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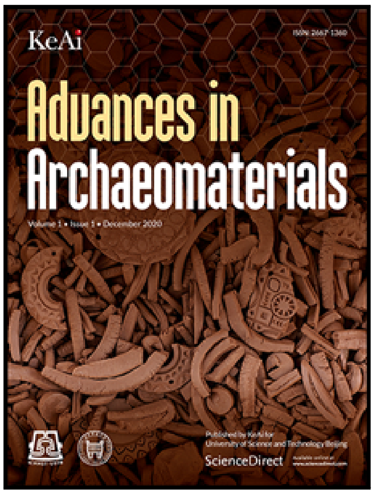

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A journey of over 200 years: early studies on wootz ingots and new evidence from Konasamudram, India

S. Jaikishan[1], Meghna Desai[2], Thilo Rehren[2, 3]

[1] DACRI, Hyderabad and Chairman, BNS College, Hyderabad.

[2] Science and Technology in Archaeology and Culture Research Center (STARC), The Cyprus Institute, Nicosia.

[3] UCL Institute of Archaeology, London, UK.

Abstract

Recent new evidence emerged from the crucible steel production site of Konasamudram, Telangana, India. A hoard of 60 crucible steel ingots from this site offers a unique opportunity to study details of the early large-scale production of this fabled material, beginning with a detailed documentation of the weights and sizes of 45 of them. Historically, Konasamudram has been an important pre-modern crucible steel manufacturing and trading centre in India, as reported by Persian and European travelogues, and may have been the source of many of the early ingots studied during the past 200 years. Therefore, the aim of this work is to present a dimensional analysis of these ingots and interpret the data in the context of earlier studies, to address questions of consistency in manufacturing, standardization of weights and other physical attributes. The newly-discovered ingots show considerable uniformity in shape, size and weights, indicative of a single event production during the heydays of crucible steel making, while the ingots previously reported in the literature vary much more widely.

1. Introduction

As a material, wootz steel was legendary for its outstanding toughness, flexibility and resistance, while its exotic origin made it even more mysterious (Verhoeven, 2001). For more than a millennium, swords and daggers made of this steel, often exhibiting wavy-watered patterns, were a prized commodity and status symbol of elite warriors, such as the famous northern European Ulfberht swords of the 9th to 11th century CE (Williams 2015; Feuerbach & Hanley 2017). The high carbon, slag free homogenous alloy was a revolutionary innovation of reducing iron in closed crucibles, a technology mastered only in a few regions of Asia, but traded on a continent-wide scale. Throughout the 2nd millennium, wootz, or its Persian counterpart pulad, continued to draw interests of travellers, poets, geologists, metallurgists and archaeologists. The fascination of wootz grew among various disciplines almost into an obsession, probably because its true nature and production were never fully understood. Production in Central Asia peaked in the early 2nd millennium and seemed to all but cease several centuries later.

Southern India is a well-documented large crucible steel production ecosystem with several micro and macro production ecosystems within, which dominated global wootz production throughout at least the second half of the 2nd millennium. This vast region is understated in its culturally and technically varied modes of production. Though many production centres and individual ingots and artefacts have been studied previously, the industry whether in fragments or as a whole was not contextualised. The recipes of modes of production are still not very clear, and the first-hand British accounts often lack details and accuracy of geography, vocabulary, interpretation etc.

The spatial and temporal origin of this mode of steel making remains unknown, while several studies of developed crucible steel production centres and techniques in Central Asia (Feuerbach 2002, Rehren & Papakhristu 2000; Rehren & Papachristou, 2003), Iran (Alipour & Rehren 2014) and South Asia (Lowe 1990, B. Prakash 1990, Juleff 1998, Srinivasan 1997, Anantharamu et al. 1999, Jaikishan 2007, etc) have shown its wide distribution in space and time (Fig. 1).

Waste products such as technical ceramics and slag are frequently encountered at such sites and form the basis for most studies of these operations, including production sites across Telangana (Lowe 1989-1991, Jaikishan 2007, Srinivasan 1994, Juleff et al. 2011). In contrast to the copious production waste, very few finished ingots have been found at archaeological sites, severely limiting our knowledge of crucible steel production. In 2016, the discovery of 60 crucible steel ingots from Konasamudram, Telangana, India was brought to the attention of one of us. The circumstances of their deposition and discovery are not well documented; however, they appear to have been kept together intentionally for later retrieval and use, which for whatever reason never happened. In this paper, we present this unique collection, referred to here as a hoard, with its geometrical and morphological characteristics and place it within the historical framework of crucible steel production in Telangana, in order to facilitate a renewed discussion of the wider aspects of this indigenous Indian industry.

2. Crucible steel in India

The Indian subcontinent is home to several distinct regions known for their crucible steel production (Craddock 1995; Rehren and Papachristou 2003). Among the better-known of these are modern-day Karnataka in SW India (Craddock 1998), Telangana (Lowe 1989, Jaikishan 2007, Juleff et al. 2011), Tamil Nadu in the south of India (Srinivasan 1994; Srinivasan & Griffiths 1997), and Sri Lanka (Coomaraswamy 1908; Juleff 1998, 2015).

2.1. Early mentions of crucible steel making in Telangana

Among the crucible steel production regions in the Indian subcontinent, Telangana was historically known as a prosperous region with abundant production of bloomery iron and crucible steel. The origin of the crucible steel industry in Telangana remains unknown, but its last remnants survived until the mid-19th century (Bilgrami & Willmott 1883, Coomaraswamy 1956, Jaikishan 2007).

In his '*Travels to India*,' (1676-originally in French) Jean-Baptiste Tavernier conveyed to his European readers the admiration of the riches of the Kingdom of Golconda which included diamonds, precious stones, extravagant fabrics, iron, and steel. Descriptions of the production of crucible steel begin from the 17th century onwards by Tavernier (1676), Thevenot (1687), Buchanan (1807), Heyne (1814), Voysey (1832), Heath (1839), and Ball (1883) etc. These accounts range in their geographical locations from the 'Kingdom of Golconda' stretching mostly from its capital, Hyderabad in modern-day Telangana State, to the east coast of India, and to the District of Mysore in the south. The production descriptions are difficult to locate geographically.

Bronson (1986) already points out the confusion this caused amongst the colonial authors and their audiences on the provenance and details of crucible steel production. He also makes a significant effort in distinguishing the descriptions of crucible steel from bloomery steels. Different and sometimes diverging observations were written from these individual locations, reporting multiple production methods. Therefore, it is quite possible that even contradictory first-hand observations are potentially all correct, while at the same time they may also quite possibly be incorrect due to limited familiarity of the early authors with the process and the intangible aspects of production. The problem of 'borrowing' earlier descriptions and passing them on as first-hand accounts continued far into the 19th and early 20th century reports (e.g., Schwarz 1901), resulting in further confusion and potential blurring of chronological and geographic detail.[1]

[1] This was because the area of the Nizam dominion was never scientifically or systematically studied, limiting access to first-hand observation by western scholars. For the first time in 1876, the then Nizam offered a mere area

Dr. Voysey (1832) anchored his notes on the crucible steel production at the village of Konasamudram, which he confirms having seen in person. His brief account of the process of production and trade of crucible steel formed for many years the basis of studying crucible steel production. The technical descriptions provided by him are fairly congruent to those provided by blacksmith M. Gangaram of Konapuram, interviewed by Dr S. Jaikishan (2007), which builds a firm ground of technical consciousness from a craftsman standpoint. One drawback of Voysey's account could be issues in proof reading or pending corrections, as the notes from his diary were published only posthumously by Prinsep.[2] The exact time period of Voysey's presence in Konasamudram is not documented; however, his geological survey reports were submitted in 1821 to the Asiatic Society (Torrens 1842), stating that he began his survey in 1819. Therefore, Voysey's presence in Konasamudram must be placed between 1819 and 1821.

Several decades later, Dr Walker (1850) comments that, due to the choice of ore, Konasamudram steel was better compared to that from contemporary villages in Yelgandal district and Ibrahimpatnam. Another forty years later, the steel produced at the latter places failed to yield even half the price of Konasamudram steel, even though being prepared with similar caution (Bilgrami & Willmott 1883). Konasamudram potentially also fits the description of an 'obscure Indian village' which was difficult to access (Ball 1883). In the view of Dr Ball, the crucible steel industry then surviving was just a shadow of a more complex earlier system.[3] The compilation of the survey of the Nizam's territory (Bilgrami & Willmott 1883) described the presence of furnaces in Konasamudram, producing the same quality of steel that had earlier led to its fame. Ambiguity remains though regarding the profitability of the production, noting that the presence of blisters or an unequal surface of the ingots rendered them useless. The customers were reported to be Persians and Mughals, who purchased the steel directly from the furnaces. The notes of Voysey, published five decades earlier than the Bilgrami & Willmott survey, introduced the readers to his first-hand interaction with Haji Hosyn, a Persian merchant from Isfahan, who frequented Konasamudram to buy steel ingots and was personally supervising the production (Prinsep 1840).

of a twenty-mile radius from Hyderabad for studying its geology to E.G. Lynn - former Assistant Superintendent of the Geological Survey of India. He was also the compiler of the Gazetteer of Hyderabad and the territories of the Nizam (Bilgrami & Willmott, 1883). Two important works came out from this survey. One was by geologist Dr Valentine Ball and the other was the in-depth report of government officials Bilgrami and Willmott. Both these reports were published in 1883 and contain somewhat similar information to the making of crucible steel. The primary interests of this survey were to document the diamonds and the iron ore.

[2] This was also an issue with Heyne's (1814) account of iron and steel production in Andhra Pradesh, who states in the introductory section of the text that his work was published without his knowledge or corrections.

[3] He compared the industry to the vestigial organs of the animal kingdom.

Even today, Konasamudram[4] boasts a strong presence of blacksmiths and bronze smiths, most of whom do not practise the hereditary trade anymore. The historical socio-cultural practices of blacksmiths from Northern Telangana and their standing traditions have been documented by Jaikishan & Balasubramaniam (2007) and Neogi & Jaikishan (2011), while archaeometallurgical scholarship based on archaeological finds from Konasamudram (Lowe 1989-91; Jaikishan 2006; Jaikishan & Balasubramaniam 2007; Juleff et al. 2011; Srinivasan & Ranganathan 2011) has significantly aided in the understanding of Indian crucible steel making.

2.2. Preceding studies of crucible steel ingots: A discussion

Several studies of early Indian crucible steel ingots provide important insights into this material. The five ingots analysed by Mushet (1840) were provided to him by Joseph Banks, president of the Royal Society who in 1790 had received the samples from Helenus Scott, physician for the East India Company in the late 18th and early 19th century. Banks then passed the samples to several scientists (Bronson 1986). Scott, in his letter to Banks which was quoted by Pearson (1795) and Bronson (1986), mentions that wootz was of "harder temper" and is used in cutting iron on a lathe; for cutting stones; for chisels; for making files; for saws and for every purpose where excessive hardness is necessary; interestingly, no use for bladed weapons is mentioned here.

Pearson suggested that the ingots were produced directly from the ore (Pearson 1795). His specimens were in the shape of round cakes of about 5 inches (127 mm) in diameter and 1 inch (25 mm) in thickness, weighing more than 2 lbs (1 kg). In this, Pearson's description is similar to the accounts of Heath (1839) from the Salem/Trichinopoly region in the far south of India. Unfortunately, the ingots provided by Banks to Pearson and Mushet have no recorded provenance, other than that of assumption; both authors provide similar physical characteristics of the ingots which were externally of dull black colour with a smooth surface except at few places where small holes and cavities were noted. Alternatively, Pearson may have received steel from Mysore, even though the weight of known ingots reported from Mysore did not exceed 320-450 gms (Buchanan 1807, Anantharamu et al. 1999).

Mushet seems to assume that wootz was made by fusion, commenting on the crystallisation visible on the rounder lower surface (which seemed to have the form of the bottom of the crucible), on the "want of homogeneity and solidity" of most examples, and on the very high carbon content of some, which "approach very near to the nature of cast iron" (Bronson 1986).

[4] (18.7306° N, 78.5221° E), with a current population of around 4,000 people in Kammarpally Mandal of Nizamabad district in the northern region of Telangana.

Bronson's review of ingots erroneously refers to crystallisation being visible on the lower surface of the ingot, even though Smith (1960) already makes it clear that the signs of crystallisation appear on the top part of the ingot during consolidation, and not on the bottom.

There was considerable difference in the wootz samples received by Mushet and Pearson. Following his discussion with Josiah Heath, Mushet (1840: 662-5) points at the existence of two distinct shapes of crucible steel ingots, which he identified as cakes and conical shaped ingots, respectively, with each shape suggested to reflect a different district of production. While the conical ingots weigh less than a pound, they are said to be denser than the cakes, whose dimensions are given as 3.5 inches (85-90 mm) in diameter and 5/8ths to 3/4ths of an inch thick (16 to 19 mm; Mushet, 1840), with the two allegedly resulting from different production processes. From his own experiments on the five ingot samples given to him, and the implements forged out of them in England, Mushet concluded for one of them the method of production as a direct reduction from the ore without an intermediate wrought iron step. As aforesaid, he changed his opinion after communicating with Heath, an industrialist who was interested in exploiting the 'wootz ores' from India and producing his own quality steel, based on a method of production followed in Mysore/Salem-Trichinopoly region (Bronson 1986; Lowe 1990). Despite having changed his mind in the main text, Mushet in his notes still says that he was tempted to maintain his conclusions at least from 'one district' which may have practised wootz production by reduction of the ore and precipitation of steel. His examination of 'cakes' concludes that they were not fully melted. This conclusion was also supported independently by Buchanan (1807) and Wilkinson (1837). Campbell (1842) reports manufacturing "natural steel" directly from the iron sand in the furnace and adds a further observation on production of good quality steel from cast iron with the same iron sand as the raw material. Thus, the 19th century accounts, written while the industry was still operating and building on a century of first-hand reports, unfortunately still give rather incomplete and often contradictory or at least vague descriptions of the actual wootz making processes. Therefore, no firm conclusions are possible, due to the procurement and study of samples without proper identification, and despite the personal gains and interests of colonial metallurgists and industrialists. The metallographic study in 1956 of the cross-sections of one of the conical ingots, given in the late 19th century to the Royal School of Mines by Thomas Holland, who in 1903 became Director of the Geological Survey of India, did not change this situation. It revealed that the ingot had been entirely melted, showing a distinct dendritic structure with a carbon content of 1.34%, contradictory to the former conclusions of incomplete melting of the ingot (Smith 1960).

An isolated description of a wootz cake from Cutch, a region in north-western India, is mentioned by Wilkinson (1837), who proposes that the quality of the wootz steel cake depends on the ore. The cake he examined from Cutch weighed 2.5 pounds, nearly equal to a little over a kilogram. Unfortunately, no further physical features are provided for this ingot, preventing further discussion here.

After a long interval, more direct evidence and analysis of wootz steel ingots from Konasamudram comes from the work of the late Thelma Lowe in the late 20th century, analysed by D. Scott, then Head of the Getty Conservation Institute. There are no direct results published on the ingots collected by her, but micrographs are printed in Scott (2013) along with a picture of one of the ingots. This photograph of the ingot showed similar external features as the ingots in the hoard presented here, but appears smaller in size compared to the current hoard. Scott (2013) reports the carbon content of two of her ingots to be between 1 and 1.3%. In another micrograph of a different wootz cake specimen collected by Lowe, the formation of ledeburite was identified, indicating a carbon content of more than 2 wt%.

2.3. The decline of crucible steel production in Telangana

Reports of the decline of indigenous iron and steel making begin to appear in the early 19th century. The early travelogues of merchants such as Tavernier do not mention any threat to the indigenous industry, however Tavernier does point out that then King of Golconda made it difficult for the steel to leave his region, while his counterpart in Persia prevented the re-export of steel that had entered his realm (transl. by Ball V & Crooke W.1925; Coze, 2007). This, and Tavernier’s mention of fraud and the likelihood that some ‘pieces have not been well prepared, and which could not be damasked’ (Coze 2007), indicates the paucity of materials and high value of the steel. Whether the ‘not well prepared’ steel was intentional fraud, or unintentional lack of quality control, may reflect the then status of the industry.

The account written by Thevenot mentions a previous blade manufacturing town of Indalwai, which by his time (around the 1680s) had already ceased to exist. Two centuries later, apart from Konasamudram most of the furnaces in Northern Telangana had discontinued their production due to the import of English iron and ready-made arms (Ball, 1883; Bilgrami & Willmott 1883). Iron mines around Dimdurti, on the banks of River Godavari in Northern Telangana, were at least exploited until the 1880s (Coomaraswamy 1956), which according to Voysey could be a possible source of iron for crucible steel production. In Mysore, a crucible steel production centre in Southern India (Buchanan 1807), the production and local demand for crucible steel continued until the early 1900s, but it was sold at higher rates than the imported iron. Some suggestions were made to revive the industry, but it shortly thereafter collapsed (Coomaraswamy 1956).

Amongst the causes of decline that are discussed below, the principal ones mentioned by the British writers involve the competition with English iron and the scarcity of fuel. The unrestricted import of arms reduced the demand of locally produced iron and steel. In the catalogues and documentation commissioned by the Imperial government in the 1800s (Walker 1841; Bilgrami & Willmott 1883), English blades were camouflaged as native swords and sold in the markets. The iron imported from England was not malleable enough for the blacksmiths to forge it (Ball 1883), but, although it was less pure, it could be custom made suiting the purposes of the buyer. This quality was lacking in the indigenous iron which always provided identical types of metal. The craftsmen of the northern and eastern regions of the Nizam's dominions found it difficult to sell their steel in the Hyderabad market as it was overrun by English iron (Walker 1950: 227). Since the mid-nineteenth century, propositions were made to the imperial government time and again to undertake iron production in India, which would have circulated the funds within India, empowering both the economy and craftsmen who would be eventually employed in these enterprises. However, the government rendered the production as non-profitable and continued importing iron (Ball 1883). While this concerned the iron industry in general, it is reasonable to assume that crucible steel production would have been similarly affected.

The second cause was the rapidly depleting fuel source for the charcoal needed in the furnaces, which was what probably led to the Forests Acts passed from 1865 onwards (Burton 1884:111; Reddy et al. 2010) and the Land Revenue Settlement of 1869. These Acts, created in harmony between the Nizams and the Presidency, were applicable to the newly created administrative districts as well as to the tracts of Godavari. The Act prohibited the exploitation of forests by the natives, with the state monopolising the utilization of these vast resources for their quality timber for its own needs, such as shipbuilding. The Forest Act was complemented by the Land Revenue Settlement which placed all the previously independent areas belonging to the blacksmiths and other tribal settlers into the hands of landlords (*zamindars*), with ultimate ownership by the state (Bukhya 2013). As a result, the occupational classes turned to agriculture to ensure their livelihoods. This is presumably the reason for blacksmith Mr Gangaram in his interview (Jaikishan 2007) to comment on increasing developments in agriculture leading to the withdrawal of blacksmithing operations in the areas around Konasamudram.

The local landlords were instrumental in damaging the industry. Voysey speaks of a landlord who seemed to have controlled steel production of Konasamudram. This landlord would take the amount given in advance by the buyer and therefore, the buyer has to bear the entire expense of the product again, increasing the cost of steel. In the 1830s, the produce of one furnace was 50 seers[5] (roughly around 48-50 kgs) of metal, or 37 Rupees[6] in value. The ingots weighed about 1.5 lbs[7]. The exact prices of steel per ingot still remain unknown due to the changing weights standards and currency values.

According to Walker (1850: 183, 226), a ‘Mogul’ ‘who rents the furnaces at Konasamudram’ and ‘farms the famous steel manufacture of Konasamudram’ attempted to monopolise ore supply and steel production. Whether this ‘Mogul’ is a member of the Mogul monarchy or an individual with vested interests remains unclear from Walker’s description. The decline of the traditional iron and steel industry is still felt today; currently, there are 60 surviving families of blacksmiths in Konasamudram, who have quit the craft due to the scarcity of work (Jaikishan 2007b).

3. The hoard

In 2016, Dr S. Jaikishan was informed by a resident of Konasamudram, Mr Sabbani Poshanna, that he had unearthed 60 wootz ingots in the backyard of his house adjacent to the wall of the house while digging a gutter for his tap connection. Some 15 years prior, Mr Poshanna had purchased the house from Kammari Hanumandlu, a blacksmith hailing from a family of wootz steelmakers who earned his survival by sharpening and forging iron implements for agricultural use.[8] Due to paucity of work, Mr Hanumandlu and his family left Konasamudram in 2008. Mr Poshanna, the current owner of the house, agreed to sell 56 of the ingots to Dr Jaikishan, two were taken by Mr Poshanna’s son, and one ingot was sold to a teacher from Siddipet. One ingot was kept by Mr Poshanna.

[5] Seer was a common market terminology for exchange in India.
1 Indian seer = 933.1 gms = 80 tolas. The weights were standardised differently in the Nizam’s dominion and were subjected to regular change. The British weights in India were based on that of wheat berries, while those prior to the Imperial system depended on a grain of rice or barley corn (Prinsep, 1840).

[6] A cake weighing 110 rupees is sold on spot for 8 annas (Voysey, 1830). According to different parts of the Nizam’s territory, the rupee weight changes. However, 1 seer ranges between 108-120 rupees, but in Ahmednagar close to Hyderabad it is 80 rupees = 1seer. Nizam’s territory also has pusseree as the until which meant five seers but varies greatly due to incomprehension and deceit (Martin, 1839). In Heyne (1814) 96 rupees = 1 seer, therefore, 110 rupees should be approximately around 1.2 seers which is close to the weight of ingots examined in this study. Heyne and Voysey’s accounts appear to be apart by not more than a couple of decades.

[7] We cannot say whether this is troy pounds or the modern-day pounds. If it is a troy pound, then, 1 maund = 100 English troy pounds = 37.3 kgs. Therefore, 1.5 troy pounds should be roughly equal to 0.56 kgs, almost half the weight of the individual ingots in the hoard currently examined in this work.

[8] The prefix ‘Kammari’ is added to his name to indicate his occupation as a blacksmith.

The ingots are flat plano-convex discs, with a smooth lower convex side and a more or less flat upper surface (Fig. 2). The upper surface of a few ingots shows a radiating dendritic pattern from the centre of the ingot, formed during the crystallisation of the metal inside the crucible along with a subtle depression in the centre. The demarcation of the formation of a slag fin throughout the circumference of the ingots is also recognisable in some pieces. The physical dimensions of 45 of the ingots are reported in Table1, based on measurements using a vernier calliper, electronic weighing scale and a measuring tape. The remaining 11 ingots could not be measured in detail, but are visually very similar. The average weight is just over 1 kg, with diameters around 95 mm and maximum thicknesses just under 30 mm. The consistency of their dimensions is remarkable, particularly regarding the diameter with a standard deviation of just 2.5% of the absolute value.

3.1. The ingots in context

The 45 plano-convex ingots range between 80-90 mm in diameter with an average weight of 1066 g. Their shape and surface texture indicate that they solidified from a fully molten liquid. The external surfaces of the ingots are of dull black colour with some rust and small gas voids and craters on the surface, formed during the solidification of the metal; however, corrosion overall is limited. Several ingots have an uneven thickness due to tilting of the crucibles while in the furnace. Remarkably similar physical observations and diagnostic features were already noted by Mushet and Pearson in their study of cakes of wootz steel. Overall, the flat cakes mentioned in the earlier description were 80-120 mm in diameter with a thickness of 20-30 mm, and weighing around 1 kg. However, a direct connection of the cakes from the 18th and 19th century analysed by Mushet and Pearson, so similar in their physical dimensions and description to those from the current hoard, to either Konasamudram or the Salem/Trichonopoly region is difficult to be established.

More clearly though, the samples of the hoard are morphologically distinct from the conical shaped ingots which were studied in the mid-19th century. The crucibles preserved at the Royal School of Mines are round bottomed, about 152 mm high and a maximum internal diameter of about 63.5 mm and gave a conical ingot of about 51 mm high (Smith 1960: 22). Their height is more than twice the thickness of the ingots from the Konasamudram hoard, while being much smaller in diameter. One of the ingots was sectioned and shown to be completely molten, exhibiting a dendritic structure throughout. The description of this conical ingot and the corresponding crucibles resemble those reported from Ghattihosahalli in the state of Karnataka (Anantharamu et al. 1999). C.S. Smith also provides a short overview of the cakes examined by

Mushet and reports Mushet's view of the incomplete melting of some 'cakes'. An example of such a conical, but incompletely fused ingot is published in Rao et al. (1970: 14, Fig. 4). The debate of partial or complete melting of steel within in the crucible may well be attributed to the analysis of ingots from different parts of southern India or to production inconsistencies. Unfortunately, the lack of documented provenance of the early ingots, and limited details of description given in the early accounts, prevent us from assigning the two distinct shapes of 'cones' vs 'cakes' with confidence to specific production regions.

A similar uncertainty persists regarding the actual steel-making process, and the different production recipes thus remain strongly contested. Craddock (2007) advocates the co-fusion method having been used in Telangana, whereby the crucible was charged with high carbon or cast iron and a low carbon or bloomery iron to produce a resulting ingot of wootz, of intermediate carbon content – in what is referred to as the Hyderabad Process. This is consistent with Voysey's account from the same region, who also appears to state mixing of two different types of iron in the crucible. Elsewhere, the historical accounts consistently refer to the carburisation of low-carbon or bloomery iron through the addition of organic plant matter to the crucible charge – the Mysore Process. A more detailed description of these is given in Bronson (1986).

It is possible that production methods changed over time or multiple methods could have been in use at the same time. Most reports are from the declining phase of the production industry, which could have materially affected many aspects of production. There is also a strong possibility that the early metallurgists have analysed steel ingots from different parts of southern India, given that their origins are not stated and their physical descriptions vary. This is not surprising, since the analysts may have been unfamiliar with the geographical setting of the production industry, and the passion of working with the fabled wootz steel appeared to supersede the logical need for a more fine-grained documentation. There is no further provenance evidence from the letters of Helenus Scott or from Joseph Banks, and the diary of Voysey which was submitted to the Asiatic Society cannot be located. Due to these literary and experimental limitations, studying the current hoard in detail becomes even more important.

3.2. Standardisation of dimensions

In crucible steel production, each ingot was formed from a unique single-use crucible, accurately preserving their inner dimensions of diameter, circumference and bottom shape. Studies of large numbers of crucible steel-making crucibles in Central Asia have shown that they were mass-produced around wooden cloth-covered templates, resulting in highly standardised diameters (Rehren and Papakhristu 2000; Alipour et al. 2011; Alipour & Rehren 2014). Contrary to metal casting, no mould twins are possible in crucible steel ingot production; accordingly, a study of finished ingots can inform on the production of multiple crucibles, and vice versa. It is therefore noteworthy that the ingot dimensions from the hoard scatter very narrowly around the mean (Fig. 3), indicating a high degree of standardization as would be expected for a product of large-scale trade, as opposed to opportunistic or ad hoc production, which would likely result in higher degrees of variability. The observation of close similarity in diameter and mass was consistent across the entire hoard, even beyond the 45 measured examples (Fig. 4).

The historical sources are mostly silent on the organisation of the crucible production in Telangana, no evidence of standardisation has yet been documented or discussed for the Indian crucibles, and the variability in crucible diameters reported in the literature suggests that no general template was used. However, some inferences can be drawn from the extant historical reports. A crucible must have an external diameter in the range of 110-130 mm to support the formation of an ingot of 100-110 mm diameter, allowing for a wall thickness of around 5 to 10 mm, as measured for the majority of crucible fragments from Konasamudram. According to Voysey's notes (1832), the diameter and height of a Konasamudram furnace was 5ft (c. 1.5 m) and 4-5 ft (c. 1.2-1.5 m) respectively. Based on this the number of crucibles of 12 cms outer diameter which can be fired in a single cycle can be determined. A schematic (Fig. 5) shows the possible arrangement and number of crucibles in a single layer, allowing for a distance of 20 mm between the crucibles to prevent them fusing together. A maximum of 61 crucibles can be placed in this furnace. Therefore, it is possible that the hoard documented in this study is a result of a single firing cycle, therefore providing a unique opportunity to demonstrate the precision with which the crucibles for these ingots were produced. The mass of the ingots varies somewhat more widely than their diameter; it seems that the metal charge was added to the crucibles without the use of scales.

From the extensive field survey of the first author, several well-preserved crucible bases from Konasamudram were retrieved with a base diameter of 110-115 mm. When digitally recombined (Figs 6, 7) with an ingot from this hoard, both components convincingly position themselves on one another. Thus, it further adds value to the hoard being produced in Konasamudram, with an archaeologically documented example of corresponding crucible base diameter that would be required for the process.

The constant mass of the ingots of just over 1 kg could indicate an intended weight of 1 seer, which during British rule over India was set at 0.933 kg; however, weights were standardised differently in the Nizam's dominion and were subjected to regular change. Elsewhere, the ingot size is said to be determined by the intended artefact to be produced from them locally, which is less likely the case for ingots destined for long-distance trade, as appears to be the case in Konasamudram.

4. Conclusion

In the last two hundred years several samples of crucible steel from Southern India were examined, often after having passed through many owners and without their provenance being recorded or documented. From these reports, two broad types of ingots appear, namely flat cakes and taller cones, potentially linked to different production regions within southern India. Another noteworthy point is the trade of these ingots to Persia. In the mid-17th century, Tavernier confirms an existing trade in wootz ingots between the Kingdom of Golconda and Persia, which was persisting in 1820s as ascertained by Vosey's report of the repeated presence of Haji Hoysn from Isfahan in Konasamudram to buy up wootz ingots.

Against the diversity of ingot shapes and sizes reported in the literature, the hoard of sixty ingots reported here for the first time shows a high degree of standardisation in production of the crucibles used in Konasamudram, Telangana. The variability in diameter is too large to be the result of a physical template around which multiple crucibles would have been formed, as was the case in early Islamic Central Asia, but small enough to indicate that they were produced by a highly skilled and experienced craftsman. They are likely to represent the product of a single furnace firing but that needs further examination. Visually and morphologically these ingots closely match ingot descriptions used for experiments in Europe in the 18th and 19th century, but there is no credible evidence that those ingot samples can be provenanced to Telangana. Therefore, any comparison between the current data and the early 18th/19th century data must be implemented cautiously. Regardless, this hoard is a unique testament to the technical capability of the craftsmen of Konasamudram, confirming the village's reputation as a specialised crucible steel production centre in pre-modern India.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 1: Physical examination of the ingots:

Sample	weight (gms)	diameter (mm)		circumference (mm)	height/thickness (mm)	
		Max	Min		Max	Min
TS-KSM 1619 SJ [ING 01]	1058	89	92	290	35	4
TS-KSM 1619 SJ [ING 02]	1034	92	96	310	31	20
TS-KSM 1619 SJ [ING 03]	1134	93	100	310	31	10

TS-KSM 1619 SJ [ING 04]	1024	90	96	295	29	13
TS-KSM 1619 SJ [ING 05]	1035	92	97	310	35	14
TS-KSM 1619 SJ [ING 06]	1128	94	95	305	29	14
TS-KSM 1619 SJ [ING 07]	1098	95	96	305	27	18
TS-KSM 1619 SJ [ING 08]	1004	90	92	295	26	12
TS-KSM 1619 SJ [ING 09]	1071	89	97	310	32	9
TS-KSM 1619 SJ [ING 10]	1008	89	94	300	29	16
TS-KSM 1619 SJ [ING 11]	954	88	96	300	32	17
TS-KSM 1619 SJ [ING 12]	1056	93	100	310	26	19
TS-KSM 1619 SJ [ING 13]	1041	92	95	300	30	20
TS-KSM 1619 SJ [ING 14]	1137	97	102	320	26	18
TS-KSM 1619 SJ [ING 15]	1039	90	94	300	29	22
TS-KSM 1619 SJ [ING 16]	1003	95	96	300	29	6
TS-KSM 1619 SJ [ING 17]	1116	96	98	310	30	20
TS-KSM 1619 SJ [ING 18]	1062	82	96	300	26	18
TS-KSM 1619 SJ [ING 19]	1063	92	95	305	30	17
TS-KSM 1619 SJ [ING 20]	1100	93	99	310	27	13
TS-KSM 1619 SJ [ING 21]	1015	91	94	300	33	10
TS-KSM 1619 SJ [ING 22]	1128	94	98	300	35	12
TS-KSM 1619 SJ [ING 23]	1139	96	97	310	28	22
TS-KSM 1619 SJ [ING 24]	1137	96	103	315	29	17
TS-KSM 1619 SJ [ING 25]	973	93	95	300	27	7
TS-KSM 1619 SJ [ING 26]	1051	91	94	290	29	13
TS-KSM 1619 SJ [ING 27]	1072	95	98	310	27	18
TS-KSM 1619 SJ [ING 28]	1134	95	99	315	28	19
TS-KSM 1619 SJ [ING 29]	1008	93	94	305	26	13
TS-KSM 1619 SJ [ING 30]	942	93	95	300	27	12
TS-KSM 1619 SJ [ING 31]	1137	95	100	310	31	11

TS-KSM 1619 SJ [ING 32]	1147	96	99	315	27	15
TS-KSM 1619 SJ [ING 33]	1123	94	98	310	27	12
TS-KSM 1619 SJ [ING 34]	1011	91	94	310	32	10
TS-KSM 1619 SJ [ING 35]	968	93	94	300	31	19
TS-KSM 1619 SJ [ING 36]	1034	100	96	310	30	18
TS-KSM 1619 SJ [ING 37]	1140	99	100	320	26	17
TS-KSM 1619 SJ [ING 38]	1150	98	99	310	29	15
TS-KSM 1619 SJ [ING 39]	1141	94	96	300	33	12
TS-KSM 1619 SJ [ING 40]	1024	92	94	300	31	15
TS-KSM 1619 SJ [ING 41]	1057	91	96	295	31	19
TS-KSM 1619 SJ [ING 42]	1025	93	96	305	28	19
TS-KSM 1619 SJ [ING 43]	1110	96	100	310	27	13
TS-KSM 1619 SJ [ING 44]	1125	92	98	310	30	19
TS-KSM 1619 SJ [ING 45]	1011	89	93	290	27	19

Fig 1: Map of India with locations of crucible steel production sites mentioned in the text.

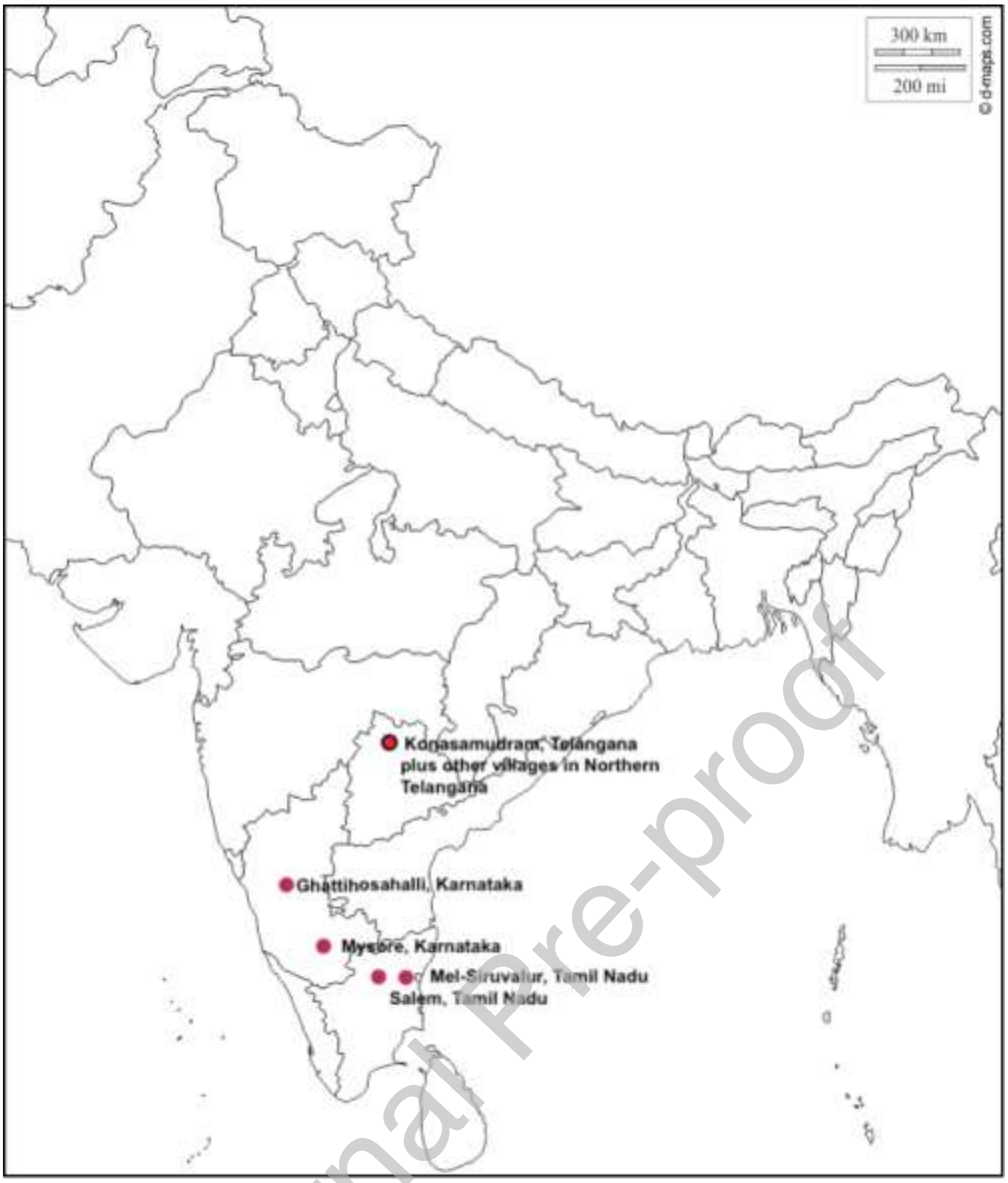

Fig. 2. One of the 60 ingots recovered in Konasamudram in 2016. Note the radial dendritic surface pattern and the circular line indicating the limit of the slag cover within the crucible. Ingot 06: 94-95 mm diameter, weight 1128 g.

Fig. 3. Dimensions of 45 of the 60 ingots recovered in Konasamudram in 2016. Note the very tight clustering of their diameter around 95 mm, and the somewhat larger scatter of their weight, with an average of 1066 g.

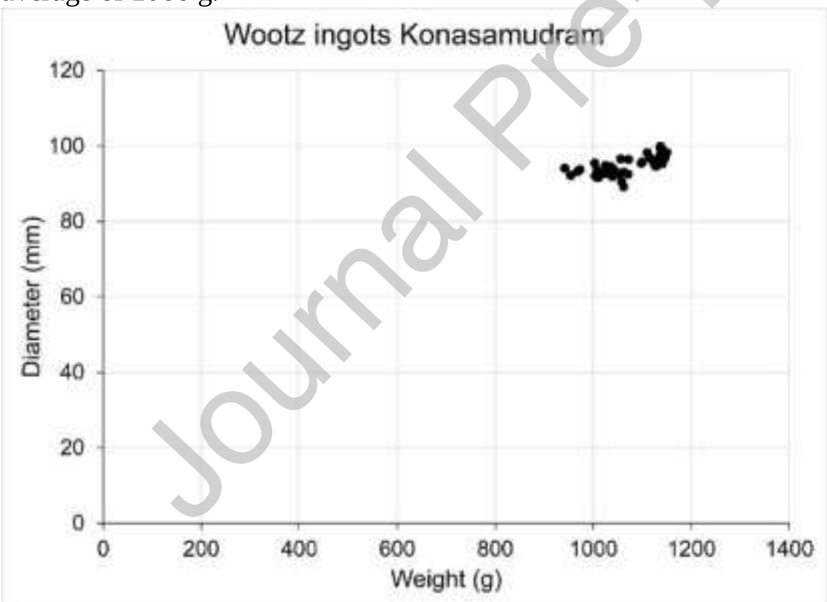

Fig 4: 45 ingots from the hoard of 60 ingots

Fig 5: Schematic displaying a potential spatial arrangement of the crucibles in the Konasamudram furnace. The centre has one crucible and is surrounded by increasingly larger circles progressing towards the circumference of the furnace. The wall thickness of the furnace is ignored in this calculation as it only shows a maximum possibility. This number may vary with the size of the crucible and the volume occupied by charcoal in the furnace. Produced using SolidWorks.

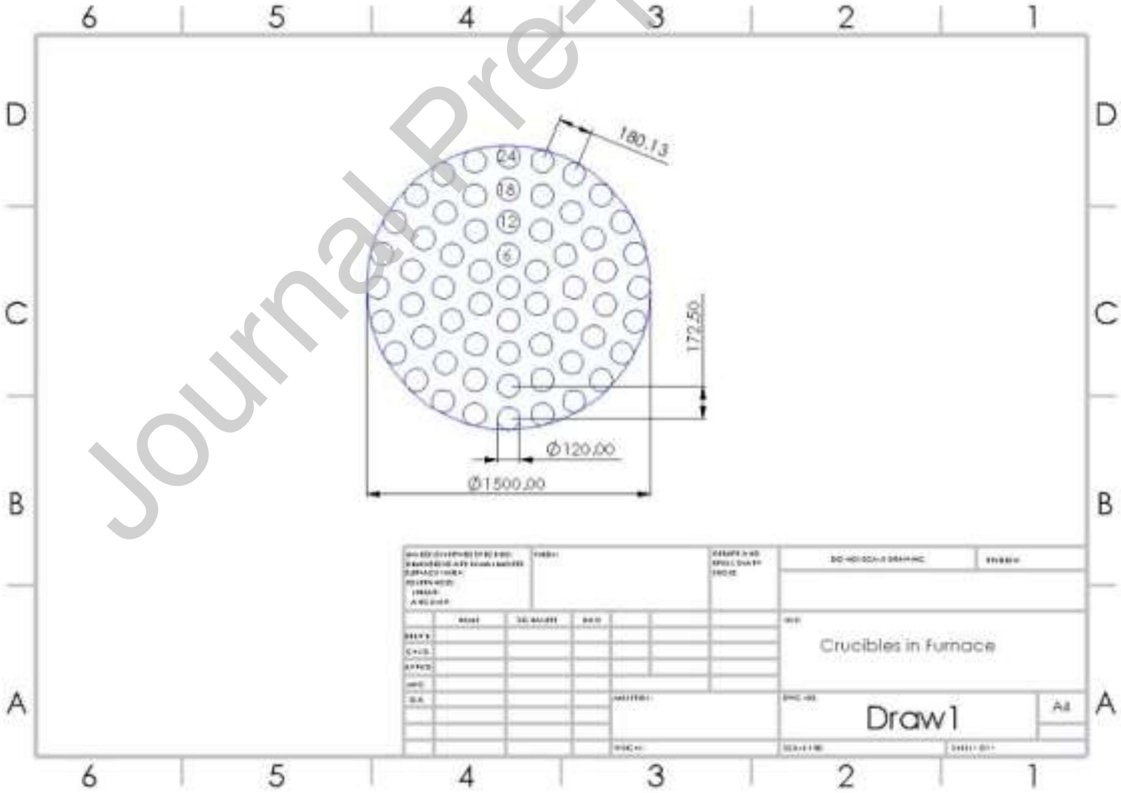

Fig 6: Photographic representation of a preserved crucible base from Konasamudram using 3D rendering in MAYA 2019.

Fig 7: The positioning of ingot TS-KSM 1619 SJ [ING 06] on the crucible, at the same magnification as the crucible base. The visual was developed using Photoshop 20.0.