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ORIGINAL PAPER

The production of crucible steel by the 'Mysore process' at Ghattihosahalli, Chitradurga District, Karnataka

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Abstract
Crucible steel production at Ghattihosahalli in the nineteenth century has been the subject of detailed study, based both on the contemporary historic record and the physical survival of the mounds of production debris at the village. The published reports have been based on the scientific study of samples collected from the mounds but left questions that could only be resolved by archaeological excavation. Preliminary excavations had already taken place which revealed the remains of a crucible steel smelting installation. Unfortunately the instigator of these investigations, Prof. K.P.N. Rao, died before these could be worked up for publication. This has now been done and the results published here. With the vital information provided by the excavation of the smelting site, it is now possible to give a much more complete description of the operations, not just at Ghattihosahalli, but of the production of crucible steel by the 'Mysore' in-situ carburisation process in general.

Keywords Crucible steel · Excavation · Furnace · Metallurgy · Mysore · Smelting · South Asia

1 Introduction

In the 1980's Professor K.N.P. Rao and his colleagues carried out a preliminary excavation at the small settlement of Ghattihosahalli, literally 'ingot town', in the Holalkere taluk of the Chitradurga district in the state of Karnataka (N 13° 59′: E 76° 17′), where crucible steel had been produced in the nineteenth century (Fig. 1). This excavation stemmed from Prof. Rao's pioneering work on the crucibles and the metallography of a collection of steel ingots made by the so-called 'Mysore process', that is, in-situ carburisation (Rao, 1980; Rao, et al, 1970; Rao, unpublished). Subsequently, T.R. Anantharamu and P.T. Craddock together with Prof. Rao and his colleagues, broadened this study to include the whole process from mining the iron ore to the finished product, based on the remains at Ghattihosahalli (Anantharamu, et al, 1999). The importance of Ghattihosahalli in the history of the 'Mysore process' was because it was one of the few crucible steel-making centres where there are contemporary accounts of its operations (Sambasiva Iyer, 1898–1899 & 1900–1901) together with surviving heaps of the process debris, containing quantities of crucibles, tuyeres and furnace fragments along with slags and even metal. There was also the strong possibility that actual remains of the smelting furnaces survived in the vicinity of these heaps. From the scientific study of these remains, and the earlier study of the ingots, coupled with the historic descriptions of process, the main operating parameters of the process were established and published (Anantharamu et al, 1999). However, as that paper noted in its conclusion 'As yet there is little firm evidence on the nature of the furnaces. The reports of Buchanan and of Sambasiva Iyer were apparently contradictory (see below), clearly there is a need for a programme of research including controlled archaeological excavation'. The problem of the actual form of the furnace operations was as follows. Francis Buchanan in his travels in southern India, made in the early nineteenth century, had described the crucible steel smelting operations at Devarayanadurga and at Chinnarayandurga, also in the Chitradurga district in the then Mysore state (Buchanan, 1807, and see below). These descriptions, backed up by drawn sections (Figs. 2 & 3), revealed a distinctive arrangement, very different from the usual iron-smelting lay out, yet almost a century later Sambasiva Iyer could write that at Ghattihosahalli the process took place in an ordinary smith's furnace (see below).

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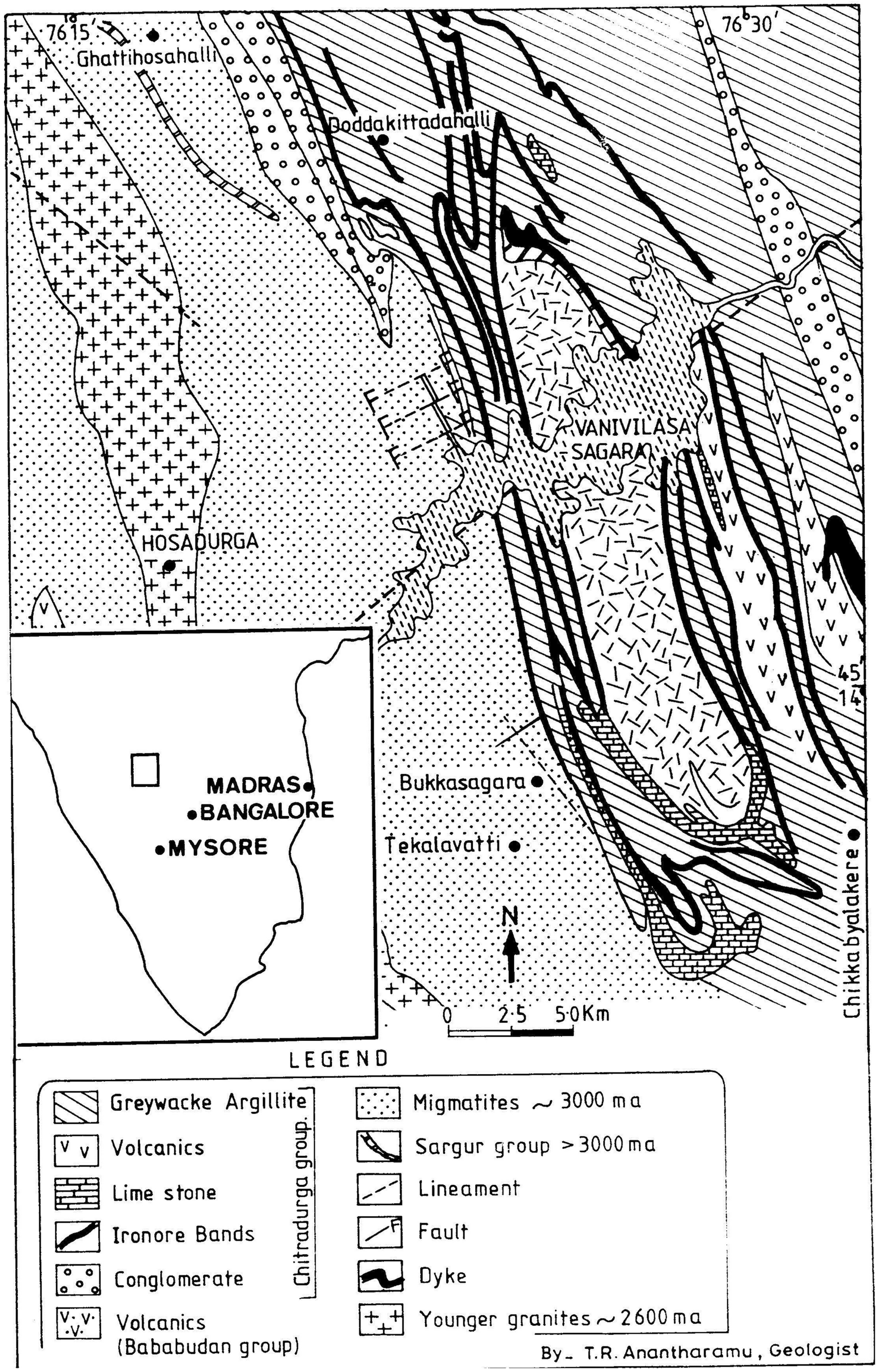

Fig. 1 Geological map of the Chitradurga District showing the location of some of the sites mentioned in the text. (T.R. Anantharamu, with inset map by B. R. Craddock)

As stated above Prof. Rao and his colleagues had already undertaken a preliminary excavation and had discussed further work with T.R. Anantharamu and P.T. Craddock. Unfortunately ill health prevented this and a last meeting in 1991, shortly before his death, Prof. Rao gave P.T. Craddock copies of the sketches and notes on the 1980's excavation

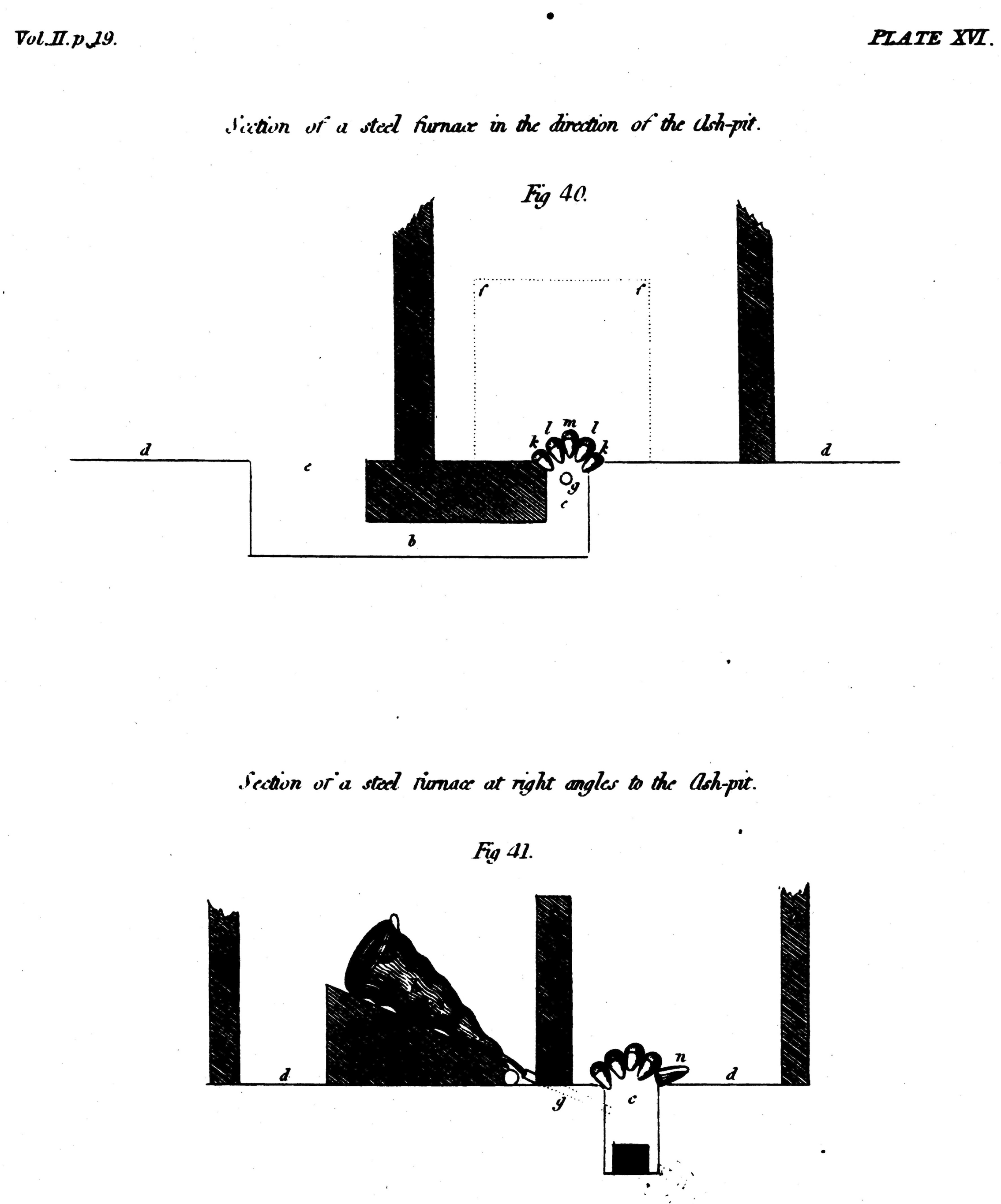

Fig. 2 Upper: Section of a steel furnace in the direction of the ash pit. Lower: Section of a steel furnace at right angles to the ash pit. (Figs. 40 & 41 respectively, comprising Plate XVI vol. 2 of Buchanan (1807)

with a request that the text be augmented and the measured sketched field plan and sections be redrawn and published.

Other commitments delayed this from taking place for some twenty five years, and several other investigations of the crucible steel industry of south India have been undertaken (Balasubramanium, 2007; Srinivasan, 2013; Srinivasan & Ranganathan, 2004; Sriperumbudur, 2013), but still no actual excavation of the steelmaking sites have taken place as yet. Thus this publication is still relevant and at last provides real excavation evidence. This complements the existing historical documentation and scientific investigation of steel production at Ghattihosahalli with archaeology.

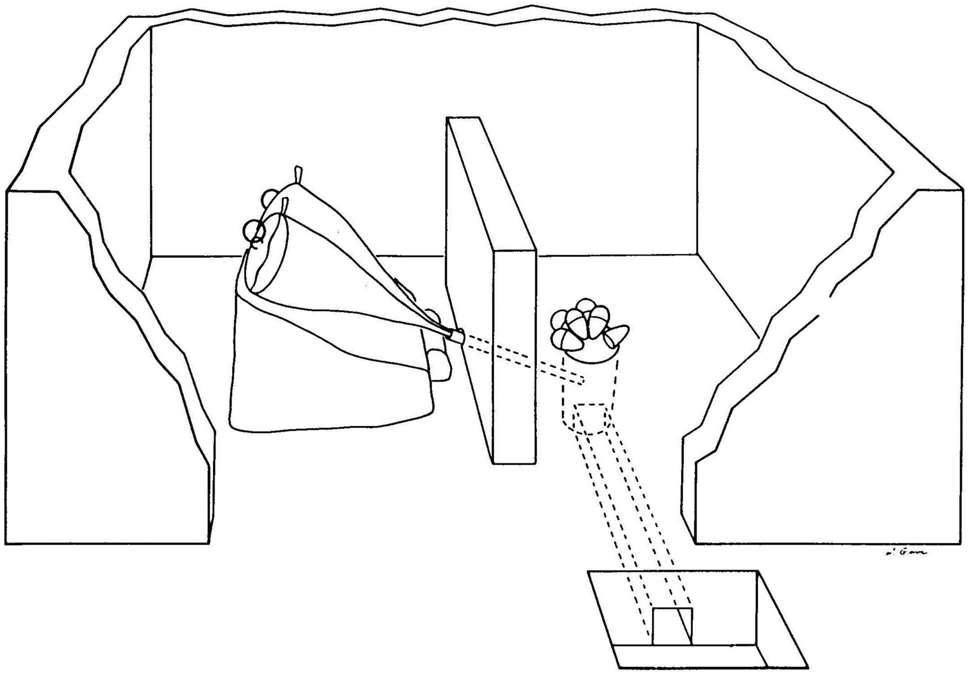

Fig. 3 Simplified isometric reconstruction drawing of the furnace described and illustrated by Buchanan (1807). (Lori Grove, from Bronson (1986)

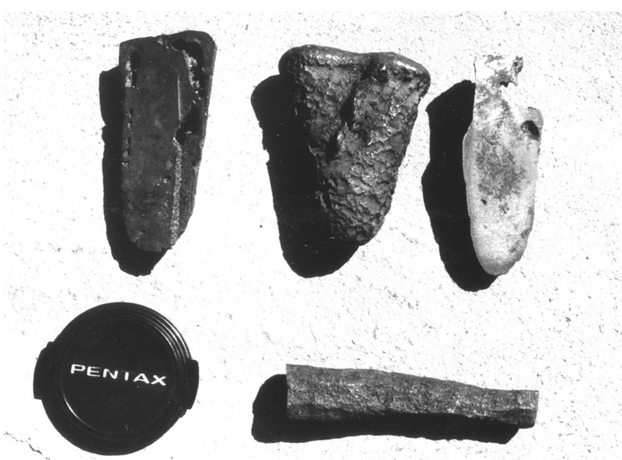

Fig. 4 Selection of iron and steel ingots collected by Prof. K. N. P. Rao, and photographed at his house. Top left and right: Sectioned ingots where the carburisation was incomplete and the ingots had only partially melted and had been discarded. Top centre: An ingot of steel where the carburisation was successful and the ingot completely melted. Bottom: Ingot of wrought iron hammered to shape ready to be placed in the crucible. (P.T. Craddock)

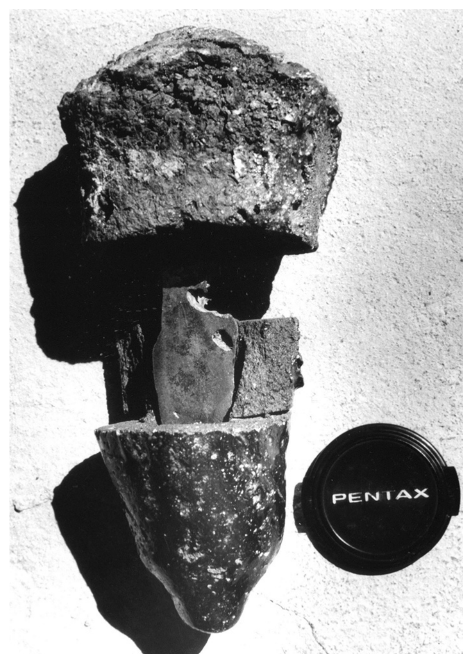

Fig. 5 Sectioned crucible and lid collected at Ghattihosahalli, with a sectioned crucible steel ingot placed inside. (P.T. Craddock)

Crucible steel has been produced in Central Asia, Sri Lanka and South Asia for at least two millennia (Craddock, 1998). In South Asia two distinct processes were used, in-situ carburisation and co-fusion (Balasubramanium, 2007; Bronson, 1986; Srinivasan & Ranganathan, 2004).

In the former process wrought iron (Fig. 4) with a low carbon content was strongly heated in a lidded crucible (Fig. 5) with a variety of plant materials, typically wood shavings, twigs and bark and carburised. This process was prevalent in the south of India (Srinivasan, 2013, 2017; Srinivasan & Griffith, 1997), Sri Lanka (Coomarasawamy, 1908; Juleff, 1998; Wayman & Juleff, 1999) and apparently in Central Asia in antiquity (Feuerbach et al., 1997; Rehren & Papachristou, 2000). There the process continued into the nineteenth century (Anossoff, 1841), although Masalaski (1841), also in nineteenth century, described only the co-fusion Process.

In the co-fusion process cast iron with approximately 4% of carbon and wrought iron with only traces were strongly heated together in a lidded crucible. The cast iron melted and absorbed the wrought iron thereby creating a crucible steel. In India, the co-fusion process was certainly carried out in the central Deccan, most famously at Konasamundrum, now in Telangana, where the operations were recorded in the early nineteenth century by H.W. Voysey (1832) (Bronson, 1986; Lowe, et al, 1991). This raises the question of the source of the cast iron which is not supposed to have been produced in India (Craddock, 2007). To complete the confusion, there is one record of the production of cast iron in the early nineteenth century, specifically described as a feedstock for the co-fusion process, but this was at Trinomally in the south, the heart of the in-situ process region (J.M. Heath, reported by David Mushet, 1840, pp. 627–31). Clearly excavation of the slag heaps at some of the many reported iron smelting sites in Telengana is required (Jaikishan, 2007, 2013; Juleff et al., 2014).

As stated above, in the in-situ process plant material was the carburisation medium rather than pure carbon in the form of charcoal. This may seem idiosyncratic and even counter-intuitive; surely to attain the carburisation of the iron the conditions should be as reducing as possible. Carbon, rather than organic material containing both oxides and hydroxyls, should be the reductant. Indeed, some commentators doubted the necessity for the plant material at all, as stated by Bronson for example, in his discussion of the South Indian processes, expressing his puzzlement over the insistence on plant material 'the gases given off by the heated fresh vegetable matter, often emphasized in the writings of the earlier theorists, did not play an essential role in the conversion. Charcoal would have worked just as well', and Tylecote (1976, p. 66) went so far as to state that the charred plant material in the crucible walls would have been sufficient to carburise the iron. In practice this is not the case for reasons that have more to do with the physical state of the reactants rather than their reducing power. Most chemical reactions take place when at least one of the components is in a vapour or liquid phase. Solid – solid reactions are very slow even between finely powdered reactants. This is well illustrated by the attempts at the in-situ carburisation of iron made in Britain at the beginning of the nineteenth century using just charcoal and wrought iron (Craddock, et al, 2016). It was found that no reaction took place until the wrought iron began to melt at temperatures well in excess of 1500°C. This was not only extremely expensive in fuel, but the crucibles only had a very short life and the process was abandoned.

In the South Asian process as the temperature inside the crucible rose, the plant material charred producing quantities of carbon monoxide which could interact with the surface of the iron:

$$CO + Fe \leftrightarrow FeO + C$$

Under equilibrium conditions this reaction lies well to the left, but some of the carbon momentarily produced would instantly react with the iron and be removed from the gaseous phase and thus the reaction is not in true equilibrium.

$$C + Fe \rightarrow \text{liquid iron} + \delta \,\&\, \gamma \text{ iron solid phases at temps.} > 1400\ ^\circ C$$

The introduction of the carbon into the iron lowers the melting point at the surface thereby enabling further carbon to be absorbed directly into the now molten surface more readily until all of the iron has melted, producing crucible steel, typically containing 0.8–1.5% of carbon.

In Buchanan's 1807 record of the iron and steel smelting operations in the Chitradurga district there is no mention of Ghattihosahalli and it is likely that production only began there after his visit. At the end of the nineteenth century the steel making activities there were recorded in some detail by Sambasiva Iyer (1898–1899 & 1900–1901), including invaluable data such as chemical analyses of the iron ores, the wrought iron feedstock and the resulting crucible steel. The major omission in his reports, as noted above, were details of the smelting arrangements, just noting that the crucibles were fired in ordinary smith's furnace (see below). It was by then the only site in the Chitradurga district producing steel and although production was still considerable, it was apparently declining with only two furnaces in operation and then only for two months duration each year. The end of operations is not recorded, but with the establishment of the Visveswayara Iron Company at Mysore at the time of the First World War, the production of wrought iron by the traditional solid state, bloomery processes at centres such as Bukkashagara and Dodkittadhalli were terminated and it is likely that steel production at Ghattihosahalli ceased at about the same time.

2 The excavation

The major slag bank which lies along the northern edge of the present settlement is approximately 250 m long with a maximum width of about 40 m and the height varying between three and six metres (Figs. 6 & 7). It is estimated that the volume of the heap is more than 15,000 cubic meters.

Three sites were selected for excavation:

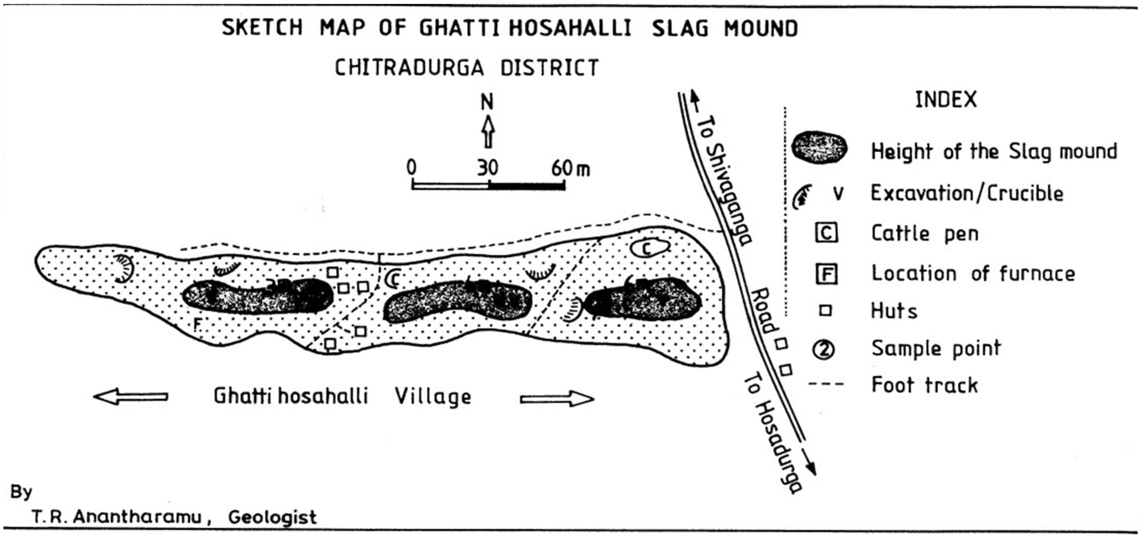

Fig. 6 Plan of the main slag mound at Ghattihosahalli (T.R. Anantharamu).

Fig. 7 The main heap at Ghattihosahalli photographed from the main road looking South (P.T. Craddock)

2.1 Location A

The first location was situated at the east end of the bank about 100 m from the main road (Fig. 6). The site was excavated in two strips both of two metres width. At this point the heap contained slag, ash, tuyeres, broken crucibles and charcoal. No intact crucibles, ingots or in-situ furnace remains were encountered.

2.2 Location B

The second location was on the bank towards the western residential area of the village (Fig. 6) where there were some houses. The site belonged to Thimmaih, the son of Sanningajja. The site lay between two houses, respectively East and West of the site. Immediately to the North ran a road and to the south was a midden. The site sloped down from the West

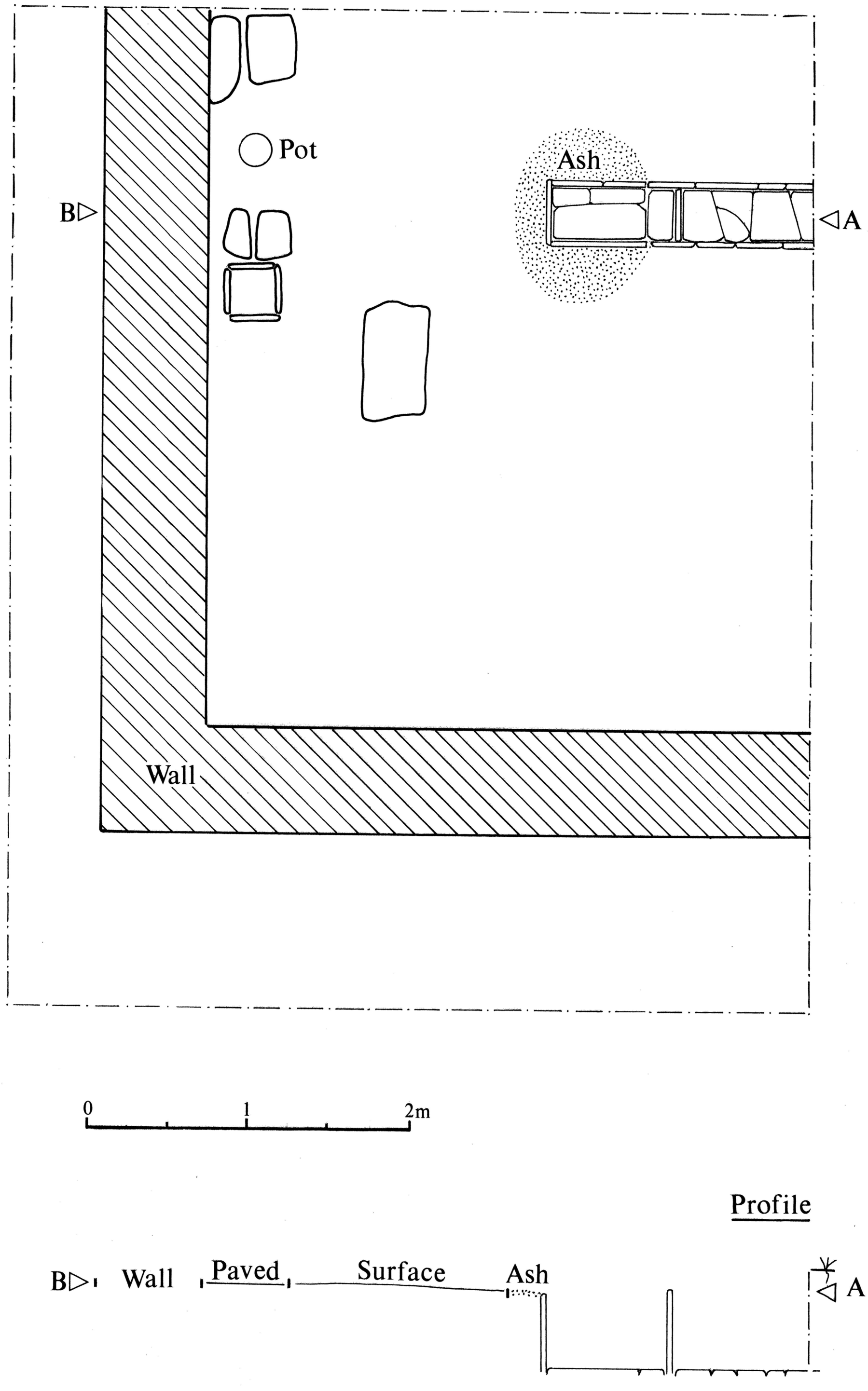

Fig. 8 Plan and section of the furnace at Ghattihosahalli. (Drawn from K.N.P. Rao's roughfield sketches by B.R. Craddock)

to the East. A six by five metre area was opened (Fig. 8). Almost immediately the remains of a wall running east–west was exposed. The excavation was continued using the strip method. First the east–west wall was more fully exposed in a 1.1 m wide strip. The section at the southern end was not uniform in height, being 0.25 m high in the south-eastern corner and 0.65 m high in the south-western corner.

In the south-western corner the disturbed soil was mixed with ash, slag and broken crucibles together with a few pieces of iron. This black ashy soil extended almost up to

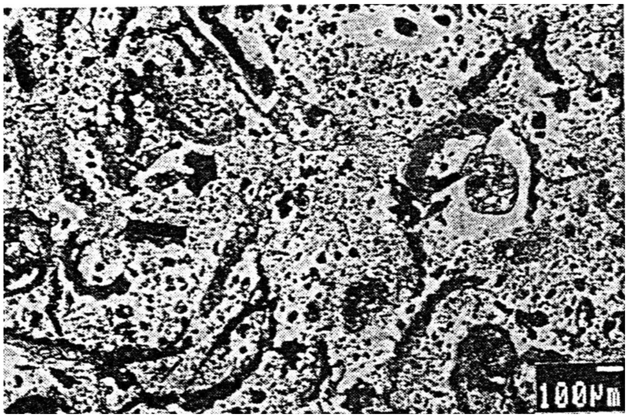

Fig. 9 Rice-husk temper clearly visible in a section of a crucible from Ghattihosahalli. (from Freestone & Tite, 1986, Fig. 17)

the end of the south-eastern corner. Four courses of rubble stones survived of the east–west wall which was approximately 0.75 m in height and approximately 0.65 m wide.

After tracing this wall the excavation was continued to the north. The top layer was of humus and beneath this was the debris of the upper courses of the wall which clearly had collapsed in that direction. Beneath this were the remains of another wall running in south–north orientation and joining with the east – west wall. At a depth of about 0.65 m slabs of a stone floor were found in the western portion of the trench, and against the south–north wall. A stone-lined chamber and a large intact pot were also found here.

The stone chamber was filled with red soil mixed with rice husk. It is possible this may have been intended for the preparation of the crucibles and/or their lids, certainly the impressions of burnt-out rice husk are very evident in the fragments of the used crucibles (Fig. 9).

In the south–eastern corner of the trench a rice-husk pot was found by the side of the east–west orientated wall, and some fragments of iron were also found. These were presumably the wrought iron feed-stock rather than ingots, as there was no indication that they had been molten. In the northern part of this trench there were traces of blood-red clay indicating burning. Beneath the top layer of debris the remains of a furnace were exposed. Only the base of the furnace together with the channel for removing the ash survived.

The furnace remains comprised only some clay of its base burnt black, together with the surrounding annulus of red burnt clay and charcoal as well as the ash channel which was constructed of stone slabs. The superstructure of the furnace was not found. The overall dimensions of the furnace at its base and the ash channel were 2.15 m east–west by 1.1 m north–south.

2.2.1 Nature of the furnace

The nature of the furnace is interesting. For the operation of the furnace the smith had cut a rectangular channel in the natural subsoil and over this had built the furnace. The channel enabled ash to be periodically removed with a long-handled shovel without having to approach too close to the base of the extremely hot furnace. After a few smelting operations the sides of the channel may have become unstable. To avoid the collapse of the channel, it was lined and paved with stone slabs (Fig. 10). These were held in place and also protected from the direct heat of the furnace with mud plaster.

The dimensions of the channel were 1.65 m in length and 0.37 m in width. The depth of the channel varied with its bottom sloping down from west to east, being 0.46 m deep in the west, 0.5 m in the middle and 0.62 m at the east end. In the middle was a vertical stone measuring 0.25 by 0.40 m that

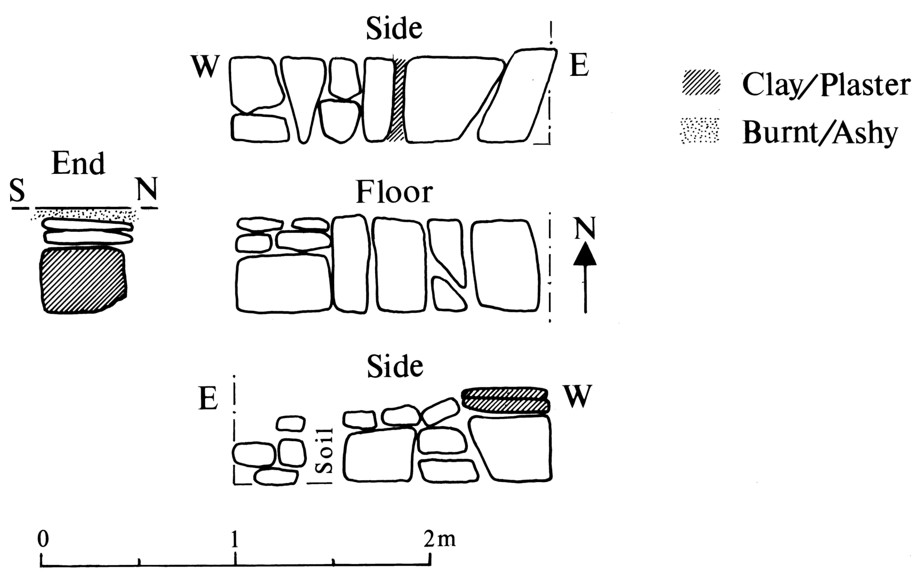

Fig. 10 The stone sides, ends and paved floor of the ash pit at Ghattihosahalli (Drawn from Rao's measured field sketches by B.R. Craddock)

Description	Sample No.	Sample	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_2	Cl
Wootz, tuyere	25980	Bulk	63.3	0.8	24.0	5.7	1.0	1.2		2.7			0.2
		Matrix	58.1	1.0	27.5	6.8	1.1	1.1		2.9			0.2
Wootz, crucible	25960	Bulk	62.7	0.8	24.7	5.5	0.9	0.9	1.0	2.7			
		Matrix	60.7	0.9	27.6	4.7	1.0	1.0	0.9	2.5			
		Surface Glaze	60.3	1.0	22.2	6.2	1.5	4.5	0.8	3.5			
		Matrix between	69.0	0.3	22.7	1.0	1.3	1.1	1.2	3.0			
		iron droplets (2)	66.0	0.2	27.3	0.6	1.0	1.1	0.6	3.0			
Wootz, furnace lining	25959	Bulk	73.7	0.6	15.5	3.8	1.2	1.3	1.0	2.5			
		Matrix	56.2	0.9	28.2	6.3	1.1	1.2	1.6	4.0			
		Glaze	49.0	0.5	11.7	8.7	3.6	21.6		3.4	0.7		
		Feldspar inclusion	65.9		19.5	1.4	0.3	0.6	2.4	9.7			
Huntsman crucible	25981	Bulk	55.6	0.9	37.9	1.8	0.6	0.4		1.4		0.5	0.2
		Matrix	57.1	0.6	37.4	1.0	0.8	0.3		1.7			0.2

Fig. 11 Energy dispersive X-ray fluorescence analyses of the ceramic bodies of the crucibles, tuyeres and furnace linings from Ghattihosahalli. Note the great similarity between the crucible and tuyere compositions, also reflected in their tempering. Note also the higher alumina content and much lower iron and potassium content of a nineteenth century Huntsman's crucible steel crucible from Sheffield. (from Freestone & Tite, 1986, Table 4)

effectively divided the channel into two sections. The western half from beneath the furnace to the stone the clay was heavily burnt and there was other evidence of fire, but in the eastern section from the vertical stone there was no evidence of burning.

From the fill of the channel samples were obtained of slag, crucible pieces, iron fragments, burnt clay tempered with rice husk, a pot and a fragment of a tuyere.

2.3 Location C

This site lay at the West end of the bank immediately against the main road (Figs. 6 & 7). The excavation did not encounter any in-situ features.

3 Discussion

As already stated many parameters of the process at Ghattihosahalli have already been published by Anantharamu et al (1999), and will only be outlined here but incorporating the archaeological evidence including the form of the melting unit.

Sambasiva Iyer (1898–99) had stated that at the time of his visits the wrought iron feedstock for conversion to steel came from Dodkittadhalli, approximately 10 km distant (Fig. 1). However, the heaps contain large amounts of primary fayalitic iron-smelting slags and a piece of primary iron bloom that had not been forged was also found (Anantharamu, et al, 1999, Fig. 23). Thus it seems very likely that as well as importing wrought iron, Ghattihosahalli had at some time, probably prior to Sambasiva Iyer's visit, also produced primary wrought iron. Large quantities of refractory materials including furnace linings, tuyeres and of course the crucibles were recovered from the heaps.

Sambasiva Iyer had little to say on the composition of the crucibles etc., but samples of these were examined both by Rao and his team (Rao, 1980; Rao et al., 1970) and by Freestone and Tite (1986) at the British Museum (Figs. 9 & 11–12). The refractories were found to be of ordinary ferruginous clay, of the type used for coarse domestic ceramic wares generally (Figs. 9 & 11). Rao et al. examined two crucibles of the Mysore process, but of unknown provenance, one used and partially vitrified, the other unused and indeed unfired. The unused crucible was described as being a light brick red with a fine dispersion of black particles. On

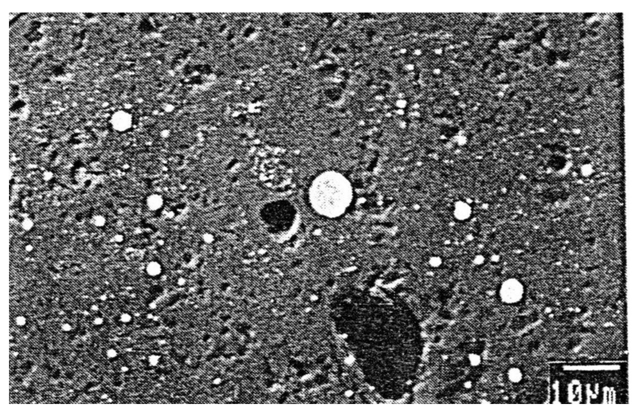

Fig. 12 The extreme reducing conditions in the crucible during the steel-making operation reduced much of the iron oxides in the clay to droplets of cast iron (white), thereby making the clays much more refractory. (from Freestone & Tite, 1986, Fig. 18)

ignition there was a considerable loss of weight (11.25%), suggesting to Rao and his colleagues that the black particles were carbonaceous. The high weight loss confirms that the crucible was unfired and almost certainly had contained the unburnt rice husk. This supports previous reports from south India of the crucibles being used unfired, and a crucible presented to the Royal School of Mines in London by Thomas H. Holland, who studied the iron industries of southern India in the late nineteenth century, was examined by R.F. Tylecote (1962, p. 294) and found to be unfired. Buchanan also stated that the crucibles were used unfired, and were only tempered with burnt rice husk. In addition, Holland (1893) recorded that at several other crucible steel centres in south India charred rice husk was used (as also recorded in Krishnan, 1954 and Bronson, 1986, p. 36), as well as in central India at Konasamundrum (Lowe et al., 1991). Both Rao (1980) and Freestone and Tite noted that the crucible and tuyere clays had been heavily tempered with rice husk (Fig. 9) and that during the process this had charred locally creating very reducing conditions such that the iron oxides in the clay were reduced to metallic iron, thereby making the ceramic much more refractory (Fig. 12).

Thus combining the evidence from several sources it seems likely that at Ghattihosahalli, the crucibles and tuyeres at were of ordinary clays tempered both with charred rice husk and with fresh rice husk. The crucibles were dried to leather hardness but used without further baking.

Sambasiva Iyer (1898–99) described the actual process as follows:

> The process of conversion appears simple. Fifty to fifty five bits of wrought iron from three to four inches (8–11 cm) in length are introduced into an equal number of specially prepared clay crucibles with a few bits of wood – *thangadichakkey* (probably *Cassia auriculata*) – in each and the mouths of the crucibles stopped by clay. These crucibles are then laid in the form of a semi-conical heap into an ordinary smith's furnace worked by bellows for about five hours. They are then cooled suddenly by water. Short dark-grey and honeycombed bits of the shape of a truncated cone indicate steel of the first quality whereas the bits of the shape and appearance of the bits of iron put in, indicate the worst type.

With the approximate dimensions of the furnace now ascertained (Fig. 8), it is possible to make a rough reconstruction of the arrangement of the crucibles. Presumably the semi-conical grouping was in the form of a frustum. The external diameter of the furnace was approximately 100 cm, which given the usual wall thickness of about 20 cm leaves an internal diameter of about 60 cm, quite typical of Indian iron-smelting furnaces, and a circumference of about 190 cm. The crucibles have an internal diameter of about 6 cm with walls about 1 to 1.5 cm thick, giving an external diameter of about 8 cm. Thus laid in a circle the first layer could have had about 24 crucibles. The slumping of the crucibles shows that they must have been positioned at quite a steep angle, much as depicted in Buchanan's Plate XVI, Fig. 40 (our Fig. 2). Their tops would have extended by about 6 cm into the furnace space, This would have reduced the available circumference to about 150 cm for the next layer, which could thus have accommodated about 18 crucibles. By the same calculation the next layer could contain about14 crucibles. The crucibles were approximately 25 cm in length and thus because of the now restricted space a further layer would have been impossible to accommodate. Thus the furnaces are likely to have held three layers, here calculated to have totalled 56 crucibles which tallies well with Sambasiva Iyer's figures of 50 to 55.

Buchanan stated that steel production was carried on at four sites in *Chin'-náráyan-durga* taluk and one in *Déva-Ráya-durga*. His detailed description of crucible steel production in the Chitradurga district is as follows (Buchanan, 1807 II, pp. 19–21):

> The furnace, Plate XVI, figs. 40, 41, (our Fig. 2) is constructed in a hut (a) and consists of a hollow ash pit (b), and a vertical fire-place (c), both sunk below the level of the ground (d). The ash–pit is about ¾ of a cubit (~ 50 cm) in height and width, and conducts from the lower part of the fire-place to the outer side of the hut where it ends in a square pit (e), in which a man can sit, and with a proper instrument draw out the ashes. The fire-place is a circular pit, a cubit in diameter, and descends from the surface of the ground to the bottom of the ash-pit, being in all two cubits (~ 140 cm) deep. Its mouth is a little dilated. Parallel to the ash-pit and a little distance from the mouth of the fire-place, in order to keep the workman from the sparks and glare of the fire, is erected a mud wall (f) about five feet high. Through the bottom of this passes an earthen tube (g) which conducts into the fire-place the wind of the two bellows (h). The bellows are as usual supported on a bank of earth (i), and consist each of a bullock's hide; they are wrought, as in other places of this country, by a workman passing an arm through a leather ring.
>
> The crucibles are made, in a conical form, of unbaked clay, and each would contain about a pint (~ 0.7 litre) of water. In each is put one third part of a wedge of iron, with three *rupees* weight [531 grains, (~35 gms[1])] of the stem of the *Tayngada* or

[1] This seems a remarkably small weight, especially as at the end of the process each crucible now contained 24 *rupees*, ~ 280 gms of steel! At Ghattihosahalli the typical weight of a steel ingot was 13 oz, 370 g.

> *Cassia auriculata*, and two green leaves of the *Huginay*, which is no doubt a *Convolvulus* or an *Ipomea* with a large smooth leaf. The mouth of the crucible is then covered with a round cap of unbaked clay and the junction is well luted. The crucibles, thus loaded, are well dried near the fire, and are then fit for the furnace. A row of them (k) is laid round the sloping mouth of the fire-place, then within these another row is placed (l); and the center of this kind of arch is occupied by a single crucible (m), which makes in all fifteen. That crucible in the outer row (k) which occupies the place opposite to the muzzle of the bellows is then taken out, and in its place is placed horizontally an empty crucible (n).This the workman who operates the fire, can draw out when he pleases, and throw fewel into the fire-place. The fewel used is charcoal prepared from any kind of tree that grows in the country, except the *Ficus Bengalensis* (the banyan tree), and the *Chloroxylon Dupada* (probably *Vateria Indica*, a species of dammer) of my manuscripts. The fire-place being filled with charcoal, and the arch of the crucibles being covered with the same of fewel, the bellows are plied for four hours; when the operation is completed. A new arch is then constructed, and the work goes on night and day: five sets of 14 crucibles each, being converted into steel.

It is immediately clear that although there is an overall similarity between the smelting arrangements at Ghattihosahalli and those described by Buchanan, there are major differences. At Ghattihosahalli, the only feature below ground is the ash pit, which presumably was just an open trench, with the actual furnace set over the trench above ground. Buchanan's furnace or fire-place is sunk in the ground, with the tuyere also set in the ground where it enters the furnace appearing beneath the crucibles as depicted. The combined depth of the fireplace and ash pit beneath is approximately 140 cm, much deeper than the depth of 0.46 m for the ash pit at the centre at Ghattihosahalli. Thus in Buchanan's furnace the crucibles sat on top of the furnace and formed a complete cone. At Ghattihosahalli the crucibles were at the base of the furnace and a space had to be left at the centre for the ash to fall through to the ash pit. Buchanan states that one crucible was left empty as it had to be removed periodically to allow more fuel to be charged to the furnace beneath. At Ghattihosahalli the 'ordinary smith's furnace' set over the crucibles, the fuel could be charged from the open top. The furnace would certainly have been blown with bellows but the tuyere would have entered the furnace above ground and so no evidence survives, beyond the numerous tuyeres. It is likely that the arrangement of the bellows at Ghattihosahalli would have been similar to those recorded by Buchanan set at right-angles to the ash-pit, and with the bellow operative also protected by a mud screen, for which once again there is no surviving evidence. Thus it is not possible to say whether the bellows were on the north or south side of the furnace.

Both furnaces were enclosed in a rectangular building of which two walls were located at Ghattihosahalli. Buchanan's ash pit apparently went under one wall ending in a square pit in which sat the operative charged with shovelling out the ash whereas at Ghattihosahalli the ash pit had no such arrangement. It was however divided into two sections by a stone set approximately half way along, that under the furnace to collect the ashes and the other section to accommodate the shoveller, although with a width of only 37 cm it would have been a tight fit! It might be conjectured that the dividing stone was a later addition to provide additional support, but the evidence of burning and ash confined to the western section beneath the furnace suggests that it was always there.

4 Conclusions

The plan and sections of the smelting arrangements at Ghattihosahalli allow for a much more complete understanding of the process there in the final years of the crucible steel process in south India. Although the actual furnace was not preserved except for its base which sat over the ash-pit, it demonstrates that Sambasiva Iyer's brief description was accurate. The arrangements really were different from those described by Buchanan approximately 100 years earlier. It is not a case that the differences, almost a century apart, show either an improvement or decline in the technology, as revealed by the actual production of steel at the two sites. At Buchanan's furnace there were 14 crucibles per smelt, and the process ran day and night such that five sets, i.e. 90 crucibles per day each producing about 280 gms, giving a total daily production of about 25 kg. At Ghattihosahalli 50 crucibles, apparently only one smelt per day, each producing about 370 gms of steel, i.e. a daily production of about 22 kg. Thus actual production figures per furnace per day were very similar, no evidence for decline or improvement, instead it demonstrated that there are likely to have been many variations on the process, based on local demand and traditions as much as anything else as Bronson (1986) also believed. This diversity is further exemplified by Buchanan's record of steel production at Rama-giri near Magadi also in Chitradurga (Vol. 1, p. 174) with a rather simpler furnace arrangement. There was no ash pit instead two stones each about 30 cm tall were set in the ground parallel to each other and over this space the furnace was built of clay to a height of about a meter.

One of the defining features of the crucible steel furnaces wherever they have been excavated, be it in India or Central Asia (Feuerbach et al., 1997) are the long ash pits set in the ground beneath the furnaces themselves. Their function was primarily to collect the ash and enable it to be periodically removed during the smelting by the operative with a long handled shovel at a distance. In ordinary metal smelting operations the ash and other waste material becomes incorporated with the slag which can be periodically tapped. The crucible steel process does not generate slag in any quantity beyond the small amount caused by the vitrification of the refractories. Thus the ash has to be manually removed and protection from the extreme heat of both the furnace and ash itself was essential.

This work together with the earlier studies demonstrate the continuing importance of Ghattihosahalli for our understanding and appreciation of the process, demonstrating that important remains of the smelting operations are likely to be still buried inside the mound. This underlines still further Prof. Rao's plea that the site be recognised and protected as an essential part of Mysore's history.

References

Anantharamu, T. R., Craddock, P. T., Nagesh Rao, K., Murthy, S. R. N., & Wayman, M. (1999). Crucible steel of Ghattihosahalli, Karnataka. *Journal of the Historical Metallurgy Society, 33*(1), 13–25.

Anossoff, P. (1841). On the Bulat (in Russian) *Gorny Journal*, Moscow (Translated into French). *Journal des Mines de Russie*, 192–236.

Balasubramanium, B. (2007). New insights on classification of iron-carbon alloys specially, high carbon steels. *Indian Journal of History of Science, 42*(2), 427–444.

Bronson, B. (1986). The making and selling of Wootz: A crucible steel of India. *Archeomaterials, 1*(1), 13–51.

Buchanan, F. (1999). *A Journey from Madras through the Countries of Mysore, Canara and Malabar 23rd April 1800 to 6th July 1801* (3 vols.). London: T. Cadel and W. Davies and Black, Perry and Kingsbury. (Reprinted from 1807, Delhi: Asian Educational Services).

Coomarasawamy, A.K. *Medieval Sinhalese Art*. New York: Pantheon Books. (Reprinted from the original 1908 publication).

Craddock, P. T. (1998). New light on the production of crucible steel in Asia. *Bulletin of the Metals Museum of the Japan Institute of Metals, 29*, 41–66.

Craddock, P. T. (2007). Cast iron: The elusive feedstock of crucible steel. *Indian Journal of History of Science, 42*(2), 593–607.

Craddock, P. T., Andrews, P., & Spataro, M. (2016). 'Not even if we offered him £ 50': Early crucible steel production and the history of the Huntsman process. *Journal of the Historical Metallurgy Society, 50*(1), 28–42.

Feuerbach, A., Merkel, J. F., & Griffiths, D. R. (1997). Production of crucible steel by co-fusion: Archaeometallurgical evidence from the ninth-early tenth century at the site of Merv, Turkmenistan. In P. Vandiver, J. Druzik, J. Merkel, & J. Stewart (Eds.), *Materials Issues in Art and Archaeology* (Vol. V, pp. 105–110). Warrendale, P. A.: Materials Research Society.

Freestone, I. C., & Tite, M. S. (1986). Refractories in the Ancient and Preindustrial World. In W. D. Kingery (Ed.), *High-Technology Ceramics Past, Present and Future. Ceramics and Civilisation, III* (pp. 35–64). Westerville, Ohio: American Ceramic Society.

Holland, T.H. (1893). Iron resources and iron industries of the southern districts of Madras Presidency. *Imperial Institute Handbook of commercial products No. 8*. Calcutta.

Jaikishan, S. (2007). Survey of iron and wootz steel production sites in northern Telangana. *Indian Journal of History of Science, 42*(2), 445–460.

Jaikishan, S. (2013). New insights on the *wootz* steel of Telangana. In J. Humphris & T. Rehren (Eds.), *The World of Iron* (pp. 116–123). London: Archetype.

Juleff, G. (1998). *Early Iron and Steel in Sri Lanka*, AVA-Materialien, 54. Mainz: Philipp von Zabern.

Juleff, G., Jaikishan, S. and Srinivasan, S. (2014). Northern Telangana, an iron and crucible steel production landscape in India: pioneering metallurgy field Survey 2010. In K. Nagata, E. Izawa and E. Yamasue (Eds.), *Proceedings of the BUMA VIII: Cultural Interaction and the Use of Metals* (pp. 80–87). Tokyo: Yabuuchi Satoshi.

Krishnan, M. S. (1954). Iron ore, iron and steel. *Bulletin of the Geological Survey of India, Series a: Economic Geology, 8*, 1–236.

Lowe, T. L., Merk, N., & Thomas, G. (1991). An historical mullite fiber-reinforced ceramic composite: Characterization of the "Wootz" crucible refractory. In P. B. Vandiver, J. Druzik, & G. S. Seagan (Eds.), *Materials Issues in Art and Archaeology, II* (pp. 627–632). Pittsburgh: Materials Research Society (MRS).

Masalaski. (1841). Preparation of Damascus steel in Persia, (in Russian) *Gorny Journal*, Moscow, translated into French in *Journal des Mines de Russie*, 192–297–308.

Mushet, D. (1840). *Papers on Iron and Steel*. London: Weale.

Rao, K.N.P. (1980). Iron and steel technology in India in ancient and pre-industrial time periods. *The Metallurgist and Materials Technologist*, 468–70.

Rao, K.N.P. (1987). Scientific investigation on ancient metal working of copper and iron in Karnataka, *"Wootz": Indian Crucible Steel*. Unpublished but intended for the annual report of the centre for History and Philosophy of Science. Bangalore: Indian Institute of World Culture.

Rao, K. N. P., Mukherjee, J. K., & Lahiri, A. K. (1970). Some observations of the structure of ancient steel from South India and its mode of production. *Bulletin of the Historical Metallurgy Group, 4*(1), 12–17.

Rehren, Th., & Papachristou, O. (2000). The Ferghana process of crucible steel smelting. *Metalla, 7*, 55–69.

Sambasiva Iyer, V.S. (1898–99). Report on prospecting work in parts of the Chitaldroog and Tumkur districts during the field seasons of the years 1896–9. *Records of the Mysore Geological Survey II*, 102–10.

Sambasiva Iyer, V.S. (1900–01). Notes on the economic mineral products of the Chitaldroog and Shimoga districts. *Records of the Mysore Geological Survey*, *III*, 240–46.

Srinivasan, S. (2017). Ultrahigh-carbon wootz from crucible carburization of molten iron: hypereutectoid steel from Tamil Nadu Process at Mel-siruvalur. In A. Giumlia Mair (Ed.), *Aspects of Ancient Metallurgy*: *Materials and Manufacturing Processes, 32*(7 & 8).

Srinivasan, S. (2013). Indian iron and steel with special reference to southern India. In J. Humphries & Th. Rehren (Eds.), *The World of Iron* (pp. 83–90). London: Archetype Publications.

Srinivasan, S., & Griffith, D. (1997). Crucible steel in south India: Preliminary investigations on crucibles from newly identified sites. In P. Vandiver, J. Druzik, J. Merkel, & J. Stewart (Eds.), *Material Issues in Art and Archaeology V* (pp. 111–125). Warrendale, P. A.: Materials Research Society.

Srinivasan, S., & Ranganathan, S. (2004). *India's Legendary Wootz Steel*. Bangalore: National Institute of Advanced Studies and Indian Institute of Science.

Sriperumbudur, J. (2013). New insights on the *wootz* steel of Telangana. In J. Humphries & Th. Rehren (Eds.), *The World of Iron* (pp. 116–123). London: Archetype Publications.

Tylecote, R. F. (1962). *Metallurgy in Archaeology*. London: Arnold.

Tylecote, R. F. (1976). *A History of Metallurgy*. London: The Metals Society.

Voysey, H. W. (1832). Description of the native manufacture of steel in India. *Journal of the Asiatic Society of Bengal, 1*, 245–247.

Wayman, M. L., & Juleff, G. (1999). Crucible steel making in Sri Lanka. *Journal of the Historical Metallurgy Society, 33*(1), 26–42.

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