

As noted above, ore, fuel, air, and a vessel to contain them form the basic ingredients for any ironmaking recipe. Archaeology provides only a fractured record of these factors, the rest of which must be modeled and evaluated through the incremental feedback of relevant experimentation. Nonetheless, meaningful experimentation must be constrained by the archaeological facts and the critical use of prior archaeological and laboratory findings.

Ore

The chemical and morphological characteristics of a given ore can place enormous constraints on a bloomery technology (Gordon and Killick 1993). Similarly, ore selection and processing tasks impact the economics of production and place operational constraints on the furnace. A common ore processing task is roasting, involving the heating of ore in an open fire to drive off water and volatile compounds. The ore is enriched in Fe and made more porous through micro-cracks created by the escaping gases. This makes it more friable and reducible due to a greatly increased surface area to volume ratio. Roasting converts the iron hydroxides into Fe_2O_3 giving it a bright red color, though it may also oxidize to magnetite, creating a black color.

Prior scholarship concerning the ores used for smelting at Meroe is limited and contradictory. Wainwright (1945: 20) reports the analytical results of an ironstone sample collected at Meroe as being of "very coarse oolitic structure" and "suitable for smelting in a bloomery." Following Young's (1989) terminology, oolitic is taken to refer to a rock comprised of small (< 2 mm) spheroidal grains with concentric laminae called ooids. Tylecote (1982: 29) notes that ironstone "with a crenelated lamellar structure" containing "dark concretions and ironstone balls" is found at Meroe. Whether or not the "ironstone balls" refer to ooids is unclear. Abdu and Gordon's (2004) analysis of Kushite iron objects suggest an oolitic ore source, citing the high phosphorus concentrations found in both the oolitic ironstones and the artifacts.

Tylecote analyzed and reported in brief on a "nodular" stone (1970, 1982), but deemed it unsuitable for smelting and turned his attention to material referred to as "red roasted iron ore" deposited within one of the slag mounds. Analysis of this light porous material showed that it was rich in iron oxide, "likely to be a weathered siderite from the hills on which … the cemeteries were built." (Tylecote 1982: 39–40). Later surveys by the Meroe Joint Excavation identified two types of ironstone in the hills to the east (Rehren 2001).

Recent excavations within slag mounds at Meroe also revealed intermittent layers of reddish orange crushed material (FIGURE 2). Analysis by hand-held x-ray fluorescence (HH-XRF) showed this material to be rich in iron with a high proportion of SiO_2 relative to Fe_2O_3, and thus probably the remains of ore processing (the small pebble [< 2 mm] and sand sized particles were judged too fine for effective smelting). Assuming this material is ore processing waste, its presence within the slag heaps suggests that ore was processed close to the furnaces. The limited quantities of small roasted and unroasted ore fragments found within the metallurgical debris suggest that the size of ore particles added to the furnace was approximately 1–2 cm in diameter.

Charcoal

The characteristics of charcoal can influence the required ore reduction time, the flow of gases through the furnace, and the amount of fuel required per unit of ore. Tylecote (1982: 34) states that the average charcoal size used by the Meroitic smelters was about 3 × 3 cm based on finds of cinder: "thin films of slag surrounding pieces of acacia charcoal." Recent excavations of later and post-Kushite iron production waste support this size estimate, while recent wood species analysis has demonstrated the almost exclusive use of *Acacia* type *nilotica* charcoal for smelting at Meroe (Jane Humphris and Barbara Eichhorn, personal communication 2017). It has long been suggested that the region around Meroe was an Acacia-rich wooded landscape during the Kingdom of Kush, and that the local area was capable of supplying the fuel-thirsty needs of the iron producers (Trigger 1969: 44; Haaland and Haaland 2007: 381). An alternative hypothesis suggests that fuel may have been imported along the Nile to meet the demands at Meroe. A further theory is that iron production may have been responsible for the loss of woodland around Meroe (Haaland 1985). However, until an educated estimate of the quantity of charcoal consumed per smelt is available, the ecological implications of the iron production at Meroe must remain unknown.

Furnace workshop

The design of the furnace and the workspace that surrounds it is the evolved product of socially learned iron making behaviors biased by fluctuating environmental constraints that include access to resources and economic demands. The role of innovation may also be critical to the development of a successful furnace design. While furnace characteristics must permit the minimum thermochemical requirements for reducing ore to metal (Rehren et al. 2007), the shape, size, and operation also reflect accumulated knowledge for smelting with a particular set of resources including ore and charcoal, to achieve a desired level of output relative to investments in labor and resources used. The social status and organization of the iron makers may also influence the final workspace design and location. Features such as furnace height, volume, wall thickness, internal shape, lining refractoriness, and especially air supply have a strong influence on the smelting process, including the resultant thermochemical profile, bloom size, and slag characteristics. The design traits employed by the smelters, along with material and furnace operation choices, constitute a recipe within which each contributing factor coevolves towards a production optimum that satisfies all engineering constraints and the socio-economic demands of the population it serves.

Previous excavations revealed that iron smelting, at least during the later Meroitic times, took place within a workshop space demarcated by a rectangular working area, sunk ca. 40 cm below ground level, measuring approximately 2.5 m wide and 4 m long. Slag-tapping furnaces were positioned at each end of this space, which was lined with red bricks. One Meroitic furnace survived in the archaeological record to a height of 90 cm above the floor, and the excavators estimated the original height of the furnaces to have ranged from 0.90 to 2 m tall (Shinnie and Kense 1982). The furnaces were dome- or cone-shaped structures with relatively wide internal diameters at the bottom of the shaft (in one case, almost 1 m in diameter), sloping inwards towards the top of the furnace. From ca. 30–40 cm above the base of the furnaces, the shafts were lined with a refractory material highly tempered with large grains of sand. This indicated that the working base of

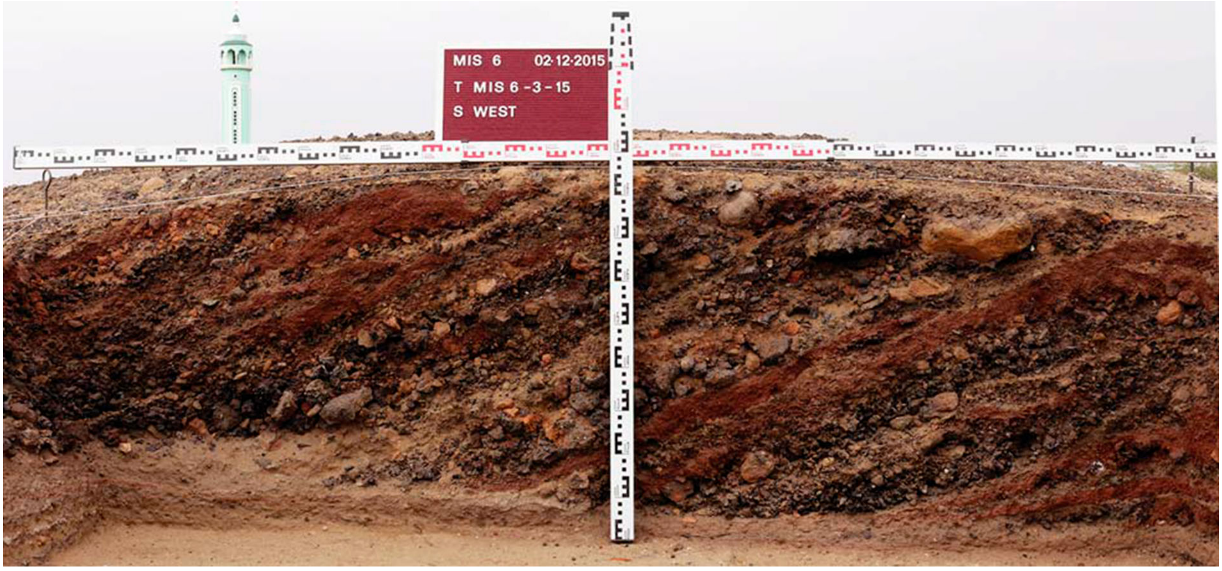

Figure 2. West section of trench MIS6-3-15 showing intermittent layers of reddish orange material, probably representing the remains of ore processing.

the furnace was raised above true ground level. Tapping arches of ca. 47 cm high and 75 cm wide opened onto the sunken floor, with channels leading to a pit in the center of the workshop space that the excavators theorized may have been used for water storage/ water run-off (Shinnie and Kense 1982). Up to six ceramic pot bellows, measuring ca. 32 cm high and 44 cm in diameter, were positioned at ground level around the furnaces, behind the slag tapping arches. Air was pumped through *tuyères* which were angled down into the furnace and attached to the bellows with clay through a hole ca. 20 cm above the bellows' base. The size of the furnaces combined with their placement in permanent structures, and the quantity of lining fragments encountered on the slag heaps, suggests that they were designed to be used for multiple ironmaking campaigns.

The Meroites responsible for constructing the furnace workshop excavated in 2014 cut a platform into the remains of an earlier Meroitic building. On this platform they excavated a sunken working space and lined this with reused red bricks. The workspace contained a central, shallow oval pit, and the truncated remains of a furnace with an internal diameter of 55 cm at the eastern end. Evidence of high temperature activity was also found at the western end of the workshop space, though erosion due to the shallow nature of the slag deposits overlying the structure because of the steep slope of the mound, made it impossible to determine if this represented a second furnace or a smaller feature such as a bloom refining hearth. A probable smithing hearth was identified in the workshop floor towards the western end of the workshop (FIGURE 3).

Air supply

The air delivery system is critical to the success of a smelt, determining the volume of air entering the system, the rate of combustion, and the thermal profile. Earlier excavations indicated that up to six ceramic single-pot bellows were situated around the back of the later furnaces (Shinnie and Kense 1982: 21; Tylecote 1982).

The tuyères were inserted into the bellows and the furnace at a down angle of ca. 20–25° from horizontal (estimated from Shinnie and Kense [1982: fig. 1]). Conical protrusions were built into the furnace walls around the area of tuyère penetrations, perhaps to offer them additional resistance to thermochemical attack or the build-up of slag (Shinnie and Kense 1982). Tylecote (1982: 30–32) documents extensive variation in diameter and shape of tuyère design at Meroe. His visual assessment

Figure 3. Annotated photograph of key features identified during the excavations of a furnace workshop at slag heap MIS6.

of the tuyères indicated that they had been hand formed over wooden dowels.

The construction and operation of the diaphragms used to power the bellows remains unclear in terms of the manner in which air was drawn into or expelled from the pots, and how much effort was required to pump them. Whether they occupied fixed positions, and whether the bellows were in constant usage during a smelt or sporadically, for example if a rise in temperature was required, was also unknown.

Smelting techniques

Little is known of the Meroitic smelting techniques other than that the later furnace operation included a proviso for tapping slag. Recent excavations show that significant amounts of slag also formed within the furnace, and that much of the slag was either produced as small pieces or broke into small fragments upon removal (Humphris and Carey 2016). Slag analyses reveal a clean fayalitic slag with little *wüstite* present (Rehren 2001; Tylecote 1982; Humphris 2014). This is indicative of an efficient smelting process and a tendency towards a high carbon metal. Rehren (2001) estimated, with caution, yields of ca. 50%, a little less than 50 kg of metal per 100 kg of slag, and the production of steely blooms.

Experimental Iron Smelting at Meroe: The 2014 Campaigns

The relatively sparse information outlined above makes the interpretation of much of Meroe's archaeometallurgical record impossible. With this in mind, as well as a desire to stimulate local and wider interest in the current research and its findings, the project director (Humphris) planned a one-week iron smelting festival at Meroe, to take place in early 2015. This would include: an education tent featuring artifacts, display boards, and public lectures; an entertainment tent showcasing local musical talents; market stalls for local artisans; and, at its core, a set of four ironmaking experiments conducted in a reconstructed Meroitic furnace workshop. While it was hoped that the experiments would enthuse festival visitors, they were designed to address long-standing archaeological questions and to test existing hypotheses. These included questions concerning resource exploitation, scale of production and furnace operation. The use of a workshop modeled from those excavated at the site would serve to add pragmatic insights into their distinctive design features.

Preparations for the festival took place in February and November 2014, including sourcing a supply of charcoal, testing the properties of local clays, prospecting potential ores, and exploring furnace construction practices. Three practice furnaces were built at the UCL Qatar house compound to begin practical experimentation and lend experience in working with unfamiliar resources. Test Meroe Smelts (TMS) 1–5 were conducted in the practice furnaces during the 2014 preparations.

To construct the practice furnaces, molds made of *halfa* (sedge found in abundance near Meroe), bricks, and sand were trialed. Various mixes of locally available materials were tested before the furnace clays were mixed and applied to the molds. The halfa mold was covered with a simple mix of crushed and wetted, locally produced mud bricks worked into balls of about 10 cm in diameter. This simple and accessible furnace mix has a macroscopic resemblance to the Meroitic furnace material and proved to be a reasonable construction material. The clay mixture used to cover the sand-brick mold consisted of (by volume) eight parts crushed mud brick, two parts crushed kaolin, and three parts tibbin. The local sand, which contains a small proportion of clay, proved ideal for holding its shape during mold making. A smaller shaft-shaped mold was built of two thin layers applied vertically. The inner layer consisted of one part mudbrick, one part kaolin, and one part tibbin. The outer layer was comprised of one part kaolin and one part tibbin.

Ore

Based on previous hypotheses, the source of the ore was assumed to lay within the iron-rich sandstone hills ca. 3 km east of the Royal City, behind the pyramid cemeteries. Multiple ironstone varieties were identified and collected in March 2014, including two varieties of lamellar ironstone and a lateritic ironstone—so named based on appearance, texture, and assumed mineralogical characteristics. The Grade 1 lamellar ironstone consists of smooth homogenous plates with color varying from brown to black. The Grade 2 lamellar is lighter in color and consists of concentric rinds surrounding sandy cores and was collected from wadi beds near the hills. The Grade 3 lateritic ore is a dark grey-black stone that is found scattering the surface of the region. Several kilograms of each were shipped to the UK for Keen (the lead smelter) to test in his seasoned furnace. All ores were roasted prior to smelting in these and in subsequent experiments. None of the UK tests yielded a bloom, although the Grade 2 variety produced a small number of metallic iron prills (1–1.5 cm) embedded in slag.

In November 2014, a second series of ironstones was collected, this time sorted with the aid of an HH-XRF (Charlton and Humphris 2017b). Most of the prospecting took place within the confines of the same survey area, though other areas were sporadically explored. The most promising ironstones were termed crimson/purple, mottled ochre, lamellar, and doline based on color, texture, morphology, and geological context. Others included a red building stone and a black wind-scoured variant of the lamellar ironstone. The crimson/purple ironstones form bands within the geology of the hills east of the Meroe pyramids. They are marked by their coloration, visible only after removal of a brown surface patina, and have a soft gritty texture. These grade into the mottled ochre ironstones (black, orange, and purple mottled stone with a soft gritty texture) and are interdigitated with lamellar bands (hard undulating layers of homogenous stone with colors varying between yellow, brown, pink, and black). The so-called doline ironstone is a dark blackish brown fine-grained rock that breaks with a conchoidal fracture, found within geological dolines (sinkholes). These doline ores were visible in a road cut north of Meroe. A cursory examination of HH-XRF data in the field indicated that the crimson/purple and doline ironstones were the best candidates for smelting based on an expedient indicator of richness: Fe_2O_3/SiO_2 (TABLE 1) (see Charlton and Humphris [2017b] for the complete dataset).

Performance evaluations of the doline and crimson/purple ironstones took place during Test Meroe Smelts in the trial furnaces (TMS1–TMS4 [TABLE 2]). The doline smelts provided the highest iron yields and more fluid slags. The

Table 1. Summary of HH-XRF analyses of ironstones prospected for the Meroe experimental smelts. The Innov-X Systems Delta, Model DP-4000 HH-XRF was not calibrated or optimized for materials rich in iron oxides. All data are semi-quantitative (ratio scale but inaccurate). Fe_2O_3 data are generated with a quadratic internal calibration, and therefore have a truncated range. Without calibration details, the derived Fe_2O_3/SiO_2 ratios are treated as ordinal scale measures.

Ore type	Measure	Concentrations (in wt%)									
		MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	Fe_2O_3 /SiO_2
Construction n = 1		11.7	14.1	44.8	1	1.5	0	0.3	0	26	0.6
Crimson/Purple	$\bar{y}$	21.6	26.5	11.8	0.9	1.4	0.3	0.2	0.6	36.3	3.1
n = 8	s	2.6	1.1	1.4	0.2	0.2	0.4	0.1	0.2	1.3	0.4
Doline	$\bar{y}$	22.7	23.9	12.3	1.0	2.3	0.6	0.2	0.6	34.9	4.6
n = 20	s	6.6	2.9	9.4	0.2	1.6	1.2	0.2	1.1	4.2	3.1
Lamellar	$\bar{y}$	16.9	24.1	19.0	0.7	4.1	0.9	0.3	0.5	32.2	2.0
n = 53	s	5.2	4.3	7.3	0.1	5.5	1.2	0.1	0.4	4.3	1.0
Mottled Ochre	$\bar{y}$	18.1	26.7	14.5	0.8	1.8	0.3	0.2	1.1	35.9	2.9
n = 7	S	5.1	2.4	5.7	0.2	0.9	0.3	0.1	1.2	2.4	1.3
LTM red Layer	$\bar{y}$	15.7	26.4	15.1	1.4	2.5	1.5	0.2	0.3	36.2	2.4
n = 7	s	1.8	1.8	0.5	0.3	0.0	0.7	0.0	0.0	0.4	0.0
Wind-scoured	$\bar{y}$	19.4	25.1	13.4	0.7	1.8	0.2	0.1	1.0	37.8	2.8
n = 2	s	2.0	0.2	1.1	0.0	0.0	0.0	0.0	0.1	1.0	0.2

crimson/purple smelts yielded some iron, but failed, in absence of the doline, to produce fluid slag.

Following the poor performance of the crimson/purple ironstones, efforts were made in the weeks leading up to the smelting festival (January 2015), to find a suitable ore in closer proximity to Meroe than the doline source sampled from the road cut. Prospecting ventures located small quantities of oolitic ironstones on the surface of the hills behind the pyramids. These ironstones contain small spheroidal grains visible at the surface and in fresh breaks of otherwise homogenous stone matrices. They range in color from yellow to greyish black with occasional rust-colored patches.

In the absence of detailed chemical characterizations, a fire assaying technique developed by Sauder (lead blacksmith) was used to assess the richness of ironstones. For this, a small closed crucible made of kaolin, heavily tempered with sand, is filled with 25 g of roasted ore and 8 g of charcoal (both crushed to powder). This is brought to a white heat in a smithing hearth and held at temperature for a minimum of 15 mins. Successful assays produce a bead of cast iron, with the richest ironstones producing a bead of 12 to 15 g (TABLE 3).

Fuel

Approximately 500 kg of charcoal was purchased from a supplier ca. 40 km south of Meroe in the town of Shendi. The charcoal was cut into pieces of 2–4 cm in maximum dimension, a size chosen based on the experience of the team and one that matches the archaeology of Meroe. Unfortunately, an Arabic translation of *Acacia* type *nilotica* proved difficult, as did confirming that a particular supply of charcoal was in fact this type. Botanical analysis of the charcoal used during the spring 2014 smelts confirmed that the majority was at least *Acacia*, with an infrequent quantity of *Acacia* type *nilotica* present.

Construction of a full-scale furnace and workshop

The available dimensions of the late-post-Meroitic workshop and furnace excavated in 2014 were combined with details published regarding the other furnaces excavated at Meroe to produce a replica model for the smelting installation constructed for the experimental smelting festival in spring 2015 (FIGURE 4). With agreement from The National Corporation for Antiquities and Museums in Sudan (NCAM), the experimental workshop was created ca. 20 m to the east of the largest slag mound at Meroe (MIS4). This area lies outside the fenced area of the main site, and geophysics confirmed no substantial archaeological features such as subsurface buildings or graves would be disturbed by the construction or the festival.

The experimental furnace, based mainly on the largest excavated furnace at Meroe, with a minimum internal diameter of 67 cm and 6 tuyères arrayed around the back, was constructed on a platform of red bricks that were positioned ca. 30 cm deep into the ground. To enable the construction of the large furnace shaft, a post was positioned in the middle of the brick platform and fixed firmly in the ground. The post was wrapped tightly with bundles of halfa drawn together at the top creating a strong mold to support an estimated 1000 kg of wet clay. Preparing the base and fashioning the mold took one day. The furnace shaft was created using wetted crushed mud bricks with tibbin added to speed drying and reinforce the structure. Clay balls were pounded into position against the mold and these dried quickly in the hot moisture-free air. This enabled them to support the increasing load above them as the walls grew higher. Some slumping of the walls did occur, resulting in a partially asymmetrical profile and basal wall thickness that exceeded the planned 20 cm in some places. The walls of the upper half of the furnace were tapered towards the rim to a thickness of 12 cm in order to reduce the load. Tuyère ports were created by setting

Table 2. Summary descriptions of the test smelts.

TMS	Ore type	Air supply	Ore (kg)	Ore:fuel (kg/charge)	Rate (min /charge)	Bloom kg (per kg ore)	Notes
1	Doline	Electric (1 then 2 tuyères)	14	1:2		2.48 (0.18)	Steely bloom; cast iron; glassy slag
2	Crimson /Purple	Electric (2 tuyères fast)	16	1:1	8	1.5 (0.09)	Steely bloom; cast iron
3	Crimson /Purple	Electric (slow)	23.5	1:1; 1.5:1	14	0	
4	50% doline; 50% crimson/purple	Electric (2 tuyères)	19.7	1.25:1	14 (then 9)	2.75 (0.14)	More fluid slag than other trials

Table 3. Results of assaying tests.

Ore type	Trials	Cast iron ball (g)
Crimson/Purple	2/1	12/9
Doline	1	12
Lamellar	2	7
Oolitic	2	12.5
MMA M1 A	1	0
MMA M1 B	1	7
MMA M1 M2	2	11.5
MMA M1 M1	2	0
MMA P 1	2	7
MMA P 2	2	8.5
EOR C	2	13.5
EOR G	2	14.0

2 L plastic bottles filled with water in the wall at the desired angle and position, and building the furnace shaft over them. The tapping arch was formed over a sand-filled sack. The construction of the shaft took one day, involving Keen, an assistant to prepare the clay balls, and five workmen to crush the mud bricks.

After three days, the clay was firm enough to permit removal of the central post and halfa mold. Water was released from the plastic bottles and sand released from the sack to allow for easy removal of these construction aids. The furnace was 127 cm high from the base, with an internal diameter of 67–72 cm and a maximum external diameter at the tuyère level of ca. 90 cm. The top of the furnace (the mouth), had an internal diameter of 25 cm and an external diameter of 38 cm. The tuyères were positioned 30 cm above the base of the furnace, while the tapping arch was 50 cm high and 41 cm wide at the base.

While some features noted from the archaeological excavations were replicated, including a sunken workshop floor with a central pit, other aspects of the workshop's spatial organization were less clear even from the combination of archaeological evidence available, notably the location of the smithing area. Given the spatial constraints of the working space and the need to provide a public display, Sauder used his experience to site the smithing area to the southwest corner of the workshop. The recreated workshop and furnace were covered by a two-walled, roofed shelter that provided shade and protection from wind.

Air supply

A design for the bellows pots was produced based on examples described by Davey (1979). Potters working in Khartoum were commissioned to make nine ceramic bellows pots, the dimensions for which were approximately 38–39 cm interior diameter and 22 to 26 cm deep with a nozzle located just above the base. The manner in which air could be drawn in and pumped out of the bellows was an important focus of experimentation before the smelting festival. Shallow goat skin diaphragms with 4 cm flap valves were bound to the top of the pots with twine. Two handle designs were trialed: a simple goat skin loop sewn to the center, and a smooth dowel bound to the center. Bellows action varied with each pot, and no consensus was reached on which handle type performed better. The average bellows stroke was estimated to deliver ca. 3 L of air, calculated by measuring the volume of the sphere cap when the bellows skin was drawn. The design was simple to operate and functioned best when the pots, not fixed to the working surface, were not connected to the tuyère. A small space between the outlet and the tuyère aspirated additional air and prevented excessive intake of hot furnace gas back through the pot's outlet. However, this also meant a reduction in the effective volume of air reaching the furnace and a corresponding drop in pressure (Rehder 2000: 175–179).

Multiple recipes for the tuyère clay were tested under furnace conditions, and samples of these retained for later comparison with the archaeological record. The tuyères were created by molding clay around a slightly tapered wooden mandrel with an average diameter of ca. 3 cm. The mandrel was covered with mutton fat to facilitate release of the clay. The tuyères were allowed to dry in the sun. Some warped as a function of poorer clay recipe and these tended to be more fragile. The rough tuyères were trimmed to final lengths of ca. 50 cm long.

Smelting techniques

A final test smelt (TMS5) took place in the small dome shaped trial furnace with the aims of organizing the bellows operators and air flow configurations (i.e., alternating or simultaneous bellowing and periods of natural draft), structuring spatial logistics, and practicing record keeping. The purple ironstone was trialed based on the assumption that this was the likely source of Meroitic ore. A standard 1:1 fuel to ore charging ratio (by weight) was maintained throughout the smelt. The air supply strategy was mixed between natural draft and forced draft, a decision that emerged from discussions relating to furnace height, which created the possibility of utilizing natural draft to conserve labor. Internal temperatures were measured with an Omega Engineering KHXL-316U-RSC-24 utility handle 600 mm K-type thermocouple probe (rated to 1372° C) connected to an Amprobe TMD-52 Thermometer. External temperatures were measured with a Nubee Infrared thermometer gun. To measure internal furnace temperatures the probe was inserted into the furnace at set heights through a series of holes located to the left of the furnace tapping arch. The horizontal probe depth was set to 15, 30, and 45 cm with respect to the first probe hole. The readings taken from these locations represent the temperatures along the wall (15 cm), just above the tuyère nose (30 cm), and at the center line of the furnace (45 cm). The center line measure was the only reading taken for TMS5 (FIGURE 5C). External temperatures were recorded at the walls, bellows junction, and bellows of select bellow pot locations.

The furnace was preheated by lighting a wood fire at the furnace base and then filling it with charcoal. Natural draft was employed for the first two hours of charging, and then forced draft for the remainder of the smelt. Several bellowing strategies were tried, including: free form—everyone for themselves; alternating—two or three sets of bellows blown with an alternating rhythm; and coordinated—all bellows blown in unison. The action of the bellows increased the furnace temperature to great effect. Figure 5C shows this change in temperature, as well as its somewhat chaotic nature. External temperature recordings showed that hot gases were being pulled out of the furnace during the bellows upstroke. This led not only to a few diaphragm burns, but also an unacceptable environment for the bellows operators of 40–48°C (about 20°C above ambient). Both problems were resolved by bellowing in unison.

Figure 4. The replica furnace workshop under the semi-permanent shelter. The furnace can be seen on the left and the smithing area on the right, between which is the sunken floor.

TMS5 resulted in the production of a viscous slag and 1.5 kg of bloom from 20 kg of charged ore. The low yield was thought to be a consequence of a poor ore and poor air management. Both hypotheses were carried forward in the planning of the festival smelts.

The 2015 Festival Smelts (MS1–4)

The scientific goals of the festival smelting campaign included the experimental production of bloomery residues that corresponded to those found in the archaeometallurgical record, the identification of the most likely source of ore, and the development of a general model of the smelting recipe practiced in the excavated (later and post-Meroitic) workshops. Each Meroe Smelt (MS) was designed to test specific configurations and build on the insights gained from preceding smelts. Records of each smelt were kept by individual team members detailing start and end times, charging times and amounts, changing air flow configurations and bellowing rates, and furnace temperatures. Recorded thermocouple measurements were not used to guide smelting behavior during the experiments. The results of the experiments conducted during the festival (TABLE 4), indicate that these four smelts were unsuccessful—at least in terms of their ability to produce large quantities of iron. However, within these failures are a number of findings that shed significant light on the stated aims of the project and that have helped guide subsequent archaeological investigations and experimental approaches.

MS1

The first full-scale festival smelt was designed to explore the behavior of a familiar ore combination (50% doline, 50% purple) in the new and much larger furnace, using a standard fuel to ore ratio of 1:1 (by weight) and a mixed air supply strategy. No additional lining was added to the furnace base or walls. The furnace arch was closed with blocks containing 13 tuyères, all initially plugged with clay stoppers.

The furnace was filled with charcoal to tuyère level, and charcoal fines were dropped into the furnace to fill the area where the wall met the base. Tinder (grass) was ignited and additional wood kindling added for the preheat. Charcoal was added slowly for the next hour, totaling 62 kg, and it was noted that as the furnace stock level rose above 55–60 cm, there was a corresponding drop in temperature and draw. The first ore charge was added 2 hr. 25 min. after ignition and a decision was made to maintain a stock level of 110 cm above the base.

Unreacted ore was observed at tuyère level 4 hr. into the smelt and viscous material noted at all tuyères after 5 hr. Keen decided to increase furnace temperature by initiating the bellows with the goal of producing a more fluid slag. Bellows were blown in unison to the drum beats of the festival musicians. The bellows were operated at ca. 60 strokes/min., with two teams alternating every 20 min. Following the observation of more unreacted ore at 6 hr. 23 min., Keen added a seventh bellows at the furnace arch, at the same height as the others. The bellows continued to be operated in unison although at a varying pace, increasing to more than 100 strokes/min. by the time of the final charge (8 hr. 14 min. from ignition).

The furnace stock was allowed to burn down under forced draft, and the arch was opened after 9 hr. 5 min. Most of the furnace contents were removed by 9 hr. 30 min. The bloom was identified and Sauder began some preliminary smithing. This proved difficult in the failing light and the experiment came to a close. In total, the furnace consumed 41 kg of ore and 105 kg of charcoal.

Slag, bloom, and part-reduced ore from the experiment were gathered the following day. Recovery was incomplete and biased toward larger materials. The fine fraction, including much unreduced ore, was lost to the sandy floor of the workshop. The collected products totaled 4 kg of part-reduced ore, 14 kg of magnetic slag, 4 kg of non-magnetic slag and 4.3 kg of unconsolidated bloom (although no

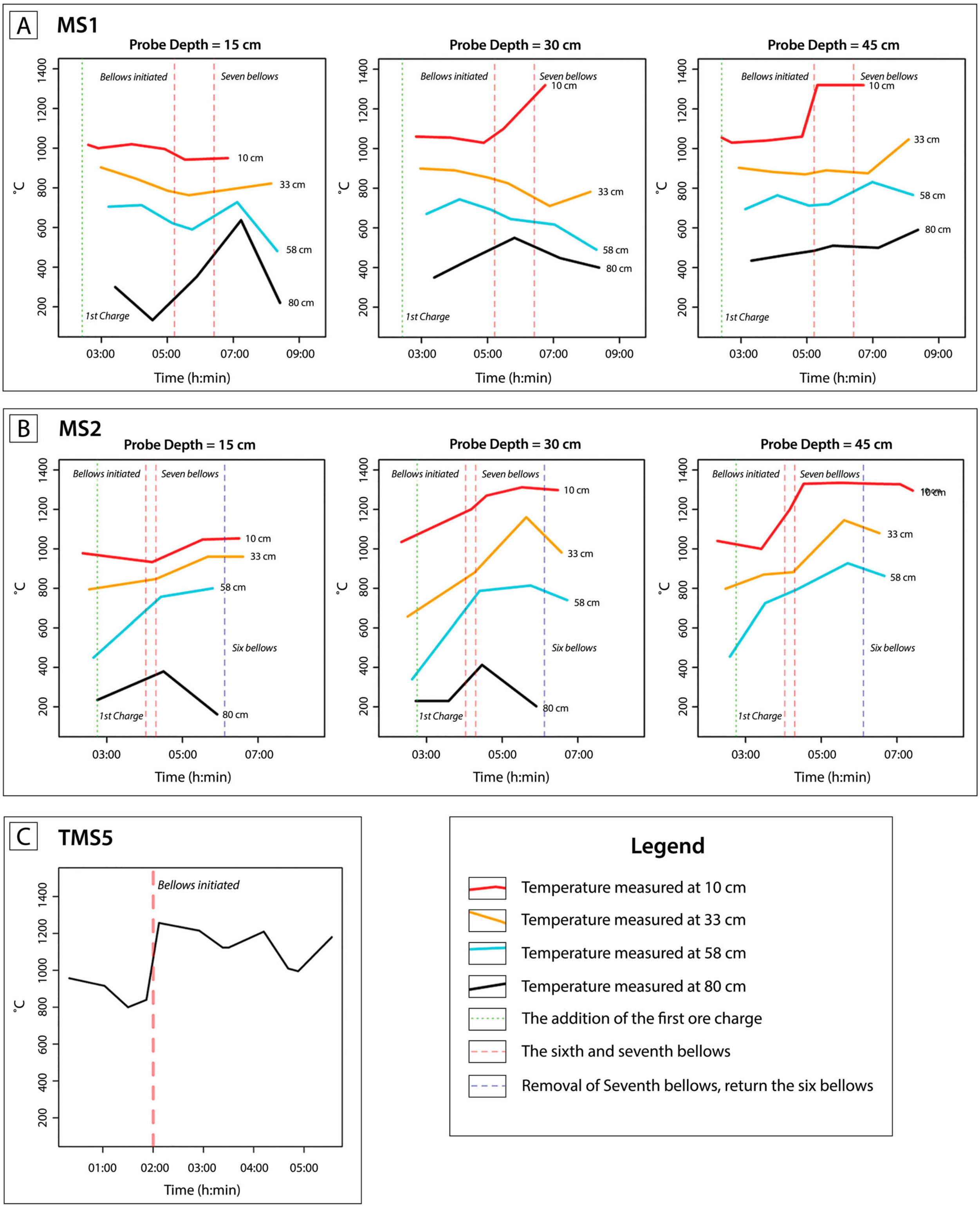

Figure 5. A) Temperature profile, MS1; B) temperature profile, MS2; and C) internal temperature profile, TMS5. Probe depth relates to the horizontal penetration distance of the thermocouple relative to the lowest probe hole. The vertical distance of the thermocouple from the furnace base is given at each data series.

estimate was made of materials that were fused to the tuyères or the furnace wall). The slag was brittle and displayed few flow patterns. The ratio of bloom to ore masses, while disappointing, was consistent with results from the test smelts. Initial hypotheses to account for the results varied, ranging from problems with the ore, a furnace environment that was too reducing, and the lack of heat generated in an unseasoned furnace.

Examination of the furnace temperature profiles (FIGURE 5A) offers deeper insights into smelting processes. Effective reduction of ferrous oxide begins at ca. 700° C (but varies with surface reactivity), while slag tends to form at around 1100° C and be fluid at temperatures above 1200° C (Rostoker and Bronson 1990). The timing of initial reduction and slag formation are critical and varies depending on furnace design and operation as well as ore richness and reactivity/reducibility. If the atmosphere is reducing, but temperatures are not high enough to form slag at the appropriate time, partially-reduced ore will become a significant furnace product. If temperatures are high and a slag forms early, it will engulf

Table 4. Measurable parameters of all smelting campaigns. The iron and slags produced in these smelts have yet to be fully analyzed.

Smelt (Date)	Furnace	Ore type	Air supply	Ore:Fuel (kg) (# of charges)	Total ore (kg)	Preheat Charcoal (kg)	Total charcoal (kg)	Total time (first ore to end)	Bloom (kg) (ore/bloom)	Observations
TMS5	Small-scale	Crimson/purple	Natural draft, then 4 bellows.	1:1	20				1.50 (0.08)	
MS1 (1/22/15)	Full-scale	50% doline 50% purple	Natural draft and bellows with membrane.	1:1	41	64	105	9:36	4.325 (0.105)	Decent iron, viscous, non-tapping slag.
MS2 (1/25/15)	Full-scale	Purple	Natural draft and bellows with membrane.	1:1	30	69	99	7:52	0 (NA)	No iron, very little slag.
MS3 (1/26/15)	Full-scale	Oolitic Pyramid hills	Natural draft and bellows with membrane.	1.5:1	30	66.5	86.5	6:08	1.5 (0.05)	More fluid slag.
MS4 (1/28/15)	Full-scale	Oolitic Pyramid hills	Natural draft and bellows with membrane.	2.5:3 (×4) 3.5:3 (×4) 5:3 (×2)	17	36	54	5:19	0	Pre-charged with ore and charcoal. Small amount of fluid tapped slag.
MS5 (11/30/15)	Full-scale	Oolitic EOR-C	Natural draft and bellows with folded cone	2:2 (×9) 3:2 (×4) 4:0 (×1)	34	30	56	7:00		Pre-charged, with no additional ore. Some bloom.
MS6 (12/3/15)	Full-scale	Oolitic EOR-C	Natural draft and bellows with folded cone	7:8 (×7) 6:0 (×1)	55	24	92	6:30		Pre-charged, natural draft, bellows for last 2.5 hrs.
TMS6 (12/6/15)	Small-scale	Oolitic EOR-G	Electric blower	4:4 (×1) 4:8 (×1) 4:4 (×2) 2:2 (×12) 1:0 (×1) 1:1 (×1)	42		55 No preheat figures	7:10	9.8 (0.23)	Pre-charged, with ore additions. Mostly natural draft. Bloom at each tuyère.
MS7 (12/8/15)	Full-scale	Oolitic EOR-G	Natural draft and bellows with folded cone	1:1	55	30	91	8:50		Pre-charged, with ore additions, keeping furnace stock low to maximize draft. Mostly natural draft. Both bloom and fluid slag.
MS8 (12/8/15)	Full-scale	Oolitic EOR-G	Natural draft					Over night		Pre-charged, all natural draft, left unattended overnight.

the ore and inhibit further reduction unless reducing gasses are blown through it at high pressure.

During MS1, the first 2.8 hr. of ore charging (16 kg of ore) using natural draft resulted in a shallow, low temperature reduction zone incapable of producing a liquid slag above the oxidizing combustion zone. Most of this ore therefore passed down to tuyère level in an unreacted or semi-reacted state, perhaps a situation made more pronounced by the dispersal of the charge across the furnace diameter. Initiation of the bellows led to a notable rise in temperature above that necessary for slag formation, and expansion of the reduction zone. The final 25 charges, therefore, experienced conditions that were more suited to bloomery iron production. Ignoring the first 16 charges, the ore to bloom ratio becomes 0.17 and is on par with the best results from the practice smelts.

MS2

The second smelt was planned as a test of the purple ironstone without mixing. Again, natural draft was followed by bellowing although this was planned to commence sooner to generate more heat. The arch configuration was identical to MS1 and no additional lining was added to the furnace base or walls. Charcoal fines were spread across the furnace base to a depth of about 10 cm. The tuyères were of lower quality than the first smelt and exhibited warping. Charging followed a 1:1 ore to fuel ratio.

The furnace was filled with straw and ignited. Wood kindling was added to help maintain the fire, followed by 6 kg of charcoal and some additional wood. In total 69 kg of charcoal was added to furnace for preheating. The first ore was charged 2 hr. 45 min. after ignition and bellowing began approximately 1.5 hr. later. The seventh bellows was added to the arch c. 15 min. after forced draft was initiated. Bellowing started in unison at a rate of about 60 strokes/min., increasing steadily to about 85 strokes/min., and spiking at 132 strokes/min. Keen noted viscous material at the arch tuyère after an hour of bellowing and after 2 hr. the seventh bellows was removed. At this point, four of the six tuyères were found to be blocked or in the process of becoming so and were cleared with a probe. Probing at 6 hr. 52 min. from ignition revealed a solid mass toward the rear of the furnace.

The final furnace charge was added at 6 hr. 55 min. and the burn down was initiated. Bellowing continued and probes found evidence of cast iron but no fluid slag. The furnace contents were removed at 8 hr. 37 min. In total, the furnace consumed 100 kg of charcoal and 30 kg of ore but produced no recognizable bloom. Slag, part-reduced ore, and any magnetic material were collected in haste because the next experiment was planned for the following morning. Recovery included 4 kg of magnetic slag, 4 kg of non-magnetic slag, 3 kg of slag formed at the tuyères, and 9 kg of part-reduced ore. Cast iron was noted but not quantified, and it is possible that this material was incorrectly grouped with the part-reduced ore. The slag was glassy and friable, as with MS1, but did exhibit flow patterns.

Hypotheses to explain the failure of this smelt ranged from a poor ore containing high concentrations of alumina to a furnace environment that was too reducing. Both possibilities were considered in planning the next smelt. The thermal profiles (FIGURE 5B), of the furnace suggest that MS2 was much cooler at the beginning of the smelt when compared to MS1. While the tuyères were lower quality and could have reduced the air pressure, a better explanation is the much higher humidity experienced on this day of smelting: atmospheric moisture will produce an endothermic reaction with hot charcoal that reduces furnace temperature at the combustion zone (Rehder 2000). The result, in this case, was an effective loss of the first 6 kg of ore added to the furnace. Once the bellows were activated, however, temperatures rose and exceeded those of MS1 at all measured locations (excluding the highest probe). This suggests that the ore charged after this time was exposed to sufficient temperatures and reducing conditions. It also indicates that the later ore charges might have been exposed to reducing conditions that were too high (leading to cast iron production) or, alternatively, that slag may have formed too soon, preventing contact of unreduced particles with CO gas.

MS3

The third full-scale festival experiment was designed to test the feasibility of the oolitic ore found in the same hills as the purple ore. However, the poor results of MS1 and MS2 also led to other changes. The ore to fuel ratio was increased to 1.5:1 by weight and the bellows operated at a slower pace. The arch configuration contained 13 tuyères, as before, but with minor adjustments to position. Failure of the thermocouple probe prevented any further measurements of internal furnace temperatures. Tuyère quality was lower than in previous smelts.

Preheating followed similar procedures to MS1 and 2, lasting approximately 2 hr. and using ca. 66.5 kg of charcoal. The first 10 ore charges took place under natural draft, taking just under 2 hr. to complete (FIGURE 6). The stock line was kept at 110 cm above the furnace base and the burn rate increased from ca. 30 min./charge at the start to 6 min./charge at the end. Natural draft was employed after the 10th charge and blown at a starting pace of about 60–65 strokes/min. When the bellowing began, however, the burn rate fell to 11 min./charge and the bellows team was instructed to increase the blowing rate to 75 strokes/min.

The final charge was added 5 hr. 28 min. from ignition and the furnace stock was allowed to burn down. The bellows were halted and removed at 7 hr. 9 min. for a tuyère inspection which showed all were beginning to close and boiling slag was present at tuyère level. The bellows were placed back in position after 10 min. and blown at a higher rate of around 100 strokes/min. for 20 min., following which the bellows were stopped and the furnace arch removed. Dripping viscous slag was observed inside the furnace and a large mass of slag was removed. Within the mass was a small bloom, one fragment of which underwent a brief episode of smithing. In total the furnace consumed 30 kg of ore and 86.5 kg of charcoal.

Slag, part-reduced ore, and magnetic material were collected the following day. Sorted residues included 1.5 kg of bloom, 15 kg of slag, and 4 kg of partially reduced ore. The quantity of bloom was far less than hoped, but the slag was more familiar in character to that of Meroe's later metallurgical record. Team members drew different conclusions from the results: Charlton (lead archaeometallurgist) suggested that the better slag flow was a consequence of increasing the ore to fuel ratio resulting in a less reducing furnace environment. This, if correct, produced a slag richer in iron oxide and so less viscous at low temperatures; Keen and

Figure 6. Smelting underway.

Sauder hypothesized that the oolitic ore was superior, probably containing lower concentrations of alumina relative to the purple ore. These hypotheses are not mutually exclusive and will be the subject of future laboratory evaluations.

MS4

This festival smelt was intended to test an alternative furnace charging model that, in theory, would enable a more efficient use of fuel. The model, formulated by Sauder, involved pre-charging the furnace in layers of ore and charcoal in systematically varying ratios. The first ore charge was positioned low in the furnace, exposed to more heat and less time for reduction. The hope was that this mass would form a liquid slag into which iron particles from the more reduced ores above would fall and form a bloom of manageable size. Less fuel would be required for preheat, with an additional charge of 33 kg of charcoal, followed by: 4 charges of 2.5 kg of ore and 3 kg of charcoal; 4 charges of 3.5 kg of ore and 3 kg of charcoal; and finally, 4 charges of 5 kg of ore and 3 kg of charcoal. The arch was closed with blocks containing 11 tuyères, all initially plugged with clay stoppers.

The local oolitic ironstone was selected, and bellowing began once the furnace was full. Unlike the previous smelts, a lining was added before this smelt to the furnace base. The lining comprised a mix of 1 part wadi sand (un-sieved) and 1 part Nile clay (by volume). The tuyères were the poorest quality of those originally made—both slightly warped and with smaller bore radii. The lining was completed on the day of the smelt (FIGURE 7), and was still wet when MS4 began, although the furnace was ignited and kept alight with wood to induce slow drying. After an hour 3 kg of charcoal were added to maintain the fire, and a few minutes later the initial 33 kg of charcoal was added, which filled the furnace to 88 cm from base, which was higher than anticipated. The stock was allowed to burn down for the next 25 min. and then the first 6 charges were fed into the furnace as planned, filling it beyond the shaft height. The bellows were initiated and helped the charge drop faster. The next three charges were added as the stack height permitted, though the furnace temperature was cooler than hoped. A decision was made to drop the stockline to 110 cm above base. At 4 hr. 2 min., slag tapped on its own through the middle tuyère in the furnace arch—a phenomenon that corresponds well with the archaeological record.

The 10th charge was completed at 4 hr. 48 min. and a decision was made to discontinue charging. Shortly after, some of the tuyères became blocked, while more heat was recognized at other tuyères. An additional 5.25 kg of charcoal was added to the furnace. The arch was opened at 6 hr. 47 min. and the furnace contents removed at 7 hr. 3 min. A large mass was situated to the back of the furnace, mostly formed on a tuyère, and no bloom was identified.

The furnace consumed 71.25 kg of charcoal and 34 kg of ore. The collected residues included 18.7 kg of mixed slag and 5.5 kg of partially reduced ore. Additional slagging had occurred on the furnace wall and at the arch. Though this smelt failed to produce iron, it did produce a run of tap slag through a tuyère that included the sandy bottom texture often observed on slag fragments from Meroe's ancient slag heaps. The best hypothesis to explain the lack of bloom was insufficient heat caused by the wet lining at the furnace base.

Research Following the Campaign

A number of planned research activities (and one unplanned) were initiated to further evaluate and build on the results of the first experimental campaign. Planned activities included

Figure 7. Lining the furnace before MS4.

laboratory evaluation of experimental results (Charlton and Humphris in press, 2017a), closer examination of excavation samples to acquire ore specimens, and a second series of smelts.

Just prior to the final smelt of the 2015 festival, serendipity favored the project with a new lead on the investigation of Meroitic ore mining. While searching for additional quantities of local oolitic ironstone in preparation for MS4, Keen and Humphris encountered a local man who expressed knowledge of a mining area ca. 9 km to the northeast of the Royal City. Subsequent research at this location indicated that the area had been mined in ancient times, specifically for oolitic ironstones (Humphris et al. in press).

A series of smelts was conducted in late 2015 to build on ideas that had emerged during the festival. Chief among these were desires to test a better ore, engineer a better air supply system, further explore the mixed air supply strategy, and continue the development of the pre-layered furnace charges. Due to last minute changes in project funding, resources for this campaign were significantly diminished. It was therefore neither possible to keep detailed records nor to quantify residues.

Oolitic ironstones from unexploited areas of the mining landscape (designated Meroe Mining Area 1 [MMA1]) (FIGURE 8), as well as a second variant of oolitic ore (named End of Road [EOR]), were gathered for the additional smelting campaign. Charcoal was restricted to leftover Acacia from the festival and local supplies of unknown species. The new charcoal was also not sized to a consistent dimension. However, larger sizes were selected for the early stages of the smelt, to allow easy gas passage for the natural draft segment for the smelts.

The furnace was extended to a height of 145 cm above the base, and the walls made thicker at the top to enhance the chimney effect and provide greater heat retention. A refractory lining, like that used in MS4, was also retained in each smelt.

Archival and literature research, as well as offsite experimentation during the summer of 2015, led to a change in the design

Figure 8. MMA1 area under excavation.

of the pot bellows. Rather than attaching the diaphragms as flat membranes, the diaphragms were attached as wrapped cones, with the edges of the wrap serving as a valve. Though this diaphragm configuration required more skill to use, it delivered an estimated 5 L of air/stroke (a 70% increase) from the same sized bellow pot. The greater intake surface created by the valve also allowed the tuyère to be firmly attached to the pots, more closely resembling the archaeological evidence. This meant hot furnace gases were not sucked back and a lower pressure drop at the tuyère juncture, with correspondingly reduced work from the bellows teams.

Tuyères followed the same recipe as the festival campaign, but with greater quality control. Their noses were also pulled backwards, toward the furnace wall. The distance between tuyère noses was approximately 33 cm. The goal was to produce several small blooms as opposed to the single central bloom attempted during the festival.

Smelting techniques involving the mixed air supply and layered charging techniques were refined across five autumn 2015 smelts (including four in the large furnace and one in the small furnace at the compound) (TABLE 4; FIGURE 9). Results must remain anecdotal without detailed records and quantifications. However, the better ore and air supply system, combined with manipulation of nascent blooms toward the tuyères, led to a doubling of previous ore to bloom ratios, higher quantities of tap slag and internal flows that more closely matched archaeological slag, and steely blooms.

Lessons Learned

Valuable information to help reconstruct furnace operation, resource utilization, and the quantities and qualities of products and debris which were produced in the past was provided during the experiments. Importantly, finer, more nuanced impressions were gained of the logic behind the architectural features of the workshop.

The workshop space

The sunken workshop floor not only provided differing elevations required for bellowing and slag tapping/bloom removal, but also defined a space for the smelters to operate without impediment from other workers. It meant that the bellows operators were at eye level with the smelters, making communication easier, and provided a safe area for hot material to be removed from the furnace in a contained space where only one or two people were standing. It further ensured those operating the bellows were at a safe distance from the hot zone at the front of the furnace.

The experiments demonstrated that earlier interpretations of the central pit as a water bosh were incorrect. The space constraints of the workshop prohibit movement without stepping into the pit and water made the area slippery—discovered when hot materials were quenched. At the end of the smelts, slag, charcoal, and bloom were moved down into this area, as suggested by the archaeological evidence and during the experiments. However, the experiments provided further insights: the pit provided a lower vantage point from which to observe internal furnace dynamics; it was the only practical place for the smelter to stand during slag tapping or bloom removal; and it allowed long tools to reach farther into the furnace at steeper angles for probing, manipulating, and removing furnace contents.

The reason for the apparent double furnaces of the workshops excavated in the 1960s and 1970s remains puzzling. It is difficult to conceive how two furnaces would be in simultaneous use in the limited workspace, and both operated at optimal levels. The experiments, combined with recent excavation findings, offer a few possibilities. The optimum time

Figure 9. A small-scale Meroitic furnace at the UCL Qatar house compound.

for bloom working is immediately after the bloom is removed from the furnace. During the 2014 excavations it was proposed that the archaeological workshop had a smelting furnace at the eastern end and a secondary furnace at the western end, possibly for bloom re-heating. Similar modes of operation have been suggested for other workshops (Crew 1986). Current geochemical analysis of samples collected from across the workshop space will further understandings of the use of this space.

Another possibility is that if two furnaces were being operated consecutively, one furnace could be prepared and loaded during a natural draft phase of the other (assuming that a mixed mode of air supply was employed with tall conical furnaces). This would be an efficient use of time and labor but lacks sufficient evidence at present to build a convincing argument.

Furnace design and operation

Two observations were made regarding the size of the experimental Meroitic furnace. First, the volume was much larger than that used in the shaft furnaces used by Keen and Sauder (0.3 m^3 versus 0.1 m^3, respectively). Modern experimenters tend to preheat their shaft furnaces with charcoal and add charges as the charcoal burden drops below the rim. The large volume of the Meroitic furnace means that, following such practice, it consumes an enormous amount of charcoal per smelt and risks generating an overly reducing environment. Experiment MS4 aimed to overcome this issue by layering the ore and charcoal before lighting the furnace, thus conserving charcoal and labor and managing the reducing atmosphere. This conservation of fuel could help explain how the Meroites were able to use one species of wood charcoal through their smelting history. More experimentation with this method will be required to assess its viability.

The second observation was the natural draft effect created by the height of the furnace, which was used in most of the experimental smelts. Though the natural draft did not generate temperatures high enough to produce a fluid slag, it did create a hot reducing environment. If managed effectively, it could reduce labor costs.

The Meroitic ore source

Experimental evidence indicates that an oolitic ore source proved to be the most promising of the ores acquired near

Figure 10. School children learning about iron production during the smelting festival.

Meroe. The identification of an ancient mining location associated with oolitic ironstones lends strong additional evidence. Ongoing laboratory analysis of samples collected in the slag heaps also agree with the hypothesis that an oolitic ironstone was the primary ore exploited for iron production.

Was this furnace designed to produce steel?

During forging of blooms from some of the more successful, later smelts, it was noticed that some had the molten appearance of excessively high carbon blooms. Surprisingly, these were forged to bar relatively easily. Subsequent experiments in the USA by Sauder with a Meroitic type furnace, operated as described above by pre-charging and utilizing natural draft, has also produced a high quality and easily worked steel. This corresponds with ongoing laboratory analysis which reveals the archaeological slags to have low concentrations of wüstite. The lack of wüstite, or free FeO, implies the presence of strongly reducing conditions in the ancient smelting furnaces, and the potential for surplus of carbon available to enter the iron.

What Next?

Fundamental research questions include how much iron was produced at Meroe, at what intensities over time, and where it was distributed. Answering these questions will help reveal the ebb and flow of social, political, and economic aspects of the Kingdom of Kush and of Meroe per se, and the role and impact the iron technologies had on this. Archaeological excavations and laboratory analysis can go far in helping to illuminate the past, but the experiments have demonstrated that while we may have a better understanding than before we began of the ancient smelting practices, in fact we have raised more questions that must be answered before we can really understand the iron smelting at ancient Meroe, during only the late and post-Meroitic period of Kushite history.

Laboratory analysis of ores, slags, blooms, and ceramics is ongoing, comparing the archaeological and experimental samples. The identification and understanding of the oolitic ores has enabled mass balance calculations to begin which will, in conjunction with the chronological framework being generated from the archaeometallurgical excavations (Humphris and Scheibner 2017), for the first time allow for a greater confidence in defining the quantities of iron produced at Meroe. Future experiments to test the evolving hypotheses are also planned.

Conclusion

While the archaeometallurgical record of Meroe provides abundant information about iron smelting practices, it paints a sterile picture of a once vibrant technology and generates a great number of problematic research questions. Experimentation has provided an opportunity to simultaneously bring the technology to life and address questions through testing unknown variables. Thorough prospecting of wide areas of the landscape was required to find suitable materials. Once potential ores and clays were identified, they were tested analytically and experimentally. However, even with suitable ingredients, an appreciation of the operating parameters of the Meroitic furnaces remains fundamental for estimating the fuel, labor, and temporal costs per smelt, and for understanding the organization of labor and resources in Meroitic times.

The experimental smelting campaigns described here explored a small fraction of possibilities for bloomery operations at Meroe. They neglected the variability in furnace design observed in the archaeological record as well as change over time evident in the one thousand plus years of smelting debris present at the site. Available archaeological data was used to create a general replica model to re-enact ancient smelting in an experimental manner. Smelters Keen and Sauder followed a trail through the possibilities and arrived at a mode of viable furnace operation. Right, wrong, or somewhere in the middle, this model generates new hypotheses that can be explored through future archaeological, laboratory and experimental investigations. If the large Meroitic furnaces were designed to produce steel, we expect to find greater quantities of this material distributed across the socio-economic network that embodies the Kingdom of Kush and its relations. At present, few steel items have been found amongst Meroitic finds and more emphasis seems to have been placed on phosphorus and arsenic alloys of iron (Abdu and Gordon 2004). However, the currently available sample of ferrous objects is far from sufficient to be able to draw firm conclusions.

In addition to the academic aspects of the iron smelting episodes, the major community engagement endeavor of the smelting festival succeeded in providing significant educational opportunities both during the events and subsequently with the production of an open access film (https://www.youtube.com/watch?v = SPU8Uwa-jBQ [English]; https://www.youtube.com/watch?v = PBCrKLx0R0I&t = 1367s [Arabic]), and a bilingual information point constructed around the experimental furnace workshop. The success of the community engagement (FIGURE 10) alongside the strong academic results from the ongoing archaeometallurgical research give these iron smelting experiments at Meroe particular value.

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Notes on Contributors

Jane Humphris (Ph.D. 2010, University College London) is a Principal Research Associate at University College London (UCL) Qatar. As head of UCL Qatar's Sudan project, Jane's research focuses mainly on ancient iron production associated with the Kingdom of Kush. Alongside the research she runs a community engagement and capacity building program, which involves meetings, interviews, and lectures, as well as training Sudanese students. She recently began a new research project concerning ancient iron production in Ethiopia.

Michael F. Charlton (Ph.D. 2007, University College London) is a specialist in the application of materials science methods to residues of pyrotechnological processes. In addition to materials science, he also uses statistical methods to investigate patterns in compositional datasets for ceramics, glass, metals and other materials. He is currently a team member on the Sudan project where he leads laboratory investigations of ironmaking residues.

Jake Keen founded and directed The Ancient Technology Centre, Cranborne, (www.ancienttechnologycentre.co.uk) from 1985 to 2003. This outdoor education center is devoted to Experimental Archaeology and provides hands-on facilities for students of all ages. Since 2003 Jake has focused on freelance projects with university groups, specializing in iron smelting.

Lee Sauder is a professional blacksmith and sculptor who has subsisted solely by his craft for more than 35 years. For the last 20 years, the major focus of his work has been independent research into the practical techniques of bloomery smelting and forging the resulting iron into contemporary sculpture.

Fareed Alshishani (MSc 2014, University College London, Qatar) is the capacity building coordinator for the SCHEP Project (Sustainable Cultural Heritage Through Engagement of Local Communities Project) which is directed by the American Center of Oriental Research (ACOR) in Jordan. Before returning to Jordan he worked as a Research Assistant for UCL Qatar's Sudan Project.

ORCID

Jane Humphris http://orcid.org/0000-0001-6963-2143
Michael F. Charlton http://orcid.org/0000-0002-9526-5743

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