Crucible steel production at Derwentcote Forge, County Durham

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ABSTRACT: In 2010 an archaeological evaluation was undertaken by Channel 4's Time Team *at Derwentcote, County Durham, the site of one of the best examples of how the ferrous metal industry evolved in Britain during the Industrial Revolution and now a Scheduled Ancient Monument. The results of the evaluation, along with analysis of the crucibles and metallic residues, are of significance in providing information on the 19th-century crucible steel operation at Derwentcote, the first such installation to have been excavated outside Sheffield.*

Introduction

Wessex Archaeology was commissioned by Videotext Communications Ltd to undertake site recording and post-excavation work on an evaluation undertaken by Channel 4's *Time Team* at the site of Derwentcote Forge, County Durham (NGR 4132 5566; Fig 1).

The site, approximately 14km south-west of Newcastle upon Tyne, forms a Y-shaped area, just north of the A694 and east of Derwentcote Farm. It lies within the Derwent valley and occupies a position immediately south of the river. The underlying geology includes boulder clay, glacial drift and undifferentiated alluvium, overlying Coal Measures (British Geological Survey, sheet 20 (Drift edition)).

The nationally important Derwentcote industrial landscape (Scheduled Ancient Monument No 28536) consists of a largely extant and now restored cementation steel furnace (SAM 948809) on higher ground to the south, and (on lower ground) a headrace, a forge with remains of the associated millpond (SAM 22576), workers' cottages (SAM 948808) and a 20th-century coal mine (Forge Drift colliery).

Most of the 2.12 hectare site is in the care of English Heritage. The main visitor area is centred on the cementation furnace, the earliest surviving and most complete example in the country, and is the only part of the site not covered by vegetation. The headrace survives as a tree-covered earthwork within privately-owned pasture, and the remaining features lie within woodland (much of it on steep and rough terrain).

Historical research into the development of the entire site, as well as excavation and building recording of the cementation furnace, was undertaken by David Cranstone in the late 1980s (Cranstone 1997; 2008). This utilised a photogrammetric record of upstanding walls provided by English Heritage and a landscape survey covering most of the scheduled area undertaken by the then Royal Commission on the Historical Monuments of England (RCHME 1990).

In 2009 English Heritage commissioned a gazetteer-style descriptive survey (by David Cranstone), supplemented by a measured survey (by North Pennines Archaeology (NPA) of those parts of the scheduled area not covered by the earlier RCHME survey (Cranstone 2009).

Aims of the 2010 work

The project design (Videotext 2010) outlined three research aims. The first was to investigate the iron finery forge. It was clear from the comprehensive survey work already conducted that details of the forge, believed to have been first constructed *c*1718–9, are poorly understood. Maps dating to the 19th century show that the forge consisted of two building complexes, one (north range) to the north of the mill pond and the other (south range) straddling the main outflow channel from the mill pond. The remains of these now demolished structures are visible as building platforms, the majority covered by dense woodland.

The second aim was to locate and investigate the historically attested crucible furnaces which were in use during the second half of the 19th century; their possible remains were recorded in the 2009 survey (Cranstone 2009).

The final aim was to clarify the construction sequence and use of the workers' cottages. An 18th-century origin has been suggested for the structures, with continuing alterations until the mid-20th century (Cranstone 2009).

Methods

Prior to the excavation of evaluation trenches, a geophysical survey was carried out across the site using a fluxgate gradiometer (GSB 2010). However, the widespread presence of slag resulted in strong responses throughout. Magnetic susceptibility readings were, as anticipated, high in the vicinity of furnaces and hearths. A landscape survey and analysis of the cartographic evidence was also undertaken, the relevant findings from which are incorporated into the discussion below.

A total of seven evaluation trenches were excavated (Fig 2), placed according to specific research objectives: trenches 1, 2, 4 and 6 on or near the southern building of the forge complex, in operation from the early 18th century and possibly incorporating or existing alongside a water-powered corn mill; trench 7 on a probable charcoal store; and trenches 3 and 5 on the workers' cottages. The limited results from trenches 3, 5 and 7 are not included below, but details can be found in the assessment report (Wessex Archaeology 2011).

Of the trenches within the area of the forge, trench 1 was located adjacent to a sandstone wall believed to be the most easterly extent of the complex, whilst trenches 2 and 4 (subsequently amalgamated into trench 2) were sited around part of the dam walling, and trench 6 was located over two fixing points on a wall on the south side of the southernmost head race east of the dam, in order to confirm the existence of a wheel-pit/waterwheel in this location.

The structural remains

Details of individual contexts are retained in the archive, with summaries in the assessment report (Wessex Archaeology 2011). The finds assemblage is entirely of post-medieval date, and largely comprises debris related to steel production, which is discussed below. A list and description of all artefacts from the site can also be found in the assessment report.

Trench 1

Trench 1, subdivided into Areas A, B and C (Fig 3), was located adjacent to and south of an extant wall that ran from north to south at the east end of the forge complex. It provided a section across the forge buildings in this area and allowed evaluation of their nature and sequence of use. It was extended as excavation progressed to investigate the extent and relationships of the archaeology uncovered. Three phases of activity (phases 1–3) were identified within the 18m-long trench, though some elements remain uncertainly phased or unphased.

<u>Phase 1: Pre-crucible furnace</u>

The northernmost part of Area A contained the southern end of a NE-SW aligned wall (1003) which incorporated a redbrick culvert that ran from west to east, from the area believed to contain the original corn mill towards one of the tailraces of the later forge/steel production works. Wall 1003 was built from well-hewn and regularly coursed sandstone, which contrasted with the more irregular nature of wall 1004 which abutted it and was assigned to phase 3 (see below).

Within Area B was an L-shaped, cellared structure approximately 1.5m deep. This was defined by sandstone walls 1006 to the north, 1009 to the east and 1038 and 1039 to the SW. Wall 1038 contained an opening through which an apparently uncovered tailrace ran from east to west. This tailrace was later covered with red brick (1037 and 1041) in phase 2. The four walls were built on natural gravel and constructed of regularly coursed sandstone, with larger blocks used in the basal courses. Although the structure pre-dates phase 2, later rebuilding has removed any evidence of its function relating to phase 1.

<u>Phase 2: Crucible furnace</u>

The phase 1 cellared structure formed a focus of activity in phase 2 (at least within the excavated area), and it is clear that this was associated with crucible steel production.

Overlaying the western part of wall 1006 was a rectangular sandstone structure (1051), measuring at least 2m by 1.15m, which formed the base of a chimney. This was part of structure 1033 which incorporated at least two refractory/fire-brick lined chambers (Fig 4). These chambers, each measuring 1.4m by 0.4m and at least 1m high, formed by fire-brick walls 1007, 1049 and 1050, were partly accessible from the cellar to the south, with a pair of associated flues built into the chimney structure to the north. Structure 1033 is typical of the arrangement of crucible steel furnaces, which showed little change from that believed to have been used by Huntsman in 1740 to those in use at the beginning of the 20th century. The upper part of each of the chambers (the ‘melting hole’) would have held a crucible (surrounded by coke and supported on fireclay blocks placed on an iron grill) that was accessed from a floor above (which does not survive), with an ash pit below and access from the cellar.

The base of the cellar was covered with a floor (1043) constructed of re-used redbrick and refractory brick, laid flat, with the bricks generally running in north to south rows. Floor 1043 was built around structure 1033 and lay approximately 1.5m below existing ground level. The floor was bounded to the east by further bricks (1045) laid on edge and running north to south approximately 2m east of structure 1033, suggesting some division within the cellar, with cellar wall 1009 a further 1.75m to the east. Perhaps the area between 1045 and wall 1009 was for temporary ash storage, for example, or housed a free-standing stairwell or hatch for entrance into the cellar.

To the south, floor 1043 was built up against a 0.8m-wide double-skinned redbrick culvert (1037) which covered the earlier tailrace. A narrow redbrick wall (1041) defined the southern extent of the cellar, and abutted sandstone walls 1039 and 1038 (identical in construction to 1006 and 1009), which formed an L-shape to the north, comprising part of the cellar walls.

At the northern end of the cellar, part of wall 1006 was overlain by wall 1005/1032 which also butted structure 1033 to the west. This suggests more than one phase (or sub-phase) of structure is represented. Wall 1005/1032, constructed of sandstone, ran north to south, turning to the east at the southern end where it overlay wall 1006; wall 1005/1032 was butted by wall 1004 (phase 3) at its northern end.

The structural remains in area B were overlain by a demolition layer (1012) containing ganister (furnace lining), heat-affected fire-bricks and failed crucible pots.

Area C lay to the south of the cellared structure. The phasing of features here is uncertain, though they have been provisionally assigned to phase 2. Terminating within this area was a north-south aligned foundation trench (1042) which contained the remains of a brick wall that appeared to have been robbed. At the northern end of this wall was a small area of redbrick (1040) interpreted as a possible machine base. Various machine fittings were recovered from a layer of grey silt (1029) containing frequent iron concretions, possibly a deposit resulting from inundation of this area, with collapse/demolition rubble (1028) sealing this.

<u>Phase 3: Forge?</u>
Phase 3 developments appear to have been largely confined to area A . Wall 1004 formed an angled arrangement in the gap between phase 1 wall 1003 to the north and phase 2 wall 1005/1032 to the south. It was relatively poorly constructed in comparison to the two earlier walls. The 1898 Ordnance Survey map appears to show a building not present on the 1856 OS map (Fig 2), part of which appears to correspond with wall 1004.

To the west of and abutting wall 1005/1032, north of and abutting wall 1006 and south of wall 1004 was a C-shaped arrangement of redbricks (1024, 1025 and 1027) measuring approximately 2m by 1.75m. No mortar was present on the upper surface of these bricks, suggesting that they did not originally continue above the layer uncovered. Inside this arrangement of bricks and abutting wall 1032 were two sandstone pads (1053 and 1054), possibly the base for a hearth/forge, though they could have been foundations for a superstructure that covered this area. Bricks 1034 also appeared to form part of this arrangement. Brick ‘edging’ 1027 to the west bordered a cobbled area (1035), suggesting that this was a working surface or that the west side of the structure was open.

Overlaying the area enclosed by the redbricks was a deposit of hammerscale (1023). This suggests that the area housed a hearth or hammer for small-scale forging. A brick fireplace (1020/1021) lay to the north of wall 1025, in the angle between walls 1004 and 1005/1032, and was filled with soot (1019 and 1022). The small size and location of the fireplace indicates that it did not serve an industrial function.

Trenches 2 and 4: Dam structure

Built into the natural gravels was 2008, a 4.5m-square, sandstone structure, and abutting this was a roughly built north-south sandstone wall (2007) with large sandstone blocks pushed up against its west face (Fig 5). Structures 2007 and 2008 together formed the facing to the earthen dam at the east end of the mill pond containing the water that would have powered waterwheels located to the east (see below).

Trench 6: Wheel-pit
Trench 6 was located along the south side of the southern wall of the southernmost tail-race or leat, to the south of the furnaces and forge in trench 1. Excavation revealed what was probably the south wall (1m wide) of a stone-lined wheel-pit with the fixing points for a waterwheel (Fig 6). These were partly overlain by a rubble wall, perhaps a later modification or the disturbed upper courses of the south wall. A deposit of iron slag was exposed on the south side of this wall and suggests that this area was used for dumping waste during the operation of the forge.

Crucibles
The vital role of the crucible in the Huntsman method of crucible steelmaking is perhaps often overlooked, and the following specific requirements give some idea of the demands placed upon the crucible:

> ‘It had to withstand temperatures of 1500°C to 1600°C for periods of 4-5 hours. At the same time, it had not to be unduly eroded or attacked by the steel, or by any quantity of slag which formed upon the surface of the steel, and had to retain sufficient strength to sustain the lifting out process and subsequent [repeated] use as a pouring vessel’ (Barraclough 1984, 33).

The temperature that the crucible had to withstand was far higher than had previously been used in either metal or glass working. Another technological challenge was the problem of containing the ‘corrosive’ molten steel within what was a relatively fragile container. Successive experiments by Huntsman led to the development of the familiar Huntsman-type clay crucible. It is known from archive sources that Huntsman used or experimented with graphite to temper his crucibles (Barraclough 1984, 10), and graphite-tempered crucibles, containing up to 40% or more graphite (Barraclough 1984, 40), were preferred in Germany and the USA (Harbord 1905, 229). However, the normal practice adopted in the Sheffield area was the use of coke-tempered clay crucibles (Harbord 1905, 229). This may not have simply been because coke was cheaper, but also because coke-tempered crucibles were less likely to affect the carbon content of the steel compared to graphite-tempered crucibles, and retained heat better (Barraclough 1984, 40).

Graphite crucibles were in general much more robust than clay crucibles, which as well as making them less likely to fail within the furnace, also meant that they could withstand the rigours of being transported. The relative fragility of clay crucibles meant that it was common practice for them to be made on site at the steelworks. The job of ‘potmaking’ was a specialist one and the whole process of mixing and treading the clay to the correct consistency, moulding the crucible and then slowly drying it out, would take around three weeks (Barraclough 1976, 13). It is thought that most medium to large sized crucible works would employ their own potmaker, who would work to his own specific recipes. Smaller works would either employ furnacemen who were also experienced potmakers, or sub-contract the work to itinerant potmakers, who might work for several smaller works.

At Derwentcote both coke- and graphite-tempered clay crucibles have been identified (see below), and it is also of interest that one of the fragments of graphite-tempered crucible analysed was taken from a partially complete crucible, which had a different morphology and generally thinner walls and base shape than the examples of 'Huntsman type' crucibles found at the site (D3 below)

Ceramic compositional analysis
by Patrick Sean Quinn
A total of 24 fragments of used steel-making crucibles weighing *c*28kg were recovered from demolition material in the crucible furnace cellar (Fig 4, Area B) with further finds from the overlying topsoil (Wessex Archaeology 2011, 36). As they are some of the first to be found outside the Sheffield and South Yorkshire area, the opportunity was taken to investigate their composition to see if there were any regional variations. Visual observation revealed the presence of at least two different fabrics, and one sample was taken of each of these (Derwentcote 2 and 3), as well as from a third crucible (Derwentcote 1) with a similar fabric to Derwentcote 3 (hereafter D1−3). All three crucible fragments came from the crucible furnace cellar (contexts 1002 (D3), 1008 (D2) and 1016 (D1))**.**

Methods
Three crucible samples were examined in petrographic thin section and sub-samples embedded in an epoxy resin block, polished to 1μm and examined using a Phillips XL30 scanning electron microscope fitted with an Oxford Instruments INCA Wave energy dispersive X-ray spectrometer (SEM-EDS). The SEM was operated at 20kV and a working distance of 10mm. Elemental compositions were calculated as weight percent oxides using stoichiometry. Accuracy was evaluated using two basalt standards: BCR-2 (Columbia River Basalt) and BIR-1 (Icelandic Basalt) and was found to be <10% relative error for all detected elements (Table 1). Data are presented in Table 1 normalized to 100% for ease of comparison

The composition, raw materials and technology of the Derwentcote crucible samples were compared to two steel-making crucibles from Tenter Street, Sheffield (Quinn 2013b) as well as to other reported data.

Results
Analysis confirmed the presence of two distinct fabrics. Samples D1 and D3 are characterised by the presence of sparse, altered, rounded sand-sized inclusions and abundant graphite flakes (Figs 7A and 7B). The rounded inclusions, which vary in size from medium to very coarse sand, have an isotropic grey or slightly yellow colour in thin section in crossed polars (XP) and a grey to yellow colour in plane polarised light (PPL). They appear to have been altered by the high temperature operation of the crucibles, with one or two containing vesicles from melting. On the basis of their characteristics in thin section it is difficult to be sure what these inclusions were prior to their alteration, but they were probably composite quartz-clay grains which have melted. Their chemical composition varies, but all those analysed were rich in silica (Table 1, nos 1–3). Several such inclusions returned analytical totals of 50% or less, with the measurable component of these being silica. Given the

high abundance of graphite, as well as carbon in the steel, it is possible that the quartz reacted with carbon to form silicon carbide (SiC) or carborundum. Several other analysed grains also contained an appreciable proportion of alumina, as well as small amounts of elements such as potassium, calcium, iron and titanium (Table 1, nos 1–3). The sand inclusions may have been added as temper due to the relative absence of silt sized mineral grains.

The other inclusion type in the fabric of samples D1 and 3 are elongate flakes and aggregates of a carbon-rich material identified as graphite (Fig 7A and B). It may have been naturally occurring in a graphitic clay source (Martinón-Torres and Rehren 2009) or added as temper. The nearest known graphite-rich clay deposit occurs in Borrowdale in the Lake District, and this contains other intrinsic rock and mineral clasts, which may explain the presence of the quartz sand material described above.

The clay matrix of the ceramics is fine, and well-vitrified, containing almost equal amounts of alumina and silica, and 2-3% each of FeO and TiO_2 (i.e. a kaolinitic clay; Table 1, nos 4–6). The high alumina, high silica and low percentage of fluxes such as K_2O, FeO, CaO and MgO would have given the clay a high melting point. The addition of graphite would have further increased the crucibles' ability to withstand the high temperatures required to produce liquid steel (Craddock 2013, 16). Graphite is extremely refractory and is also a very good conductor of heat, and its platy nature might also have provided the crucibles with extra strength (Martinón-Torres and Rehren 2009).

Sample D2 has a very different composition to the other two. It is characterised by the presence of abundant argillaceous inclusions and less frequent carbon-rich inclusions, in a fine well-vitrified clay matrix (Fig 7C and D). The argillaceous particles, which are equant, elongate and well-rounded, range in size up to 2mm (Fig 7C). They are composed of grey to brown, highly vitrified clay and contain significant porosity that appears to be due to the release of gases during heating, causing fine bloating pores. Some of these inclusions contain internal alignment that is reminiscent of bedding, thus suggesting that they are some sort of mudstone or shale.

Chemical characterisation of the clay matrix and argillaceous inclusions (Table 1, nos 7–12) confirms their close similarity in composition. This may suggest that the latter are residual lumps of the raw material that was used for the preparation of the crucible paste. Tylecote (1982, 237) reports that early Sheffield steelmaking crucibles were made by mixing together dry ingredients, adding water and leaving this to be absorbed by the clay mix. The argillaceous lumps could therefore be clay particles that were not sufficiently hydrated and remained as aplastic inclusions.

The other inclusion type in D2 is vesicular fragments of coke (Fig 7D). Coke fragments have been reported within the fabric of 19th-century early steel-making crucibles from Sheffield by Freestone and Tite (1986), Eccleston (2003) and Quinn (2013b), which appear petrographically similar to D2, and were also composed of fine clay with argillaceous inclusions and opaque coke fragments. An account of the paste recipes used for 19th-century Sheffield steelmaking crucibles by Barraclough (1978), suggests that coke dust was added (Tylecote 1982, table 3, 237). Chemical analysis of the inclusions indicates that they are carbon-rich, which would support their interpretation as coke fragments.

Chemical analysis of the clay matrix of sample D2 indicates that it has a high proportion of silica, relatively high alumina and low or below detection limits K_2O, FeO, CaO and MgO (Table 1, nos 10–12). This composition suggests that the clay would have been highly refractory. By plotting the chemical composition of D2 and the Tenter Street, Sheffield crucible (Quinn 2013b) alongside crucible data collected by Freestone and Tite (1986, fig 22, 57) (Fig 8), it is possible to see that they have compositions very close to that of a Huntsman crucible from Sheffield (*ibid*). It is therefore likely that all three crucibles were made from similar raw materials and perhaps by the same workshop.

Possible sources of refractory raw materials used in the manufacture of the Sheffield crucibles include 'fireclay' that occurs in the Stannington and Loxley area on the outskirts of the present city. These were extracted for the production of crucibles for the early steelmaking industry in the city (Battye 2004). Based on the compositional data quoted by Tylecote (1982, table 4, 238) for different clay sources used for the production of early Sheffield steelmaking crucibles, the clay matrix and argillaceous inclusions in D2 and the Tenter Street crucible (Quinn 2013b) might be a match for 'Derby Clay'. This clay is similar due to its high silica and alumina content, as well as its low levels of FeO, CaO and MgO. It is interesting to note that 'Stannington Clay', which was presumably extracted from Stannington near Sheffield, appears not such a good match, though the difference is not as large as it first appears as the data Tylecote is quoting is not normalised.

Metallic residues and slag

by Roderick Mackenzie

The finds assemblage contains several possible spillages of iron or steel and the main aim of the metallurgical analysis was to determine whether any of them could relate to cast iron rather than steel production. The secondary aim was to investigate whether the spillages relate to more than one event.

One of the most unusual and potentially interesting pieces is a large solidified mass of what appears to be slag and metal with part of a crucible stand embedded within it. The presence of the fragment of crucible stand, and the drip pattern on the underside of the mass, strongly suggest that it had solidified on the fire-grate of a working crucible furnace, possibly as the result of a crucible which had failed catastrophically within the furnace during a steel melt.

Methods

Small samples for metallographic analysis were removed from four individual pieces of slag/metal, two from context 1001 (topsoil) and one each from contexts 1008 (demolition material in crucible furnace cellar) and 1017 (silting deposit above floor of cellar).

The samples were mounted in cold setting resin and prepared for metallographic analysis using established methods, as described by Vander Voort (1999). After a final polish with 1µm diamond paste, the surface of the samples was etched with 2% Nital, before being examined and photographed using a reflected light metallographic microscope and digital camera. Where necessary, hardness testing of specific components within the microstructure of the samples was performed to aid their identification. Due to the strong likelihood of contamination of the metal during its burial, quantitative chemical analysis of the samples has not been carried out.

Results

The microstructure of samples 1001A and 1008 (Figs 9A and 9C) both consist of proeutectoid cementite and fine pearlite; the cementite in both samples is predominantly concentrated on the prior austenite grain boundaries. The microstructures of the samples suggest that both have a carbon content of around 1.2–1.4%.

The microstructure of sample 1017 (Fig 9D) also consists of proeutectoid cementite and fine pearlite, although the cementite is more evenly distributed than in samples 1001A and 1008. The microstructure of the sample suggests a carbon content of around 1.1–1.3%.

The microstructure of sample 1001B (Fig 9B) consists of ferrite with colonies of pearlite and, compared to the other samples, the microstructure is more heterogeneous. One of the original (presumably outer) surfaces of the sample has a layer of an iron oxide-rich slag attached, and traces of slag can also be found within the metal as non-metallic inclusions. The microstructure of the slag layer shows that it is composed of the minerals fayalite and wustite. The amount of pearlite in the metal increases significantly as one moves away from the slag-metal boundary area. Moving across the surface of the sample, the carbon content varies from <0.1 to around 0.7%. The overall carbon content of the sample is estimated to be between 0.4–0.6%.

The microstructures of all four samples are characteristic of cast steel that has cooled relatively quickly and not been heat-treated following solidification.

Discussion of the residues

The analysis has revealed that all four ‘spillage’ samples are either medium or high carbon steel, which is quite typical of the carbon content of crucible steels. The confirmation that the fragments of metal are cast steel, the morphology of the pieces of metal that the samples were removed from, and their archaeological context strongly suggest that all of the pieces relate to the catastrophic failure or leakage of a crucible, or crucibles, whilst they were in the furnace during a melting cycle.

There are differences in the microstructures of samples 1001A, 1008 and 1017, but the carbon content of the samples are very similar, and the differences in microstructure could be the result of differences in the rate that they cooled within the lower part of the furnace. Although it is not possible to be absolutely certain, these three samples may all relate to the same event.

The microstructure of sample 1001B is intriguing, as the difference in carbon content between this and the other samples suggests that it may relate to a separate crucible failure/event. Morphologically, the large mass of metal that the sample was removed from is, without doubt, the solidified contents of a crucible that had burst or leaked whilst in the furnace and when it was at, or very close to its full operating temperature of around 1600°C. The marked reduction in the carbon content near the original outer surface of the metal was probably caused by partial decarburisation of the steel as it solidified in the oxygen-rich environment in the grate of the furnace.

Slag
The slag in the assemblage appears to consist of three groups: blast furnace or cupola furnace slags, fuel ash slags and possible metalliferous slags that are undiagnostic of their production process.

The blast furnace/cupola slags range from the typical glassy type of varying porosity, to dense iron-rich tap slags with coke inclusions. Although the blast furnace/cupola slags form a large proportion of the slag assemblage, there does not appear to be enough to suggest that a blast furnace was ever present at the site. However, it is possible that larger quantities of blast furnace slag are deposited outside the area of the excavation, and on-site work by Gerry McDonnell convinced both him and David Cranstone of the possible existence of an undocumented charcoal furnace on or close to the possibly later forge site. Fragments of blast furnace slag were also recovered from stratigraphically early contexts during the excavation of the cementation furnace (Cranstone 1997), although only a small amount (less than 1kg) was found.

The fuel ash slags all appear to relate to the burning of coal or coke. Both of these fuels would have been used at the site for steel production: coal in the cementation furnace and coke in the crucible furnaces and smiths' hearths.

Discussion
Derwentcote as an industrial concern possibly developed out of agricultural processing, specifically corn milling, as recorded in a confiscation of land from John Swinburne in 1569 (Surtees 1820). The site, on a slight plateau in a river bend with a slope immediately to the south, was topographically conducive to the construction of industrial structures such as a cementation furnace, a forge, crucible steel furnaces and possibly a charcoal blast furnace. All the required elements (multiple levels and a source of water power) were present for metalworking to be established there. However, as the industry developed and Derwentcote attempted to stay in line with its evolution, it found itself being left behind by more advanced infrastructure, in particular the development of river navigation and canals between Hull and Sheffield from the late 18th century, allowing the economic transport of Swedish bar iron for steelmaking close to the major market provided by Sheffield.

The forge at Derwentcote was in operation by 1719, perhaps re-using an earlier water-powered mill site, and possibly also the site of an undocumented charcoal blast furnace. The cementation furnace was probably constructed between 1719 and 1742, converting imported Swedish wrought iron into 'blister' steel (Berg and Berg 2001). The water-powered forge converted pig iron to wrought iron, initially using the finery-chafery process; in the 1780s it participated in the development of the puddling process. It also worked the blister steel from the cementation furnace into high-quality 'faggot' and 'shear' steel, and subsequently a small crucible steel works was added, melting the blister steel to produce cast steel. The 1861 census recorded a 'steel melter' as living within the works cottages, the earliest evidence of a crucible furnace on site. At the same time a 'steel roller' was listed as an occupant, suggesting a rolling mill had been erected within the forge.

The crucible furnace appears to have been built into an existing building within the forge. The photograph from the 1860s or 70s (Fig 10) shows a block of at least four chimneys, of characteristic crucible furnace form, on the north side of the building, a location which corresponds with the position of the excavated furnaces. Spencer (1864, 125) records that there were six melting furnaces (or ‘holes’), of which two were exposed in the excavation, and that these used blister steel (presumably from the nearby cementation furnace), rather than mixed Swedish wrought iron and cast iron, which by then was more commonly employed elsewhere. No ancillary rooms, such as ‘pot-room’, weighing up/charge room, or coke storage area were identified, though this probably reflects the limited excavations and the fact that some of these activities probably took place on the floor level (which did not survive) above the cellar in trench 1. The crucible furnace is the first excavated example outside Sheffield and South Yorkshire, and in this instance the failed crucibles are of some interest.

Crucible failure and steel leakage was a serious issue for a steelworks, particularly given the extremely dangerous nature of molten steel and the relatively high monetary value of crucible steel. The problems of leaking crucibles and how they were dealt with are mentioned by Barraclough (1984); so although leakages obviously did occur, so far the archaeological evidence from numerous crucible steelmaking sites in the Sheffield area suggests that spills of crucible steel were very rare.

What makes the evidence of crucible leaks at Derwentcote more intriguing is that the analysis of fragments of crucibles from the site (above) found that both graphite- and coke-tempered clay crucibles were being used for steelmaking; this is the first time that both crucible types have been identified at the same site. In addition, the presence of a graphite-tempered crucible of somewhat different form and with thinner walls than the others has been noted.

It should of course be borne in mind that the examples of crucibles from Derwentcote that have been analysed might not necessarily be representative of the crucibles that had failed. However, the evidence of crucible leakages or failures, and the presence of two different types of steelmaking crucibles, do suggest the possibility that the steelmakers at Derwentcote were experiencing problems with their production process.

One possible explanation for the presence of the steel spillages and different crucible types is that the steelmakers were having quality problems with their coke-tempered crucibles, so decided to change to using graphite-tempered crucibles as these were known to be more robust. The reason for the possible problems with their coke-tempered crucibles is uncertain; perhaps it was due to the subtle differences in composition or production processes compared to crucibles produced in Sheffield, or possibly that they had to be transported to the site from elsewhere, and had become damaged in transit.

Both furnace and forge closed between 1875 and *c*1891, when the census records only one person living at Derwentcote forge associated with metal working (Charles Winter, steel manufacturer), though no workforce is indicated and steel production may have ceased. Ordnance Survey maps of this date show the forge and furnace as abandoned. The limited excavations here in 2010 have shown remains survive well and that any future work on the forge area should produce valuable results. What has not been revealed so far are any remains of the corn mill or evidence of the finery/chafery operation and short-lived puddling experiment in the forge complex.

The 19th-century photograph (Fig 10) shows a blocked off chimney (foreground) and a free-standing chimney (background) that may have been associated with one or more of these processes.

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Figure captions

Figure 1: Site location plan.

Figure 2: Trench locations superimposed on extract from 1856 Ordnance Survey 25" map.

Figure 3: Plan of trench 1, showing crucible furnace remains.

Figure 4: Crucible furnace bays 1012 within cellar viewed from the south. Scale = 2m.

Figure 5: East face of dam structure 2008 viewed from the north-east. Scales = 2m.

Figure 6: Wheel-pit wall 6009 with waterwheel fixing points 6003 viewed from the north-east. Scale = 2m.

Figure 7: Scanning electron micrographs of steel-making crucibles. A: D1 in secondary electron mode; B: D1 in back-scattered electron mode; C and D: D2 in back-scattered electron mode. See text for identification of phases present. Scale bar = 2.0 mm, except D = 700 µm.

Figure 8: Ternary diagram illustrating the chemical composition of steel-making crucible D2 from Derwentcote. Contemporaneous Sheffield crucibles analysed by Quinn (2013b) and Sheffield Huntsman crucible analysed by Freestone and Tite (1986)) are added for comparison, along with analyses of other metalworking crucibles (after Freestone and Tite 1986, fig 22).

Figure 9: Metallic residues. A: sample 1001a. Pearlite and cementite along prior austentite boundaries of etched microstructure; B: sample 1001b. Boundary between iron oxide-rich slag layer and surface of metal, etched microstructure; C: sample 1008. Proeutectoid cementite along prior austentite grain boundaries in etched microstructure; D: sample 1017. Pearlite and pro-eutectoid in etched microstructure.

Figure 10: Derwentcote Forge in the 1860s or 1870s, viewed from the west. Note the block of crucible furnace chimneys, top left.

			MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	FeO	K_2O + … CaO + …
Sample	Analysis	Details									
Derwentcote 1	1	Sand sized inclusion		38.25	57.85	0.56	0.74	1.63		0.98	
	2	Sand sized inclusion	0.45	17.30	79.71	1.65	0.37	0.53			
	3	Sand sized inclusion		2.77	96.48	0.75					
	4	Clay matrix		43.42	51.07		0.47	2.56		2.48	2.95
	5	Clay matrix		48.29	46.13			2.93		2.65	2.65
	6	Clay matrix		50.58	44.64		0.40	2.29		2.09	2.49
		Average clay matrix		47.43	47.28		0.43	2.60		2.41	2.70
Derwentcote 2	7	Argillaceous inclusion	1.16	33.81	60.35	2.47		0.86		1.34	4.97
	8	Argillaceous inclusion	0.87	35.61	59.23	2.19	0.33	0.64		1.12	4.52
	9	Argillaceous inclusion	0.63	40.20	53.47	1.66	0.46	0.71		2.19	4.94
	10	Clay matrix	0.76	37.06	58.17	2.14		0.81		1.07	4.00
	11	Clay matrix	0.76	36.74	58.50	2.08		0.82		1.09	3.93
	12	Clay matrix	0.63	37.63	56.93	2.04		0.73		1.30	3.97
		Average clay matrix	0.72	37.30	58.00	2.03		0.79		1.17	3.97
		Average fabric	0.80	37.00	58.00	2.10	0.13	0.76		1.40	4.38
Accuracy			-1.57	0.45	1.55	6.56	4.87	9.28	9.77	2.40	

Table 1: Selected SEM-EDS analyses of clay matrix and inclusions within steel-making crucibles from Derwentcote, based on area analyses. Data presented as normalised wt%, with average clay matrix composition calculated from three analyses per sample. Average fabric for sample Derwentcote 2 calculated from the average of three clay matrix and three argillaceous

inclusions. Accuracy for the reported elements is expressed as relative percentage difference between the average analysed and average given values of two basalt standards.