Bole lead smelting technology and the Linch Clough (Derbyshire) bole

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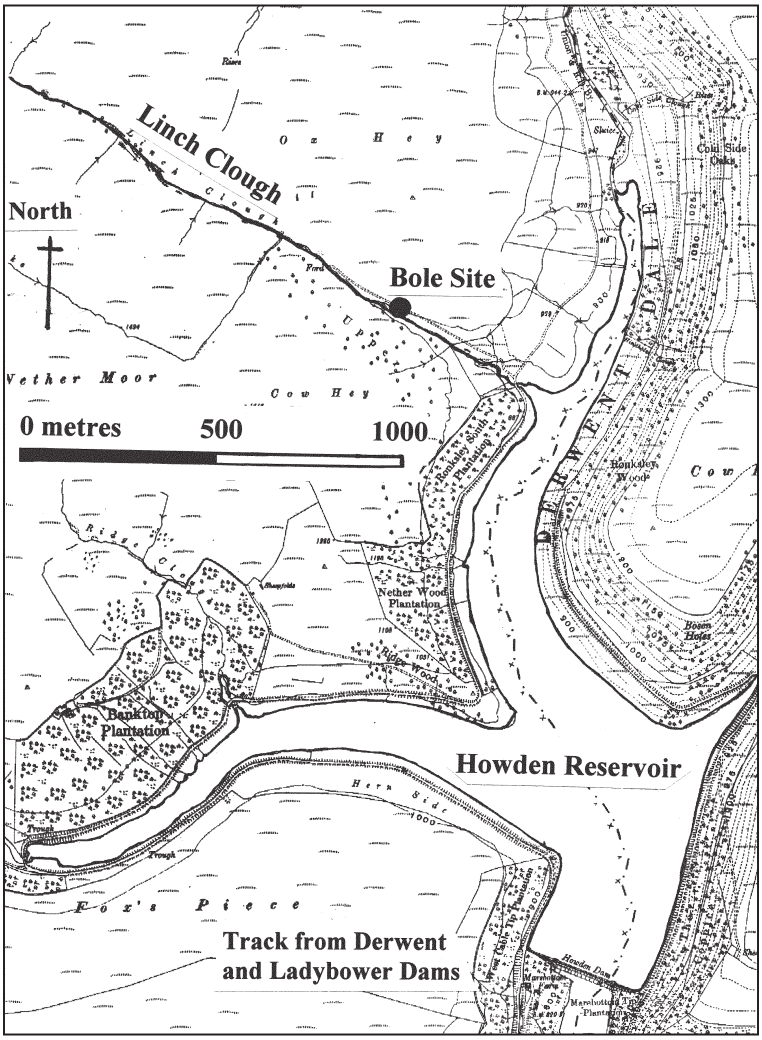
ABSTRACT: A technical model is presented of lead bole smelting as it is known to have been practised in late medieval and early post-medieval Derbyshire and elsewhere. It uses known parameters of fuel characteristics and reaction temperatures, together with contemporary descriptions of the technology. These are applied to the Linch Clough bole (SK165943) excavated in 1997. A hypothesis is offered for its operation, differing from the interpretation presented by its excavators.

Introduction

Our knowledge of bole (*ie* wind-blown hearth) lead smelting is still rudimentary, and it is not possible to provide an adequate evaluation of all types of bole smelting technology. The model developed below, described by Bevan, Doonan and Gale in their report on Linch Clough (Bevan *et al* 2004) as traditional, is limited to the large bonfire (over two metres in diameter). It would not necessarily apply to smaller-diameter bole hearths, especially those below one metre in diameter, in which there was a smaller thermal mass, limited chimney effect due to lack of height, less exclusion of excess air by an ash mantle and little opportunity to add fuel and ore during the process. It does not apply to hearths, whatever their location, in which bellows were used. Whether all types of smelter were known as boles by contemporaries is not known, although all may appear in places where the term 'bole' survives as a place-name.

Kiernan (1989) has provided the most data, based on historical sources; this is supplemented by papers and discussion from an HMS conference (Willies and Cranstone 1992). The most significant subsequent publication on technical aspects of bole smelting, apart from the report on Linch Clough, has been by Smith and Murphy (2003), a study of bales (boles) in the Yorkshire Dales. There is also relevant information in late-19th and early-20th century metallurgical texts (*eg* Collins 1910).

The Linch Clough bole, in the uplands near the head-waters of the Derbyshire river Derwent in the northern part of central England (Fig 1), was excavated in 1997 (Bevan *et al* 2004). This excavation was the first comprehensive investigation of a large bole, whose late-medieval technology is only partially understood. The present paper began as a review of the original article, for this journal, but it became clear that the excavation results could be interpreted in different ways. The paper questions the interpretation of this bole site; to do so it is necessary to understand details of the process. This background forms the first part of the paper, which is followed by the re-interpretation. The writer is grateful to Bill Bevan (the excavator) and to Roger Doonan (post-excavation) for the opportunity to visit and discuss the excavation: his own views are limited to the technological aspects of the bole, leaving the detail of the site and its metallurgy, and the wider picture painted by Bevan *et al*, to be read in the original article.



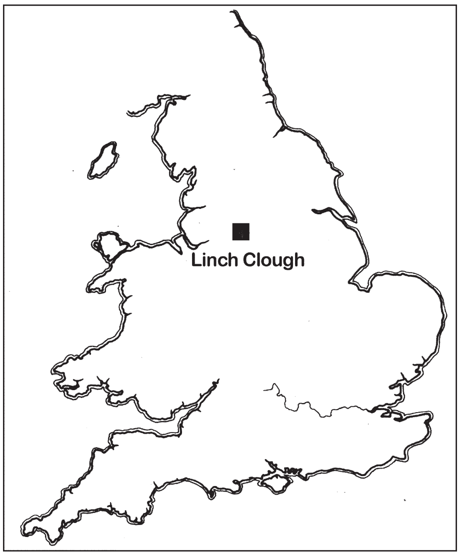


Figure 1: Location of Linch Clough bole, sited in the upper Derwent valley, Derbyshire. Based on the Third Edition Ordnance Survey 1928.

The bole smelting process

Key questions surrounding the study of bole smelting sites, in general and for Linch Clough are:

- What was the bole process, and does Linch Clough fit this model?
- What fuel (or fuels) were used and what were the smelting reaction and residues?
- What structures, such as walls, flues and tapping features were necessary?
- What was the capacity of the hearth?
- What are the implications of temperatures of 750˚C and around 1200˚C at Linch Clough?
- What associated features can be expected?
- Were hilltop locations necessary?

There are several basic needs for smelting lead ore in boles. The 'traditional' bole was certainly used in Derbyshire and Yorkshire and there is accumulating evidence for widespread use in the North Pennines and probably in Wales and Devon (Claughton 1992, 12–13). The somewhat different types of smelting hearths described by Megaw (1960–61) in the Isle of Man, Fairbairn in West Allendale (2007) and Timberlake at Cymystwyth in Wales (2002) will have had some similarities in operation.

The bole described here had a substantial hearth, a pyre of fuel—normally air-dried wood (from a number of mature trees), an abundant air supply—usually from a strong and steady wind, a means of ignition, a method of maintaining the ore in oxidizing and then reducing conditions, and a means of accumulating and casting the molten lead, usually by ladling into ingot-moulds. There was sometimes an association with a blackwork oven, in which residues from the bole (commonly but usually misleadingly called slags) could be re-smelted. This latter was a small charcoal-fuelled foot-powered blast furnace, possibly developed in the late 15th or the 16th century, although it had predecessors (Willies and Cranstone 1992). As it would be difficult to blow a hearth of more than about one metre diameter manually, anything substantially larger will have been wind blown.

Suitable locations for bole smelting seem generally to be away from limestone, which is not refractory and from which, in Derbyshire, many woodlands had long been removed. It was usual to avoid habitations and good land. Sites which were particularly windy, which were close to wood reserves and which were convenient for local and more distant market-directed transport, were favoured. A water supply was useful for dressing bole residues for re-smelting and, possibly, for a water-wheel to operate the blackwork oven bellows. The gritstone areas to the north and east of the lead-mining field provide suitable sites and most boles are found on the gritstone, within about 12km of the ore deposits.

Bole-smelting reactions using wood fuel

The main smelting reaction with wood fuel is, in principle, a simple one. Tylecote found that it could be carried out in a small wood-fired brazier (1986, 54–58). The ore, lead sulphide (galena), supported by the fuel (wood-brash) at the top of the fire, is first partially oxidized (or roasted) to oxide or sulphate and then reacts with the remaining sulphide ore (at the surface of each fragment) to form metallic lead and sulphur dioxide (the double-decomposition reaction). Unpublished experiments in Italy by the writer and others have shown that plenty of air is the main requirement for the reaction to take place in these conditions. The open nature of a wood fire, Tylecote noted (1986, 223), probably makes wood the preferred fuel, and the double-decomposition process can continue as the fuel/ore mix, or brouse, descends to the hearth bottom. In a more sophisticated fire, reduction of air supply, particularly at the bottom of the fire, can lead to conditions where remaining oxide or sulphate reacts either with carbon (*ie* charcoal) or with carbon monoxide, and is reduced to lead metal (the roast-reduction reaction). In reality the chemistry is complex, and different constituents of the ore such as silica, lime, fluorspar, barytes, oxides of iron, and clay, as well as the actual temperature and gaseous environment—oxygen (air), sulphur dioxide, carbon dioxide and monoxide—all affect the process.

An historical or 'traditional' model of smelting using wood in the bole

The model provided by Kiernan (1989) for fuel-use was drawn from evidence for the bole at a late stage in its development, just before its replacement by the ore hearth (*c* 1580) as the dominant lead-smelting technology. The bole he describes was a large structure, walled on three sides, up to six or seven metres across and open on the windward side. It was fairly permanent, and sometimes had a removable roof placed on it between the one or two operations annually, to protect the hearth from the weather. Boling was a large-scale batch operation, designed to smelt as much as 30 or more tonnes of ore at a time, using a similar mass of good fuel-timber to do so, and a high mass of oxygen to burn. The intended output with such a charge was some 15–16 fothers, up to about 20 tonnes.

The bole used tree-trunks, known as blocks, at the base of the pyre, which was constructed above a saucer-shaped hollow. The blocks were covered with a layer of blackwork, the residue of a previous smelt, or coarse ore supported by brash (small branch wood). Above this were one or more layers of smaller but still substantial trunks or branches known as shankards, with layers of ore above, kept in place by brash. The pyre rose to a considerable height above the hearth base; Kiernan's sketch suggests that it rose vertically about three metres, but the actual height is unknown. The higher it was built, the greater the burning-reaction rate. About two tonnes of wood were needed to produce a tonne of smelted lead. To ignite the pyre, a large bonfire of fire-trees or brash was ignited at the windward side. The saucer or bowl-like hearth had two tapping channels running from its shorter ends, uniting in one channel leading steeply down-slope for several metres to a collecting sump. The channels seem to have been lined with sand or possibly loam.

Contemporary wills suggest that there was a reluctance to disturb the hearth and blocks after a firing, or the hilling (part-smelted slaggy material) between smelts, and it is possible that substantial amounts of lead remained in the hearth. The material smelted was preferably good ore, known as bing, of about 25mm pieces, but ranging down to a coarse ore of about 12mm, with efficiency falling rapidly if ore below this size (wash ore) was used. The best quality ore would have a lead content of about 85%, but the wash ore would have had considerably less, because of adulteration with gangue minerals.

Operations depended on a reasonably strong and constant wind, over the two days and nights required for the process and, for this reason, winter was the preferred time of operation, with sites on the scarps of high hills favoured. Failure of the wind was a risk, leaving the mass in an uncompleted reaction, but this did not seem a major problem in practice. For instance between 1566 and *c* 1576 William Madder and Richard Needham carried out 40 smelts at two bole hearths on Brown Edge without a failure (Kiernan 1989, 45).

Practical considerations for wood-fuelled boles

We can reasonably assume that the timber for the operation was well prepared, as for fire-setting in mining and in other metallurgical operations using wood as fuel (Percy 1861; Philips and Bauerman 1891; Collins 1910). The wood would be winter-cut, debarked and/or split, and air-dried for a year or so. Deciduous species would be preferred to pine because of higher density and lower water content, which drying would reduce to between 15–20% in preferred species, or about 25% in the less-favoured. Coppice-product was suitable for the small wood and possibly for shankards. Kiernan (1989, 45), using contemporary documentary evidence, suggests that about two tonnes of wood were required per tonne of lead produced. He also suggests that better woodland management in the 16th century reduced the price of wood for smelting: the implication is that coppicing may be a late, post-medieval, development, at least in the remoter areas. We can also assume, if only because such a large investment in materials was entrusted to the boler's care, that this wood-burning smelting technology was well understood: the choice of wood, its sizes and positioning in the fire would approach the optimum.

Each feature of the bole had its function. The hearth acted as a receiver of molten metal and of residues, usually but dubiously called slag, perhaps allowing them to separate and be stored, and/or directing the molten lead via a tapping channel to where it could be ladled or run into moulds to make saleable ingots. It is not known if a dam or slag barrier was placed at the entry to the tapping channel or at the edge of the hearth. Such a dam would be removed for tapping. A restraint on tapping must have been the high density of lead (sg 11.3), from which a depth of say 200mm would produce a head equivalent to well over two metres of water, leading to a risk of premature and dangerous release of molten lead. Whether tapping was continuous or intermittent might be determined by the capacity of the receiving sump.

It is not known whether the hearth and/or the tapping channel were lined before firing, or whether the first firing hardened the lining for subsequent smelts. Maintaining the lining was probably the reason for leaving the hilling, the remains of the blocks and slaggy material, in place. The walls contained the timber and ore, and as they were on three sides they acted as a vertical flue, whose chimney effect turned the mass of air in the wind into a heat-accelerated flow through the fuel and ore layers. The reported use of similar pyres to the bole for heap-roasting of ores at the end of the 19th century (Collins 1910, 70) suggests that it was advantageous to line the floor with clay, and that the sides of a bole unsupported by walls would be fairly steeply inward-sloping, to keep the ore in place. Molten lead has a low viscosity: at 703°C it would be 1.35 cp and at 844°C, 1.19 cp, somewhat similar to milk (Keith Gregory pers comm). Further, any weaknesses and cracks would lead to loss of molten metal. Loose material—soil and stone—would also float out of position unless there was a substantial incumbent load. Heap roasting required flue-ways to be left within the timbers and brash, to ensure that sufficient air gained access for the reaction to take place.

The brash had two functions; firstly, it supported the ore until it agglomerated sufficiently to bridge gaps in the larger shankards below. Secondly, the relatively open brash, in layers between the ore and the thicker shankards, would have provided channels into the brash itself and among the larger timber, and into the ore-mass: its rapid burning would raise the temperature of the mass of ore. Because of this air circulation, the early oxidizing stage would take place throughout the fire. The burning of the brash would also lead to movement in the mass of ore and brouse (part-smelted ore); this would be followed by a slower collapse caused by the large timbers burning below, exposing fresh surfaces to the heat and air, promoting the reaction.

The thinner trunk-pieces and the substantial branch timbers (shankards), cut to length and possibly split into billets to allow good drying and dense packing, would have provided the main mass of fuel required over a sustained period. Gaps (some perhaps deliberately constructed) would have acted as channels for the large amount of air needed to supply oxygen, and for any lead produced to pass down to the hearth. The shankards would have been slower to get to the vigorous-burning stage, but were probably responsible for raising the temperature at a critical time, as well as sustaining it for many hours. Experience with domestic fires burning wood of this size suggests a burning time perhaps equal to overnight, up to eight hours. Further heat, after the temperature was sufficiently raised, would have been derived from the exothermic oxidising reaction of the ore itself.

The large timber blocks would have acted as a grate through which molten lead could seep into the hearth, whilst the agglomeration of fuel, ore and half-smelted ore was held above. In later slag smelting (Willies 1990, 10), cinder was used to separate molten lead, which passed through it, from slag which was more viscous and flowed over it: the part-smelted ore may have had a similar function. The magnitude of the blocks caused a relatively slow burn, ensuring a continuing supply of fuel, probably much carbonized. With the gradual dying down of the fire as the shankards were consumed, the mass would descend or collapse in on itself, as an ember pile over the remains of the hilling. The restricted air supply would give highly reducing conditions (carbon monoxide), acting on any remaining oxidized material at a late stage in the process, completing the series of reactions over a period of some hours, possibly as much as a day.

In this sequence of events, lack of consistency of the wind was a difficulty, although once ignition was well advanced its role would lessen. A further problem must have been the quality of ore when lower grades (wash ore) were used. This was due both to the smaller particle size of the lead ore and to the higher proportion of non-galena material such as sludge and gangue mineral present, which would coat the ore particles. The air was occluded by the less open structure of the ore mass (browse), preventing the smelting reactions taking place at the particle surfaces. In some cases the gangue mineral would absorb heat, so the temperature rise might not extend through the mass, and the ignition of the sulphide in particular might not fully be achieved. The proportion of ore successfully smelted would be reduced.

We know, from descriptions of lead-smelting processes of all periods and types, something of the parameters for success in the bole process. Succeed it did, with a metal-to-ore ratio of up to 58% (Kiernan 1989), the ratio falling with poorer ore. This was a very respectable result, comparable with the later ore hearth, and only a little worse than the best results from the much later reverberatory furnace, which used coal as fuel (Willies 1990). The fuel efficiency was, however, probably much less than achieved by the later methods, and the scale of operation and capital requirement, with the dependence on natural wind conditions, added to risk. However, the quality of output, of soft, easily merchantable lead, was high.

The process required temperatures well in excess of 600˚C, which are easily achieved in a wood fire. Experiments in fire-setting (Willies 1994; 2002) showed that an ordinary bonfire achieves 750˚C, a small dried wood fire against a rock face nearly 800˚C, and a wood fire with wood placed to form a muffle around 850˚C. The exothermic reaction during roasting would also elevate the temperature, and Scott (1927) commented that like other forms of pyritic (metal sulphide) smelting, the reaction could be self-fuelling. He noted that it was necessary to add lead oxide as a moderator to keep the temperature down during assay work. In the reverberatory furnace, however, the inrush of air as the doors were opened during the oxidation/double-decomposition phase, cooled the reaction, and it is possible that there was a similar counter-effect restricting the uncontrolled rise of temperature, due to the largely open structure of the bole.

Oxidation of galena begins at around 500˚C and in the later coal-fired reverberatory furnace the ore was maintained between 500˚C and 600˚C, a low red heat (Collins 1910, 27), for the oxidation stage of the process. That brash could achieve similar results is shown by its 19th-century use in the traditional Spanish *boliche* hearth. At the lower end of the temperature range, the product would be mainly lead oxide, but with slightly higher temperatures lead sulphate becomes dominant. For double-decomposition, the temperature in the reverberatory furnace had to be raised to a cherry-red heat: for this reaction to take place with oxide, 720˚C had to be maintained, but only 670˚C with lead sulphate: in the much less controllable temperature regime in the bole, all these reactions would take place interchangeably and/or simultaneously. In the bole, lead sulphate formation may have been inhibited by the rapid removal of sulphur dioxide in the upper part of the fire.

The maintenance of the lower temperature required for successful oxidation in the early stage of heating, by combustion of the brash, was probably a result of the need to heat the ore from cold and by the cooling effect of the flow of air. Descent of the heated brouse into the hotter shankard heart of the fire probably led to the double-decomposition reaction dominating, and emission of much sulphur dioxide in a white plume, whilst oxidation continued at the outer margins. As in the later reverberatory furnace it was important that the brouse in the bole remained pasty rather than liquifying, allowing the molten lead (melting point 327˚C) to separate.

As the shankards' contribution to the fire began to decline, the heavy brouse would have descended on to the surface provided by the burning blocks, and the ash and charcoaly embers of the upper fire would form a domed hood above and around, limiting the air supply and providing insulation. The reducing environment of carbon monoxide at a dull red heat would decompose sulphate, and at a cherry-red heat both sulphate and sulphide, *ie* galena (Collins 1910, 13) producing more lead metal, the reaction continuing whilst these conditions were maintained, for a day or two.

Probably a major advantage of burning wood in the wind-blown bole was that operating as opposed to transitory temperatures were between about 500˚C and 750˚C, and exceeding 800-850˚C was probably unusual. Galena melts at 935˚C (Collins 1910, 11), although other writers suggest a higher temperature: lower melting temperatures may be caused by the presence of fluxes such as the common gangue mineral fluorite (fluorspar, calcium fluoride), but increased by the other common gangue minerals baryte (barium sulphate) and calcite (calcium carbonate). Melting the galena would have removed it from the reaction zone prematurely, or prevented, at a later stage, complete separation of chemically unchanged ore from the molten lead metal. Above about 850˚C, lead sulphide begins to volatilise, and consequent loss of lead can be substantial in percentage terms. Smelting can continue (as it does in modern furnaces) above 850˚C, but in the bole, disadvantages would begin to outweigh advantages.

Charcoal as an alternative fuel

Charcoal is a possible alternative fuel to wood for the bole: it has been suggested for Yorkshire bale (bole) sites, although the evidence for charcoal rather than wood at two sites in Yorkshire (Smith and Murphy 2003) is restricted to lumps of charcoal found in heaps away from the actual hearth, without lead brouse, slag, blackwork or condensate. There appears to be no documentary evidence for its use in the large bonfire-type bole in Britain.

Smith and Murphy (2003, 63), citing Agricola and use in Westphalia, note that charcoal was used in large heaps: Agricola states in 1556 that these took 10 wagon loads of charcoal, with the ore placed on the top of a bed of straw to hold it in position for the oxidation phase (Hoover and Hoover 1950, 391). Piled brash, wood shavings and ling have also been suggested for this. Ignition of the charcoal, presumably by using a mass of kindling, as in the bole, would produce a very hot fire, which in a good wind would cause the initial oxidation, some double-decomposition and the melting of the oxide, which would require temperatures around 900˚C or more. Any lead metal, and the liquid or solid oxide, would descend into the heap, and be reduced rapidly to the metal in the high concentration of carbon monoxide (the roast-reduction reaction).

Smith and Murphy point out that a charcoal fire would be more controllable, as it can be more easily approached, and the higher temperature would reduce reaction time. Agricola (Hoover and Hoover 1950, 392) mentions scattering 'a few hundred pounds' of ore on the charcoal fire during the process, when it was going well. This would have been easier with a charcoal fire, although given the high density of the ore, the scattering must often have caused too rapid a descent through the fire. By and large, the bole process was a single batch operation, but closer access allowed by the use of charcoal may have made handling the molten lead easier. The cost of making charcoal may have been balanced by the lower expense of transport compared with wood, although the friability of charcoal restricted the distance it could be carried.

If charcoal did achieve higher temperatures, its use on the Continent may have had another purpose. High temperatures produce a greater proportion of the lead from the ore, more quickly, but with more impurities which render it harder and less malleable. This is useful for silver-rich lead, where the lead would be refined later, producing pure silver and, after re-smelting of the litharge residue, pure lead. Most other contaminants would be less desirable. Much continental lead was worked for silver, but in Derbyshire it is rare to find levels of silver worth extracting. Bole-smelted lead was also valued over ore-hearth lead for its malleability, useful for roofing. This requirement would favour the lower temperatures of wood fires over charcoal. Some British ores have higher silver contents, notably in Wales, Cornwall and Devon, the North Pennines and Scotland. There has been speculation (*eg* in the unpublished discussion following Todd's paper (1996) on Roman lead/silver mining in the Mendip) that lead ores found near the surface in Derbyshire, Yorkshire and the Mendips may have had higher levels of silver than was later found in ores at depth, which would account for known instances of lead smelting for silver content. There is no obvious paragenetic mechanism for this, which may result from secondary mineralization processes.

The possibility that silver rather than lead was the objective in the 15th century is suggested by the appointment in 1444 of William, Marquis of Suffolk, as surveyor of mines of gold, silver, copper and lead, with emphasis on silver (Raistrick and Jennings 1965, 88). It is therefore possible that Continental methods were adopted to maximize the ore-to-metal ratio, making higher temperature methods of smelting more credible (but, in the present writer's view, not very likely).

However, Blanchard (1992, 11) considered that bole smelting had ousted an older technology based on charcoal-furnace silver extraction by late in the 12th century. So, boling in the mid-15th century was hardly a charcoal-burning relic of an older silver-production system, and Blanchard specifically gives data based on the amount of wood burned: three cords of brushwood per ton of ore. A cord of wood is a stack usually 8 by 4 by 4 feet, very close to two cubic metres of solid wood, assuming a regular diameter and gaps between the timbers in the cord stack, and probably weighing a little over a tonne. It is difficult to assess the equivalent for the cord of brushwood. At Bere Alston in Devon, late in the 13th century, the bole was specifically used in lead-for-silver production, with a productivity gain over old methods of about 45% (Claughton 1992).

The problem in determining whether charcoal or wood was used is that although most of the wood was burnt in a wood-burning bole, the reducing conditions found in parts of large boles would have led to some charcoal formation. Charcoal is commonly found with other smelting debris on boling sites: it was usually removed near the end of the process, as embers, on to heaps just outside the hearth limits, to expose the hearth and its contents. It is thus possible that good-quality charcoal was dragged from the pyre during the last, cooling phase of the process and placed aside, as coke cinders were separated in later coal-fired smelting processes (Farey 1811, 391) for use when smelting slag. In the medieval period charcoal was used in a foot-blast furnace, for re-smelting blackwork from the bole, although when this was introduced is not certain. Charcoal also had domestic uses. A suggestion that charcoal from a wood-burning bole might be identified by its lack of coaled bark conflicts with Percy's comment (1861, 73) that air-dried wood also needed de-barking when intended for metallurgical purposes, probably to allow more thorough drying. Bark from oak, at least, had a separate market for tanning.

Historical evidence, mainly from the 16th century, for Derbyshire mentions only the use of wood for the bole, for which a large amount of great timber as well as small wood was required (Kiernan 1989, 41ff). It seems unlikely that charcoal was used often, at least where the ore was low in silver, although it cannot be entirely ruled out. A high-temperature product was not, at least in Derbyshire, easily sold. Evidence for charcoal-use is slight, the comparative complexity and probable higher first cost of charcoal, the possible technical advantage wood has in its open structure and load-bearing capacity in the fire, the resistance of wood to abrasion during transport, and the solid historical evidence for use of wood, makes wood the likely choice for boling.

The double-decomposition and roast-reduction reactions could take place in either a wood or charcoal fire. In either, the reactions would normally not finish, since the support mechanism for the ore would often fail. Thus, as well as the desirable lead metal, the process resulted in partially oxidized galena and a matte of reduced lead and lead sulphide dissolved in each other, both occurring as slag or blackwork, either at the base of the fire or floating on the partly-consumed blocks. Charcoal may

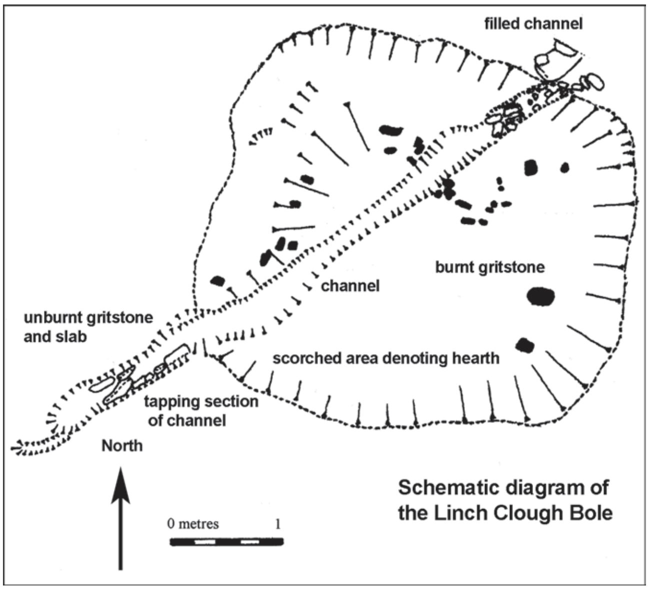


Figure 2: Schematic plan of the Linch Clough bole (after Bevan et al *2004, 116, 118).*

have led to higher temperatures, so that the blackwork would be more likely to be partly vitrified, although the wood-fired bole could also have attained the required temperatures of over 750°C for this to happen.

Review of the Linch Clough excavation report

Location and main features

The bole site (SK165943) is in a side-valley (Fig 1), immediately west of the uppermost Derwent dam (Howden Reservoir) and about 15km north of the main Derbyshire orefield. Bevan has found several other smelting sites nearby, as well as the place-name Lead Hill. Unlike many bole sites it is located in a steep-sided valley (clough), at about 310m OD, rather than on the top of a hill or scarp, although other examples of such siting are known in Derbyshire and elsewhere (Smith 2006, 99 and fig 5). The local rocks are gritstone (coarse sandstone of felspathic and sub-greywacke types) and shale, with weathered products of these forming the soil and sub-soil. The area is close to woodland, probably extant in medieval times, and the site is adjacent to, but a few metres higher than, a strongly-flowing stream.

Bevan *et al* (2004) describe the site of the bole hearth as a scoop in the hillside, sub-rectangular, about 20cm deep and 3.5–3.8m across (Fig 2). The bottom is irregular, due to protruding stones, but otherwise virtually level. The subsoil within this area is pink due to heat, and analysis of the residues shows that lead was smelted here. The other prominent feature is a shallow trench, 140–320mm wide and *c* 150mm deep, which runs diagonally across

Figure 3: Linch Clough, seen from the west, under melting snow, showing the excavation area fenced off. The bole is sited to the left of the two figures, who are standing by the melting pit. A charcoal-rich patch can be seen further to the left, where animals feed.

the hearth, aligned roughly with both the prevailing wind and the valley bottom. At its NE end the trench had been partly dug into the hillside, but a short length had been filled in, whilst on the SW side the trench continues beyond the hearth for about 2m, with a gritstone flag or flags covering part of it. The trench external to the hearth was not scorched and reddened. The hearth is within a shallow declivity which forms a platform, with the hillside rising to the north and falling away more gently to the south towards the stream (Figs 2 and 3). There were scattered burnt gritstones within the hearth, some of which were glazed, but there was no evidence of the footing of an enclosing wall. Part of the external section of the trench had unburnt grit stones along one side. A shallow charcoal-rich deposit was found on a platform on the north side adjacent to the hearth. About 2m to the south was a pit, *c* 1m in diameter, *c* 370mm deep, burnt pink on the sides, and containing burnt material with a white powdery material at the base which appeared to be a lead compound.

The charcoal was derived from oak, hazel and birch; its partially-burnt condition suggesting debris rather than a fuel store. Archaeomagnetic sampling of the hearth placed the date of final use around 1430–1470 AD. Olive-green glassy slag residues suggest that temperatures were at or above 750°C for prolonged periods and, unexpectedly, altered potash feldspar found in vitrified residues suggest a temperature of *c* 1200°C, at least momentarily and possibly for prolonged periods.

The apparently dominant oak, plus birch and hazel, are amongst the better, more compact metallurgical-fuel hardwoods, with a lower percentage of water when air-dried than most others (Philips and Bauerman 1891; Percy 1861). Despite poor upland growing conditions, a source in this valley is likely for cutting, splitting and drying, as access from woods elsewhere would have been difficult. There were also charcoaling sites not far away, one close to a lead smelting site, so its use was possible.

The published interpretation

Bevan (in Bevan *et al* 2004, 131–8) concludes that the hearth, within the reddened area, was for smelting lead ore (galena) and possibly lead slags (smelting residues), using charcoal and forced draught. There was no evidence of an enclosing wall, but the high temperatures deduced would have been 'difficult to achieve without using forced air and some form of structure'. Because the trench was not reddened outside the hearth, Bevan suggests that it was not for tapping the lead, as might be suggested based on evidence from other bole hearths; therefore it might be a flue for directing air into and under the charge. There might therefore have been a foot bellows at the end of the channel remote from the hearth. As there was no connecting channel, the authors argue that the pit was not to receive the molten lead, though it had a function in connection with the smelting platform. Doonan (in Bevan *et al* 2004, 126) referred to burnt gritstone as possibly at the base of the fuel stack, and suggests the temperatures achieved (presumably the 1200°C in this context rather than the 750°C) could not be expected in a simple bonfire (though he also describes it as a traditional bole), and the technology 'effectively managed the induction of air through the arrangement of a channel either by force or by harnessing prevailing winds'. He states that stones with an adhering white crust were most likely to be from high in the hearth structure, representing condensed lead fume. Bevan finally considers the hearth as a variant on the traditional bole, adapted to local circumstances.

However, the present writer argues that at 3.5m in diameter, this is one of the larger hearths found in Derbyshire. It is much larger than that found on Beeley Edge by Radley (1969) and it appears larger than a hearth seen by the writer below Harland Edge on Beeley Moor. It is, however, smaller than hearths described by Kiernan (1989), based on both archaeological and historical evidence, and perhaps smaller than those examined in Yorkshire by Smith and Murphy (2003). The key point, apart from size, is that the writer considers it to have been wind-blown, and thus can be described as a traditional bole. Most references to Derbyshire boles state or appear to assume a hilltop or scarp-edge location, which, because the fuel and ore had to be brought there, might be considered as a fixed-site model. Linch Clough, however, being sited within a wooded valley, suggests a shifting model, the bolers following the fuel supply. Both practices could use the same traditional wind and wood-based technology.

The superstructure of the bole

The small amounts of burnt gritstone and the lack of evidence for a foundation trench suggest to the present writer that the bole was not substantially walled, although it is possible that walling materials have been removed for re-use or to minimise lead contamination of pasture. Had there been a wall, the materials for it would have been local. Gritstone fragments were found with oxidised or reduced slaggy material attached, indicating exposure within the hearth at appropriate but undetermined horizons. Possible uses for this stone might have been for a wall or for some form of flue or channel-lining within the hearth. The gritstones found in the area are only marginally refractory. Most gritstones are felspathic sandstones or even arkoses, with abundant (often potash) felspar as well as quartz, or greywacke types with quartz particles bound by clay. The differential inter- and intragranular expansions of these minerals, and the breakdown of the cementing agents leads to reddening and crumbling when exposed to strong fires, as this would have been. Willies (1994) considered the susceptibility of rock to fire, and subsequently (2002) that of felspathic rock in particular. Such stone would be satisfactory for a limited number of smelts, as a wall, but burnt stone would have been weak, possibly severely contaminated. It would thus be unsuitable for subsequent building or walling to control stock, on grounds both of toxicity and strength, and of little or no value for other purposes since unaffected stone occurs throughout the area. Removal of material from sites because of contamination is not uncommon today, but the bad record of lead poisoning of animals in lead-contaminated areas of the Peak does not suggest that it was common in the past. Therefore the lack of stone on site suggests that the hearth was not enclosed by a wall.

Some of the remaining stone may have consolidated the sides of the channel in the hearth bottom. The channel in its external section was partly lined with stone. Since the open structure of the fire allowed access of air, the use of an internal stone chimney is unlikely, and would have required much more stone than was found. It is feasible that such small amounts of stone may have been used to support timbers above the floor of the bole, to raise the 'blocks' above the hearth, as suggested by Roger Doonan (pers comm), to maintain a good under-draught in the early stages of firing.

The present writer argues from these points that the Linch Clough bole was a single wide hearth created in a slight depression. This contained a pyre on which ore was placed, on top of the fuel or in layers within it, the whole probably forming a steep-sided, truncated cone. There is no possibility of hand, foot or water powered bellows being used to blow such a large hearth at that period (with a requirement of perhaps 20–25 tonnes of air for combustion and oxidation), whilst the amount of heat produced in such a large fire would make use of bellows in the suggested position uncomfortable, at least. The amount of additional air provided by bellows, through any putative flue, would be overwhelmed by natural induction of heated air within the fire. A substantial increase of air-flow could easily be produced by simply raising the height of the pyre or by a construction of larger, more slowly burning, timber blocks or shankards, placed at two or three of the leeward sides. As well as increasing the chimney effect, these would act as a muffle, raising the temperatures achieved. Timber was used in this manner in fire-setting in mining, reflecting radiation back into the fire.

The channel across the hearth

This channel was recorded (Bevan *et al* 2004, 120–2) as about 150mm deep and 140–320mm wide, dimensions affected by damage due to removal of the hearth bottom, and possibly by subsequent soil creep. Within the hearth the channel was scorched, but outside, where it was partially lined with stone (and perhaps loam), burning was not apparent. It was not aligned with the centre of the hearth, but near the centre its top appears to have been at the lowest point of the contextual material, although possibly not at the lowest point of the subsoil. There were two successive linings, indicating at least two smelts. This suggests deliberate building-up of the hearth bottom by leaving lining material at the necessary profile. The channel was approximately horizontal (Bevan, pers comm) rising a few centimetres at either end. At the southern end, outside the hearth, it widened, where it was partly covered by slabs.

The present writer argues that at smelting temperatures, molten lead is very mobile, as its melting point is only 327°C. As it was 'non-wetting', the lead—apart from losses in the fume—would have migrated downwards to this collecting channel. Without a channel, it would have spread over the base of the hearth and would not have been easily recoverable. Any use of the channel as a flue (which is unlikely to have provided more than a minor proportion of the air required) would cease as it became full of lead, or ash from burning of the brash. Reddening of the channel within the hearth implies either intense heating before the lead began to flow, or that the lead which flowed there was hot enough to cause oxidation of the iron in the soil.

The outer end of the channel has features which may be associated with ladling, although there was no evidence for a dam. At the south end the channel widens, possibly to form a ladling sump. The substantial gritstone slab covering the channel near the edge of the hearth may have provided a secure footing for ladling hot metal or for an ingot mould. The sides of the channel were lined with gritstone, which was not reddened by heat. This implies that the lead was cooling or, more likely, that the channel was lined with clay or loam to prevent loss of lead between the stones. A brown silty sand was found in this area, similar to that in the tapping channels at the Totley bole (Kiernan and van de Noort 1992, 20), but as it was a post-working deposit its use as a lining at Linch Clough is not proven. It would have been necessary to dry a lining but, by analogy with the 16th-century process, the brash fire used to ignite the main pyre, if placed over the external channel on the windward side, would achieve this. Because the latent heat of fusion (freezing) of lead is relatively small (5.89 cal/gram, compared with 80 cal/gram for water/ice), solidification is rapid once the temperature has fallen sufficiently. Some form of heating, or an insulating cover, may have been necessary: the charcoaly ash from the initial brash fire could have been used. Modern smelting practice (Keith Gregory, pers comm) is to spread powdered anthracite (charcoal would do as well) over the surface of lead left molten, to prevent drossing (rapid oxidizing of the hot surface). To summarize, the channel and a possible need to support the basal timber blocks of the hearth, could account for both the heat-affected and the unaffected gritstone found on the site. In the absence of finds elsewhere, for instance down the nearby stream, most of the stone used may have been left on the site and was found during the excavation.

Lead may have been ladled into pig-moulds from the channel, outside the hearth, or, more likely, left in the hearth until the fire died down. Ladling at two metres distance from the hearth would not have been possible until the conflagration and the red-hot surface ember-stage was over. Only the embers over the channel would be removed at first to give access for ladling. This would be a slow process as the lead would need time to solidify in the mould or moulds before their re-use. It is likely that embers in the main hearth were moved aside only after the removal of most of the molten metal from the channel; they would provide heat and insulation, keep the lead molten, and possibly continue the reduction of the ore. Burnt ember deposits were found close by, and may have been piled on the bank above the hearth and around the western margin.

The capacity of the hearth

The most convenient arrangement would have been to dig the channel to give a capacity equivalent to that of the hearth, allowing, within the limits of cooling, ladling to be done when the smelting process, and high-heat emission, had virtually ceased. The rate of solidification of the lead would probably have been slow enough for this, because of its high initial temperature, compared with its melting point. This is supported (but not proven) by two features: first, the channel crosses the whole hearth, rather than the hearth being tilted to it (and thus requiring either a dam or ladling during the process); second, though capacity could easily have been increased by widening or deepening the channel, in fact the north end of the channel was blocked off, reducing capacity. Handling a sow of lead the size of the likely channel would have been impracticable so as much lead as possible would have been ladled into moulds. The remainder may have been left as a long sow, which could have been axed into convenient lengths if required. Kiernan (1989, 85–6) notes production of sows of about half a ton weight at a slightly later date. Alternatively any thin layer of lead left in the channel bottom could been cut up using an axe and re-melted at a separate hearth or left in place until the next smelt.

Therefore, the writer considers that depending on the mode of operation, the volume of the channel may suggest the size of smelt carried out. Later boles of the Totley type produced from 10 to 16 fothers (up to 1.5 tonnes each) of lead per smelting (Kiernan 1989, 46). The hearth at Linch Clough would produce less. On the basis of a hearth area of about a quarter of those which Kiernan is considering, and a pyre of similar height needed to produce similar operating conditions, 2–4 fothers (2.5 to 6 tonnes in total depending on the size of the fother) would be produced. Given lower economies of scale with the smaller hearth, it is likely to have been at the lower end of this estimate, suggesting a volume of lead (specific gravity of 11.3) of 0.22 cubic metres (at the higher end, the figure would be 0.5 cubic metres). If the channel were 5.6m long, with a depth and width each of 0.2m (8 inches—the span of a hand or a spade) then, if base and top were both horizontal and full to the brim, it would hold about 0.22 cubic metres (2.5 tonnes) of lead. There is thus a match between hearth area and channel capacity, at about 2.5 tonnes.

The fundamental difference between the Totley hearth (Kiernan 1989, 42) and Linch Clough, apart from size, was that the tapping channel at Linch Clough was not inclined. The inclined channel at Totley and its distance from the ladling sump may have made handling molten lead more convenient when using the larger bole hearth and fire, and may imply continuous tapping.

The residues of bole smelting

Residues reported were: slaggy material, more accurately described (by Doonan in *Bevan et al* 2004, 124–8) as a matte or as blackwork, greenish and reddish glazed or slaggy surfaces on gritstone, yellow and white oxides on stone, and reddened crumbly stone. A white powder containing lead was found in the small pit nearby. Charcoal was found adjacent, including several pieces of lump charcoal apparently separate from the main deposits.

The following points are relevant. Siliceous rocks within the fire would be affected by heat, causing them to redden and to disaggregate into crumbly masses. The combination with lead compounds would produce greenish glazes, whilst partial melting of faces in oxidizing conditions would produce red-glazed surfaces. Yellow and white oxides of lead (and contaminants such as oxide of zinc, which is a common association) would form sublimates on less heat-affected surfaces.

The most substantial original residues are what is known as blackwork: grey, black and sometimes yellowish half-smelted material (as described by Doonan), some of it a matte, much of which was probably re-cycled in the next bole-smelt for the reaction to continue. According to Kiernan, blackwork was placed in the zone above the blocks (or left there) where it was most likely to encounter the necessary reducing conditions to complete the reaction. Blackwork left at the abandoned site would be removed, then or later, for re-smelting elsewhere. It was a more attractive source than mined ore, explaining the small amounts remaining on bole sites. Slag, in the sense of cooled molten waste with no anticipated future value, would have been rare, or difficult to separate from other material. It was often a product of later processes in which a small blast hearth was used to raise the temperature to even higher levels: this may have taken place later than the mid-15th-century working at Linch Clough.

There would have been deposits of dross skimmed from the surface of the molten lead as it emerged from the hearth; these would form particularly if the lead were left molten and exposed to air. This dross would consist mainly of oxides, probably contaminated with other slaggy and carbonaceous material which floated from the hearth with it. It might be returned to the next smelt or, later, be charged into the small blast-hearth or 'smilting oven'. Finally there would have been adhesions of metallic lead left in the channel and the hearth and adhering to blackwork, gritstone etc. or infilling small declivities in the hearth-bottom. These would be gathered, at least after the final smelt, and re-melted, possibly in the melting pit discussed below.

Charcoal residues were found on the bank north of the hearth and extending a considerable distance on the west side. On other sites the writer and David Kiernan have found banks of similar charcoal residues in heaps close to the margin of the hearth, almost certainly representing the removal of hot embers when the hearth and its contents were uncovered. The wide scatter at Linch Clough may be the result of restoration of the site for agricultural use.

Gaseous products would have included carbon dioxide and sulphur dioxide, and products of the burning of fuel and its reactions with the ore, together with residual water from the timber; there would also be substantial particulate and vapour emissions of ore and smelted material, resulting in wind-borne lead-rich deposits. These would have issued as a white plume until the final ember stage of the reaction, leaving a geo-chemically distinct pollution trail downwind, which should be detectable today. On well-used sites this trail extended for a kilometre or more. The condensation of the plume on the rear bank and possibly even on the nearby hillside would have been visible at the time. The impact on soil and vegetation close by would have been severe, and if smelting was in one location for a long time, plants and animals would have been affected, probably for centuries. Geochemical and botanical investigation of soils and vegetation, and comparison of results with other sites, may give further indications of the level of usage at Linch Clough, but the excavator (Bevan) comments that visual ecological damage is not obvious, unlike on other sites in the Upper Derwent Valley: this suggests that the site was short-lived.

To date there has been no direct comparison of residues found at the Derbyshire and Yorkshire sites but, for the latter, Smith and Murphy (2003) have produced a typology of slags and have related it to the furnace conditions which must have been necessary to produce them.

Comments on the evidence for high temperatures

The ordinary green slaggy coatings which were found at Linch Clough could have formed at around 750°C, which would have easily been achieved. A more intriguing find was a lead silicate slag with a vitrified potash feldspar within the residues, which indicated a transitory or more prolonged temperature of *c* 1200˚C. The known temperatures of vitrification are a well-established means of determining the heat achieved within a fire or kiln, Usually, such a high temperature would require some form of air-blast, but this is inconceivable in a bole. To have used the channel as an air duct or tuyère is impracticable: its cross-section is too large for anything but a very large mechanically-powered bellows or blowing cylinder, and it is difficult to conceive of a suitable nozzle position to form a useful blast. There is however an alternative which would have a similar, possibly very localized, effect in a large fire such as a bole.

Experiments on temperatures within a wood fire (Willies 1994) were mainly concerned with a fairly open, small, soft-wood fire. The impact of the cold air entering could be seen in a localized blackening of the burning fuel, and a clear depression of the average temperature. The pyrometer used was inserted in a substantial steel block to reduce fluctuations: without the steel block the temperature reading fluctuated wildly and widely. The wood-fired bole was very different: gas velocities are considerable above a well-burning bonfire, and had to be higher still within the burning mass of a bole because of obstruction to their passage. The average temperature inside the pyre (but not necessarily at its margins) was thus likely to be high, perhaps, even probably, higher than that achieved in the experimental burn. At the heart of the fire, at its most intense, combustible gases may have evolved from burning wood at temperatures approaching 850˚C and would mix with high velocity air streams preheated to a similar temperature. These would impinge on near-molten masses of already incandescent galena, resulting in an exothermic reaction in conditions which would resemble those in a muffle furnace. In these circumstances, at their most favourable, a localized temperature level of 1200˚C seems attainable. Such localized (if such they were) high temperatures would have helped ensure a rapid oxidation or reduction reaction, countering the tendency of the ore mass (browse) to liquefy and descend too quickly for process-completion to the base of the fire. They may also be responsible for the air-borne lead pollution associated with boles.

The possible melting pit

The pit found at Linch Clough was about one metre in diameter and 0.37m deep, on a separate platform, somewhat heat affected and containing a bottom layer of white powder containing lead with layers of process waste, charcoal and slag (Bevan *et al* 2004, 123). There was no channel running to the pit, so it was not a lead sump for the main bole, but it did have uneven reddening of the sides, indicating heating, perhaps due to dumping of hot material into it, or a small fire. The bottom was narrower and offset to one side.

As a comment, it is noted that similar pits have been seen at Yorkshire sites: Smith and Murphy (2003, 63–4) note pits at their 13th- and 17th-century sites and report others elsewhere. These had similar dimensions to that at Linch Clough. Two possible uses are discussed, the first that they were an alternative process for smelting ore (the Austrian Carniolan process is cited). A second suggestion seems more likely, both for the Yorkshire pits and for Linch Clough, in which a small fire was used to re-melt small scraps of lead (see residues, above). The metal scraps would probably be placed on a small wood fire over, or partly in, the pit, with the resultant drips of lead accumulating as a bun in the bottom. Smith and Murphy suggest that this would leave little trace of metallurgical activity. To produce a regular bun, or a bar shape, at the bottom of the pit would probably require a purpose-made bottom of clay or loam. Particular attention should, obviously, be paid to such pits, and to deposits such as the white powdery material found at the bottom of the Linch Clough pit.

How big a bonfire?

The writer suggests a likely order of size, using broad approximations from evidence cited above. With a higher ratio of perimeter to volume, and without a partially encircling wall, Linch Clough was probably less efficient than the later boles described by Kiernan. Thus the fuel requirement was probably higher: the Devon bole (Claughton 1992, 12–13) used about six cubic metres (three cords) of wood per ton of lead (about 4.2 tonnes). The later boles described by Kiernan used about two tons of wood per ton of lead, but their perimeter-to-volume ratio was much better than here), so about three tonnes of wood per tonne of ore is suggested as used at Linch Clough.

The output suggested earlier of about 2.5 tonnes of metal lead is assumed: the 3.75 tonnes of lead ore required indicates, in rounded figures, around 10–11 tonnes of wood needed. At 0.7 tonne/cubic metre, this is a minimum of about 14.28 cubic metres of solid wood. Assuming 75% interstitial space between timbers, this would occupy 19 cubic metres (the lead ore would partially fill this interstitial space, so its volume is discounted, but would be positive). With a hearth about 3.5m square, but assuming a truncated cone form with a top of 1.5m (thus averaging 2.5m square) to prevent spillage of ore, this indicates a pyre some three metres high. This is roughly the height which Kiernan indicated on his diagram—the height would be very important in raising the flue draught, so this is perhaps unsurprising, but if the truncation was less severe, to reduce the perimeter/volume ratio, the height would be somewhat less, but certainly would be likely to be well over two metres.

Conclusions

In contrast with the conclusions put forward by Bevan *et al*, the evidence points to the Linch Clough site being wind blown, smelting ore rather than slag (apart perhaps from some blackwork), and with only a slight possibility of using charcoal as fuel. The re-interpretation of the near-horizontal channel under the hearth is that it was used for tapping, and not for a forced air-blast. In operation, Linch Clough would have been very similar to the larger bole hearths described by Kiernan, based on wood and wind to achieve the necessary temperatures and metallurgical reactions, but was without permanent stone walls. The operating differences were in the smaller scale of the Linch Clough bole, which probably made it less fuel-efficient, and in the method of tapping, which left perhaps 2.5 tonnes of molten lead in the tapping channel until the smelting had virtually ceased. This was in contrast with continuous tapping, as seems to have been the practice with Kiernan's boles at Totley, probably to cope with the much larger amounts (*c* 20 tonnes) of lead produced. The valley location of Linch Clough demonstrated that scarp tops were not a pre-requisite for boling: it is an example of shifting location, based on very local woodland fuel resources. This is in contrast with the larger and supposedly later bole types to which the timber was brought from a wider area. In each case we can presume that the boles were sited where fuel, ore and lead transport costs were optimised, with allowance for ownership and pollution. The woodland-fringe siting of Linch Clough and similar boles nearby could have compensated for the lower fuel efficiency of their small hearths. Whether the larger and smaller hearths were time-sequential or parallel developments reflecting a different scale of entrepreneurship is uncertain. Radiocarbon dating on charcoal from a range of sites may illuminate this point (see Smith 2006 for the dating of Yorkshire sites).

Further work

Finally, it is apparent that further field-based research, possibly botanical and geochemical in the immediate area of the Linch Clough bole, and in the upper Derwent area in general, could yield further data. This may throw light on the degree of pollution and thus the relative length of use of sites. Stream sediment and soil surveys may reveal further bole locations. There is also potential for comparison of slags from this site and from elsewhere in Derbyshire, and from other ore fields, such as the Yorkshire Dales. Given current Health and Safety constraints, it will not be possible to mount a full-scale experimental smelting of a large bole because of the associated pollution, but thermodynamic modelling by a metallurgical specialist may be feasible, to test and extend some of the points raised above.

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