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New methods for investigating slag heaps: Integrating geoprospection, excavation and quantitative methods at Meroe, Sudan

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ABSTRACT

This paper describes a multifaceted approach to the investigation of iron slag heaps, focusing on one of the slag heaps at the Royal City of Meroe in Sudan. This study marries together geoprospection data (gradiometry and electrical resistivity transects), topographic data and quantitative excavation data, to provide an analysis and comparison of the total volume, slag component and slag composition of a slag-heap. Significantly, the results demonstrate the limitations of using a topographic only model, but also demonstrate how volumetric modelling must be integrated within quantitative characterisation of slag-heap composition. In this case, quantitative sampling of the slag deposits revealed the composition of the slag assemblage was dominated by a newly defined category of slag which has major implications for reconstructing iron technologies in the Meroitic civilisation. This research highlights the dangers of applying simplistic models and basic investigative strategies to iron slag heaps and furthers the debate on applying volumetric modelling and excavation sampling to unexcavated areas of the finite and important resource of archaeometallurgical deposit sequences.

1. Introduction: iron production in the Kingdom of Kush

The Kingdom of Kush was a powerful African State that flourished from around the eighth century BC to the fourth century AD. At its height this kingdom controlled an area encompassing hundreds of kilometres along the east and west banks of the Nile from south of modern Khartoum to the Egyptian delta and beyond (Welsby, 1998: pp. 7–9). Meroe Royal City was the capital of the Kingdom of Kush from *c.* 300BCE to 350 CE. Along with its pyramids, temples and palaces, Meroe is renowned for vast remains of iron production, with slag heaps being prominent features within the landscape of the city environs (see Humphris and Rehren, 2014 for literature concerning Meroitic iron production). Although Meroitic iron production has been studied superficially in the past (Sayce, 1912: p. 55; Arkell, 1961: p. 147; Tylecote, 1970, 1982; Shinnie and Kense, 1982; Shinnie, 1985; Rehren, 1995), a systematic study using modern field and laboratory methods was only initiated in 2012 by UCL Qatar. This research aims to investigate and contextualise the role of iron production within the social, political, economic and environmental contexts of the Kingdom of Kush.

Throughout the Royal City of Meroe the slag heaps vary in size, from less than 10 m to over 50 m in length, potentially indicating chronological differentiation. Of particular significance at Meroe is that while some slag heaps appear to contain mostly metallurgical debris from the upper surface of the heap to ground level, others are comprised of a relatively thin horizon of metallurgical debris above sand and/or earlier architecture, giving the superficial appearance of a slag-heap. This, coupled with the inherent heterogeneous nature of slag-heap deposits, has necessitated an innovative approach to the survey, excavation and sampling at Meroe in order to produce estimates of quantities of raw materials used and iron produced, both major research questions of the investigations. If the potential iron yield from a smelt can be estimated from the slag analyses, then the quantification of the volume of slag within a heap is a critical question (Historic England, 2015: 1, 9, 11, 14). When addressing such research questions, investigations into ancient iron production often include estimates of slag-heap volumes based on macroscopic observations during excavation. For example, Cleere (1971b: p. 206) produced a 50,000 ton estimate for the slag-heap at Beauport Park, Battle, although he subsequently warned about complexity of issues affecting such calculations (1981: pp. 191–193).

The investigation of ironworking site-scapes requires an

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integrated combination of methods to understand ironworking remains at a variety of scales. This paper describes the use of geoprospection methods and quantitative excavation as part of the investigation of slag heaps. It is argued that combining these two methods adds significant data to the ideally multifaceted investigation of the archaeometallurgical deposits. The case study area is located at the Royal City of Meroe, an area famed as much for its pyramids as its rich ironworking legacy. The iron slag-heap is MIS6 (Meroe Iron Slag 6; Fig. 1).

2. Investigating slag heaps

The evolution and complexity of ironworking technologies and the associated production of technological debris have been subjects of academic discourse from the Middle Ages through to modern archaeometallurgical excavations (e.g. Biringuccio, 1942;Agricola, 1950; Straker, 1931; Cleere, 1971a, 1971b; Miller and Killick, 2004; Florsch et al., 2011; Perret and Serneels, 2009; Charlton et al., 2010; Killick and Miller, 2014). The fascination with metal producers of the past continues as progress is made to understand their technological innovations and choices, as well as the impacts their technologies and products had on society. The diversity evident in metallurgical processes across space and time is as captivating as the similarities that are dictated by the physical properties of the materials with which they worked and the physical wastes they left behind.

The dominant artefact from the production of iron in the archaeological record is iron slag, often deposited into discrete dumps or heaps. The term *slag-heap* is used here to define archaeometallurgical material dominated by iron slag, although significant variation exists within their deposit structures, including the composition of archaeometallurgical debris and non-metallurgical material/sediment components (Craddock, 1995: pp. 12–15, 204). Variability in composition can occur within and between slag heaps, and at site, regional and (inter)national levels. Technological factors, societal choices and post depositional processes can all influence slag-heap composition. *Archaeometallurgical material* within this paper is used to define all materials associated metalworking, such as slags, furnace lining, tuyeres, ore fragments, charcoal, etc.

Although slag heaps represent the durable waste debris of the production process, archaeometallurgists strive to locate and identify the remains of iron smelting furnaces as the primary evidence of the technological, historical and social aspects of metalworking technologies (Pleiner, 2000: p. 194). However, across many ancient smelting locations, it is the iron slag which forms the resilient, ubiquitous and valuable archaeological remains where furnaces have long since disappeared. In such cases, analytical approaches must be used to reconstruct an understanding of the past ferrous technologies through the investigation of slag heaps (e.g. Cleere, 1971a; Tylecote et al., 1971: p. 342; Gordon and Killick, 1993: p. 247; Juleff, 1996; Birch et al., 2015; Historic England, 2015: pp.

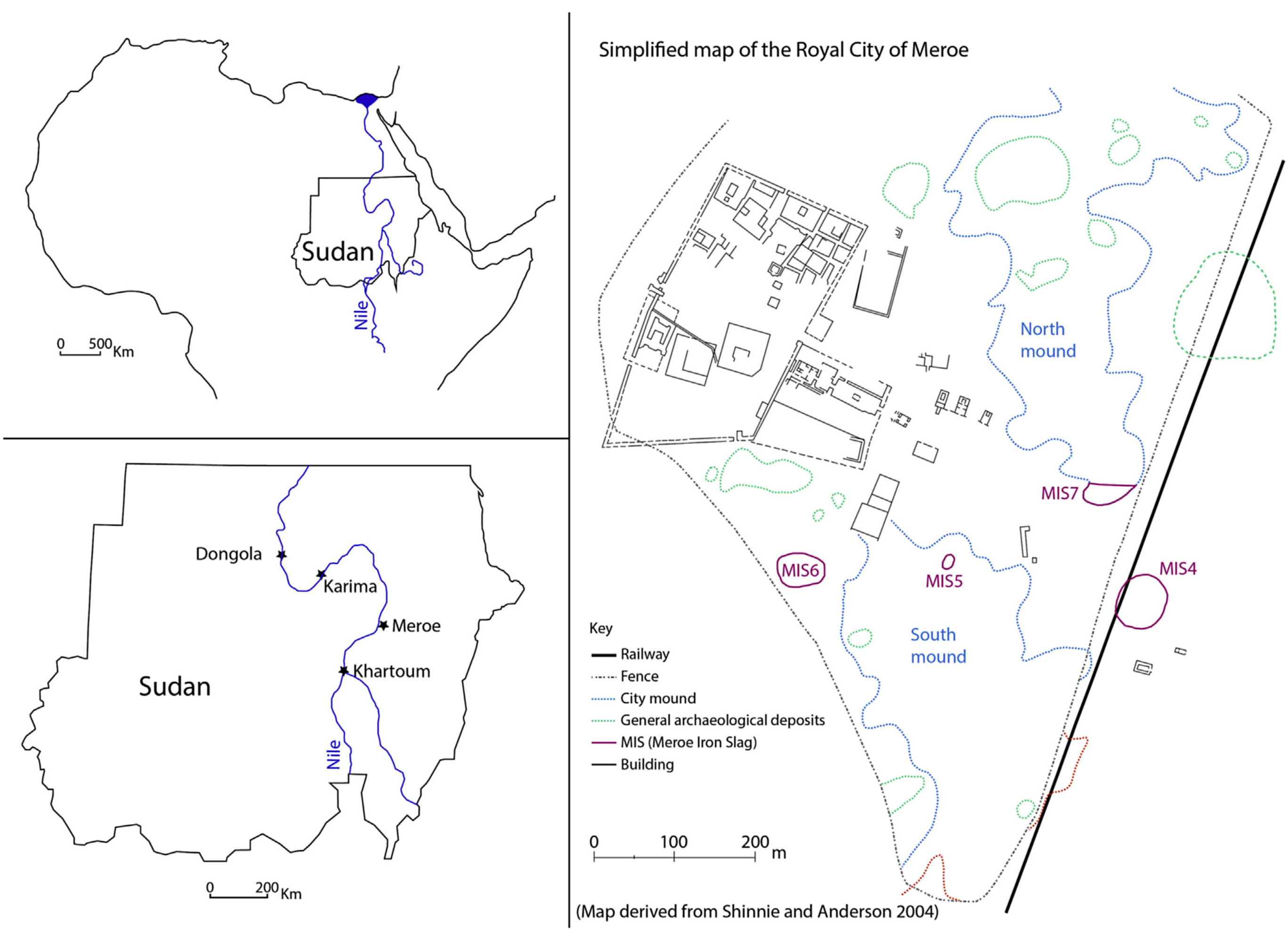

Fig. 1. Location of Sudan, with Meroe and a number of other key sites on the Nile marked. Inlay depicting the Royal City of Meroe and the slagheaps mentioned in the study.

7–14).

There are many challenges to investigating slag heaps, not least their scale that often makes complete excavation impossible (Crew, 2002). Excavation frequently reveals a heterogeneous composition and abundance of artefacts including iron slags, necessitating a different excavation and sampling strategy when compared to more common archaeological deposit sequences. As furnace styles and the raw materials used (e.g. ore, clay mixes and charcoal) varied within and between smelts, and as the skill levels of different smelters and their social traditions evolved, so the slag-heap compositions reflect these changes (or continuities in traditions). A single slag-heap could be the product of multiple furnaces or workshops operating over a long period of time, or one workshop operating intensively for a shorter period of time (e.g. Cleere, 1971a: p. 204). Combining these factors with the variable nature of the slag itself (slag produced during a single smelt can vary in microstructure, composition and form) reveals a major challenge for reconstructing past iron smelting technologies from slag heaps: how can we collect representative samples of metallurgical debris from a large heap of arbitrary smelting debris (e.g. see Humphris et al., 2009)?

Despite the inherent complexity of slag-heap deposits, previous excavations of slag heaps have made significant contributions to the archaeological knowledge of ironworking (e.g. Cleere, 1971b; Crew, 1988; Craddock, 1995: pp. 12–15; Eigner, 1996; Juleff, 1998, 2009; Bray, 2006; Perret and Serneels, 2009; Humphris, 2014). The excavation of slag heaps and detailed laboratory analysis of samples has revealed a wealth of technological, social and economic detail, at two complementary scales of archaeological investigation. These scales are intimately linked, with the excavation of the slag-heap providing characterisation of the deposits and the opportunity for sample collection, and the laboratory analysis providing technological information on past smelting parameters.

3. Archaeometallurgical aims

A fundamental aspect of this project was to marry geoprospection, excavation and post-excavation data, providing a continuum of integrated archaeometallurgical investigation (Carey et al., 2014). Within this project geoprospection was undertaken to evaluate and characterise the ironworking remains; these geoprospection results have subsequently been integrated with the quantitative characterisation of the archaeometallurgical deposits. Significantly, geoprospection not only had to be a 'mapping tool', but was also required to be a tool of analysis, with the capacity to work in both spatial and depth dimensions.

A combination of techniques was selected that had the capacity to measure the depth of the slag heaps (electrical resistivity survey) and map the spatial extent of the slag heaps, with the potential to identify furnaces and furnace workshops (gradiometry). The excavation methods aimed to record the stratigraphic complexity of the slag heaps, in order to understand the evolution of the metalworking site-scape as well as the relationship of the industrial remains with the surrounding archaeological structures. Archaeometallurgical material from every trench underwent systematic quantification, allowing modelling of the composition of the slag-heap deposits within volumetric estimates.

This approach has allowed a comparison of the results obtained from surface survey, electrical resistivity survey and excavation in defining the volume of archaeometallurgical materials within the slag-heap. This comparison is coupled with an analysis of the results of quantitative sampling of archaeometallurgical materials, discussing intra and inter trench variability. This analysis allows production of volumetric and mass models for MIS6, and provides a platform for a more general discussion on geoprospection and excavation programmes for archaeometallurgical site investigation.

4. Justification of methods

There are many difficulties in applying geoprospection and excavation methods to ironworking complexes. In geoprospection terms, whilst utilising magnetic survey to identify magnetic and dipolar signatures can be fruitful (Vernon et al., 1998; Kozhevnikov et al., 2001; Abrahamsen et al., 2002; Crew et al., 2002; Powell et al., 2002; Smekalova and Voss, 2002; Walach et al., 2011; Carey and Juleff, 2013) the sheer volume of magnetised and iron rich material at a site such as Meroe where the underlying geology is a ferricrete sandstone, with derived surficial deposits, can make this difficult. If furnaces are buried under several metres of slag, it becomes impossible to identify their magnetic structures from conventional surface gradiometer survey. Likewise, estimating the depth and volume of slag is a key challenge, with this area of geoprospection having seen relatively little development, with the notable exceptions of Florsch et al. (2011, 2012), utilising induced polarisation for mass and volume calculations of slag deposits, Ullrich et al. (2015) identifying slag deposits from high resistivity contrasts and Ullrich et al. (2009) using a mix of resistivity and induced polarisation readings to model slag heaps.

The comparatively limited development of geoprospection methods to investigate metalworking sites is surprising given the nature of these deposits and the potential for geoprospection to characterise deposits that cannot be excavated. When faced with archaeological remains such as those at Meroe, where slag heaps are so large and of such great historical importance that complete excavation is impossible, it is necessary to marry geoprospection to the excavation and post-excavation data, producing a synthesis on both macroscopic and microscopic levels. The advantages of this are significant: more accurate quantification of smelting debris; more precise identification of ironworking foci (hearths and furnaces) and iterative feedback between excavation and prospection data allowing interpretative extrapolation of features/technological debris over unexcavated areas of the site/landscape.

Field survey utilised a total station and differential GPS to topographically survey and map all slag heaps at Meroe. Gradiometer survey was undertaken across a swathe of Meroe Royal City to provide an understanding of the location and extent of the slag heaps. On identification of key areas of ironworking debris, detailed gradiometer survey was undertaken to look for structures within the slag heaps and attempt to identify dipolar anomalies from *in-situ* furnaces or hearths. After the topographic and gradiometer surveys, electrical resistivity survey was utilised to detail the gross morphology of the slag heaps in section. The data was interpreted to identify slag deposits and any subsurface features, e.g. pits, buildings, walls, etc. The data from the gradiometer survey was used to define the total area of slag-heap MIS6 based on magnetic signal. The surface survey, electrical resistivity and excavation datasets were analysed to produce volumetric models of the slag-heap and combined with the data from the quantitative sampling.

Excavation trenches were located based on the interpretation of the combined survey results. The heterogeneous and mixed nature of the archaeometallurgical deposits meant that single context excavation was not a feasible excavation strategy. Consequently, the trenches were excavated in defined spits (see below) to allow sampling for quantitative analysis. The sections of each trench were then drawn and individual contexts were identified and documented, allowing context specific samples to be collected. This approach allows mass quantification of metallurgical materials, stratigraphic interpretation, and context specific sampling, all within the same intervention.

5. Materials and methods

5.1. GPS and total station survey

Topographic survey was undertaken at MIS6 using a differential GPS collecting 2001 data points walking over the slag-heap, with a precision of 0.02 m. A total station was used to record variation in the surface structure of the slag-heap and the visible edge of the slag deposits prior to excavation. The total station was used to set-out and record the 30 m grids for the gradiometer survey and the transects for the electrical resistivity survey.

5.2. Gradiometer survey

The gradiometer survey used a Bartington twin sensor grad 601-2. Large areas of Meroe were surveyed using real time gradiometer survey collecting data on 30 m grids, with a 1 m traverse interval collecting 4 samples per metre, walking a systematic zig-zag pattern along the grids. After initial analysis of this data, specific grids that were considered to have high potential to contain furnaces/furnace workshops and slag deposits were selected for static point gradiometer survey, walking 0.5 m traverses, collecting data at 4 readings per metre. The gradiometer data was downloaded into the Archaeosurveyer software with a simple processing methodology of destriping and clipping applied, before export of Ascii data to ArcGIS.

5.3. Electrical resistivity survey

Three electrical resistivity transects were undertaken utilising an IRIS SYSCAL PRO 72 electrode resistivity rig (Fig. 2). The transects used a 1 m electrode spacing, taking data readings over 14 depth levels, giving a total depth penetration of *c*. 5 m, collecting data in the Wenner Schlumberger array. The Syscal Pro was programmed through the Electre II software, with data modelling in Res2DINV, via download in PROYSIS II. All data was topographically corrected, with an inversion routine utilising a smoothness constrained least squared method. Processed data was exported from Res2DINV into Adobe Illustrator for the interpretation of key anomalies and macro-stratigraphic units. Once this interpretation was complete, the depth of key macro-stratigraphic units was measured and digitised at a 1 m resolution along the resistivity transects, providing 85 data points for calculation of the volumetric model. This data was imported into the GIS for modelling.

5.4. Excavation and quantitative sampling

Four trenches were excavated at MIS6 in 2014 of which three were excavated for the purpose of quantitative sampling and recording slag-heap stratigraphy. Trench 2 was 1 × 5 m, and trenches 3 and 4 were 1 × 10 m (Fig. 2); trench 1 (which is not further discussed in this paper) was 10 × 8 m and was excavated over the area of a furnace workshop, and was not subject to field quantification of slag deposits. The archaeometallurgical materials from trenches 2, 3 and 4 was excavated in horizontal spits of defined depth. All material from one spit was removed and placed on a plastic sheet. The material was homogenised by mixing and then successively halved, until a (representative) 1/8th sample was left. Buckets of this 1/8th were weighed (kg) and then sieved (3 mm mesh) to remove sediment. The remaining material was classified into categories, weighed and subsampled for laboratory analysis, as follows:

- Category 1: light, porous furnace slag (*c.* >3 cm).
- Category 2: large, heavy furnace slag (*c.* >3 cm).
- Category 3: fragmented tapped slag (*c.* >3 cm).
- Category 4: large tapped slag (*c.* >3 cm).
- Category 5: dominated by small tap, furnace and indiscriminate slag fragments (*c.* <3 cm^3), and a residue of all other small undiagnostic non-slag fragments.
- Furnace material, tuyeres, ore, charcoal, pottery, bone and other material were also weighed and subsampled.

This slag processing of the 1/8th spit contents was repeated for each spit until the end of the metallurgical debris was reached. On completion of the excavations the sections of the trenches were

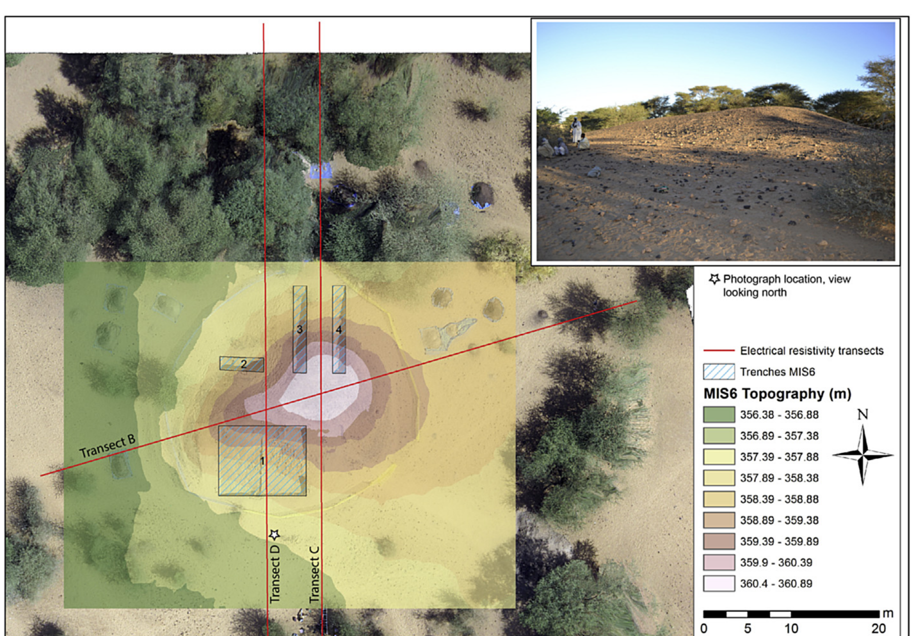

Fig. 2. MIS6 showing the position of the electrical resistivity transects and the excavated trenches. Inlay showing MIS6 at ground level, looking north.

cleaned and documented, contexts were assigned and described, and samples taken of all material categories visible in each context. Charcoal for species identification and dating was sampled throughout the contexts, where possible from embedded within slag fragments. Section drawings were also used for the construction of the GIS models. The excavated trench sections were subdivided into macro-stratigraphic units, with a simple divide made between contexts with/without metallurgical debris, providing a depth at which the slag deposits stopped. This depth was then digitised within the GIS at a 0.5 m data resolution along the sections, providing 113 data points for interpolation.

5.5. GIS modelling

All the data was archived and interrogated within ArcGIS (version 10.3). The data from the earthwork survey, the electrical resistivity and the excavated sections were translated to interpolated surfaces through a Kriging function. The edge of the slag-heap was identified from the gradiometer data and a clipping mask made from this data for interpolation of all surfaces/models. The surface morphology of the slag-heap was modelled from the topographic data. This allowed construction of three volume models of the slag-heap, based on the total modelled depth of archaeometallurgical materials:

1. Surface survey model: a volume model based on the topographic data only.
2. Electrical resistivity model: a volume model based on the electrical resistivity data only plus surface topography.
3. Excavation data model: a volume model based on the excavated sections only plus surface topography.

The volume of each model was calculated using the cut/fill tool on the two surfaces in ArcGIS (the modelled base of slag deposits from the different models and the top surface of the slag-heap from the topographic data). This produced a binary raster output representing topographic increase/decrease, which recorded the volume values within the raster attribute table.

5.6. Mass and density estimates

From the excavation data the total volume of metallurgical debris excavated from the trenches was calculated. With the data from the quantified archaeometallurgical material it was possible to produce a density model for each trench, using mass data (based on the calculation of the 1/8th of each spit, multiplied by 8), divided by the cubic volume excavated, to produce a figure of kg/m^3 of archaeometallurgical material. This density was placed within the overall volume estimates from the surface survey model, the electrical resistivity model, and the excavation data model, to produce estimates of total mass of archaeometallurgical materials within the slag-heap.

6. Results

6.1. Geoprospection data

The gradiometer responses were expectedly noisy due to the naturally iron-rich geology combined with a high level of anthropogenic materials (e.g. pottery and fired brick). The plots clearly revealed the slag-heap and indicated potential internal structures. The resistivity transects also produced extremely noisy data, a product of sand dominated substrates in arid conditions, and also due to slag rich contexts containing air voids creating some poor electrical contacts. Data editing required removal of *c.* 20% of the original data as 'suspicious' values, creating difficulties with the subsequent inversion modelling. Inversion routines varied between 15 and 27% (Table 1), much higher than ideally expected. Other researchers have reported similar difficulties in obtaining resistivity data near Meroe due to the challenging environmental conditions (Ullrich et al., 2015; see also Berking et al., 2011).

The gradiometer survey also identified variability within the composition of the slag-heap (Fig. 3), as did the electrical resistivity transects: an interpreted example is given of transect D (Fig. 4). Unit 1, a high resistivity unit at the top of the slag-heap, was interpreted as archaeometallurgical material which thickened on the western edge of the heap. Underlying unit 1, unit 2 was a medium resistivity unit interpreted as a spread of general archaeological deposits, but specifically not containing archaeometallurgical material. Units 3, 4 and 5 indicated some form of archaeological deposits of strong resistivity contrast, of unknown character. Unit 4 is interpreted as an unfired mud-brick structure with the base of this structure as Unit 5. It is possible that Unit 5 represents an earlier phase of slag-heap on which the building was placed, or another type of archaeological deposit; it can only currently be described as a high resistivity unit of unknown character. No excavation continued to this depth, and the fact that the slag-heap above the building (Unit 1) is separated from Unit 5, means it has not been included within the volumetric models.

The interpretation of transect D demonstrates the slag-heap (Unit 1) to be a heterogeneous deposit. In places it is a relatively thin layer of archaeometallurgical materials, with areas of thicker deposits up to *c.* 0.95 m along the northern edge of the top of the slag-heap. The slag has been deposited on top of an older building/series of archaeological deposits. This interpretation was subsequently supported by the excavation of trenches within this slag-heap (Figs. 5 and 6).

6.2. Volumetric data modelling of the slag-heap

As described, three volumetric models were constructed for slag-heap MIS6: a surface survey model, a resistivity model and an excavation model. Each of these models is a proxy of reality: the surface model involved no sub-surface investigation; only 3 electrical resistivity transects traversed the slag-heap, and only four (albeit large) trenches were excavated. The interpolated total slag depth from the electrical resistivity model calculated from the depth of Unit 1 (Fig. 7) compares reasonably well with the total slag depth calculated from the excavated model (Fig. 8). The electrical resistivity slag depth produces two anomalies which show areas of considerably deeper slag deposits. The northern area corresponds with a deeper slag deposit revealed in the eastern end of trench 2, while the southern deeper area was not targeted by the excavation units so is therefore not highlighted in the excavation model. There is good general agreement between the bottom of the metallurgical deposits as described by the electrical resistivity and the excavation data, with both models showing a division between metallurgical debris and the underlying material, although overall the electrical resistivity model overestimate the deepest parts of the slag-heap.

Table 1
Inversion routines for the electrical resistivity transects at MIS6.

Resistivity transect	Inversion/iterations
Transect B	6 Iterations Inversion error 17.7%
Transect C	7 iterations Inversion error 26.6%
Transect D	5 Iterations Inversion error 15.6%

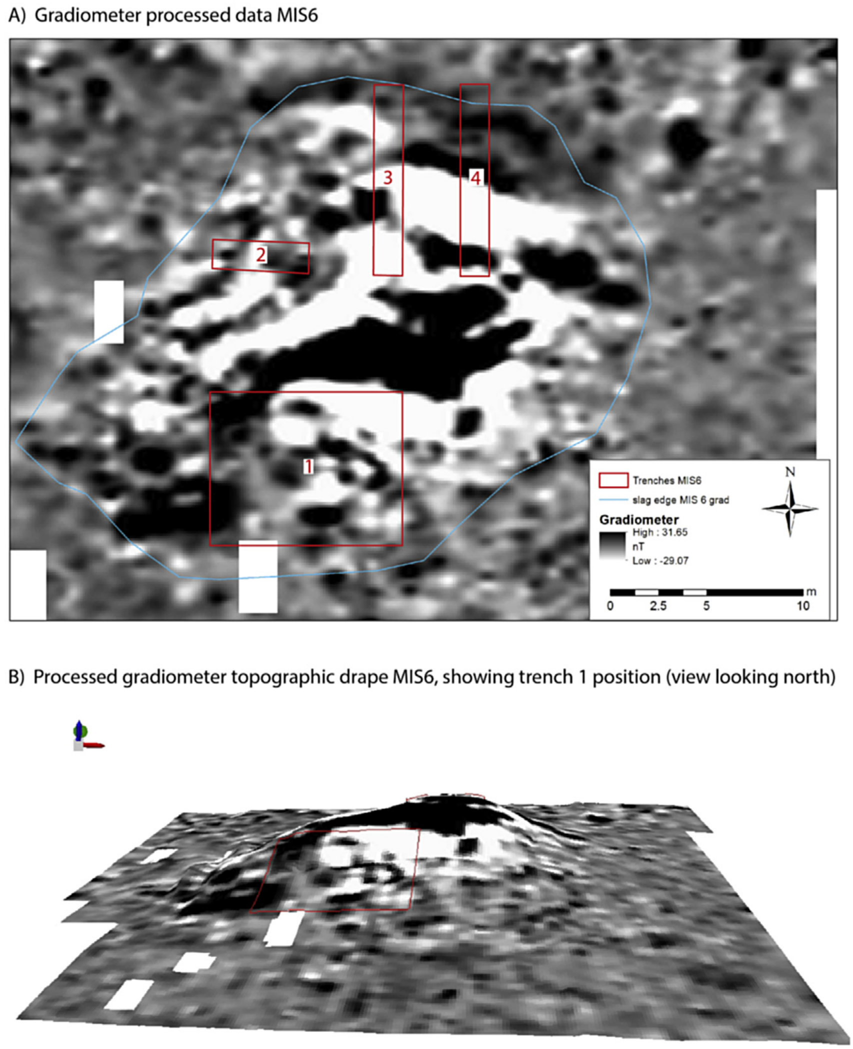

Fig. 3. Gradiometer data indicating the extent of MIS6 and magnetic variability within the composition of the slagheap.

From these modelled surfaces, a volume estimate was constructed (Table 2).

These figures demonstrate that the surface survey model substantially overestimates the volume of the slag-heap, producing a metallurgical volume of almost double that calculated from the excavation model. This is not surprising, given there is no way of knowing that there is a Meroitic building underneath the slag-heap from topographic modelling. The electrical resistivity model underestimates the volume of the slag-heap in comparison to the excavated model, although both models indicate a significantly lower volume of slag in the slag-heap than the volumetric model created from surface survey.

6.3. *Quantitative sampling*

The quantification methods applied to the slag-heap excavations showed variability in the amount and categorisation of metallurgical debris between trenches 2, 3 and 4. Although the trenches were set out subject to the topography of the slag-heap and the interpretation of the gradiometer and resistivity data, the actual mass of material recovered from each trench for quantitative sampling was comparable (Table 3). Of the total mass of material from each trench, there is clear variability in composition, with trench 3 having a higher overall total mass of archaeometallurgical material, trench 4 having the lowest and trench 2 displaying a middle value. Of this total mass of archaeometallurgical material, slag was the dominant component in all trenches. Again trench 3 had the highest mass of total slag (all categories), trench 4 had the lowest mass of total slag, and trench 2 had an intermediate value.

These figures were converted into percentages, reflecting not only the composition of the slag-heap at each trench location, but also the composition of the archaeometallurgical material within each trench. The total amount of archaeometallurgical material as a percentage of total sample was highest in trench 3, lowest in trench 4, with trench 2 displaying a medium value (Fig. 9, A). Trench 4, being on the north east corner of the mound, contained more frequent sandy, non-metallurgical deposits towards the middle and bottom of the trench. Trench 2, on the western end of the heap, contained a deposit sequence dissimilar to trenches 3 and 4, with a higher proportion of non-slag dominated contexts.

However, the mass of total slag as a percentage of the total archaeometallurgical material was remarkably consistent between trenches (Fig. 9, B), with a variance of 3.3%. Although there is evident variation in the composition of the slag-heap, i.e. the amount of archaeometallurgical material to non-archaeometallurgical material varies within a heterogeneous

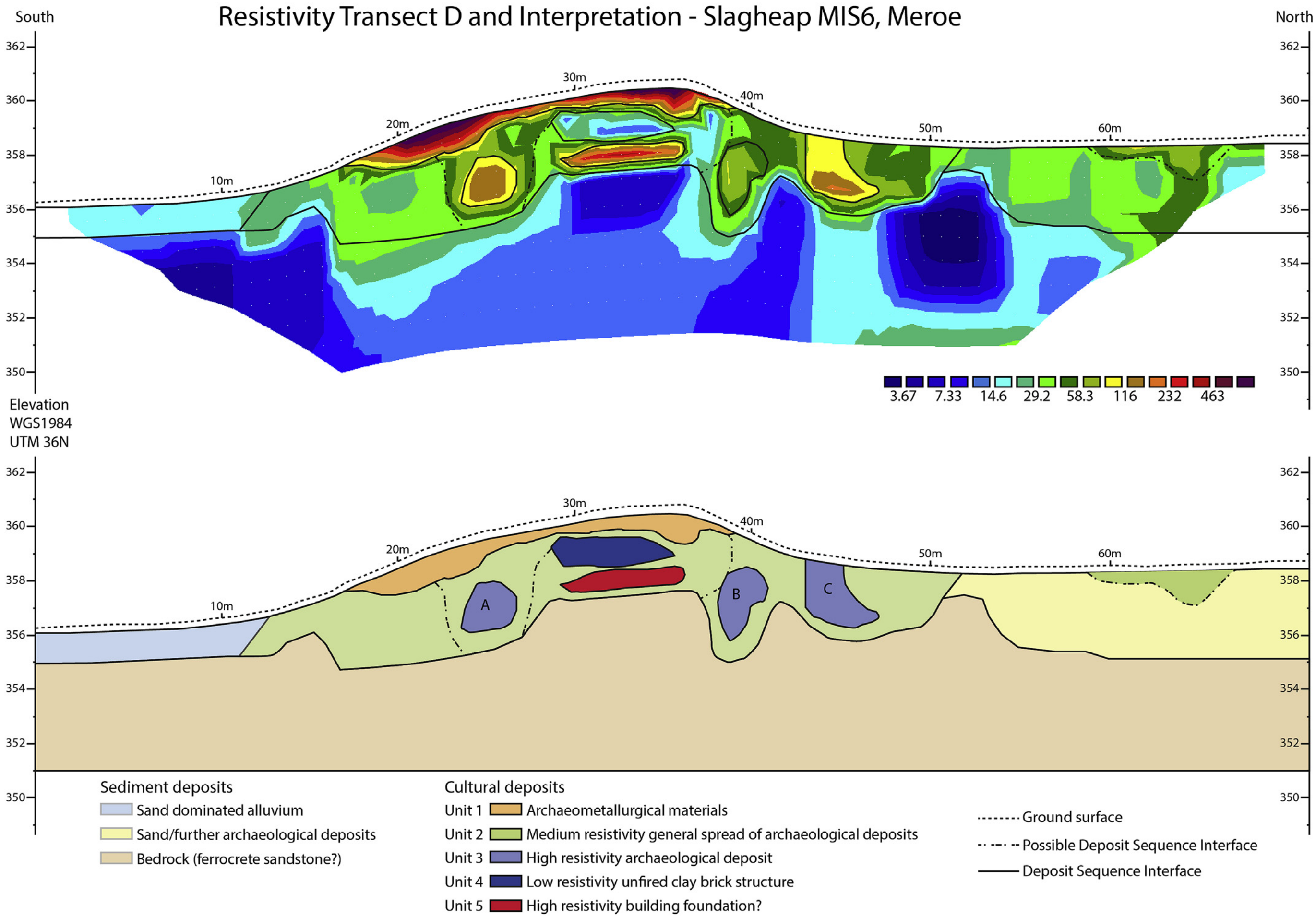

Fig. 4. Interpreted resistivity Transect D, demonstrating variability within the structure of the slagheap.

Fig. 5. Photograph of the south section of trench 3 showing mudbrick wall, MIS6. Also visible within the metallurgical section are three tubes, at the end of which (40 cm into the section) are dosimeters used for luminescence calibration.

Fig. 6. Photograph of the south section of trench 4 showing mudbrick wall, MIS6.

heap, when archaeometallurgical deposits are present, the total amount of slag within these deposits is consistent. This can be interpreted as a high degree of standardisation of technological process (see Martinón-Torres et al., 2014: p. 555 for a discussion on levels of standardisation in technological practices), producing a consistency of metallurgical waste.

The mass of each slag category within each trench demonstrates the significance of category 5 within the assemblage; a category of slag that was small, fragmented, and potentially formed both within the furnace as furnace slag and also outside of the furnace as tap slag (Fig. 10, A). The category 5 material as a percentage of the total highlights the dominant nature of this category within the slag assemblage (Fig. 10, B). This figure also demonstrates that whilst the percentage of slag to the total archaeometallurgical

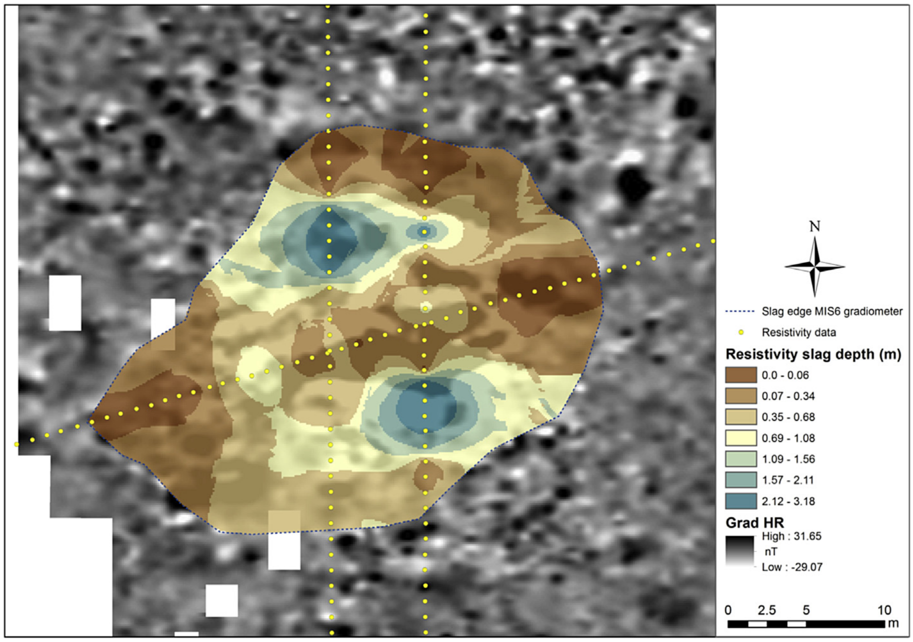

Fig. 7. Interpolated slag depth generated from the electrical resistivity model.

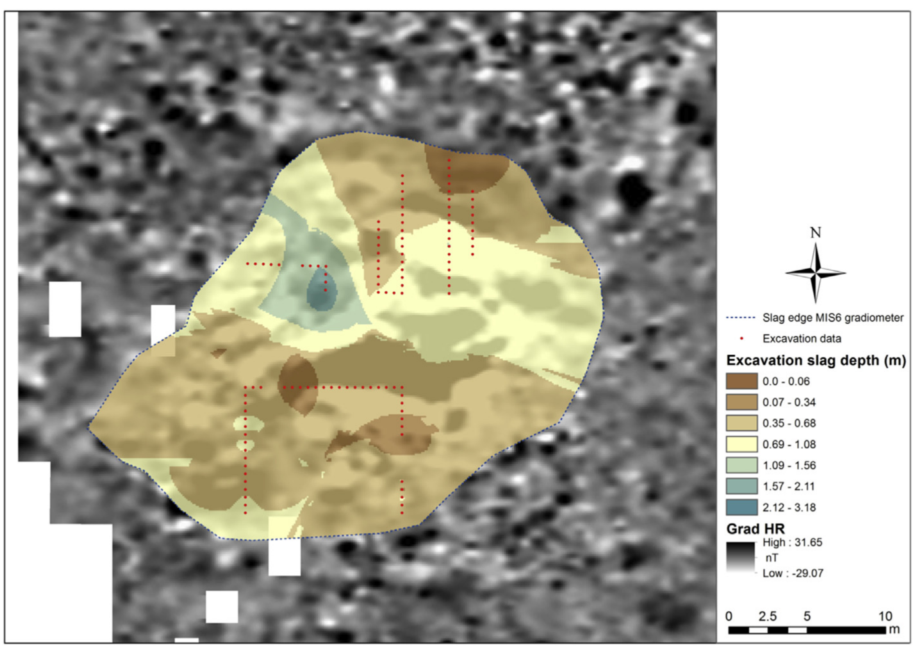

Fig. 8. Interpolated slag depth from the excavation model.

Table 2
Volume calculations of the total slag-heap based on the gradiometry, resistivity and excavation data.

Surface	Volume m^3
Surface survey model	447.15
Electrical resistivity survey model	151.30
Excavation model	218.73

sample remained broadly consistent between trenches, there is some variability within the composition of the total slag sample. Trench 3 has a higher percentage of category 5 material compared to trenches 2 and 4, although category 5 slag is the dominant category of slag in all trenches at MIS6 (see also Crew, 1988). These results of the composition of the total slag material, in particular the importance of category 5 slag, has led to a revised emphasis in the archaeometallurgical investigation.

In order to integrate the data from the slag sampling with that of the volumetric models for MIS6, the data were converted to a density figure of kg/m^3. Again clear trends are evident within the data. The density of the total sample and archaeometallurgical materials was much lower in trench 2 compared to trench 3, with

Table 3
Data from MIS6: volume of excavated material; the total mass of processed sample; the total mass of archaeometallurgical material, the total mass of slag and category 5 slag per trench (after the removal of all other types of debris) and converted percentages.

Trench	Volume of total excavated material for quantification m3	Total mass of sample (1/8th sample) (kg)	Total archaeo-metallurgical material (kg)	Total slag (kg)	Total category 5 slag (kg)	Archaeo-metallurgical material: Total sample (%)	Total slag: total sample (%)	Total slag: total archaeo-metallurgical material (%)	Category 5 slag: total slag (%)
2	4.68	1055	495	437	276	46.28	40.72	87.71	62.74
3	3.3	1061	547	482	344	52.12	45.81	88.09	71
4	3.7	1047	414	353	224	41.47	35.97	84.76	63.30

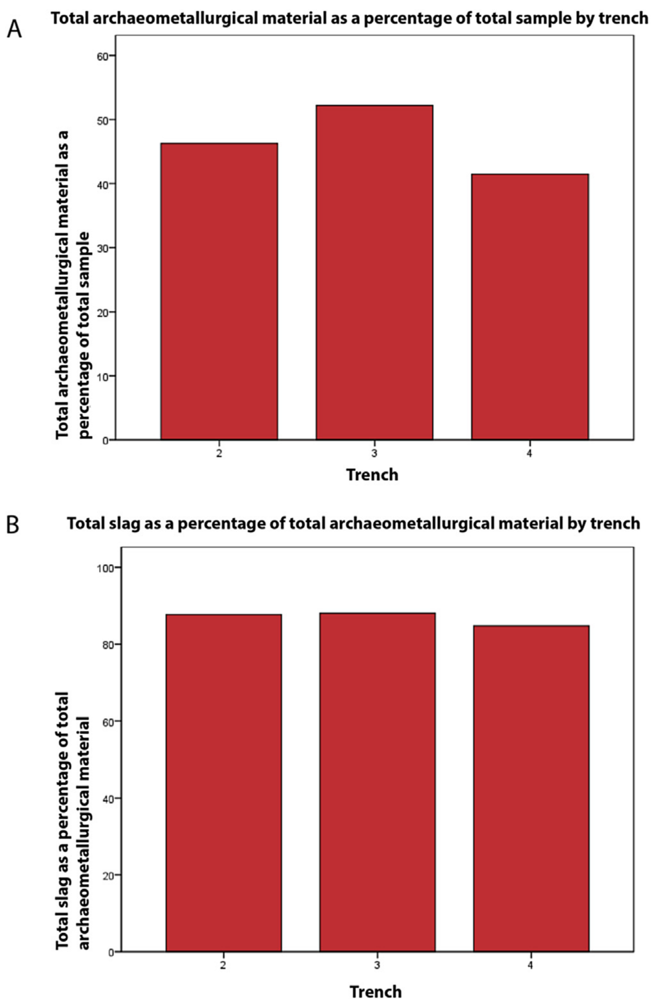

Fig. 9. Total archaeometallurgical material as a percentage of total sample (A); Total slag as a percentage of the total archaeometallurgical material (B).

trench 4 displaying an intermediate value, but closer to trench 3 (Fig. 11, A). The density of total slag (Fig. 11, B), and the density of category 5 material are highest in trench 3, with trench 2 the lowest and trench 4 slightly higher than trench 2, further demonstrating the heterogeneity of the slag-heap deposits and the prevalence of category 5 slag.

6.4. Integrating the data

It is clear from the three volume models constructed and the mass/density calculations from the quantitative sampling, that a number of figures could be used to calculate the amount of archaeometallurgical material within MIS6. Three density values have been calculated, using the highest value from trench 3, lowest value from trench 2 and a mean value from all three trenches, (Table 4), and have been added to the three volumetric models. As demonstrated, the proportion of slag relative to the total archaeometallurgical material remained constant between trenches (Fig. 9, B), although the total volume of archaeometallurgical material did vary between trenches.

These estimations (Table 4) of total mass of archaeometallurgical material within the slag-heap from the three models reveal, somewhat unsurprisingly, that the surface survey model exaggerates the amount of slag in MIS6 for each of three density estimates. The electrical resistivity model and the excavation model produce more comparable data, although the excavation model predicted a higher amount of archaeometallurgical material when compared to the electrical resistivity model. Thirdly, the variation in the density composition of the three trenches highlights the heterogeneous nature of deposits within the slag-heap. This is further complicated at MIS6 by the slag-heap being placed over an earlier building, and hiatus events visible within the localised trench stratigraphy of the slag-heap. Consequently, the mean figure is suggested as the more representative figure of density of total archaeometallurgical material. This produces a value between 154.07 t from the electrical resistivity model through to 223.64 t in the excavation model, with the surface survey model producing a figure of 457.19 t of archaeometallurgical material.

7. Discussion

The analyses of these data sets have demonstrated the applicability of marrying together geoprospection data, excavation data and quantitative sampling to produce volume estimates of entire slag heaps. They confirm that the depth and form of the slag-heap, and the quantity of archaeometallurgical material within are highly variable. In this example, the gradiometer data allowed the spatial definition of the slag-heap based on magnetic signature, whilst the electrical resistivity modelling allowed the depths of the deposits to be estimated. The electrical resistivity model clearly identified different components within the slag-heap, which the excavated data demonstrated to be an earlier building. This was not evident from the surface survey and consequently, the volumetric model of the slag-heap produced through a surface survey model overestimated the amount of archaeometallurgical remains within the slag-heap.

However, without full excavation of the slag-heap, it is impossible to know which of these models is closest to reality: all have unavoidable limitations in data collection. Primarily, the resistivity model was constructed from three transects, with some of the quadripole measurement points unusable due to the sub-surface conditions. In addition, the electrical resistivity model interpolates between points, and interfaces are interpreted from this interpolation, all of which provide a degree of approximation of the position of the interface. The excavation data only focused on part of the slag-heap, so some areas (in fact the majority of the slag-heap) are unknown from an excavation perspective.

The quantitative sampling aimed to populate the volumetric

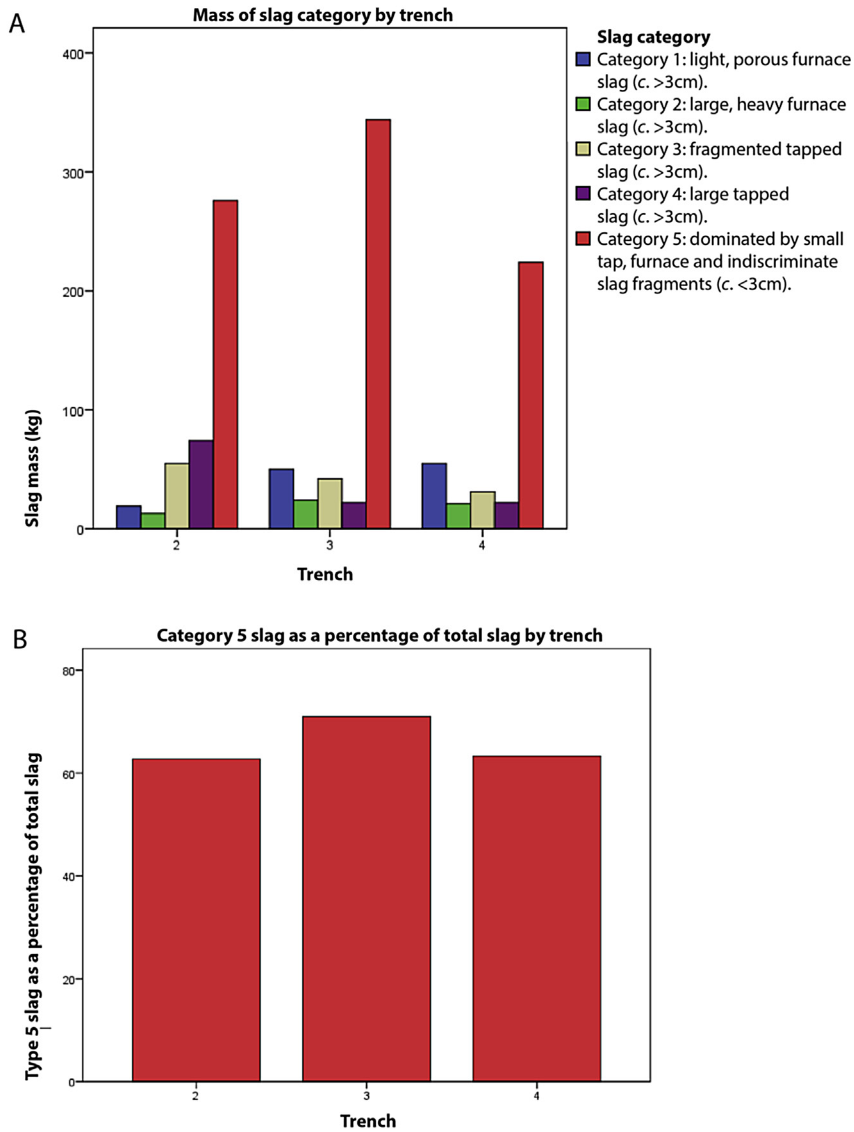

Fig. 10. The total mass of each slag category by trench (A); category 5 slag as a percentage of the total slag assemblage by trench (B).

models, as well as characterise the archaeometallurgical materials within the slag-heap. This data revealed complexity and variation within the deposit sequence of the slag-heap, a trait common throughout all slag heaps excavated so far at Meroe. As a result, archaeometallurgical deposits were shown to have a remarkably consistent percentage of total slag as a percentage of total archaeometallurgical material. This can be interpreted as a significant degree of standardisation of the smelting process, producing similar masses of archaeometallurgical waste per smelt and throughout the lifetime of the workshop(s) operation that produced the waste that formed MIS6. Such consistency hints at standardisation and routine of this industry.

The sheer volume and relative abundance of category 5 material comes out as a strong trend in the data (and is also noted during the excavation and slag processing of other slag heaps excavated during this research at Meroe). This category 5 slag is the dominant material within the archaeometallurgical remains of MIS6 and consequently is the most important in understanding the ironworking practices at Meroe. The small nature of the slag in category 5 is produced through the ironworking technologies employed at Meroe. Indeed, given the current state of knowledge of the smelting processes at Meroe and the dominance of this type 5 material, it calls into question whether this iron smelting should be considered as a classic slag-tapping industry. Further analysis of this important material group is underway and will provide a critical insight into the ironworking technologies at the royal city. The importance of category 5 slag has only been realised through the quantitative approach that has been detailed here. Although this is a time-consuming activity, the results support the effort to continue with this slag processing strategy to provide a more complete understanding of the excavated deposits.

It is also a sage point to note that often sample collection from slag heaps will focus on larger, more easily understood pieces of slag, e.g. tap slag, and will ignore smaller pieces such as category 5 slag. Such unrepresentative sample selection can become the basis of laboratory investigation, and subsequent reconstruction of past technologies. It is clear that at Meroe at least, such approaches would be unrepresentative of the slag assemblage as a whole. However, it is important to realise that different projects have different scales, experience, resources and field conditions for sampling of archaeometallurgical remains, and that smelting techniques across space and time are variable and so leave variable

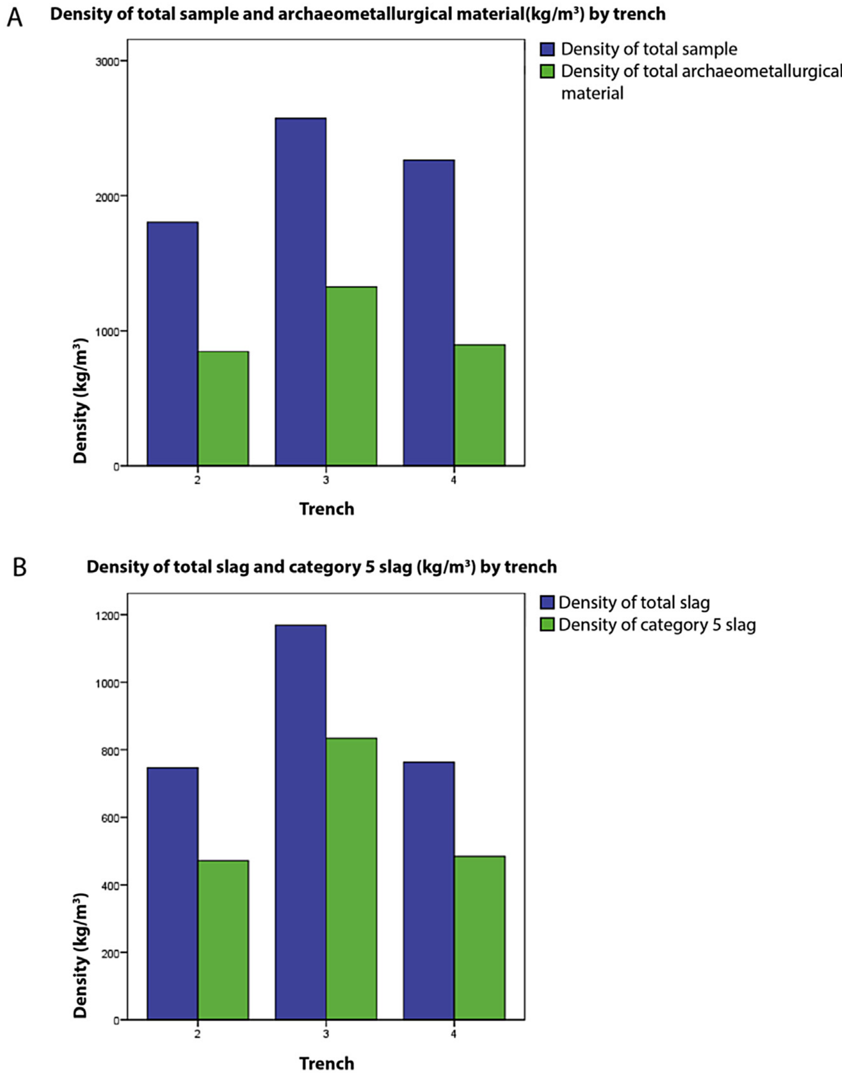

Fig. 11. The density of total sample and density of archaeometallurgical material by trench (A); the density of total slag and category 5 slag by trench (B).

Table 4
The total volume of archaeometallurgical material within the slag-heap, using the three modelled volumes of the slag-heap, with a minimum, maximum and mean calculation of total archaeometallurgical material.

Density label	Calculated from	Density value	Excavation only volumetric slag-heap model ($218.73\ m^3$) of archaeo- metallurgical material	Resistivity only volumetric slag-heap model ($151.30\ m^3$) of archaeo-metallurgical material	Ground surface earthwork only volumetric model ($447.15\ m^3$) of archaeo-metallurgical material
Highest density of archaeometallurgical material	Assemblage in trench 3	1326.06 kg/m^3	290,049.10 Kg 290.05 t	200,633 Kg 200.63 t	592,947.73 592.95t
Lowest density of archaeometallurgical material	Assemblage in trench 2	846.15 kg/m^3	185,078.39 Kg 185.08 t	128,022.50 128.02 t	378,355.97 378.36t
Average density of archaeometallurgical material	Mean value of trenches 2, 3 and 4	1022.45 kg/m^3	223,640.49 Kg 223.64 t	154,696.69 154.70 t	457,188.52 457.19t

remains. The issue of sampling is important for process understanding, and has been previously inadvertently ignored in some field programmes, hence the reason for critical discussion of this issue in the archaeological literature (see earlier section) and this paper. Across the sub-discipline of archaeometallurgy even when quantitative sampling has occurred, it is usually not to pre-defined standards that have been robustly and statistically tested against other sampling methods. There is not a body of literature that the authors are aware of that discusses the excavation of entire slag heaps, analysing all samples and retrogressively modelling suitable representative sampling methods for that particular site. Consequently, this is a major gap in the field which requires synthesis and critical analysis of data from academic and commercial spheres.

The quantitative sampling also revealed insights into depositional process. Variability was discovered in the composition of the slag-heap between trenches. Trench 3 had the highest amount of archaeometallurgical material, the highest mass and the highest density of total slag, and was excavated in the most slag-dense area of the slag-heap. Trench 2 demonstrated the lowest density of archaeometallurgical materials. The reasons for this difference at trench 2 are unclear, but one possible interpretation is the deposits in trench 2 represent a deliberate infilling episode of part of the earlier building by human agency, through the re-deposition of slag. A further intriguing aspect of trench 2 is that a number of kg of pottery were retrieved, which was far higher than trenches 3 and 4, indicating a different depositional history to trenches 3 and 4. Further analysis of this trench 2 material is ongoing.

The quantitative data from trench 4 is easier to interpret, with a density of archaeometallurgical materials that was between the values obtained from trenches 3 and 2. On excavation this trench was interpreted as having hiatuses between some slag dumping episodes, with contexts evident in section containing sand/sediment, deposited between contexts rich in archaeometallurgical materials. The presence of sand dominated contexts between archaeometallurgical waste contexts indicates some form of periodicity in the deposition of iron slags, at least in trench 4, i.e. multiple smelting wastes deposited in the same place before a hiatus/sand accumulation, before a further campaign of smelting.

8. Conclusion

On a pre-excavation basis, topographic modelling, electrical resistivity survey and gradiometer have been demonstrated to be a powerful package for the estimation of archaeometallurgical structures and deposit sequences within slag heaps. This has allowed the positioning of targeted excavation areas and key facets of slag heaps to be identified before excavation, such as the underlying buildings and depth of archaeological deposits at MIS6, guiding the positioning of the excavation trenches to answer specific questions.

The quantification of slag categories from the excavations has provided significant insight, which can be coupled to both the laboratory and geoprospection data sets. Critically, the importance of the category 5 slag has been brought into focus; a defining characteristic of the slag assemblage at MIS6. The quantification process has demonstrated that selecting a representative sample of ironworking deposits, such as those at Meroe, requires a detailed analysis of the structure of the slag heaps: surface collection of individual pieces or hand picking during excavation is liable to yield an unrepresentative sample population for further analysis.

The combination of the quantitative data with the geoprospection data has allowed the volume and mass of the archaeometallurgical materials within MIS6 to be estimated. However, these calculations demonstrate just how difficult it is to estimate slag volumes and deriving production figures. The data modelling clearly shows that topographic survey alone is insufficient, and although the combination of methods used in this study represents a step forward, new emphasis needs to be given to geoprospection methods within ironworking site-scapes, combined with detailed quantitative sampling.

The number of large-scale excavations in academic research has arguably diminished in recent decades, with archaeologists well aware of the old archaeological maxim – 'excavation is destruction'. Comparatively smaller excavations are now more common, seeing increasingly complex methods of scientific analysis to increase data yields from smaller interventions. Due to financial constraints as well as more rounded academic appreciation of the finite nature archaeological record, smaller excavations are being used more and more to construct models of reality. More data is needed and expected from these smaller excavations to make our interpretations closer to the archaeological realities. In contrast, the opposite maybe true of western commercial field projects driven largely by development led archaeology where largescale excavation of slag heaps is more frequent, but this is not feasible at sites of such importance as Meroe. Indeed the most recent Historic England Archaeometallurgy Guidelines for Best Practice, are written mainly for, 'curators and contractors within archaeology in the UK' (2015, p. 1), highlighting the different challenges facing archaeometallurgists working in different sectors of the discipline. In the academic sub-discipline of archaeometallurgy it is usually not possible or appropriate to completely excavate such large slag heaps (Crew, 2002: p, 165, 180). Therefore, finer models of characterisation are required to maximise knowledge whilst minimising impacts. Much work is yet to be done at Meroe, both in the laboratory and the field. However, by attempting to provide an integrated programme of geoprospection, excavation, quantification and the ongoing laboratory analysis, the secrets of the Meroitic slag heaps are slowly being revealed.

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