2013

North
Yorkshire

Laboratory
Testwork

Hagg Farm Industrial Landscape
Fremington
Swaledale, North Yorkshire

SE 05946 99141

Laboratory Testwork
Report 001-2013-RS | October 2013

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Northern Mine Research Society

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Laboratory Testwork
subsequent to the excavation of
12 - 19th August 2013

by the

Swaledale & Arkengarthdale Archaeology Group

and the

Northern Mine Research Society

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Summary and conclusions

In 2012, the Swaledale and Arkengarthdale Archaeology Group (SWAAG) led by Tim Laurie identified clear evidence of lead smelting and a potential lead bale site centred at SE 05939 99137. The site was noted to be under direct risk of severe damage from rabbits, and was characterised by looking at slag and charcoal within and outside the rabbit burrows. A joint project was then set up in the summer of 2013 between SWAAG and the Northern Mine Research Society (NMRS) to archaeologically investigate the bale site, with Richard Smith of NMRS directing the fieldwork alongside Tim Laurie of SWAAG, with Tony Liddell of Vindomora Solutions providing professional archaeological recording support.

Initially, a geophysical survey was undertaken of the earthworks by Dr Robert Vernon, which identified features consistent with bale technology, including a large 'pseudohorseshoe shaped anomaly' interpreted as the remains of a lead-smelting bale along with a channel running from the bale, as well as three areas of lead slag.

The five day excavation was conducted on the 12-19th August 2013 and uncovered what appeared to be a natural spring line and bank that had been filled with slag debris from hill-wash, as well as several small areas of slag deposition. The feature of most interest, F2, was interpreted as being either a slag dump or a smelting site, probably a charcoal-fired furnace which had been partly destroyed. The absence of hard-baked clay was the only evidence to suggest that F2 was not a smelting area. Despite this there were fire-cracked and reddened stones, some with adhering baked clay; a slag 'ooze' between two fixed stones suggested that smelting had indeed taken place here. F2 was unusual in that there was a patch of small slags mixed with roughly equal proportions of soil. This covered an area about 2 m in diameter and was about 150 mm deep. The deposit lay immediately underneath the turf and was quite unique within the excavation area. Removal of the loose slag/soil deposit revealed fixed stones embedded in the natural underlying clay. One of the aims of the laboratory testwork was to establish what the ground under a bale or furnace would have looked like. This work shows beyond doubt that the medieval turf layer on which the bale/furnace was laid would have been converted to a fragile crumbly texture which was very resistant to congealing back to clay when wetted and would have subsequently been easily converted to soil - exactly the conditions found at F2. This would have insulated the underlying clay and prevented it baking hard; even so clay plugs heated to 500 ^{o}C and 650 ^{o}C broke down fairly easily on repeated freezing and soaking with water - the product similarly formed a crumbly gritty sand which showed no tendency to congeal back to clay. Clay heated to 200 ^{o}C broke down immediately on freezing/soaking and clay heated to 105 ^{o}C broke down solely on soaking; in both cases the wetted material returned to a clay-like material. Had these results been available before the excavation, there would have been no doubts that smelting had taken place at F2.

Work on slag densities showed that the large lumpy slags, most prevalent at F2 probably contained more lead than slags found elsewhere in areas where it was supposed that slag might have been spread to make a hard standing.

Slag melting points were determined and give an indication of the temperatures which were obtained in the production of the slags. This information was then used in heat

transfer calculations to determine the temperature of the subsoil during smelting and to show the effect of heat on the underlying natural clay.

Twelve charcoal samples were sent to Durham University for wood identification. All but one were hazel, the exception being maloideae a subfamily which includes hawthorn, rowan, apple and other fruit trees.

Three samples sent for radiocarbon dating returned calibrated dates for the early fifteenth century, corresponding with similar dates found earlier for bale sites having charcoal dumps.

This report should be read in conjunction with the archaeologist's report for the excavation. The same nomenclature for contexts and samples has been used.

1.0 The effect of heat on clay plugs

1.1 Natural clay was taken from the Test Pit at Context [24] which was dug on the west edge of the smelting area F2. It was made into 35 mm diameter plugs 12-15 mm thick using a plastic adhesive tape core and a closely fitting piece of steel. The clay was pounded into a plug using a lump hammer and the plug expelled using the steel. The plug was finished off by wetting and smoothing with a trowel.

1.2 Ten clay plugs were made initially and used in pairs, one of each pair was used for subsequent tests and the other reserved as a record. All the plugs were dried at 105 ^{o}C for 16 hours and then weighed. The average moisture content of the clay was determined on a large piece of natural state (NS) clay and was found to be 22% (NS).

Table 1

Summary of effects of heating and simulated weathering on 35 mm diameter clay plugs.

Plug No.	Temp ^{o}C	Time Hrs	Colour	Effect of soaking in water for 1 hour	Effect of freezing and soaking four times
5&6	110	16	Light grey/ brown	Completely disintegrated - residue returned to clay on compressing	-
1&2	210	8	Grey/brown	Severely damaged	Completely disintegrated - residue returned to clay on compressing
11	250	4	Grey/brown	-	-
12	300	8	Grey/brown	-	-
13	350	5	Grey/brown	-	-
14	400	5	Grey/brown	-	-
15	450	5	Red/brown	-	-
9&10	500	8	Orange/red	Significantly softened	Almost completely disintegrated - residue does not return to clay
11	550	8	Orange/red	-	-
3&4	650	6	Orange/red	Surface softened	Almost completely disintegrated - residue does not return to clay
7&8	950	6	Orange/red	Little effect	Surface softened

1.3 Eight of the plugs were then heated at 210 ^{o}C for 8 hours, two taken as samples and the rest heated at 500 ^{o}C (8 hours). This was repeated by heating at 650 ^{o}C (6 hours) and 950 ^{o}C (6 hours). The choice of the various temperatures was based on:

105 ^{o}C - determines loss of superficial moisture.
210 ^{o}C - determines loss of loosely-bound water of hydration.
500 ^{o}C - below the quartz transition temperature of 573 ^{o}C which is said to give problems in pottery making.
650 ^{o}C - above the quartz transition temperature of 573 ^{o}C.
950 ^{o}C - high temperature but below those at which pottery is normally made. It was felt and later shown that clay heated above 1,000 ^{o}C would be baked to a ‘brick’ and would have reasonably predictable properties.

Two plugs were taken for each temperature.

1.4 The plugs were all weighed at each stage and generally showed losses beyond 105 ^{O}C of the order of 5-10 %.

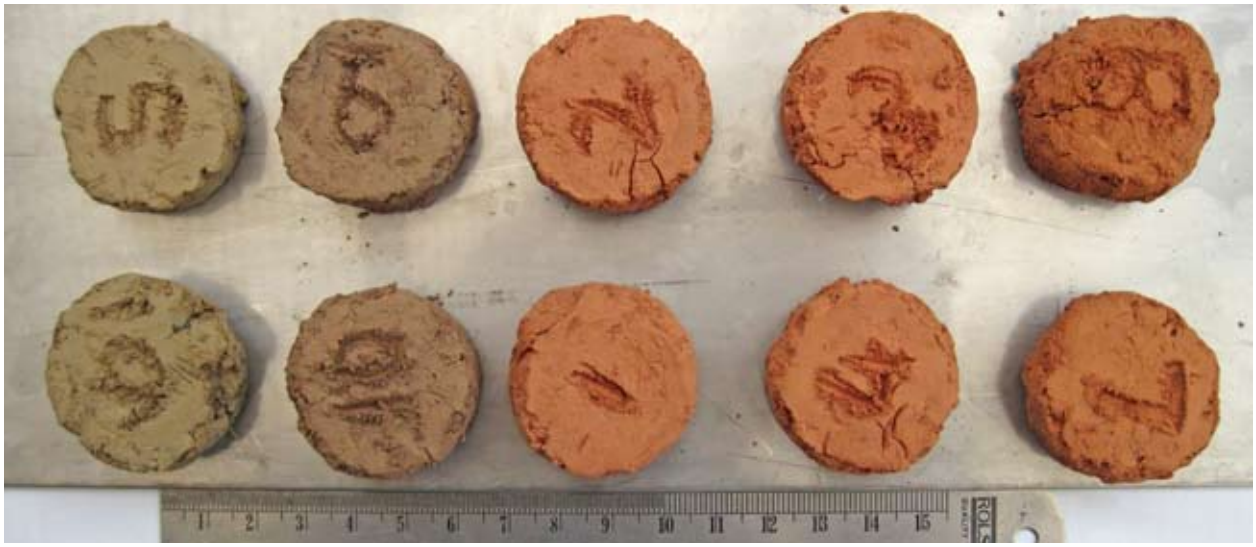


Figure 1. Pairs of clay plugs heated to (from left) 110 °C, 210 °C, 300 °C, 500 °C, 650 °C and 950 °C. The lower row is a duplicate of the upper row. The reddening temperature was defined more closely by a further test and shown to take place between 450 °C and 500 °C.

Figure 2 (left). Plugs after soaking in water for one hour. From top left: 500 °C, 650 °C and 950 °C and from bottom left: 105 °C and 210 °C.

Figure 3 (right). Plugs (from left) heated to: 500 °C, 650 °C and 950 °C after four freeze/soak cycles. The small piece in the lower right corner is natural state clay which has been heated to 950 °C. It was somewhat porous and broke easily but withstood the simulated weathering test as well as the corresponding plug No. 8.

1.5 The colour of the plugs was noted and their hardness measured by scratching with the point of a scriber (see Table 1). Those exposed to temperatures of 500 °C or above had changed from a dark grey/brown colour to an orange terracotta shade (Figure 1).

1.6 On soaking in water for 1 hour, the 105 °C plug disintegrated to mud, the 210 °C plug was severely damaged and the 500 °C plug had softened significantly (Figure 2). The debris from the 105 °C and 210 °C plugs could be moulded back to clay.

1.7 After freezing then soaking in water for four cycles, the 500 °C plug had disintegrated almost completely, the 650 °C plug had deteriorated significantly and the 950 °C plug was

unaffected apart from some softening of the surface. None of the debris showed any tendency to congeal back to clay (Figure 3).

1.8 In order to determine the temperature at which reddening took place a series of 12 mm diameter plugs were made using a similar technique with a piece of copper pipe as the mould and a steel rod. These were heated at 250 °C, 300 °C, 375 °C and 450 °C and showed no significant change, although there was a slight alteration in the colour of the 450 °C plug. This was repeated with 35 mm diameter plugs heated to 250 °C, 350 °C, 400 °C, 450 °C and 550 °C. The 550 °C plug came out the same colour as the orange 500 °C from the original run and the 450 °C plug had changed somewhat.

1.9 These tests established the temperature at which reddening takes place (with this particular clay), the resistance of the baked clays to weathering and the behaviour of the disintegrated clays after soaking. It established that only the clay baked to 950 °C was resistant to weathering and that after disintegration the residues formed a crumbly sand which would eventually form soil if it were near the surface.

2.1 It is important to realise that the above tests were conducted on compressed plugs

2.0 The effect of heat on natural state clay

Figure 4. A piece of natural state clay (left) compared with a similar piece which has been heated to 950 °C and slightly moistened.

and that the action of compression would impart a degree of resistance to weathering. A piece of natural state clay was heated to 950 °C (Figure 4) and subjected to four freeze/ soak cycles; it retained its shape but was somewhat porous and broke easily - otherwise it behaved similarly to the clay plugs. However, as it was considerably weaker, it is possible that extended freeze/soaking would eventually cause deterioration. Residue from this piece showed no tendency to reform back to clay.

3.1 A piece of turf about 3 inches x 4 inches x 4.5 inches thick (110mm measured) was

3.0 The effect of heat on turf

Figure 5. Effect of heat on a piece of turf. (A) Piece of natural state turf. (B) After calcining for 4 hours. (C) Ash formed from the vegetable content of the turf. (D) Residue from the mineral content of the turf.

taken for test (Figure 5A). It consisted of roughly $^{2}/_{3}$ plant material grass and 'thatch' and $^{1}/_{3}$ soil by volume. It was dried at 105 ^{o}C for 7 hours to determine the moisture content (34.7 % of the natural state weight) then heated on a gas barbecue with additions of white spirit to burn off the organic matter. This resulted in only superficial burning and carbonisation.

3.2 The residue was heated at 650 ^{o}C in the furnace for 4 hours and reweighed to give a measure of the vegetable content - the loss on ignition was 39.8 % of the dry weight (Figure 5B) . The furnace product showed two distinct types: a fragile, fibrous light residue from the plant fibres (Figure 5C) which was slightly soluble in water and a friable orange sandy residue from the mineral content which disintegrated on adding water but showed no tendency to congeal back to clay after adding water (Figure 5D). The water from the plant residues and the clay was mildly alkaline pH 8-9 (Universal Indicator paper test).

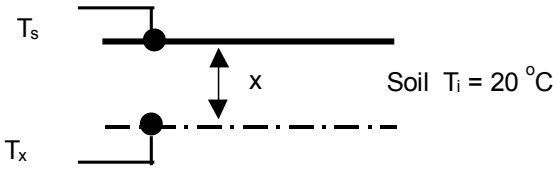
3.3 Approximately half of the material was heated further to 950 ^{o}C, after which no significant change took place. There was no tendency for the mineral part of the residue to congeal back to clay after adding water. The water from the plant residues and the clay was mildly alkaline pH 8-9 (Universal Indicator paper test).

3.4 In practice, the voluminous fragile vegetable residue would have almost certainly disintegrated and most of it blown away or been washed into the subsoil. The orange-coloured mineral residues would have remained as a crumbly granular sandy material. Over time this would have become converted to soil, aided by the nutrients from the vegetable ash or would have remained substantially unchanged if not exposed to soil-forming conditions. This explains the reason for finding an absence of compacted burnt clay at the site, the presence of an unusually deep deposit of soil mixed with small pieces of slag only at F2 and the perhaps the presence of rabbit burrows here and at the lower bale site. Unfortunately the slag/soil mixture from F2 was separated by sieving to remove the soil and has been lost

4.0 Heat transfer calculations

4.1 The aim of the calculations was to determine the temperature gradient between the bale fire and the underlying clay to determine the thickness of the heat-affected layers. The method used is that developed by Incropera F.P. and De Witt D.P., *'Fundamentals of Heat and Mass Transfer'*, Wiley, New York, 1981, pp. 202-6 and used to determine the depth for burying water pipelines to prevent freezing. The calculation is rather different from more normal calculations of heat transfer which calculate the steady-state temperature gradient based on one-dimensional heat flow, assuming that there is the same heat flux at the cool and hot surfaces. In this case, however, there is no loss of heat from the system; the underlying earth acts as a heat sink and heats up depending on the time of exposure. In theory, a very long (almost infinite exposure) would result in the whole of planet earth becoming as hot as the fire. An exposure time of 8 hours has been taken as being reasonable. The base data/constants etc are those for dry soil/earth and take no account of moisture which would result in a thinner layer of heat-affected earth.

4.2



The formula for transient heat transfer is:

$$\frac{T_x - T_s}{T_i - T_s} = \text{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right)$$

Where:

T_x	=	Temperature of soil at depth X, after time t	°C
T_s	=	Temperature of top surface of soil, fire temperature	°C
T_i	=	Temperature of ground before heating	20 °C
X	=	Thickness of heated layer	m
t	=	Exposure time	8 hours (× 3,600 s)
erf w=		Gaussian error function determined from tables in book	
α	=	$k/\rho c$	1.379 × m/s
k	=	Thermal conductivity of soil/clay	0.52 W/m.°K
r	=	Density of soil/clay	2050 kg/m^3
c	=	Specific heat of soil/clay	1840 J/kg.°K

Example calculation:

$$\frac{500-1040}{20-1040} = \text{erf}\left(\frac{X}{2\sqrt{\alpha t}}\right) = \frac{540}{1020} = 0.529$$

From tables of erf, for erf =0.529, $\frac{X}{2\sqrt{\alpha t}} = 0.51$

Hence X can be calculated as 64 mm thick.

Table 2

Ground temperature profiles determined by the heat transfer equation

T_s (°C)	T_x (°C)	erf w	w	X (mm)
1,000	950	0.0510	0.05	6
1,000	650	0.3571	0.33	42
1,000	500	0.5102	0.49	62
1,040	950	0.0882	0.08	10
1,040	650	0.3824	0.36	45
1,040	500	0.5294	0.51	64
1,140	950	0.1696	0.15	19
1,140	650	0.4375	0.41	52
1,140	500	0.5714	0.56	71

4.3 Table 2 shows that for a fire temperature of 1,040 °C, at which the slags were fully molten but not running freely, soil temperatures would have exceeded 950 °C only to a depth of 10 mm. This would have produced 10 mm of stable burnt clay but only if it was compacted clay to start with. This material would be resistant to repeated freezing and soaking. However, if it was 'root-penetrated' soil associated with the overlying turf it would have not have formed a stable layer of burnt clay but produced a crumbly orange layer, much of which would have later formed soil. A further 35 mm depth would have been heated to between 650 °C and 950 °C and would have also formed a crumbly orange layer available for making soil. A further 19 mm depth would have been exposed to between 500 °C and 650 °C and irrespective of whether it was compacted clay or turf originally, it would have broken down to crumbly orange material under the influence of repeated freezing and soaking. Ground below this would not have undergone the reddening transition which takes place at 500 °C and would have remained as natural clay.

4.4 It is very probable that these are maximum figures as, in practice, the underlying clay/soil would have been moist and, therefore, acted as a more effective heat sink reducing the thickness of the heated layer. Also there would have been a bed of insulating charcoal//ash/debris at the bottom of the fire which should be subtracted from the values of X derived above.

4.5 From the appearance of the slag it is unlikely, that it reached 1,140 °C and was molten to the point where it ran freely - if so, larger pieces of 'run slag' similar to those found in iron bloomeries would have been formed. Nevertheless, even had this been the case the resulting layer thicknesses would have been much the same as those found in F2.

4.6 The thickness of soil/slag found at F2 was not measured accurately but was 100-150mm in thickness and correlates well with these results.

5.0 Determination of slag melting points

5.1 Slag melting points were determined using the method described in Smith R., 2006, 'A typology of lead-bale slags based on their physico-chemical properties', *Historical Metallurgy*, 40, 115-128. A small pieces of slag were placed on a firebrick tiles and after reaching 950 °C, were heated slowly at about 2 °C/min. Temperature was measured using a Type K thermocouple enclosed in a piece of firebrick (Figure 6). This gave the same temperature, to within 5 °C, as the furnace control thermocouple which was situated in the furnace lining. Every 10 °C, the condition of the slags was tested by touching with a 2 mm diameter stainless steel rod held on a 10 mm rod. The following temperatures were recorded:

MP-1 The temperature at which softening of the slag surface could be detected.

MP-2 The temperature at which the whole piece of slag was molten and the test rod penetrated it throughout but the sample did not wet the tile.

MP-3 The temperature at which the slag was fully molten, ran freely and wetted the tile. The piece was removed at this point to protect the base of the furnace.

5.2 The samples used were cut with a diamond wheel and only the solid dark grey interior of the pieces used; the weathered exterior was rejected. Slags found on the site had the appearance of being heated to MP-1 or MP-2 but not as far as MP-3. The results are given in Table 3.

Table 3

Slag melting points

Sample	Context	Description	MP-1	MP-2	MP-3
1	[15] sample (8)	Hearth ends/lumpy slag from [F2]. Dark grey/black slag from piece A.	1,100	1,120	1,140
2	[14] sample (10)	Orange slag on outside, dark grey/black on cutting with microscopic prills of lead <2mm diameter.	960	1,040	1,140
3	[15] sample (8)	Small pieces of dark grey/black slag from [F2] after removal of soil on site - cut open to ensure slag integrity.	980	1,060	1,100
4	Two 12mm diameter clay plugs	As described on previous worksheet.	No effect noted other than darkening and hardening after cooling		
5	[5] sample (6) from TP4	Orange slag on outside, dark grey/black on cutting with microscopic prills of lead <2mm diameter.	980	1,040	1,100

5.3 These results give an indication of the temperatures which were reached in the fire and have been used in the heat transfer calculations of Section 4. Samples 2,3 and 5 behaved similarly; Sample 1 seemed resistant to softening but melted quite sharply after softening.

5.4 Two small (12 mm diameter) clay plugs were also tested and at 1,150 °C had not melted. On cooling they were found to have turned from orange/red to dark brown and had become very hard.

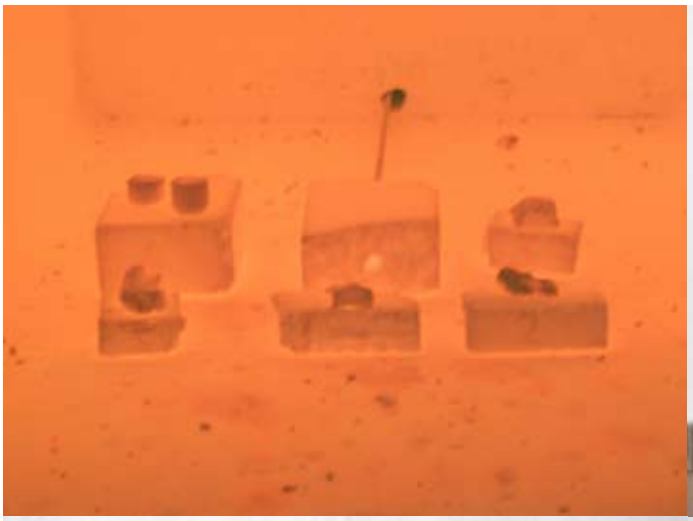


Figure 6 (top left). The furnace interior at 900 °C showing pieces of slag on firebrick tiles and thermocouple embedded in firebrick block.

Figure 7 (top right). A piece of cut slag from TP4 with entrained lead prills.

Figure 8 (middle left) Fire-reddened stone from F2 with baked clay and slag attached and Figure 9 (middle right) heterogeneous slag/hearth end material from F2 with an inclusion of dark grey slag with some baked clay and secondary crystallisation on right hand side. Figure 10 (bottom) small slag from F2 after removal of soil by sieving and washing.

6.0 Measurements of slag density

6.1 Measurements of slag density were made to see if it was possible to distinguish between different categories of slag. If secondary slag reworking had taken place at the site, one might expect to find low density waste slag together with higher density material which had not been processed. The results would be confounded by natural density variations mainly resulting from the barytes contents.

6.2 Densities were measured using a eureka can made from a baked bean tin with a 5 mm copper spout attached at a downward angle with epoxy resin and a scale weighing to 1 gram which was remarkably repeatable and appears to have been limited by its readout scale rather than its inherent precision. The results are shown in Appendix 1.

6.3 Slags having a narrow range of densities of around 3.2 g/cm^3 were found at the following contexts:

Context [5] sample (6) - orange slag, ca. 30 mm, medium-sized from TP4, possibly used as hard standing.

Context [14] sample (10) - orange slag, ca. 25 mm, medium-sized, some with sandstone attached, possibly used as hard standing.

Context [15] sample (8) - grey slag, ca. 0.3 - 30 mm, small-sized from F2 and separated from soil.

Context [1] sample (7), ca. 30-50 mm medium-sized pieces of nodular slag with gas bubbles found in TP4.

On cutting open they were all dull dark grey; many had small lead prills up to about 3 mm present but the prills were rare and mostly very fine. These slags were taken to be waste material from which it would be difficult to remove lead either by further smelting or by breaking and washing.

6.4 Large slags were recovered from the contexts listed below and varied considerably in density from piece to piece. The variation seemed to be for a number of reasons. Some slags were extremely heterogeneous and had dark grey slag embedded in what appeared to be partly smelted light grey or brown material. These had entrapped gas bubbles and other inclusions, many had embedded charcoal. These included:

Context [15] sample (8) - ca. 100 mm large pieces taken from the stones in F2 and probably ‘hearth ends’ (i.e. unsmelted accretions left over from processing},

Context [21] sample (11) - ca. 100 mm a large piece of heavy ‘leady’ material containing some matte.

Context [1] sample (7) - ca. 30-50 mm medium-sized pieces of nodular slag with gas bubbles found in TP4

Context [25] sample (13) - ca. 200 mmlarge pieces of slag from the stones at F2, some with embedded charcoal and baked clay

Some of the slags were broken in order to fit them into the eureka can. Because of their heterogeneity, densities varied widely from around 3.2 g/cm^3 to a high of 4.14 g/cm^3. (Calculations showed that a density of 4.14 corresponds to a slag having a density of 3.2 g/cm^3 but with about 32 % of entrained metallic lead.

6.5 Very little can be drawn from these measurements, although they might be useful in any further work conducted on the outlying areas of the site and assist in identifying waste slag and slag brought to site for reworking.

7.0 Charcoal identification

7.1 Methods

7.1.1 The collected samples were washed with tap water to remove soil then air-dried for 24 hours, during which time some cracking took place. The diameters of 53 pieces were measured by comparing with a series of circles drawn on paper. The diameters measured by this method agreed with those determined by direct measurement, to within 1 mm, on the seven complete roundwood samples sent to Durham University (see Table). Twelve samples of charcoal were examined for wood species identification by Dr Charlotte O'Brien, Environmental Laboratories Manager, Archaeological Services, Durham University, DH1 3LE. Extracts from the report are included here.

7.1.1 The hand-recovered charcoal fragments were identified, in order to provide material suitable for radiocarbon dating. The transverse, radial, and tangential sections were examined at up to x600 magnification using a Leica DM/LM microscope. Examination of the number of annual growth rings, growth ring curvature, growth ring pattern and the presence of pith and bark was undertaken. The fragments were weighed and where appropriate the diameter of roundwood was measured. (Where this could not be done the diameters were estimated from the surface curvature of the pieces by R. Smith and are given in Table 5). Identifications were assisted by the descriptions of Schweingruber (1990), Gale & Cutler (2000) and Hather (2000), and modern reference material held in the Environmental Laboratory at Archaeological services Durham University.

7.1.2 The works were undertaken in accordance with the palaeoenvironmental research aims and objectives outlined in the regional archaeological research framework and resource agendas (Roskams & Whyman 2005; 2007; Huntley 2010).

7.2 Results

7.2.1 Apart from a few friable fragments preservation of the charcoal was generally good. The assessment of the samples indicated a predominance of hazel (11 out of 12). The exception was Sample 1 identified as Maloideae, which is a subfamily that includes apple, hawthorn and whitebeams (rowan). The presence of complete roundwood and/or strong ring curvature, suggest all of the samples comprise the remains of small calibre wood. The eccentric growth ring pattern (Marguerie & Hunot 2007) and anatomical characteristics (vessel arrangement/grouping) indicate many of the samples are branchwood rather than small stemwood.

7.2.2 Due to the absence of either pith or bark for the majority of the samples, an estimation of age was recorded and a minimum count of growth rings indicated with a plus sign (see Appendix 1). Only Sample 6 comprised pith and bark providing a precise age of 14 years. The annual growth ring results ranged from 14 to 36 and were concentrated in the early to mid-20s, possibly reflecting random collection of material rather than the result of woodland management. All of the assessed material is suitable for radiocarbon dating. The results are presented in Table 4.

Figure 11. Piece of hazel charcoal from Context [7], one half of which was used for charcoal identification, the other as RC-1 for radiocarbon dating.

7.3 Conclusions

7.3.1 The conclusion reached by Dr O'Brien that the samples were branch/twig wood agrees with the views of those who saw the samples when they were obtained. It is probable that the stem wood was used for other purposes and that the waste material was made into charcoal.

7.3.2 The wide range of tree ages suggests that the wood was collected either randomly or as a result of casual coppicing.

7.3.3 The predominance of hazel may result from a skewed collection process: i.e. the preservation of hazel charcoal was better than that of other species and that this also led to a degree of preferential sampling.

7.4 References

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Table 4. Summary of charcoal species identification

Sample No.	HLF-13 Context	HLF-13 Sample	Species	No. of annual growth rings	Growth ring curvature	Presence of complete roundwood	Growth ring pattern	Diameter (mm)	Weight (g)	Pith/bark presence
1	7	-	Maloideae*	18+	Strong	✓	Concentric	19.24	4.978	Pith, no bark
2	7	-	Hazel	27+	Strong	✓	Eccentric	19.24	3.390	Pith, some bark
3	7	15	Hazel	25+	Strong	✗	-	(40)+	6.455	Bark, no pith
4	7	15	Hazel	36+	Strong	✓	Eccentric	21.41	6.384	Pith, no bark
5	8	9	Hazel	32+	Strong	✗	-	(40)+-	3.351	Pith, no bark
6	8	9	Hazel	14	Strong	✓	Concentric	20.61	2.479	Pith and bark
7	8	9	Hazel	21+	Strong	✓	Eccentric	22.73	4.401	Pith, some bark
8	9	3	Hazel	24+	Strong	✓	Eccentric	25.66	3.596	Pith, no bark
9	10	4	Hazel	14+	Strong	✓	Concentric	16.87	1.451	Pith, no bark
10	24	12	Hazel	23+	Strong	✗	-	(40, 25, 50)+	5.611	No pith, no bark
11	24	12	Hazel	21+	Strong	✗	-	(40, 25, 50)+	6.345	No pith, no bark
12	24	12	Hazel	26+	Strong	✗	-	(40, 25, 50)+	2.525	Pith, no bark

* Maloideae – Apple, hawthorn, whitebeams

+Diameter estimated from piece curvature by R. Smith

Table 5. Diameter of charcoal pieces determined from surface curvature.

Context	Sample	Charcoal piece diameter (mm)														Description
7	1	39	40	60	30											Sections C/D upper part of deep bowl
7	15	20	40													Sections C/D upper part of channel
8	2	30														Sections C/D lower part of deep bowl
8	9	30	23	20	25	20	25	20	28	25	40	30	50	25	30	25	Sections C/D lower part of deep bowl
9	3	25	25	25												
10	4	15														
11	5	40														
24	12	40	25	50	20	15	30	12								Charcoal lens in sondage through N1
0	0	50	40	50	25	15	40	25	15	60	30					Unnumbered context and sample

Mean diameter 31 mm, Standard deviation 13 mm.
Assuming that all the charcoal on site was from this population, then the mean diameter would have been 31 mm and 95% of the pieces would have been between 5-57 mm in diameter (I.e. 2 SD's)

8.0 Radiocarbon dating results

8.1 Method

8.1.1 The collected samples were washed with tap water to remove soil then air-dried for 24 hours, during which time some cracking took place. Three of the largest pieces were selected from Contexts [7], [8] and [10] and were sent to Beta Analytic, Miami, Fla. for analysis. After these had been prepared, it was apparent that there was insufficient sample for conventional analysis and dating was carried out by accelerator mass spectroscopy (AMS).

8.1.2 Samples were treated by washing with acid/alkali/acid before determination. Conventional Radiocarbon Age (CRA) conventions were based on (a) usage of the Libby half-life of 5,568 years ± 30 (b) use of Oxalic Acid (SRM 4990C) as the radiocarbon standard (c) correction for sample isotopic fractionation to a normalised or base value of -25.0 per mille relative to the ratio of $^{13}C/^{12}C$ in the carbonate standard VPDB - Cretaceous belemnite formation at Peedee in South Carolina (d) zero BP (Before Present) is defined as AD 1950 (e) assumes that global radiocarbon levels are constant. Calibrated ages are determined by applying dendrochronological corrections to correct for variations in atmospheric $^{14}C/^{12}C$ ratios over time. This sometimes gives two or more date ranges because of inflexions in the calibration curve - as is the case with two of the samples in Table 6. The 95 % (2 σ) confidence limits are also given.

8.2 Results

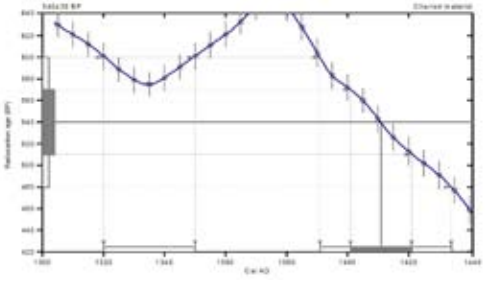
8.2.1 Results are shown in Table 6 and are typical of those reported for the later bale-smelting period (Smith R., 2006, 'Radiocarbon dating of early lead smelting sites', *British Mining*, 80, 94-110). As RC-2 only has one range of values, it is probably safe to take the later ranges for RC-1 and RC-3 as being relevant. It is worth noting that these dates are similar to those reported for smelting sites with associated charcoal dumps. (Barker J.L., 1978, 'Bale Hills in Swaledale and Arkengarthdale', *British Mining*, 8, 49-54 and Smith R., *op. cit.*)

Table 6

Radiocarbon dating results obtained by AMS

Code No.	Context	Sample	Measured age	$^{13}C/^{12}C$ Correction	Conventional Age	Calibrated Age
RC-1	7	-	540 +/- 30 BP	-25.0 o/oo	540 +/- 30 BP	Cal AD 1320 to 1350 (Cal BP 630 to 600)/ Cal AD 1390 to 1430 (Cal BP 560 to 520)
RC-2	8	9	480 +/- 30 BP	-25.1 o/oo	480 +/- 30 BP	Cal AD 1410 to 1450 (Cal BP 540 to 500)
RC-3	10	4	610 +/- 30 BP	-26.6 o/oo	580 +/- 30 BP	Cal AD 1300 to 1370 (Cal BP 650 to 580)/ Cal AD 1380 to 1420 (Cal BP 570 to 530)

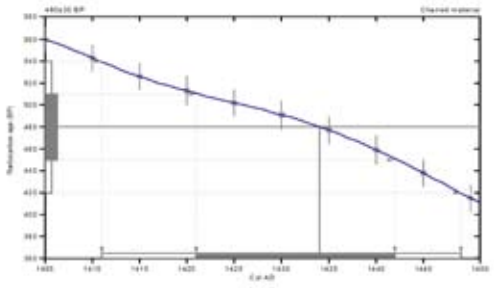
Calibration of radiocarbon age to calendar years



Sample RC-1, Context [7]

(Variables 13C/12C = -25.0: lab. mult=1)

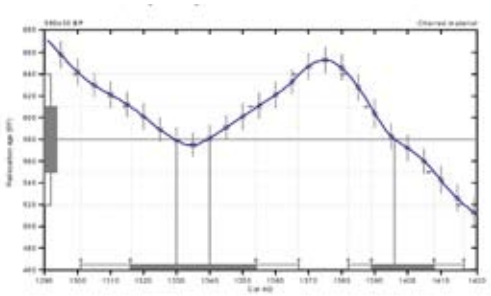
Conventional R/C age:	540±30 BP
2σ calibrated result (95% probability):	Cal AD 1320 to 1350 Cal AD 1390 to 1430
1σ calibrated result (68% probability):	Cal AD 1400 to 1420 Cal AD 1400 to 1420
Intercept:	Cal AD 1410



Sample RC-2 Context [8] sample (9)

(Variables 13C/12C = -25.1: lab. mult=1)

Conventional R/C age:	480±30 BP
2σ calibrated result (95% probability):	Cal AD 1410 to 1450
1σ calibrated result (68% probability):	Cal AD 1420 to 1440.
Intercept:	Cal AD 1430



Sample RC-3 Context [10] sample (4)

(Variables 13C/12C = -26.6: lab. mult=1)

Conventional R/C age:	580±30 BP
2σ calibrated result (95% probability):	Cal AD 1300 to 1370 Cal AD 1380 to 1420
1σ calibrated result (68% probability):	Cal AD 1320 to 1350 Cal AD 1390 to 1410
Intercept:	Cal AD 1330 and Cal AD 1340 and Cal AD 1400

References

Database used - INTCAL09

References to INTCAL09 database

Heaton et al., 2009, *Radiocarbon*, 51 (4), 1151-1164.

Reimer et al., 2009, *Radiocarbon*, 51 (4), 137-189.

Oeschger et al., 1975, *Tellus*, 27, 168-192.

Mathematics used for calibration

Talma A.S. and Vogel J.C., 1993, *Radiocarbon*, 35 (2), 317-322.

Appendix 1 - Slag densities

Context [14] sample (10), ca. 25 mm medium sized pieces of orange slag, some with sandstone attached.

Sample	Slag Weight (g)	Displaced Water (g)	Density (g/cm3)	Comments
A	12	4	3.00	Orange slag
B	41	13	3.15	Orange slag
C	9	3	3.00	Orange slag
D	46	12	3.83	Orange slag
E	70	26	2.69	8 pieces of orange slag
F	27.5	8	3.44	Orange slag
F	28	8	3.5	Orange slag
F	28	8	3.5	Orange slag
F	28	8	3.5	Orange slag
H	117	35	3.34	Slag + stone
Average of A-E slag densities				3.14
Standard deviation of slags A-E				0.42
Standard deviation of repeats on F				0.03

Context [15] sample (8), ca. 100 mm large pieces of grey slag, some with charcoal embedded.

Sample	Slag Weight (g)	Displaced Water (g)	Density (g/cm3)	Comments
A	202	54	3.74	
B	248	58	4.28	
C	263	75	3.51	
D	187	59	3.17	
E	351	107	3.28	
F	287	78	3.68	
Average of A-E slag densities				3.61
Standard deviation of slags A-F				0.39

Context [21] sample (11), ca. 100 mm large piece of ‘leady’ grey slag with some matte

Sample	Slag Weight (g)	Displaced Water (g)	Density (g/cm3)	Comments
A	173	45	3.84	

Context [5] sample (6), 30mm medium sized pieces of rounded orange slag

Sample	Slag Weight (g)	Displaced Water (g)	Density (g/cm3)	Comments
A	80	25	3.20	Orange slag
B	49	14	3.50	Orange slag
C	52	17	3.06	Orange slag
D	63	22	2.86	Orange slag
E	42	12	3.50	Orange slag
F	49	15	3.27	Orange slag, 4 similar rounded pieces
G	85	28	3.04	Orange slag, 7 similar rounded pieces
Average of A-G slag densities			3.20	
Standard deviation of slags A-G			0.24	

Context [15] sample (8), 0.3-3 mm small sized pieces of slag from [F2]

Sample	Slag Weight (g)	Displaced Water (g)	Density (g/cm3)	Comments
A	124	38	3.26	
B	141	45	3.13	
C	159	46	3.46	
D	142	45	3.16	
E	138	41	3.37	
F	99	31	3.19	
Average of A-E slag densities			3.26	
Standard deviation of slags A-F			0.13	

Context [1] sample (7), large pieces of slag from TP4 topsoil

Sample	Slag Weight (g)	Displaced Water (g)	Density (g/cm3)	Comments
A	133	42	3.17	Porous slag
B1	213	70	3.04	Nodular slag - large piece broken into 3: B1, B2, B3
B2	149	47	3.17	Nodular slag - large piece broken into 3: B1, B2, B3
B3	49	13	3.77	Nodular slag - large piece broken into 3: B1, B2, B3
Average of A-B3 slag densities			3.29	
Standard deviation of slags A-B3			0.33	

Context [25] sample (13), large pieces of slag from [F2] stones, some with baked clay or embedded charcoal - generally heterogeneous and, therefore,very large pieces not analysed for density

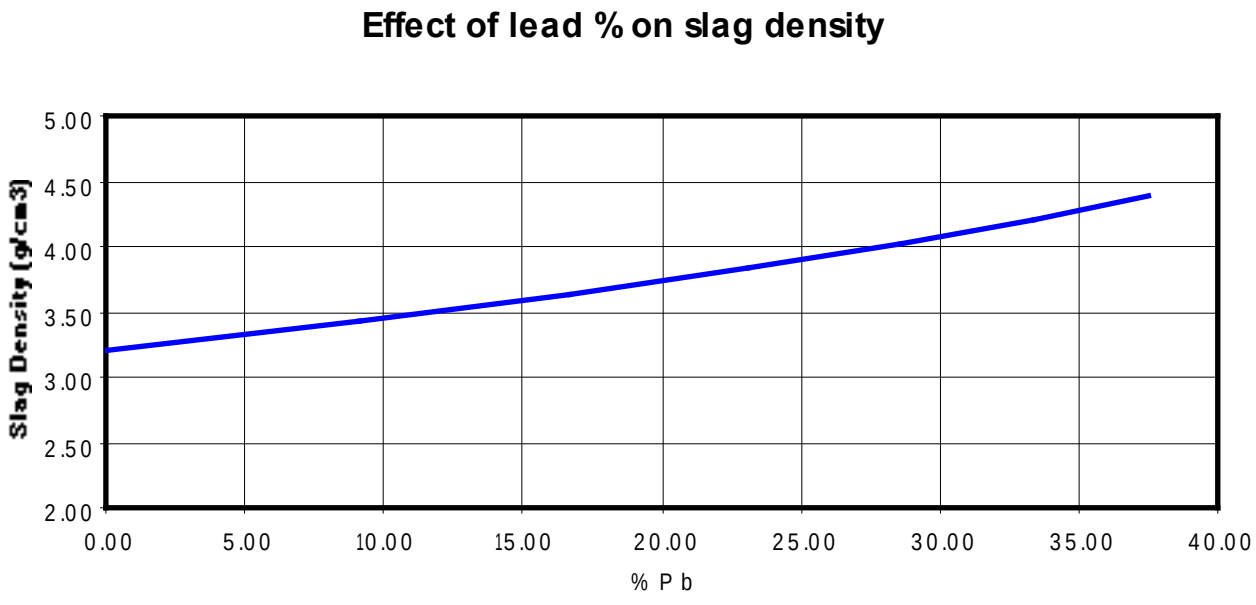
Sample	Slag Weight (g)	Displaced Water (g)	Density (g/cm3)	Comments
A	97	28	3.46	
B	87	21	4.14	
C	129	35	3.69	
D	90	38	2.37	
Average of A-D slag densities				3.42
Standard deviation of slags A-E				0.75

The eureka can had a diameter of 7.3 cm and area of 41.85 cm^2. The best accuracy which can be expected is a 0.5 mm change in height or +/-2.1 cm^3 error.

Effect of entrained lead prills or barytes on the density of slag

For slag of density 3.2 g/cm^3 with lead of density 11.4 g/cm^3 $\rho_2 = (1 + W_{Pb}) / (\frac{1_1}{\rho_1} + \frac{W_{Pb}}{\rho_{Pb}})$

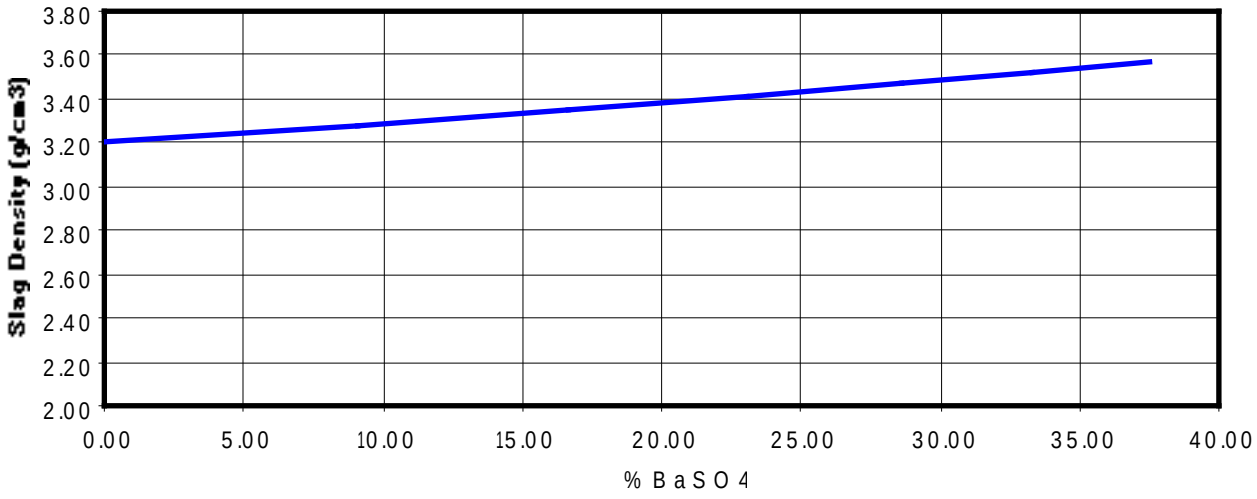
Wt. of slag	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wt of lead	0.00	0.10	0.20	0.3	0.40	0.50	0.60
% Lead	0.00	9.09	16.67	23.08	28.57	33.33	37.50
Slag density	3.20	3.42	3.64	3.84	4.03	4.21	4.38



For slag of density 3.2 g/cm^3 and barytes of density 4.4 g/cm^3

Wt. of slag	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wt of barytes	0.00	0.10	0.20	0.3	0.40	0.50	0.60
% Barytes	0.00	9.09	16.67	23.08	28.57	33.33	37.50
Slag density	3.20	3.28	3.35	3.41	3.47	3.52	3.56

Effect of added barytes on slag density



2013

North Yorkshire

Laboratory Testwork

Hagg Farm Industrial Landscape, Fremington, North Yorkshire

In 2012, the Swaledale and Arkengarthdale Archaeology Group (SWAAG) led by Tim Laurie identified evidence of ancient lead smelting at SE 05939 99137. A joint project was set up between SWAAG and the Northern Mine Research Society (NMRS) to investigate the site archaeologically during July and August 2013. The work was directed by Tim Laurie of SWAAG and Richard Smith of NMRS with Tony Liddell of Vindomora Solutions providing professional archaeological and recording support.

This report details the findings of subsequent testwork by Richard Smith to characterise the slags and clay substrate, necessary to ascertain the effects of heating on the underlying soil.

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Laboratory Testwork

Report 001-2013-RS | October 2013

Northern Mine Research Society