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Similar like White and Black: a Comparison of Steel-making Crucibles from Central Asia and the Indian Subcontinent

Summary

The paper presents an update of the archaeological evidence for the production of crucible steel in Central Asia and the Indian subcontinent, offering a systematic comparison and discussion. The ceramic tradition of these vessels apparently differs between the two regions. The Central Asian crucibles have a dense, almost white firing fabric, are cylindrical and have a relatively large volume of 0.7 to 1 litre. The Indian and Sri Lankan vessels are made from a highly porous, black firing ceramic, have a range of shapes and relatively small volumina between 0.1 and 0.2 litre. The Central Asian crucibles date primarily to the 8th to 12th centuries AD. The historical development of crucible steel production within the medieval city is discussed for Merv and Akhsiket. One site in Sri Lanka dates to the second half of the first millennium AD, all other known occurrences in South and East Asia date to the modern period, primarily to the 19th century. The metallurgical process used for the actual steel-making operation is in the autochthonous sites always the carburization of bloomery iron using organic matter; some later exceptions from India and China, probably influenced by European technology and involving pig iron, are discussed in the text.

Keywords:

Crucible steel, technical ceramic, Central Asia, India, Sri Lanka.

Zusammenfassung

Die neuesten archäologischen Belege für die Herstellung von Tiegelstahl in Zentralasien einerseits und Indien und Sri Lanka andererseits werden systematisch zusammengestellt und vergleichend diskutiert. Es wird gezeigt, dass die Tiegel in den beiden Regionen sich offenbar aus unterschiedlichen keramischen Traditionen entwickelt haben. In Zentralasien bestehen sie aus einer dichten, fast weiß brennenden Keramik, sind nahezu zylindrisch und mit einem Volumen von 0,7 bis 1 Liter relativ groß. In Indien und Sri Lanka sind sie aus einer hochgradig porösen,

schwarz brennenden Keramik gefertigt, zeigen eine größere Formenvarianz und sind mit Volumina zwischen 0,1 und 0,2 Litern sehr viel kleiner. Die zentralasiatischen Tiegel datieren überwiegend in die Zeit vom 8. bis 12. Jahrhundert AD. Die historische Entwicklung der Tiegelstahlherstellung innerhalb der mittelalterlichen Stadt in Zentralasien wird für Merv und Akhsiket diskutiert. In Sri Lanka ist ein Vorkommen aus der zweiten Hälfte des 1. Jahrtausends nach Christus bekannt, alle anderen Vorkommen in Süd- und Ostasien datieren in die Neuzeit, überwiegend in das 19. Jahrhundert. Der Prozess der Stahlherstellung ist in den autochthonen Prozessen stets der gleiche, nämlich die Aufkohlung von Rennfeuer-Eisen mit organischem Material. Einige spätere, möglicherweise von Europa beeinflusste Ausnahmen in Indien und China, die Roheisen verwenden, werden im Text diskutiert.

Schlagwörter:

Tiegelstahl, technische Keramik, Zentralasien, Indien, Sri Lanka.

Résumé

Les récents résultats archéologiques concernant la production d'acier au creuset d'un côté en Asie centrale et de l'autre en Inde et au Sri Lanka sont présentés et discutés en comparaison. On démontre que les creusets de ces deux régions se sont apparemment développés à partir de différentes traditions céramiques. En Asie centrale, ils consistent en une céramique dense, cuisant pratiquement à blanc, ils sont presque cylindriques et relativement grands, avec un volume compris entre 0,7 et 1 litre. En Inde et au Sri Lanka, ils sont produits à partir d'une céramique extrêmement poreuse, cuisant pratiquement au noir, ils présentent une grande variété de formes et sont beaucoup plus petits, avec un volume compris entre 0,1 et 0,2 litre. Les creusets de l'Asie centrale datent pour la plupart d'une période comprise entre le 8^{ème} et le 12^{ème} siècle av. J.-C. Le développement historique de la production de l'acier au creuset dans une ville du Moyen-âge en Asie centrale est discuté pour Merv et Akhsiket. Au Sri Lanka, une présence est établie pour la seconde moitié du

1^{er} millénaire ap. J.-C., toutes les autres présences datant des temps modernes, principalement du 19^{ème} siècle. Le procédé de production de l'acier est toujours le même dans les procédés autochtones : la carbonisation du fer du feu à loupe avec du matériel organique. Quelques exceptions en Inde et en Chine, postérieures et peut-être influencées par l'Europe, utilisaient la fonte brute et sont discutées dans le texte.

Mots-clés:

Acier au creuset, céramique technique, Asie centrale, Inde, Sri Lanka.

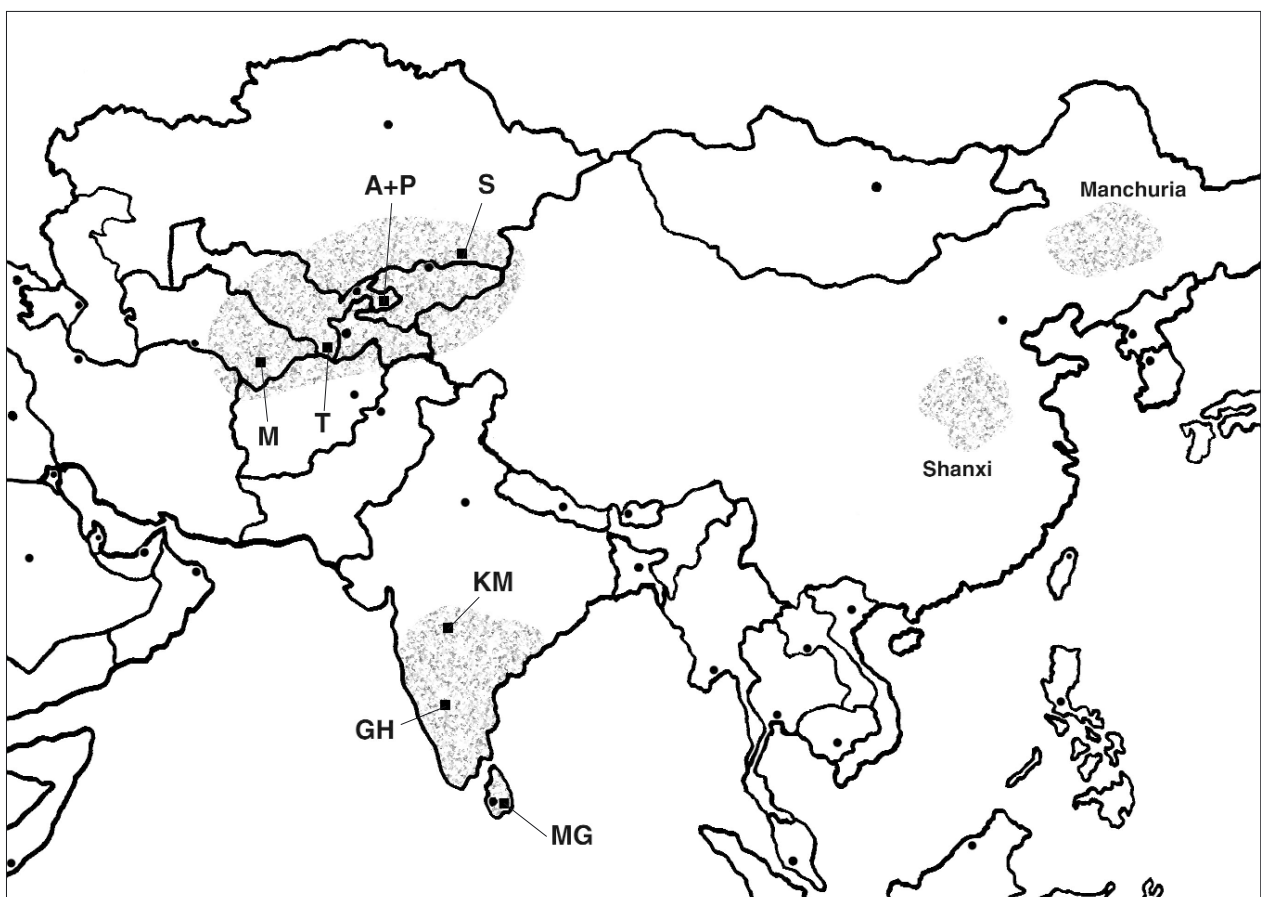
Introduction

The last decade has seen a surge of publications presenting and discussing archaeological and ethnographic evidence for crucible steel making in both Central Asia (Papachristou & Swertschkow 1993; Merkel et al. 1995; Feuerbach et al. 1997; 1998; Rehren & Papakhristu 2000; Simpson 2001 etc.) and the Indian subcontinent (Lowe

1989; Lowe et al. 1991; Craddock 1998; Wayman & Juleff 1999; Anantharamu et al. 1999). Gerd Weisgerber has a longstanding interest in the production of crucible steel, and indeed it was he who brought together the authors of this contribution to work on crucible steel from Uzbekistan, and facilitated the study of some Sri Lankan crucibles by the first author. We therefore think it is both timely and appropriate to offer this comparative study of crucible steel-making remains as our joint contribution to Gerd Weisgerber's festschrift.

The majority of the publications mentioned above are concerned with the study of a particular site or region, making little reference to the evidence from elsewhere. In contrast, Bronson (1986) and then Craddock (1998) each offered excellent overviews of the subject, though strongly based towards the South Asian evidence. Allan (1979) and Allan & Gilmour (2000) give an outstanding discussion of the historical evidence for crucible steel in the Persian world. The majority of the studies of Central Asian crucibles, however, have been published only during the last few years, thus justifying the update presented here. In addition to the limited number of comprehensively published archaeological accounts of crucible steel making,

Fig. 1: Map of Central and East Asia, showing the main regions and sites discussed in this paper. Central Asia: A+P = Akhsiket and Pap; M = Merv, T = Termez, and S = Semirechye. East Asia: Manchuria and Shanxi provinces. South Asia: KM = Konasamudram; GH = Gattihosahalli; MG = Mawalgaha. The boundaries of the shaded areas are not as well defined as it appears, but give only a very general impression of the geographical spread of the different traditions.



there are several sites for which scholars mention either the presence of such crucibles without giving details of the process or the vessels themselves (e.g. Lenkov 1974; Savelieva et al. 1998), or deduce the former presence of such crucibles based on other considerations (e.g. Terekhova 1974). These will also be included in this update, with a view to highlight the need for further study in those areas. Overall, we are offering for the first time a systematic evaluation of crucible shapes and fabrics from both regions (fig. 1), focussing on similarities and differences, and a functional and environmental interpretation of the differences between the Central Asian and Indian / Sri Lankan crucible technologies.

The separation into two major geographical regions for the purpose of this study partly reflects our belief that there are systematic differences between the two. Furthermore, it must be stressed that the material itself is chronologically diverse, in that the Central Asian finds are all from excavations and date from the 8th to 12th centuries AD, while the Indian / Sri Lankan material is much more recent or undated, and partly even ethnographic; the majority seems to relate to processes in operation during the 19th century AD. Accordingly the methods used so far to study the crucibles and the related technologies differ: an archaeological approach dominates in Central Asia, while primarily ethnographical methods are employed in India / Sri Lanka. In this article, however, we aim to compare the evidence using a consistent technological and material-oriented approach. Obviously, we will make particular use of the material which is most familiar to us. This is primarily the material from Akhsiket, an extremely rich site in terms of volume and quality of excavation and preservation of crucible fragments, and to a lesser extent from Pap, both sites being situated in the Ferghana Valley of Uzbekistan, which we use as our foundation for this study. On the Indian / Sri Lankan side, we focus on the material from Mawalgaha which Gill Juleff kindly provided for study. In addition to this primary evidence, we will draw from the published reports. Where there are discrepancies over time in the presentation or interpretation of material from one site,

such as in Merv (Merkel et al. 1995; Feuerbach et al. 1997, 1998; Feuerbach 2002), we have tried to consider the most recent interpretation available. We exclude from the interpretation, however, any material or remains from processes which are clearly related to the processing of Industrial Period material, and the experimental work which typically is much more concerned with producing and explaining a damask pattern in modern steel rather than elucidating the actual steel-making processes as conducted in antiquity.

In our interpretation we will concentrate on the possible explanation for the apparently different ceramic fabrics within the relevant environmental parameters, although we will not pursue further discussion of the chronological sequence within or between the two regions: too little reliable archaeological data for such a discussion is yet available, and the literary evidence has been summarised sufficiently in the past (e.g. Bronson 1986; Craddock 1998; Feuerbach 2002).

Central Asia

Several archaeological sites in Central Asia contain remains of crucible steel production, foremost in Uzbekistan, but also in Turkmenistan and possibly Kazakhstan. They all belong in broad terms to the same early medieval period, between the late 8th or early 9th and the late 12th century AD, and are typically from significant urban settlements, which are far from obvious sources of iron ore. The available information is summarised below on a site by site basis.

Akhsiket

The ancient town of Akhsiket in the central northern Ferghana Valley, near the modern village of Shahand, flourished as a fortified town during the Middle Ages up to the Mongol invasion shortly after AD 1220; the production of

Table 1: Comparison of crucible data (height and diameter are given as external values; volumes internal. All values in cm and ccm, respectively). The primary data is taken from Rehren & Papakristu (2000), Feuerbach (2002), and own observations of material held by The British Museum (Gattihosahalli and Konasamudram), and unpublished material from Sri Lanka. Access to the material at the BM courtesy Dr Paul Craddock / Trustees of The British Museum. The table and illustrations are typically based on idealised reconstructions done from a collection of fragments. Total volume estimated using internal diameters and heights, and ingot volume estimated using the height of the slag fin or layer above the bottom of the vessels.

	Akhsiket and Pap	Merv	Old Termez	Gattihosahalli	Konasamudram	Mawalgaha
Height (cm)	29	20	?	18	10-15	18-20
Diameter (cm)	8	8	7-8	6	3-15	4
Total volume	1000	700	?	~100	30-700	150
Ingot volume	600	250	600	~40	10-230	50
Lid type	Domed; hole	Flat; hole	Domed; hole	Domed plug	Conical plug	Flat plug
Shape	tubular	short tubular	tubular	conical	flat tubular	long tubular
Base	Hemispheric	Hemispheric	Hemispheric	Pointed	Flat	Hemispheric
Features	Corrugation	Pad	Corrugation	Outer ceramic	Outer ceramic	Tilted hot
Date (c. AD)	9-12	8-10	12-13	18-19	18-19	19

Table 2: Chemical composition of the ceramic (in weight percent; average values). The data from the Central Asian sites measured by electron microprobe is taken from Feuerbach (2002). (A. Feuerbach was given some samples by us for analysis and comparison with the Merv material during her PhD research at the Institute of Archaeology UCL, under the supervision of professors Peter Ucko and Thilo Rehren.) The crucibles from the other sites were measured by ICP and XRF giving bulk compositional data, including the siliceous temper. Dr Paul Craddock of The British Museum kindly provided material from the two Indian sites for analysis. Here, the analyses cover only the crucible fabric proper, not the outer wraps of less refractory material.

	Akhsiket	Pap	Termez	Merv	Gattihosahalli	Konasamudram	Mawalqaha
SiO ₂	61	60	60	65	62	61	64
TiO ₂	0.6	1.5	0.3	0.4	0.8	0.9	0.8
Al ₂ O ₃	28	30	32	24	25	21	24
FeO	1.4	1.0	1.0	1.1	6	10	6
MgO	0.6	0.6	0.5	0.2	0.8	0.8	0.9
CaO	0.4	0.3	1.0	0.5	1.4	1.7	1.8
K ₂ O	2.3	1.3	2.2	4.4	2.5	3.2	2.2
Na ₂ O	0.3	0.2	0.5	0.2	0.1	0.1	0.1
Total	94.6	94.9	97.5	95.8	98.6	98.7	99.8
Colour	Whitish	Whitish	Whitish	Whitish	Black	Black	Black
Porosity	Dense	Dense	Dense	Dense	Porous	Porous	Porous
Analysis	EPMA	EPMA	ICP	EPMA	XRF	XRF	XRF

crucible steel apparently covered the entire period from the 9th century to almost to the very end of the town's existence. The massive quantity of crucible remains and their very standardised cylindrical shape and size, of around one litre internal volume (Table 1; fig. 2; see also Rehren & Papakhristu 2000 and Papakhristu & Rehren 2002), attest to the industrial nature of the steel production at Akhsiket. The crucibles were typically covered with a carefully prefabricated domed lid with a central hole of about two centimetres diameter, preventing the possibly fatal build-up of pressure during the process. There is no indication (and indeed no need) for this hole to have been closed during the process (contra Craddock 1998, 50). The ceramic is too dense and tight to allow pressure release through its porosity; hence, an opening is vital to prevent the vessels from cracking. With an ongoing gas production inside the vessel, and the position of the opening at the upper end, there is no way that the surrounding, less reducing, furnace atmosphere could penetrate in any quantity into the crucible vessel, and strongly reducing conditions can be maintained inside the crucible despite the opening. A more detailed assessment of both the ceramic material and the steel making process have been published very recently, and need not to be repeated here (Table 2; Rehren & Papakhristu 2000; Papakhristu & Rehren 2002). It suffices to say that the process was based on the carburization of bloomery iron in the crucible, with a massive steel ingot filling about three-fifths of the internal volume of the crucible, and a characteristic turquoise to dark green slag cake of about four centimetres thick resting on top of the metal, being produced in these vessels. This crucible slag is thought to represent the remains of the initial slag content of the unrefined bloom, and possible fluxes added to enhance the process. The ceramic is extremely refractory, firing to a whitish or fine grained light brown 'salt and pepper' colour. According to Abdurazakov & Bezborodov (1966), it is thermally stable up to about 1650 °C. The au-

thors of this paper disagree somewhat on the technical interpretation of the finds. The actual process temperature is estimated to be about 1400 °C by Th. Rehren based on the analyses of the slag and vitrified layer of the vessels (Rehren & Papakhristu 2000), and between 1500 and 1550 °C by O. Papachristou based on archaeological considerations such as the corrugation of the vessels and the gravel bed they stood in (see below).

The outer appearance of the crucibles is slightly corrugated, and they were fired while resting in a gravel bed. O. Papachristou interprets these features as the craftspeople's response to coping with the extremely high temperatures during the process, with the corrugated surface offering additional strength and the gravel bed acting as a thermostat, slowing the change in temperature and thus reducing thermal shock. Th. Rehren sees the corrugation as an incidental feature of the manufacture process, and the gravel bed primarily as an easy way to prevent the crucibles from sticking too hard to the furnace bed (with the outer glaze acting as a 'glue'), i.e. facilitating removal of the crucibles after the firing.

Remains of the industry are concentrated in several places, both in the inner fortified city ('shakhristan'), and in the eastern and western suburbs ('rabat') of Akhsiket; some historical interpretation of this distribution of workshops over time is given later in this paper.

Pap

The site of Pap, ca. 30 km due west of Shahand in the northern Ferghana valley, is another fortified town on the northern banks of the Sir Darya river which existed up until the Mongol invasion. The metallurgical activity here probably spans from the 7th or 8th century AD (pers.

comm. Dr. B. Matbabaev) to the early 13th century AD, based on the associated domestic pottery.

The crucible steel production was apparently concentrated at the rabat just north of the main town, on a field which to this day carries the name Iron Hill due to the quantity of iron slag and crucibles to be found there. Due to intensive agricultural activity, however, the best samples are currently derived from the screening dump of the local brick factory, and hence unstratified and only broadly located. The crucible remains and the slag cakes within them are visually indistinguishable from those of Akhsiket, indicating their origin from a very similar process. However, there is a certain difference in the chemical composition between the ceramic from Akhsiket and Pap, the Pap crucibles are richer in titania and lower in potash and iron oxide than those from Akhsiket, indicating a similar, but different source of the clay used at these two sites (see Table 2).

An archaeological and analytical programme covering the spatial distribution and technological development of the crucible steel industry in the Ferghana Valley is currently in progress as part of a joint project of the Institute of Archaeology of the Uzbek Academy of Sciences in Samarkand and the Institute of Archaeology University College London, resulting from the collaboration of the two authors of this paper, initiated by G. Weisgerber.

Kuva and Termez

The third site in the Ferghana Valley known to yield this type of crucible fragments is Kuva in the south; so far, only one small fragment of the very characteristic crucible ceramic has been found here, dating to the 11th or 12th century AD. Finally in the very south of Uzbekistan, at Termez, the border town to Afghanistan, a number of fragments from all parts of the Ferghana-type crucible have been found, i.e. bottom, wall, lid as at Akhsiket (see Table 1), in contexts dating from the 12th to early 13th centuries, again indicating the existence of the very same process here as in the Ferghana Valley. The chemical analysis of the ceramic, measured at the laboratory of the Institut für Archäometallurgie of the German Mining Museum in Bochum by ICP, is very similar to the Akhsiket and Pap material, see Table 2 and Papakhristu (forthcoming).

Merv

In terms of information available and extent of the industry, after the Uzbek evidence for crucible steel production in Central Asia, comes Merv in modern-day Turkmenistan. The excavations of a joint Turkmen - British expedition at Merv during the 1990s (Herrmann et al. 1995, 1996; Simpson 2001) have uncovered the remains of a single workshop, probably dating from the 9th or 10th century AD, yielding a considerable amount of crucible remains. A se-

ries of papers has been published over the years giving some details of the crucible fragments, their furnaces and the related process. According to the most recent account (Feuerbach 2002), the process is the same as in Akhsiket, carburizing bloomery iron by some carbonaceous material added to the crucible charge. Overall, the nature and quality of the ceramic is very similar to that from the Ferghana Valley, although a considerable amount of grog has been identified as a regular component of the fabric at Merv. The basic shape and diameter of the crucibles is also similar to those from Uzbekistan, although they reach only about 18 to 20 cm total height, their lids are flat, not domed (fig. 3; Feuerbach 2002, 48), and they lack the typical corrugated outer surface pattern of the Akhsiket crucibles. Furthermore, they are resting on circular refractory pads rather than in a gravel bed, thus lifting them into the hottest area of the furnace (Feuerbach 2002). The iron bloom charged into the crucibles was apparently better refined than the Uzbekistan material; certainly the layer of crucible slag is much thinner, reaching only about one centimetre in average.

The ceramic of these vessels obviously has again been made from a clay similar, but different from the clay used at the other Central Asian sites, the Merv ceramic having the highest potash concentration found so far (see Table 2).

Further Central Asian sites

Very little technological information beyond the reference to crucible remains in the context of specialised iron workshops is available from the site of Semirechye (modern Almaty) in Kazakhstan, said to be dating from the 10th century AD (Savelieva et al. 1998). The same is true for early Middle Ages East Turkestan, modern-day Xinjiang (Litvinski & Lubo-Lesnichenko 1995). Both sites clearly deserve a more detailed study of the relevant material in the future. No other crucible steel remains are archaeologically known at present, although one might expect to find further evidence elsewhere in Central Asia, and in particular in modern-day Iran, Afghanistan and possibly Pakistan.

In terms of sheer quantities preserved, and therefore probably the amount of steel produced, the most important region within Central Asia to produce crucible steel is the Ferghana Valley in the eastern part of Uzbekistan. The key site here is the ancient city of Akhsiket, with the other Uzbek sites of Pap, Kuva and Termez yielding visually identical remains. The contemporary material from Merv in Turkmenistan differs only slightly, in that the vessels are somewhat smaller and the characteristic slag cake less pronounced. The process, carburizing bloomery iron by adding organic material to the charge, is virtually identical across Central Asia, as is the very light firing, extremely refractory and dense ceramic based on a clay rich in alumina and relatively low in iron oxide, potash and lime. Thus, we identify a common Central Asian tradition of cru-

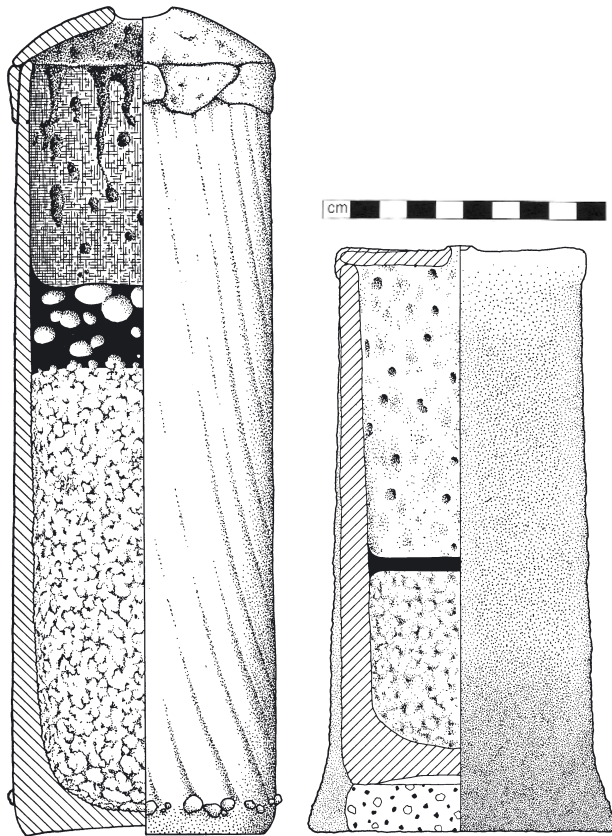


Fig. 2+3: Idealised crucible reconstructions for Akhsiket and Pap in Uzbekistan (left) and Merv in Turkmenistan (right). Note the pad underneath the Merv vessel, covered by the fuel ash glaze running down the side.

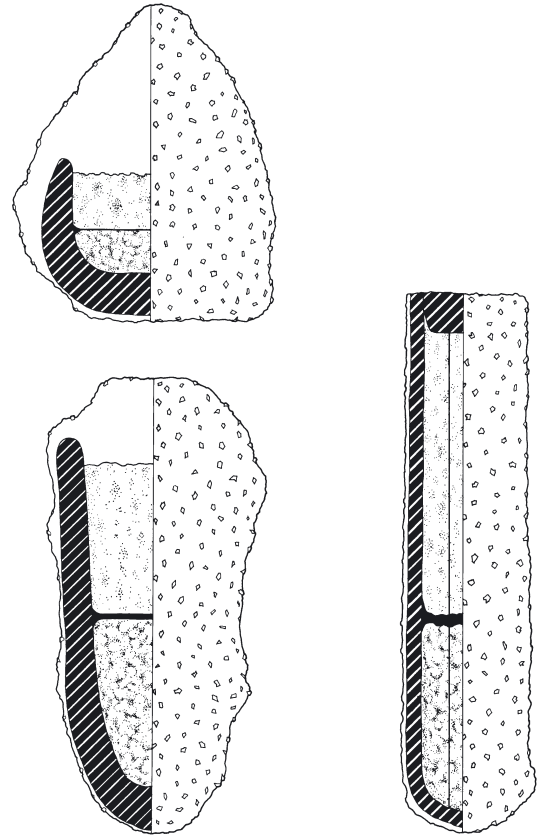


Fig. 4-6: Idealised crucible reconstructions for Konasamudram (top) and Gattihosahalli (left bottom) in India, and Mawalgaha in Sri Lanka (right). Note that the vessels from Konasamudram can vary considerably in size, with diameters up to 20 cm and down to 5 cm. The proportions, however, remain the same.

cible steel making based on the carburization of bloomery iron in dense kaolinitic crucibles, covered by a lid with a centimetre-sized hole for pressure release.

East Asia

For the sake of completeness, we must mention the Chinese crucible smelting processes for the production of cast iron which flourished principally during the late 18th and throughout the 19th centuries AD. In Manchuria (Hara 1992), this process produced pig iron from a charge of magnetite ore and mineral coal. Just under 200 crucibles, each filled to completeness by about five litres of ore and coal at a roughly equal volume ratio, were fired in a flat hearth, resulting in a raw pig iron which had to be remelted for subsequent casting. According to the detailed description available, the raw pig iron, rich in blow holes, coke, ash and slag, eventually filled less than ten percent of the volume of the crucible. This alone illustrates the stark contrast between this process and the medieval carburization of bloomery iron in Central Asia, where the resulting steel ingot filled about half of the crucible volume (slightly more in Akhsiket, slightly less in Merv; see above). A very simi-

lar process is reported by Needham (1958, 14) from Shanxi, based on ethnographic descriptions from the early 20th century AD, again producing cast iron in overly long and open tubular crucibles packed in coal-fired hearths. It should be stressed that the Shanxi and Manchuria processes produced pig iron, not steel, and have at present no identifiable archaeological pedigree beyond the earliest reports from the 18th/19th centuries.

India / Sri Lanka

Much has been written about crucible steel production in India and Sri Lanka, in terms of field reports (Juleff 1990; Srinivasan & Griffiths 1997), ceramic studies (Lowe 1989; Lowe et al. 1991), and metallographic investigations of the metal produced (Wayman & Juleff 2000). The key publication for the subject is still Bronson (1986), which critically deconstructs the inflated body of tertiary literature and petrified myths relating to the subject. The somewhat less critical update by Craddock (1998) is particularly valuable for its presentation of the Indian and Sri Lankan evidence. From the latter, it emerges that there

are two distinct processes, namely the Hyderabad or co-fusion process and the Mysore process. The former is based on the supply of locally produced cast iron from dedicated small blast furnaces and traditionally smelted bloomery iron, while the latter used plant matter to carburize a piece of bloomery iron.

Konasamudram

The Hyderabad or Deccani process is an interesting hybrid of traditional crucible technology, employing vast numbers of small, hand-made vessels to process (traditionally smelted) bloomery iron together with cast iron derived from (modern) blast furnaces (Craddock 1995, 282). The product was apparently either white cast iron or crucible steel. Contemporary descriptions of this process all date from the 19th century AD, with little archaeological work been done so far tracing its origins. The key site for this process is the village of Konasamudram in Andhra Pradesh in mid-south India, formerly known as Hyderabad. Crucibles of varied size were used, but they apparently have a 'standard' shape with a flat base, short perpendicular walls and a cone-shaped massive lid. This lid or plug is made from a less refractory clay with more mineral temper than the crucible walls proper, and this outer clay layer extends from the lid around the body of the crucible down to the bottom. Those examples available for our study, from the collections of The British Museum, differed considerably in size, with an internal diameter at the base of between three and fifteen centimetres, and a total internal height of around five centimetres (Table 1; fig. 4).

Accordingly, the ingots produced were rather small when compared to the Central Asian ingots, and would have formed a thick circular disc (Craddock 1998) of a height of probably no more than two centimetres, judging from the remains of the slag layer within the vessels. The ceramic of these crucibles has been studied in detail by Thelma Lowe (1989) and Lowe and co-workers (1991). It is a highly porous (ca. 40 vol%), silica- and alumina-rich fabric of mullite fibres and silica phases in a glassy matrix containing several weight percent of carbon and a plethora of reduced iron prills. The high porosity, the carbon content and the related in situ reduction of the iron oxide of the clay to iron metal prills are all due to the use of abundant rice husk temper. According to Lowe (1989), this ceramic bears no relation to any other Indian ceramic tradition, indicating a highly specialised material design.

Gattihosahalli

The Mysore process of carburizing bloomery iron with plant matter covers all other known crucible steel sites from India and Sri Lanka. Its key site is Gattihosahalli in south central India, with massive remains of the industry dating to the 19th century AD (Craddock 1998, 55-57). Un-

fortunately, no detailed morphological descriptions or drawings of the crucibles are published; judging from the photographs in Craddock (1998, 57, figs. 9 and 10) and our own inspection (fig. 5) of those vessels from Gattihosahalli in the collection of The British Museum, they are elongated, slightly conical with a pointed end and an external diameter at the top of around ten centimetres, a length of up to twenty centimetres and a wall thickness of around two centimetres. The lid is made as a rough plug of less refractory clay, tempered with a high proportion of crushed quartz. As in the previous site, the clay from the lid extends as an irregular outer wrap around the vessel proper. A large proportion of the fragments studied is fused together, indicating a close packing of them in the furnace. The resulting metal ingots were of the same basic shape and up to six centimetres in height.

The ceramic of the crucibles has been studied by Freestone & Tite (1986), and was found to have abundant voids resulting from the rice husk temper mixed with the clay. The overall chemical composition is much richer in iron and calcium oxide than the Central Asian crucibles (Table 2, and see Freestone & Tite 1986, 54 and Table IV). This overall composition would not qualify as a particularly refractory material, mostly due to the high iron oxide content acting as a flux. However, microscopical investigation revealed that – possibly due to the carbon content from the rice husk temper – most of the iron of the clay matrix was reduced to metallic iron, forming small prills and thus effectively reducing its ability to act as a flux (Freestone & Tite 1986, 54).

Little concrete information is published concerning the other Indian crucible fabrics; however, in a preliminary survey of known and new crucible sites from southern India, including Gattihosahalli, Srinivasan & Griffiths (1997, 111) state that “*the fabric of crucibles from all the above mentioned sites appears similar*”. They are porous, relatively friable and black throughout, with a well developed black outer fuel ash glaze containing abundant white quartz grains, and a thin honeycomb pattern of glassy slag on the inside where the ingot was initially in contact with the ceramic. They all have a 'fin' of glassy slag running along the internal circumference about halfway up, indicating the position of the convex meniscus of the molten metal and thus the height of the resulting ingot. The slag fin typically contains trapped prills of steel and/or cast iron, further confirming the allocation of these vessels to the production of crucible steel rather than the working of base metal alloys.

There are two areas in Sri Lanka with crucible steel remains, one at the Knuckles Range near the geographical centre of Sri Lanka, dating to the second half of the first millennium AD (Juleff 1998; Wayman & Juleff 1999, Figure 1 and page 29), the other near the village of Mawalga-ha in the south central highlands. The latter is most likely the site reported by Coomaraswamy (1908), where crucible steel making flourished during the 19th century.

Mawalgaha

The vessels from site SM 159 (Juleff 1998, 90-94) are tubular with a hemispherical bottom and a flat lid, about eighteen to twenty centimetres long and four to five centimetres in external diameter (fig. 6). The lids were wedged into the upper part of the crucibles, and are made from the same clay as the body of the vessels. They are about one to one and a half centimetres thick and pierced with four or more tiny holes, of less than one millimetre diameter, some of which were blocked during use (Juleff 1998, 91). When compared to the Indian lids or plugs, the Mawalgaha lids appear much smoother on the inside, and were probably pre-fabricated to fit into the opening of the crucibles. The wall thickness is between five and twelve millimetres, leaving an internal diameter of about three to three and a half centimetres. The total volume of the vessels thus is around 150 ccm, less than one fifth of the volume of the standard Ferghana crucible. The charge is given as around 400 g of bloomery iron and 150 g of wood chips (Coomaraswamy 1908). This is in agreement with an ingot volume of around 50 ccm as deduced from the position of the slag fin on the inside of the vessels, equalling 400 g of metal of a density of 8 g/ccm, while the weight of the wood chips appears slightly higher than would fit into these crucible together with the bloomery iron. Assuming a (relatively high) density of around 1 g/ccm for wood, and an available volume of 100 ccm of the crucible after being charged with the metal bar, only about 100 g of wood would fit into them.

As with the south Indian crucibles, they are of a very porous, black firing ceramic, covered by a black external fuel ash glaze with white quartz grains, and tempered with a high amount of rice husk. According to initial chemical analysis (Table 2), they are very similar to the ceramic from Gattihosahalli. The vessels were fired in an upright position for most of the duration of the process, resulting in the formation of a slag fin at roughly one third of the internal height of the vessels. However, towards the end of the process the crucibles were tilted to their side, leading to a very long and thin ingot and the formation of a second slag fin perpendicular to the previous one (Wayman & Juleff 1999). The adequate use of temper, both organic silica-rich rice husk for the body of the vessels, and of mineral silica for the outer, more vitrified layer, enabled this material to be used for steel-making crucibles, working at a temperature range well above that typically used for domestic or non-ferrous metallurgical use.

Juxtaposition

Despite the often limited information available to date, the description above allows the comparison and contrast of the crucible steel-making tradition of Central Asia with that of South Asia. The most striking difference is the colour

and consistency of the ceramic employed: white to very light brown and very dense for Central Asia, and black and highly porous for South Asia. Apparently, there are no transitional or grey shades between the two, indicating that they are rooted in very different ceramic traditions. Indeed, in both regions this crucible material represents a unique fabric, distinct from all domestic and fine ware, as explicitly stated by Lowe (1989) for India. The same can be said for Central Asia, and not only in terms of fabric, but also in the way of manufacture. The thin-walled cylindrical shapes of the Ferghana Valley crucibles have been built using a textile mould (the impressions of which are still visible in the upper parts of the vessels), unlike any domestic pottery. Copper crucibles from the region, on the other hand, are free-formed or worked on the potter's wheel. Thus, the two fabrics of the crucible steel vessels are each unique and highly specialised in both regions, and at the same time, very different from each other.

Similarly, the typical size of the crucibles in the two regions differs. The Central Asian vessels have a volume of between 700 and 1,000 ccm, while the South Asian vessels have only about 100 to 200 ccm (with the exception of the largest examples from Konasamudram), i.e. only about one fifth of the volume of the Central Asian crucibles. Despite the smaller volume the South Asian crucibles have on average thicker walls, of up to 15 mm, than the Central Asian ones which are typically less than 10 mm thick. The shape is, within a certain margin, similar, in that most of the vessels studied here are either tubular or at least elongated, and always covered by a lid. The ratio of height to width, however, is often quite different, with the Konasamudram vessels being much flatter than the very elongated Mawalgaha crucibles. Finally, the Gattihosahalli vessels are clearly conical with a pointed bottom, facilitating the stacking of them in the furnace. It should be noted that the Central Asian lids almost invariably have a central hole of around one (Merv) to two (Akhsiket) centimetres diameter, while the South Asian crucibles have only a number of tiny piercing (Mawalgaha) which, according to Craddock (1998, 58), are supposed to become blocked by the forming glaze and slag during the process, or none at all (Konasamudram and Gattihosahalli). This systematic difference clearly reflects the different porosity of the two fabrics, the South Asian ones probably allowing pressure release through their highly porous walls.

A common feature of almost all metallurgical crucibles is the occurrence of some slag on the inside, which typically contains much more information relating to the metallurgical process than the crucibles themselves (Rehren 1997). The steel-making crucibles are no exception to this rule; they all show either a fin of slag at some height along the internal circumference, or even as much as a massive slag cake as in the Ferghana crucibles. In either case this slag line or layer marks the upper level of the liquid metal at the end of the process, when the relatively less dense slag was floating on top of the much denser metal under-

neath. Not many detailed studies are published concerning the nature of these slags from either the Central Asian or the South Asian crucibles; but in both cases it is apparent that the slag is mostly glassy, with a rather low iron oxide content when compared to typical iron slags from other processes, and often tiny prills of steel or cast iron are trapped in the glass. The generally thicker slag fins or cakes of the Central Asian crucibles are partly explained by the five to ten times larger metal volume, and hence the five to ten times larger amount of bloomery slag that is inevitably introduced to the crucibles with the charge. The Ferghana crucibles, however, typically have an exceptionally thick slag cake, indicating that the iron charge here contained proportionally much more slag than in most of the other cases.

Despite this striking difference in the slag content of the Ferghana crucibles it has been demonstrated (Rehren & Papakhristu 2000) that they belong to the very same direct carburization process as most of the South Asian crucibles. Based on a thorough re-assessment of the evidence, the technical constraints and possibilities, the same conclusion has been reached in the most recent interpretation of the Merv material (Feuerbach 2002), thus overthrowing earlier interpretations which saw these as co-fusion (Feuerbach et al. 1997, 1998). As a result, of all the closed crucibles related to steel making in Asia only the Konasamudram / Hyderabad crucibles may belong to the co-fusion process, and these are partly reliant on modern raw materials such as cast iron for the charge. While the first description in the West of the Hyderabad co-fusion process predates the earliest European patent for essentially the same process by seven years (Craddock 1998, 55), one may still assume that the blast furnace / cast iron technology in that region was a European introduction, and not autochthonous.

To summarise, the fully indigenous crucible steel technologies in Central and South India are based on the same metallurgical process of direct carburization. They all developed a very lean glassy slag, derived from residual bloomery slag introduced with the iron charge, plus some ash component from the added wood / plant matter, and possible additives and fluxes as mentioned in the contemporary Islamic literature for the Central Asian examples (Allan 1979). They differ, however, fundamentally in the ceramic used, and their overall size.

Typological classification with some historical comments

Previously, we have discussed the refractory clay of the crucibles as far as we know them today (see above, and Papakhristu & Rehren 2002). However, another very important aspect is the shape of the vessel and the technolo-

gy of their manufacture. As we have seen in Table 1, the crucibles from Central Asia have a long cylindrical form like a pipe. This is a very specific form, not known for any domestic pottery. It is impossible to build on a potter's wheel or by hand; it can only be formed using a mould. In Akhsiket, the craftspeople used a sand-filled textile mould for this (Papachristou & Swertschkow 1993), a technique unique to steel-making crucibles since copper and copper alloy crucibles were formed differently. Interestingly, the same shape of crucible, mode of forming and refractory clay was used for the early modern Chinese crucibles used for cast iron production (Needham 1958; Hara 1992). Although these were much bigger, they clearly derive from the same technological tradition.

A characteristic of many Chinese iron ores used in the production of cast iron is their high phosphorous content, and their association with lime-rich geological formations. Both factors are in favour of cast iron production (Alexandrov 1979). According to the interpretation of one of the authors, the combined evidence of the corrugated outer surface and the gravel bed for the Akhsiket crucibles indicates a very high process temperature, approaching the thermal limit of the refractory ceramic, of more than 1500 °C. This very high temperature, together with a different, more refractory, ore being used in the Ferghana Valley, could explain why in the Central Asian crucibles steel was produced, and not cast iron as in China. Cast iron production was known in China more than a millennium before the earliest crucible steel production known so far from Central Asia, and the Central Asian crucible steel production becomes archaeologically visible as a fully developed technology at roughly the same time at several places with few changes in detail, and well adapted to the geological and environmental conditions of the region. This indicates that the technology either arrived from a region far away but with similar environmental conditions, or that it developed regionally, but outside the current archaeological sites. Most likely, this was somewhere in the Ferghana Valley or neighbouring East Turkestan / Xinjiang in modern-day China.

Interestingly, the earliest appearance of the crucible industry in Akhsiket is in the outer suburbs, while the more central areas were only occupied from the 10th century onwards when the former fortification walls became unnecessary under the Samanid dynasty, and were re-developed. Obviously, in the early phase of crucible production the better workshop areas near the centre of the city were already occupied, initially forcing the newly-arriving steel-making industry to utilise areas in the outer suburbs (Papakhristu 1985).

At approximately the same time, during the 8th to 10th centuries AD, we can see a very similar development in the ancient city of Gyaurkala in Old Merv in modern-day Turkmenistan. From the political history of the region we know that the Arabian seizure of the region initially de-

layed the development at Merv for a whole century. Only in the middle of the 8th century AD did development begin again with Abu Muslim, transforming Merv to the capital of his region and bringing in not only ten thousand Arabs, but also a lot of wealth and tribute from Khurasan and Transoxiana. All this created a great demand for specialised and skilled crafts (Bolshakov 1973, 214). The appearance of crucible steel technology in Merv also dates from this time, repeating in the form, refractory material and metallurgy the Ferghana Process known from Akhsiket. The physical evidence is almost identical, indicating a very close relationship between them. At the same time there are slight differences. The Merv crucibles have no corrugated outer surface, and are placed on refractory pads rather than in a gravel bed, indicating that the temperature in the furnace in Merv was probably lower than in Akhsiket, removing the necessity to strengthen the ceramic to withstand the exceedingly high temperatures. The virtually simultaneous appearance of the process in both Merv and the Ferghana Valley, together with the only very limited technological changes in the crucible manufacture and the actual metallurgical process, indicate that the process was well adapted to the environment, which was very similar in both regions.

We do not see any crucible steel manufacture in Gyaurla after the 10th century AD. Either the craftsmen had migrated to the new territory of Sultankala or the craftspeople stopped employing this particular process. From historical reports from the 11th and 12th centuries, it is obvious that the region produced a wide range of military products (Allan 1979, 98), but no crucible steel is mentioned. In this context it should be stressed that the evidence from Merv concerns a single workshop with an estimated 1,250 crucibles produced (Feuerbach 2002, 109), while in Akhsiket the production is estimated in the range of 100,000 crucibles (Rehren & Papachristou 2000).

Obviously, the archaeological material from Merv and Akhsiket points to a single centre from whence the craftspeople emerged with this technology in their secret possession, either in the Ferghana Valley, or neighbouring East Turkestan. Based on the archaeological and typological classification, O. Papachristou argues that the crucibles from Sri Lanka had to have the same form and technological process as those from Akhsiket and Merv, and are in their genealogy more similar to those from Central Asia and China than to the vessels from India. Most probably, they originate from the same centre as the Central Asian vessels, but arrived in Sri Lanka earlier, and were transformed to match the different environmental and geological conditions of the Indian subcontinent. Archaeologically, crucible steel production in Sri Lanka dates from the 6th to 10th centuries AD. This may mean that by the 6th century, the adaptation of the technology had already occurred, and indeed we see this adaptation fully developed in the archaeological evidence from Sri Lanka. The craftsmen used the local clays, and we can see the move to

smaller vessels in order to obtain smaller ingots, which is a characteristic of all the crucibles from the Indian subcontinent. It may well be that this small ingot size simply reflects a local tradition or preference among the blacksmiths.

A further important aspect of the Central Asian vessels is their possible relationship to the white-firing Chinese ceramics based on kaolin, which eventually led to the development of true porcelain during the Song Dynasty (AD 960-1279) (Pollard & Hatcher 1994; Yap & Younan Hua 1994; Leung et al. 2000), in roughly the same period that the Central Asian crucibles were developed. The very refractory nature of kaolin clay is the reason for the high quality of the Central Asian crucibles, while the white firing was exploited for the production of prestigious pottery. At present, it is difficult to assess which of the two different strands of technology inspired the other, or if they are related at all. Their origin falls into the very same time period and geographical region, suggesting a possibly close link. Clearly, much more archaeological research is necessary, focussing on the eastern part of Central Asia and the north western part of China as a region of continuous interaction and development throughout history.

Conclusion

Despite a plethora of papers on the subject, the archaeology of crucible steel production is still in its infancy, in particular in South Asia where undated surface finds and ethnographic material from the 19th century AD dominate the available evidence. However, some good indications exist for crucible steel production in Sri Lanka as early as the mid to late first millennium AD (Wayman & Juleff 1999). In contrast, the Central Asian evidence dates mostly from the 9th to 12th centuries AD. It has been demonstrated that in both regions the indigenous process of crucible steel making relied on the same direct carburization of bloomery iron, despite the visually striking differences in the appearance of the main tools of the process, the cru-

Fig. 7: Photograph of a cross section through the bottom part of a crucible from Akhsiket (left) and Konasamudram (right), for comparison. Note the different colour and thickness of the ceramic. Photo: S. Laidlaw, IoA, London.



cibles (Fig. 7). The Chinese processes of cast iron production in open crucibles is to be separated from the crucible steel technology, with which it shares only a superficial resemblance. The differences in size and fabric between the Central Asian and the South Asian crucible steel making are interpreted as reflecting different regional ceramic traditions and environmental conditions.

Ultimately it should be noted that while the tubular shape of the crucibles is unique to the process in both regions, the fabric itself is not. While certainly different from the local domestic pottery and fine ware (Lowe 1989), in both regions it is the very same fabric which was used for other metallurgical crucibles. The fabric of the crucibles from the large-scale bronze casting installations at Tissamaharama in the south of Sri Lanka, for instance, dating from the early first millennium AD (Weisshaar et al. 2001), is visually indistinguishable from the fabric of the Sri Lankan crucible steel crucibles of the 19th century. Similarly, most other crucibles we have seen so far from Uzbekistan, used for casting copper alloys and gold, are of the very same white or light brown firing clay as the crucible steel crucibles of the region. More archaeological and analytical information, however, is necessary to trace the origin of this interesting fabric; at present, it seems to appear without precedent across Central Asia around the 8th or 9th century. The similarity of this fabric to some of the proto-porcelain and stoneware of China is intriguing, and will provide stimulation for much further research, and speculation alike.

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