Cutting Edge Technology - The Ferghana Process of medieval crucible steel smelting

Th. Rehren & O. Papakhristu

Introduction

The Middle Ages saw a broad supremacy of Islamic culture over Western life and tradition. Following a rapid spread during the late seventh and early eighth centuries AD, Islam soon dominated the entire region from the westernmost parts of North Africa to Central Asia in the north-east, and the Sudan and Pakistan to the south. For many centuries to come, this resulted in geopolitical contact zones of the European West and the Islamic World throughout the Mediterranean, from Spain and Sicily to the Balkans, with repeated invasions of western forces into the eastern Mediterranean and the Middle East. The impact of Islamic culture on the development of science and medicine in Europe, and the transmission of the classical Greek heritage, has been immensely fruitful for the West, particularly through the coexistence of Islam, Judaism and Christianity in Spain and southern Italy. The most lasting legacy of this period in western perception of medieval Islam, however, appears to be based on the various military disasters Europeans experienced during the Crusades and the later struggles against Islamic expansion into eastern Europe: the allegation of Islam as a "Religion of the Sword" and the superiority of Arabic weaponry and particularly sword-making.

Despite the cutting edge reputation of their steel, dubbed damascus for its alleged origin from Damascus in Syria, and extensive research into its metallurgical properties, it still remains a matter of debate as to where and how the steel for these swords was actually made. Being merely a descriptive term in the first place, designating a particular pattern on the surface of the metal, there is general consensus that it was crucible steel which provided the superior toughness and quality of these swords, as opposed to the swords made in the West from piling and pattern-welding different types of iron. While the latter results in a laminated structure depending on the degree of mechanical reduction, twisting and the number of layers used, the former develops a finely layered structure through internal segregation into areas rich in cementite, interspersed with those dominated by ferrite or pearlite (Verhoeven & Peterson 1992). In order to avoid confusion, we propose to follow a suggestion made by P. Craddock (1995: 275-6) and others to call only material produced from crucible steel damascus and the former, pattern-welded steel damascene, in keeping with other surface ornamentation known under this name. A crucial reason for the better quality of true damascus steel is the very low amount of slag present in it, as a result of the complete separation of slag and metal in the liquid state. Pattern-welded steel, on the other hand, with the metal never having been liquid, still contains a significant amount of slag inclusions which make it more prone for cracking etc.

A flourishing trade in crucible steel ingots from India during the early Modern Period, and a wealth of ethnographic and archaeological reports from both India and Sri Lanka in the wake of British rule over the Indian subcontinent, led to the western perception of crucible steel making as a predominantly Indian tradition (Bronson 1986).

Gerd Weisgerber of the Deutsches Bergbau-Museum, Bochum should be congratulated for having stimulated (and edited) the first publication of a report of crucible steel production in medieval Central Asia, in modern Uzbekistan (Papachristou & Swertschkow 1993), based on the doctoral candidate dissertation by Papakhristu (1985). Shortly thereafter, a joint expedition of the Turkmen Academy of Science and the Institute of Archaeology, University College London, to medieval Merv identified the remains of crucible steel making there as well (Merkel *et al.* 1995, Feuerbach *et al.* 1998). With these reports, we have for the first time good archaeological evidence for the large scale production of crucible steel within the Islamic world, during the ninth to twelfth centuries AD, contemporary with the early crusades and pre-dating the Indian evidence by several centuries (but note the mid to late first millennium AD evidence from Sri Lanka; Wayman & Juleff 1999: 29). Historical and textual evidence for "Persian" crucible steel making during the early second millennium AD has been published in the seminal work by Allan (1979)

Metalla (Bochum) 7.2, 2000, 55-69

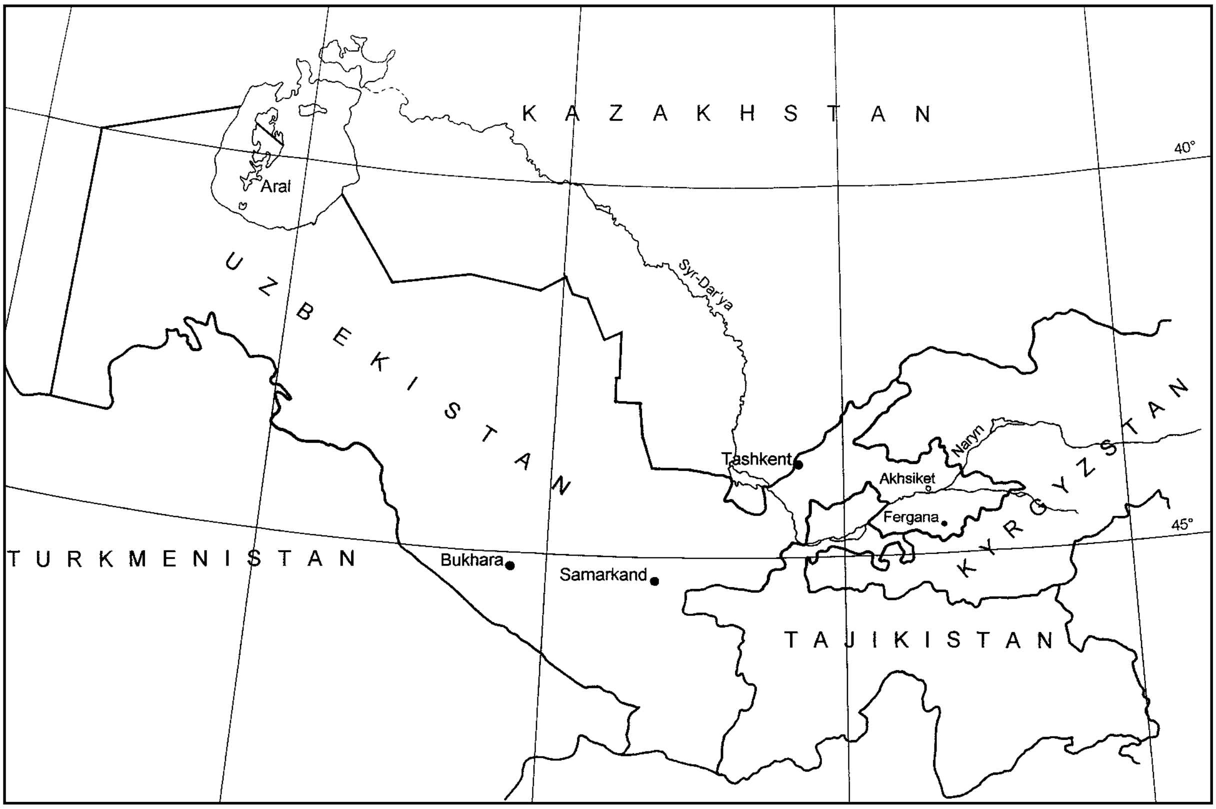


Fig. 1: Map of Uzbekistan. The Ferghana Basin is the easternmost part of the country, streching into Kyrgystan and Tajikistan.

Abb. 1: Karte von Uzbekistan, mit dem Fergana-Tal im äussersten Osten, angrenzend an Kirgistan und Tadschikistan.

on Persian metallurgy. We present now the first detailed metallurgical discussion of the material evidence for the smelting of crucible steel from Akhsiket in the Ferghana Valley in eastern Uzbekistan.

The Site

The Ferghana Valley comprises the easternmost part of modern Uzbekistan (Fig. 1), surrounded by the mountain ranges of the Chatkal-Tianshan to the north and east, and the Pamir-Altai to the south. These mountains provide a significant mineral wealth, while the fertile soils of the valley bear a rich agricultural production, supported by extensive irrigation systems. Ancient and medieval settlements followed the oases provided by the major river systems, draining the valley to the west through the Hungersteppe into the Aral Sea. The site of Akhsiket (Fig. 1) is the major, though not the only, crucible steel production site in the valley, situated on the northern banks of the Sir Darya. An archaeological and historical outline of Akhsiket and its situation within the Great Silk Road network is given in Papakhristu & Rehren (forthcoming).

The Material

The predominant material evidence for the crucible steel smelting process at Akhsiket is comprised of hundreds of thousands of crucible fragments, often with massive slag cakes adhering to the inside. The "standard" crucible as reconstructed by Papachristou and Swertschkow (1993) and Papakhristu and Rehren (in press) is roughly tubular with an external diameter of eight to nine centimetres, a length of some 25 centimetres and a hemispherical lid luted to the top (Fig. 2). The external profile of the base is flat to slightly arching, while the internal profile is hemispherical (Fig. 3). The wall thickness decreases from ten to fifteen millimetres near the base to eight to five millimetres at the top. The internal diameter of the crucibles of about seven centimetres is relatively constant along their length. The outside of the walls has a slight corrugation from the tool used in smoothing the surface (Fig. 4), while the inside shows a characteristic woven textile pattern (Fig. 5), probably from a sand-filled textile template around which the vessel was built (Papakristu 1985). The ceramic is highly refractory, fired to a light grey to almost white colour. It consists of a matrix of mullite,

Fig. 2: Side view of crucible lid fragment. Note the slight overlap of the lid at the left hand side, where it is luted to the body of the vessel with some additional clay.

Abb. 2: Seitenansicht eines Deckelfragmentes. Links ist zu erkennen wie der Deckel leicht über den Tiegel hinausragt und mit weiterem Ton verschmiert ist.

cristobalite and some glass with abundant fine quartz temper, resulting in a chemical composition of about two-thirds silica and one-third alumina, with less than one percent each of total alkalis, lime, and iron oxide (Papakhristu & Rehren in press). Experimental work has shown it to be heat resistant up to 1650 °C (Abdurazakov & Bezborodov 1966).

The most striking feature of these vessels is the slag cake. It is typically two to eight centimetres thick and situated fifteen to twenty centimetres above the base. Although the slag cakes appear to be solid, they are highly vesicular with on average half of their volume being made up of bubbles (Fig. 6). They range in diameter from a few millimetres up to two centimetres, indicating the relatively high viscosity of the liquid slag throughout the gas-producing process. The colour of the slag ranges from opaque brown, with many unreacted inclusions, to opaque grey and turquoise to bright blue and eventually translucent dark green. The proportion of inclusions, mostly angular white or brown stones of a few millimetres diameter, decreases along this sequence. The translucent green slag, in particular, often contains lumps of charcoal of one to two centimetres in length. It has to be noted, however, that these observations are based only upon a superficial inspection of surface finds at Akhsiket, and no statistical analysis of this tentative correlation of colours with inclusion frequency and type has yet been done.

An initial programme of chemical analyses of these slags was started at the Institut für Archäometallurgie of the Deutsches Bergbau-Museum, Bochum, to supplement the analyses published so far from an earlier Russian survey (Papachristou & Swertschkow 1993). The bulk compositions, determined by ICP-OES, cover a rather wide range, in particular for Al_2O_3 and FeO (3 to 15 wt% each), MnO (mostly 15 to 20 wt%, but some with as little as 10 wt%) and CaO (two groups with around 5 wt% and 15 wt% respectively). Clearly, these analyses are hampered by the varying amounts of unreacted stones mentioned above and also the frequent occurrence of ferrous metal prills trapped in the slag. As a result, the bulk compositions

Fig. 3: Cross section through a crucible base. Note the rounded internal profile and the network pattern of slag adhering to the inside.

Abb. 3: Querschnitt durch ein Bodenfragment eines Tiegels. Deutlich ist das rundliche Internprofil zu erkennen sowie das Netzwerk von Schlacke auf der Innenseite.

Fig. 4: Photograph of the external structure of a crucible, showing the corrugated appearance.

Abb. 4: Photo der Aussenseite eines Tiegels, mit deutlich erkennbarer Riefung.

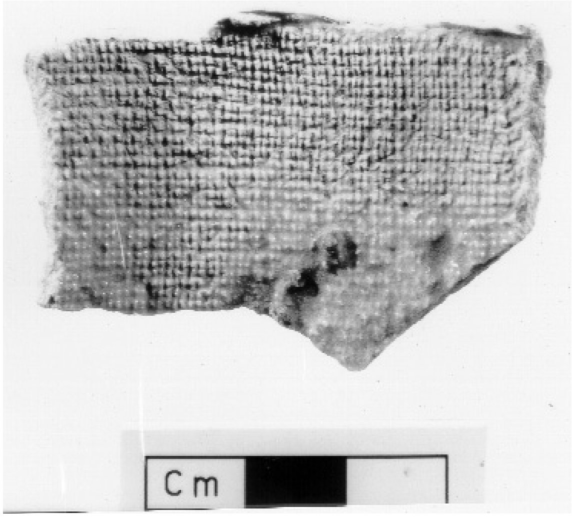


Fig. 5: Close-up of the textile pattern preserved on the upper inside of most crucibles. This is evidence for the building of these vessels around a textile template, probably filled with sand to facilitate removal (Papakristu 1985).

Abb. 5: Nahaufnahme des textilen Abdrucks auf der Innenseite, erhalten im oberen Bereich der meisten Tiegel. Dies Muster belegt die Formung der Tiegel um eine vermutlich sandgefüllte Form aus Stoff (Papakristu 1985).

Fig. 6: Cross section through a typical slag cake as preserved regularly in the upper third of most crucibles. Note the high porosity of this slag.

Abb. 6: Querbruch durch einen typischen Schlackenkuchen, wie er regelmässig im oberen Drittel der Tiegel erhalten ist. Zu erkennen ist auch die auffällige Porosität der Schlacke.

determined do not represent true melt systems. Therefore, inclusion-free areas of slag were analysed separately by SEM-EDS, resulting in a considerably tighter compositional field. The data now clusters around 60 wt% SiO_2, 20 wt% Al_2O_3, 15 wt% MnO, 3 wt% CaO, 2 wt% FeO and 1 wt% K_2O. Any values for a component in the bulk data significantly above these melt phase values are obviously due to inclusions, particularly metallic iron or steel and lime-rich stones. Bulk values for certain components lower than the melt phase values in turn represent the dilution of the compositionally complex melt phase by one- or two-component inclusions, thus enhancing the values for the one or two components at the expense of all the others.

Process Reconstruction

The substantial slag cake preserved at about three-fifth of the internal height is unique among the known finds of steel making crucibles. It suggested that the crucible charge in Akhsiket consisted of a significant proportion, if not entirely, of ore which had been smelted to metal within the crucible. This would be in stark contrast to all the other known crucible steel processes. In these, either bloomery iron and organic matter or a mixture of bloomery iron and cast iron were charged into the crucible, but no slag-forming materials beyond the odd additive of a bit of slag or glass found in some traditional recipes (Craddock 1995: 276). The idea of ore smelting was further reinforced by the nature of the slag, being similar in composition and colour to early blast furnace slags.

In an attempt to estimate the original grade, or iron content, of the crucible charge, a series of mass balance calculations were carried out, using as much direct information as possible. The directly available parameters were the volume and composition of the ingot and the slag cake, and the total volume of the crucibles (Fig. 7). The variables to be determined were mainly the iron content of the charge, and the amount of charcoal necessary to smelt the charge to steel. The limiting factor to the volume of the charge was given by the total volume of the crucible, based on the assumption that only the initial load of the crucible took part in the reaction, and that neither ore nor charcoal were added later during the process. Although the size of the central hole in the lid, typically about two centimetres in diameter, could theoretically have enabled such re-charging, it seems to be highly unlikely that this was actually done in practice, given the position of the crucible during the process in the furnace. For the sake of simplicity, and in view of the tentative character of this calculation, the crucible volume was taken as a cylinder ($V=\pi r^2 h$). Based on a typical internal radius r of three and a half centimetres and an internal height h of the crucible of 25 cm, this results in a total volume of about 960 cm^3. The volume

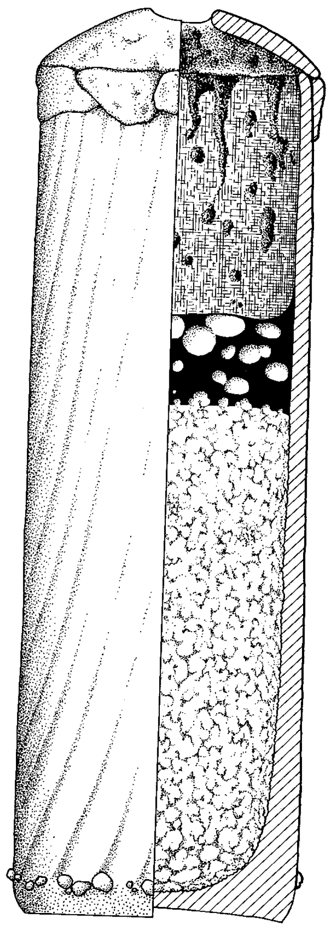


Fig. 7: The ideal crucible profile, as reconstructed from various fragments. The lid is domed with a central opening, and luted to the crucible proper with some additional clay at the side. The upper part of the crucible shows on its inside the textile pattern from its manufacture. The black area represents the slag cake, typically about 15-17 cm above the base. The inside of the crucible walls below this slag cake shows a typical network or honeycomb pattern of slag. The space beneath the slag cake is believed to have been filled with the original steel ingot, now removed. Both the underside of the slag cake and the pattern of the thin slag film on the lower inside walls confirms the former presence of a solidifying metal ingot there.
The outside of the crucibles is evenly covered by a thin glaze-like vitrification layer except for the very bottom end and the base, where the vessel apparently rested in a bed of gravel which absorbed any glaze formed in the firing process.
No scale given; the overall height of the entire vessel is about 25 to 28 cm.

Abb: 7: Idealprofil der Tiegel von Akhsiket, rekonstruiert nach verschiedenen Fragmenten. Der Deckel ist gewölbt und hat eine zentrale Öffnung; er ist mit zusätzlichem Ton mit dem Tiegelrand verschmiert. Der obere Teil des Tiegels zeigt an seiner Innenseite das Textilmuster von seiner Herstellung. Der schwarze Bereich im oberen Drittel stellt den Schlackenkuchen dar, der typischerweise rund 15-17 cm oberhalb der Sohle des Tiegels liegt. Die Innenseite der Tiegelwand unterhalb des Schlackenkuchens sowie dessen Unterseite zeigen ein charakteristisches Netzmuster als Abdruck, wo sich früher der Stahlbarren befand.
Die Aussenseite der Tiegel ist mit einer gleichmässigen 'Glasur' überzogen ausser unmittelbar am Boden, wo die Tiegel in einem Kiesbett standen, das die sich bildende Verglasung aufnahm.
Ohne Massstab; Höhe des Tiegels samt Deckel ca. 25 bis 28 cm.

of the ingot, *i.e.* the volume underneath the slag cake, seems to be fairly constant. The distance from the bottom of the crucible to the slag cake for all crucible fragments which have this part of the profile preserved is typically about 15 to 17 cm (Fig. 8). Taking 15 cm as a conservative estimate for h results in an ingot volume of about 580 cm^3, or an equivalent of about 4.5 kg of steel.

The typical slag cake volume is more difficult to estimate, due to the relatively wide range of total thickness, and the large volume proportion of vesicles in the slag. In assuming a vesicle-free slag cake thickness of two centimetres, a possible error in this part of the calculation of ca. 50 % relative has to be taken into account. This two centimetres thick solid slag cake equals about 75 cubic centimetres of slag. A further simplification had to be made for the compositions involved. Taking the ingot as pure iron neglects the one to two weight percent carbon which we have to assume for it. The error resulting from this is small when compared with the uncertainty regarding the slag volume and composition. Here, the melt phase composition as determined above was chosen, and no allowance was made for any contributions from the charcoal ash, and erosion of the ceramic body. The former will have affected in particular the lime and potash content of the slag, while the latter will have contributed primarily to the alumina content (Crew 2000). No allowance has been made for any flux addition.

Based on these parameters, several further approximations had to be made regarding the charcoal content of the charge. As mentioned above, the carbon content of the resulting steel ingot was ignored, as was the oxygen content of the air in the crucible, thus allocating all the carbon present in the charge for the simplified reduction process

$$FeO + C \rightarrow Fe + CO.$$

It appears relatively safe to assume that the oxidation of the carbon in the crucible was only to carbon monoxide, and not to carbon dioxide, considering that a high carbon steel was smelted. The assumption that all the iron oxide was present as FeO, the dominant iron phase found in the agglomerate (see

Fig. 8: Photograph of a large body fragment, showing the internal slag network and the remains of the slag cake near the upper part.

Abb. 8: Photo eines grossen Tiegelfragmentes mit dem Netzwerk von Schlacke auf der Innenseite und dem Ansatz des Schlackenkuchens im oberen Bereich.

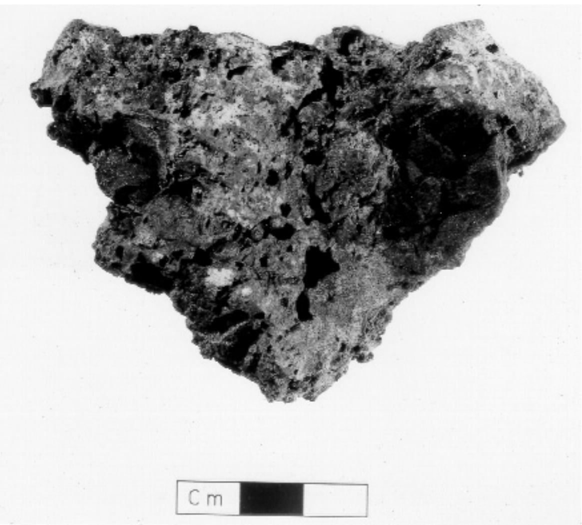
below), is also conservative for the resulting calculations of the charcoal volume in the charge. As a result, an amount of carbon matching exactly the amount of iron oxide necessary to smelt enough metal for a 580 cm^3 ingot was used for the calculations, assuming an ideal stoichiometric reaction. In accordance with other crucible reactions employing closed vessels, the entire energy required to keep the endothermic reaction going had to be provided from the outside, by heat transfer through the ceramic walls (Rehren 1997). Due to this separation of heat-providing burning of charcoal outside the crucibles from the chemically reactive carbon monoxide inside, the amount of charcoal used as fuel could be neglected as long as only the crucible content was discussed.

Smelting iron ore?

The site provided ample evidence for various possible raw materials used in such a crucible smelting process. The most suggestive of these is a coarse mixture of partly reduced iron oxide(s) and charcoal lumps (Fig. 9). It is similar in appearance, composition and microstructure to "furnace slag" in the sense of a semi-reduced furnace charge immediately above the reaction zone of a bloomery furnace, as described by the late Dietrich Horstmann (pers. comm.). This material, tentatively labelled "agglomerate" in previous publications on the Akhsiket material, would be an ideal crucible charge. Due to the initial preparation in a bloomery (or similar) furnace, most of its iron content is present as FeO and any silica-rich parts would already have been transformed into a low-melting fayalitic slag which would have been tapped and discarded (tap slag fragments occur in some amount at Akhsiket). This would have increased the iron content of the charge, and finally the large surface area of this agglomerate would allow a fast reaction, reducing the time which the crucible furnace would have to operate at maximum temperature. Smelting experiments, carried out in Kurgan, and using original agglomerate in a modern crucible, resulted in the production of a sound steel ingot, covered by a thin slag layer (Papachristou & Swetschkow 1993; Papakhristu 1995).

Fig. 9: Photograph of the 'agglomerate', a mixture of iron oxide, silicate slag, and coarse charcoal. This material is frequently found in Akshiket, but is likely not the original charge.

Abb. 9: Photo des 'Agglomerates', einer Mischung von Eisenoxid, Silikatschlacke und grober Holzkohle. Dies Material tritt in Akhsiket häufig auf, ist aber vermutlich nicht die Beschickung der Tiegel.



Tab. 1: Calculation of iron oxide concentration and volume ratios in the charge.

Tab. 1: Berechnung der Eisenoxid-Konzentration und der Volumenverhältnisse in der Tiegel-Charge.

FeO wt%	**Slag wt**	**Total 'ore' wt**	**Ore vol**	**C for FeO**	**Fe met wt**	**Fe met vol**	**Total vol of charge**
55	200	444	118	98	4309	552	768
60	200	500	128	120	4266	547	795
65	200	571	140	149	4210	540	829
70	200	667	157	187	4136	530	874
75	200	800	180	240	4032	517	937
80	200	1000	215	320	3876	497	1032

The spreadsheet demonstrates the relationship between the iron oxide content of the "ore" (see text for a definition of this term), and the volume implications of this on the resulting crucible charge. "wt" indicates weights in grams, "vol" indicates volume in cubic centimetres.

The column "Slag wt" gives the weight of the crucible slag cake as defined in the text, based on several dozen observations in the field. This slag contains only about 3 wt% FeO, which are neglected in the calculation, and consists mainly of silica, alumina and manganese oxide.
The next column "Total ore wt" gives the weight of "ore" which would contain the percentage of iron oxide specified in the first column, based on the set amount of 200 g non-FeO components. Obviously, the total weight of this "ore" has to increase with increasing FeO concentrations. "Ore vol" gives the volume of this hypothetical "ore", based on a density of 5.7 for its FeO component and 2.7 for the non-FeO component.
"C for FeO" gives the volume of charcoal necessary to bind the oxygen brought in with the FeO as CO, assuming exact stoichiometric reaction and a density of charcoal of 0.5 (which might be too high). As the amount of FeO increases with increasing FeO concentrations, the amount of charcoal necessary increases as well. The amount of pure FeO in the "ore" is the difference between the total "ore" weight, and the fixed slag weight of 200 g.
"Fe met wt" refers to the amount of iron which has to come into the charge in its metallic state, based on the set total iron output as an ingot of 4500 g, and taking into account the iron reduced from the FeO proportion of the "ore". Hence, this metallic input decreases with increasing FeO concentrations. "Fe met vol" gives the volume of this metallic input, using a density of iron of 7.8.
"Total volume of charge" gives the sum of the "ore" volume, charcoal volume, and metallic iron volume.
This value is compared to the "standard" volume of the crucibles, of 960 cm^3 (see text) based on the archaeological evidence. While an iron oxide concentration in the "ore" of nominally 77 wt% could be accommodated according to this table, one has to make allowance for non-ideal packing of the charge. Calculating a void space in the packed crucible of about 15 vol% reduces the available volume to 816 cm^3, indicating an iron oxide concentration in the "ore" of about 60 to 65 wt%. This value is more typical for bloomery slags than for iron ore, as discussed in the text.
The volume of this "ore" or bloomery slag is about 120 to 140 cm^3, while the metallic iron volume is about 540 to 550 cm^3, i.e. about four times as much. Thus, the volume proportion of "ore" or slag in the metal is about 20 percent or lower.

Beside this obvious candidate for the crucible charge, several samples of iron ore (magnetite and hematite) were also found at the site. This material, although almost pure iron oxide, would have been a less ideal charge due to its compact, dense nature, requiring laborious crushing and grinding before charging, and/or prolonged reaction time in the crucible to facilitate complete reduction. The presence of vanadium oxide, a common minor component in magnetite ore, and found in several of the crucible slag cakes, however, lends support to the magnetite hypothesis.

First scenario: smelting iron oxide
The major factor limiting the amount of metal which can be smelted in a closed crucible such as those found in Akhsiket is the volume of this crucible. The initial charge has to comprise all the oxide and charcoal necessary to produce the final metal ingot. The archaeological evidence from Akhsiket clearly shows that the metal ingots constantly had a volume of about 580 cm^3, while the overall crucible volume was typically 960 cm^3 (see above). Using the known volume of the metal ingot as a starting point for the calculation allows to determine the volume of iron oxide and charcoal needed to smelt this volume of metal:

- 4.5 kg iron metal (*i.e.* the final ingot) equal 5.8 kg iron oxide, containing 1.3 kg oxygen

- 1.3 kg oxygen in iron oxide require 1 kg carbon to form carbon monoxide.
- Assumed density of iron oxide is 5.7 g/cm^3 and of charcoal is 0.5 g/cm^3.

- The volume of 5.8 kg FeO is 1000 cm^3, and of 1 kg charcoal is 2000 cm^3.
- The total volume of the charge (1000 cm^3 + 2000 cm^3) is thus 3000 cm^3.

Comparing the result of this calculation to the average total volume of the crucibles of just below 1000 cm^3, it becomes obvious that the crucible charge could not possibly have consisted of iron ore, agglomerate or even pure iron oxide. The volume of the iron oxide alone is already more than the entire crucible can hold, and that already assumes an unrealistic tight packing of the iron oxide without any spaces or voids. In addition, twice that volume would have been necessary to hold the charcoal required to reduce the iron oxide to metal. Thus, this scenario can safely be ruled out, and it has to be concluded that the majority of the iron in the charge was already present in its metallic state. But what about the slag then? Where does it come from, and what can it tell us about the nature of the metal in the charge?

Second scenario: determining the initial slag volume
We have just seen that the bulk of the charge must have been metallic iron. The massive slag cakes, however, also imply that a slag-forming component contributed significantly to the charge. What is the maximum possible amount of this component, and how much iron oxide did it contain? In order to address this slag question, a series of calculations was done based on the assumption that all the slag found in the cake originated from the iron-bearing part of the charge, *i.e.*, again neglecting the contribution of fuel ash or ceramic, and not allowing for any flux. For the calculations, it is irrelevant whether this slag-producing part of the charge is real ore, a partly smelted product like the agglomerate, or bloomery slag trapped in the iron metal which was shown above to make up the bulk of the charge. To avoid confusion in terminology, it is necessary to redefine "ore" and "slag" for the remainder of this paper. "Ore" henceforth means that component of the charge, which is due to undergo a chemical reaction to form iron metal and a residual slag, while "slag" always refers specifically to the cake of crucible slag produced during this process.

Similar to the previous scenario, theoretical densities were used in the calculations, and a stoichiometric amount of carbon to match the assumed iron oxide ("ore") component is included. For the calculations, a constant amount of slag as found in the cakes, of 75 cm^3 or 200 g, was taken as a starting point to which multiples of its weight in FeO were added to give a theoretical composition of the initial "ore" of between 50 and 80 wt% FeO. Naturally, the weight and hence volume of this "ore" increased drastically with increasing FeO concentrations. Since the absolute amount of the non-ferrous component remained constant, 200 g of this slag equal 400 g "ore" with 50 wt% FeO, but 2000 g "ore" with 90 wt% FeO. In line with the increasing amount of iron oxide, the charcoal volume necessary to reduce the iron oxide to iron metal also increased in the same way. This significant increase in volume was only to a very limited extent compensated for by a decrease in the volume of the initial iron metal in the charge. This decrease in the initial metal volume of the charge was due to the increasing amount of metal smelted from the "ore" during the process. The calculations, borne out in Table 1, thus follow this algorithm: A fixed amount of slag (200 g) is charged with varying amounts of iron oxide to a hypothetical "ore" of various grades. The total volume of this "ore" is calculated, as is the amount of charcoal necessary to reduce the iron oxide to iron metal. The balance between this metal smelted in the crucible and the known metal volume of the final ingot is then calculated, and the volume of this metallic iron component in the charge is added to the volume of the "ore" plus charcoal. This results in a total volume of the charge, given in the last column in Table 1. The only variable to be tested in this calculation is the "ore" grade, expressed as wt% FeO. With fixed volumes for the crucible, and for the final slag and metal produced, there is a distinct mathematical solution to the equation.

Assuming a void-free packing of the charge, and a standard volume for the crucibles of about 960 cm^3, the highest possible iron oxide content of the "ore" fraction of the charge can be calculated at about 77 wt% (Tab. 1). Following a more realistic approach, however, and allowing for a void volume of at least 15 % of the total volume, brings the net charge volume down to less than 820 cm^3. The mathematical solution for this volume is about 60 to 65 wt% iron oxide in the "ore" component of the charge, which would occupy about one quarter of the volume of the metal in the charge (that is 20 % of the combined metal plus ore volume in the charge being "ore").

Interpretation

What good are all these theoretical calculations, and what do they tell us about the real charge in the medieval crucibles? A lot. Firstly, the initial assumption of a full smelting process, be it based on real ore or on the agglomerate, can be safely ruled out. Any charge of iron oxide, however pure, and charcoal would have required a far bigger volume than any of the crucibles from Akhsiket offers. Secondly, despite the dominating amount of iron metal in the charge, a still significant amount of iron oxide was part of the charge, certainly more than in other known crucible steel making processes. Finally, the estimated solution of the equations developed above supports, in particular, one of the various possibilities for the nature of the "ore"; namely that it was bloomery slag.

What are the possibilities? There is an upper limit of the iron oxide content of the slag-producing "ore" fraction of the charge, of about 60 to 65 wt%. If its FeO content would have been any higher, than the amount of charcoal necessary to reduce the iron oxide to iron metal would have been too much to fit into the crucible (see above). This material with about 60 to 65 wt% FeO could have been either a relatively bad ore, or some iron slag, or the aforementioned "agglomerate", being charged to the crucible together with four times its volume in iron metal. It will be discussed below that there are certain advantages in using as crucible charge an only partly consolidated bloom, still containing up to 20 % by volume bloomery slag, rather than a dense lump of iron which then was artificially "diluted" by adding ore, slag or "agglomerate".

This interpretation is also consistent with the relatively wide scatter of the final slag cake volume and at the same time the more tightly defined ingot volume. A wide variation in the initial bloomery slag volume ("ore" volume in Tab. 1) would translate into the same wide difference in crucible slag cake volume, while having a much more restricted effect in the final ingot volume. This is in good agreement with the archaeological evidence, indicating a much wider relative scatter in slag cake volume than in metal ingot volume. If, however, the charge had been an artificial mixture of solid iron metal and ore, slag or "agglomerate", one would probably expect a better control over the volume ratios in the charge, and hence a more tightly defined slag cake volume. In addition, it would make little sense first to consolidate the bloom in a series of charcoal-consuming and laborious smithing cycles, and oxidising a good deal of iron metal as hammerscale, only to dilute this iron billet then by adding ore, slag or "agglomerate". Finally, a slag-rich bloom has a much more suitable internal structure for the carburization process, namely a large surface area of the iron metal which, upon melting and reducing of the bloomery slag, becomes exposed to the carburizing carbon monoxide early on in the heating of the charge.

Decarburizing cast iron?

The theoretical possibility of the iron metal charge having been cast iron rather than bloomery iron is not pursued here for several reasons. First of all, there is no real evidence for cast iron technology in the

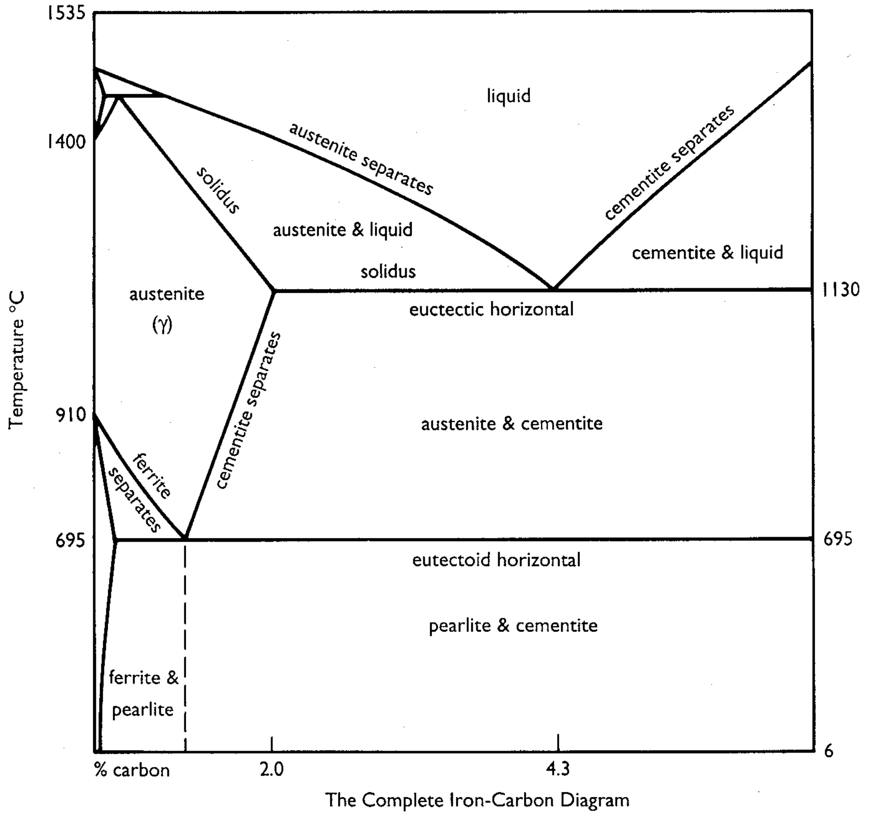


Fig. 10: Iron-carbon phase diagramme. Of particular importance for this discussion is the decrease in melting temperature with increasing carbon content from 1535 °C for pure iron to 1130 °C for iron with 4.3 wt% carbon.

Abb. 10: Eisen-Kohlenstoff-Diagramm. Hervorzuheben ist der Abfall der Schmelztemperatur mit ansteigendem Kohlenstoffgehalt, von 1535 °C für reines Eisen auf 1130 °C für Eisen mit 4.3 Gew% Kohlenstoff.

Fig. 11: Charcoal lumps (black) trapped in a glassy slag cake. The crucible wall (right) is overexposed to bring out the contrast between the dark slag and charcoal.

Abb. 11: Holzkohle-Einschlüsse in einem Schlackenkuchen. Die Tiegelwand rechts ist überbelichtet, um die Kontraste zwischen der dunklen Schlacke und der Holzkohle zu betonen.

region and at the time under discussion. Then, although it would be possible to decarburize cast iron by adding ore, slag or "agglomerate", the resulting carbon content would be difficult to adjust. Decarburizing cast iron results either in a "freezing" of the resulting metal due to the increase in melting temperature with decreasing carbon content of the alloy (Fig. 10), if there is too much oxidation, or in an incomplete decarburization, if there is not enough oxygen to burn off the carbon sufficiently. In the first case, the resulting product would be heterogeneous, as indeed it is described by several Chinese sources discussing decarburizing cast iron and the co-fusion of cast iron and wrought iron as conducted in mainland China (Needham 1980: 526 ff). In the other case, it would still be cast iron, and hence too brittle for smithing. Also, the primary cast iron would melt early in the process, and settle at the bottom of the crucible, while the iron oxide would float to the top, resulting in a slowing-down of any further reaction. Finally, there would be no reason to add charcoal to the charge at the same time, while we have ample evidence for charcoal in the charge, from preserved lumps in the crucible slag (Fig. 11).

Carburizing bloomery iron to steel, however, has several advantages over decarburizing cast iron. If the primary metal were low-carbon iron, it would retain its initial shape and hence its relatively high reactive surface area until it had absorbed enough carbon to melt. The liquid metal would collect at the bottom of the vessel, while the carburization of the remaining bloomery iron would continue until all the metal is liquid. Any residue, either surplus charcoal or residual "ore", would float with the crucible slag atop the metal bath. The slag layer would effectively prevent any contact of the liquid metal with surplus charcoal, hence preventing further diffusion of carbon into the metal and the inadvertent production of cast iron. If, however, the initial charcoal content of the charge was too low for the amount of iron oxide to reduce, and to carburize all of the iron to steel, the resulting ingot would obviously be incompletely molten, and could be returned at once for further treatment.

In this scenario, the final carbon content of the ingot would be controlled primarily by the temperature of the process, with a minimum of 1400 °C being necessary to obtain a fully liquid steel rather than cast iron. Raising the process temperature to 1500 °C would bring down the carbon content of the steel ingot to about 0.5 wt% (see Fig. 10). It is argued that it was easier to reproduce the maximum temperature to which a furnace of a given size and shape could be fired within, say, 50 °C, than adjusting the amount of iron oxide, cast iron, and charcoal in the charge precisely enough to end with a fully molten metal with not too much carbon in it. Without the possibility to determine the carbon content of the initial cast iron, and the FeO content of the "ore" , this letter alternative seems unlikely. Therefore, carburizing iron to steel results in a more homogenous, and therefore higher quality, steel than decarburizing cast iron. In addition, it allows a better quality control and reproducibility of the resulting product, inevitably necessary for the huge scale of production witnessed at Akhsiket.

The wider picture

The next step is to put this tentative crucible process reconstruction into the wider picture of the regional iron metallurgy, Central Asia's economic landscape, and the other crucible steel processes know from elsewhere. How do the peculiarities of this Ferghana process fit with other related data?

The two most prominent sites carrying the Ferghana Process are Akhsiket and Pap, both situated in the northern Ferghana Valley, about 30 km from the metalliferous Tianshan mountain range to the north. These mountains are known to have ancient smelting sites, and some areas are said to be deforested due to this past mining and smelting activity. The valley itself, fertile as its soils are, has a limited potential for fuel production, with tree growth traditionally being restricted to the oases along the river systems. It appears therefore reasonable to assume that the initial bloomery smelting, and possibly also the smithing of the blooms, took place in the northern mountains, and that the blooms were then brought to the urban valley sites for the second smelting step which transformed them into steel ingots. There are good reasons for this second step to have been done within the towns and cities, and not in the mountains. As a general rule, the more sophisticated and value-generating a process is, the more likely is it to be done in an urban context. More specifically, the decisive factor may have been the supply of the necessary highly refractory clay to build the crucibles - which were single-use vessels after all - and the furnace linings. Due to the extensive irrigation systems and agricultural development programmes of the last hundred years it is difficult, if not impossible, to survey the area for suitable clay deposits. It is, however, indicative that in the southern Ferghana Valley, near Kuva, there exists today a porcelain industry, based on local china clay. Based on these arguments - ease of transport of blooms from the mountains as opposed to carrying clay uphill, a well balanced fuel consumption pattern, the level of process sophistication, and finally the integration of the urban sites into the Great Silk Road trade network - the Ferghana Process appears very well suited to its regional setting.

Mention of the setting of the Ferghana Valley as part of the complex continental trade network commonly dubbed the Great Silk Road, moves the discussion beyond merely technical aspects. Based on the current state of excavations at Akhsiket, crucible steel smelting there thrived from the early ninth to the late twelfth centuries AD. This coincides with the heyday of the Islamic period in this region, starting with the Arab conquest of the southern Ferghana Valley during the first half of the eighth century and ending with the devastating Mongol invasion around 1220. Although this period of more than four hundred years was by no means a quiet and politically stable time, it provided enough stability for cities like Bukhara and Samarkand to develop extremely high cultural levels, and certainly enough organisation to arrange for both the supply of raw materials on a regional scale and the necessary "international" markets to absorb large quantities of steel ingots. It is estimated that the number of crucibles present in the archaeological strata of Akhsiket is well above 100.000. Taking the average weight of each ingot as 4.5 kg, this results in an average annual production of at least 1100 kg steel over a period of four hundred years for Akhsiket alone, certainly more than the local demand for this high quality material.

Other crucible steel making evidence

The full comparison of the Ferghana Process to crucible steel making traditions elsewhere in Central and South Asia is considerably hampered by the very limited information available for the latter, but a brief outline will be given here for both regions. Based on preliminary publications of the steel making crucibles from Merv in Turkmenistan, broadly contemporary to the early phase in the Ferghana Valley (Merkel *et al.* 1995), there flourished a process that produced much less slag, probably based on recycled iron scrap (Merkel *et al.* 1995) or the co-fusion of bloomery iron and cast iron (Feuerbach *et al.* 1998). The crucibles appear to be somewhat smaller than those from Akhsiket, and their lids are flat, not domed (Feuerbach *et al.* 1998: 40, Fig. 2). The ceramic, however, is very similar, having a highly refractory, light grey firing and alumina-rich body. The amount of slag generated in the crucible is just enough to produce a fin-like mark at the top end of the ingot, but far from resulting in a coherent slag cake as in Akhsiket. Obviously, the typical initial charge at Merv contained much less slag-forming material than at Akhsiket. It is to be hoped that the ongoing PhD research by A. Feuerbach will provide more analytical data to put the two Central Asian processes into relation to each other.

The South Asian processes, on the other hand, as described by ethnographic accounts and archaeological evidence from South and Central India, and central Sri Lanka, were based on the carburization of well consolidated bloomery iron by organic carbon. In order to provide the oxygen necessary to generate carbon monoxide as the main carburizing agent, the crucible fabric had to be sufficiently porous to allow air access. (In the Ferghana Process, this oxygen is provided by the iron oxide component of the charge.) Thus, the South Asian crucible steel or wootz crucibles were of a ceramic completely different from the Central Asian ones, being much smaller, black in appearance (e.g. Wayman & Juleff 1999: 28, Fig. 2), and heavily tempered with rice husk. This not only provided ample carbonaceous matter for reducing conditions throughout the vessel despite the porosity, but also a porous fabric rich in silica, *i.e.* highly refractory (Freestone & Tite 1986, Lowe *et al.* 1991). The charge of the Sri Lankan crucibles is well known from ethnographic accounts by Coomaraswamy (1908) to have been bloomery iron. This is in good accord with the archaeological record (Juleff 1998: 90-95; Wayman & Juleff 1999), showing only a faint slag fin along the inner circumference of these vessels, marking the level of the ingot surface. Thus, both the ceramic and the metallurgical tradition of the South Asian processes appear clearly separate from the Central Asian ones.

The last, though not least, question then is to determine the origin of the Ferghana Valley Process, and probably the other Central Asian crucible steel making traditions. Ongoing research by the authors of this paper is looking for possible connections to and developments from East Turkestan, modern Xinjiang in north western China. There is a rich extractive metallurgical tradition in that region, again based on the metalliferous Tianshan mountains, going back at least to the Iron Age (Mei 1999), if not earlier. Evidence for crucible steel making, though, is not known yet from Xinjiang, but little archaeometallurgical fieldwork has so far been done there. Other indications for an early and sophisticated iron metallurgy in East Turkestan are based on linguistic and palaeoethnic studies. A broader discussion of this subject, however, is beyond the scope of this paper.

Discussion

It has to be stressed that the interpretation of the archaeological and analytical evidence presented here for the crucible steel smelting process as conducted in the Ferghana Valley is based primarily on a study of the sizes and shapes of the crucibles. The volume estimate for the hypothetical steel ingot is thought to be correct to about 10 percent relative, while a larger error has to be accepted for the other volumes. Where possible, a conservative estimate has been made, assuming ideal conditions and complete use of the space available. In doing so, the volume proportion of the initial slag (or "ore") component of the charge has been rather overestimated than underestimated. The real values are hence likely to be lower, both in iron oxide content and volume proportion of the charge, arguing further against a significant contribution of real ore or the mentioned "agglomerate" and coming even closer to values one would expect from a raw or only slightly consolidated bloom. The same is true in assuming a rather high density of charcoal of 0.5, while 0.3 would probably be more realistic for coarse charcoal. Using this latter figure in the calculation brings the probable iron oxide content of the "ore" down to 50 to 55 wt%, accounting for about 15 percent of the charge volume.

Compared to the sound basis for the volume calculations, only a small number of slag analyses were available. The discussion of the chemistry of this process therefore has been very limited, and any interpretations in this respect had to be kept to a minimum. The calculations carrying the interpretation of this process as a second smelting step of a not fully consolidated bloom neglected in particular the frequently occurring "stones", or non-metallic inclusions, in the slag cakes, and the possibility of a fluxing component of the charge. The main reason for this is the lack of sufficient analytical data to characterise and interpret these inclusions. It can only be hoped that this data will rather sooner than later become available. Only then it will be possible to discuss whether they were intentionally added, probably as a flux, or were unintentional contamination. Similarly, the question of ceramic erosion and a charcoal ash contribution to the slag formation (Crew 2000) has still to be addressed.

An interesting alternative to the semi-consolidated bloom scenario presented above was brought up by P. Crew (letter dated 18.6. 2000). Based on experimental evidence, bloomery smelting produces not only slag and a dense, solid bloom, but often also a "crown" of (highly) carburised, slag-rich bloom which has to be removed before smithing. The archaeological equivalent of this has been reported as "gromps", a mixture of ferrite to high-carbon iron prills and slag (Nosek 1994). Such material, being of little use to the smith, but rich in iron metal and slag, could have been a suitable crucible charge for the Ferghana Process. There certainly is scope for further research into this sort of material, and its use or otherwise.

In view of the limitations of the present study, the proposed interpretation is open to discussion and modification as new information becomes available. The initial reason for this survey, and the trade mark of the Ferghana Process crucibles, is the substantial slag cake which solidified on top of the steel ingot. This cake exists in all the relevant crucible fragments studied so far, and distinguishes the Ferghana material from all other known crucible steel processes in Central and South Asia. Its existence alone is enough reason to single out this process, whatever interpretation for the origin of the slag cakes eventually emerges.

Conclusion

Archaeological work at Akhsiket over the last forty years, and preliminary scientific study of the material remains, has identified a crucible steel process based on the second smelting of slag-rich bloomery iron, together with some charcoal as a reducing and alloying agent of the charge. The initial slag content of the bloom as charged into the crucible was estimated to 20 vol% or less, based on mass balance calculations using a typical crucible of about 960 cm^3 total volume, a crucible slag cake of about 200 g weight and a produced steel ingot of about 580 cm^3 volume or 4.5 kg weight. This process appears to be typical of and restricted to the Ferghana Valley in eastern Uzbekistan, and it is therefore called the Ferghana Process. At present, the process can be dated to the early ninth to the late twelfth centuries AD, co-inciding with the Islamic rule over the region. Despite this link of the process to political and cultural domination from the west, it is thought that its origins lay elsewhere, probably in East Turkestan, modern Xinjiang in north west China. The period of Islamic rule, however, provided the economic and organisational infrastructure which allowed this process to thrive for roughly four centuries.

Future archaeological and analytical research will address the earliest beginnings of crucible steel smelting in the Ferghana Valley, the development and local peculiarities of the ceramic and metallurgical aspects of this process, the compositional range of the crucible slag, and the role and composition of the non-metallic inclusions in the slag cakes. It is anticipated that this latter aspect will result in a significant refinement of the reconstruction of the metallurgy involved, with the possible identification of a manganese-rich flux as indicated in several Islamic texts (Allan 1979), and the role of calcium-rich inclusions in controlling the slag chemistry.

Acknowledgement

The co-operation of the two authors of this publication - and others to be published elsewhere - was initiated by Professor Gerd Weisgerber of the Institut für Montanarchäologie at the Deutsches Bergbau-Museum Bochum. We are most grateful for his continuous interest, encouragement and advice over many years. Financial support for a study visit of Olga Papakhristu to Germany in the summer of 1999 was kindly provided through a travel grant by the Deutscher Akademischer Austauschdienst, Bonn, and for a visit of Thilo Rehren to the Ferghana Valley in early 2000 by the Gerda Henkel Stiftung, Düsseldorf. Both organisations are warmly thanked for this. A. Anarbaev, director of the Akhsiket Expedition of the Institute of Archaeology of the Uzbekistan Academy of Science in Samarkand is thanked for his generosity in allowing access to the archaeological data and material, mostly excavated by Olga Papakhristu during the seasons 1977 to 1989. Peter Crew contributed significant aspects to the interpretation and discussion with respect to the charge material, based on his experience with archaeological and experimental iron smelting and smithing. His willingness to share and discuss this on various occasions is deeply appreciated. Last, not least, Thilo Rehren is very grateful to Gill Juleff, now Exeter, for introducing him to the Sri Lankan crucible steel material during a field trip in 1996, with financial support by the Deutsche Forschungsgemeinschaft, Bonn, and to Justine Bayley and Vince Pigott for comments on and improvements made to the text.

Zusammenfassung

Die kulturelle Überlegenheit der islamischen Welt über Europa während des Mittelalters führte zu einer reichen Befruchtung der europäischen Kultur, vor allem auf medizinischem und wissenschaftlichem Gebiet. Bedeutende Zentren des Austauschs entwickelten sich vor allem in Gebieten anhaltender Koexistenz der beiden Kulturkreise in Spanien und Süditalien. Im kollektiven Bewußtsein des durchschnittlichen Europäers haben sich jedoch die oftmals leidvollen militärischen Erfahrungen mit der islamischen Welt im östlichen Mittelmeer und den Balkanländern im Gefolge der Kreuzzüge sehr viel tiefer eingeprägt. Dies manifestiert sich unter anderem in der Vorstellung des Islams als einer "Religion des Schwertes" und dem stark emotional besetzten, ja fast mystischen, Begriff des Damaszener Stahls. Trotz intensiver metallurgischer Studien zum Damast ist nach wie vor nahezu nichts bekannt über die eigentlichen Produktionsstätten und -methoden für dieses hochmittelalterliche Hochtechnologie-Material. Zusätzlich haben zahlreiche neuzeitliche Berichte über die Herstellung von Tiegelstahl in Indien und Sri Lanka den Blick in dieser Frage geographisch beträchtlich eingeengt. Mit dem vorliegenden Beitrag wird die umfangreiche Produktion von Tiegelstahl in Usbekistan während des 9. bis 12. Jahrhunderts n.Chr. vorgestellt und die ihr zugrundeliegende Metallurgie anhand archäologischer und analytischer Befunde und Überlegungen rekonstruiert.

Der Standard-Tiegel, definiert anhand zahlreicher Fragmente aus Akhsiket und Pap im Fergana-Becken im östlichen Usbekistan, ist rund 25 cm hoch, annähernd röhrenförmig mit einem Innendurchmesser von rund 7 cm und einer Wandstärke von 12 (Boden) bis 5 (Rand) Millimetern. Charakteristische Merkmale sind ein gewölbter Deckel mit einem zentralen Loch sowie ein massiver Schlackenkuchen etwas oberhald der Mitte des Tiegels. Die Morphologie dieses Schlackenkuchens sowie die Textur der Tiegelinnenwände unterhalb und oberhald des Kuchens belegen, daß der untere Teil des Tiegels bis zu einer Höhe von regelmäßig rund 15 cm von einem Stahlbarren ausgefüllt wurde, dessen Kohlenstoffgehalt anhand verschiedener Kriterien auf 1-2 Gew% geschätzt wird. Das Gewicht dieses Barrens dürfte etwa 4.5 kg betragen haben.

Anhand umfangreicher Massenbilanzrechnungen und Volumenabschätzungen wird im Hauptteil der Arbeit entwickelt, daß die Tiegelfüllung vermutlich aus einer nur wenig verdichteten Rennofen-Luppe mit einem restlichen Schlackengehalt von maximal 20 vol% sowie Holzkohle bestand. Im Verlauf des Prozesses reagierte der Schlackenanteil der Luppe mit der Holzkohle, so daß das Eisenoxid in der Schlacke praktisch vollständig zu Metall reduziert wurde. Gleichzeitig wurde in der stark reduzierenden Tiegelatmosphäre das Luppeneisen zu Stahl aufgekohlt, der bei der Prozeßtemperatur von etwa 1400 °C flüssig vorlag und so eine vollständige Trennung von Metall und verbleibender Schlacke erlaubte. Diese Tiegelschlacke ist ihrer Pauschalchemie nach einer frühen Hochofenschlacke sehr viel ähnlicher als einer Rennofenschlacke, was sich in den vorherrschenden bläulich-grünlichen Farben der Schlackenkuchen wiederspiegelt. Unterschiede in den primären Schlackengehalten der Luppe führen zu den beobachteten stark unterschiedlichen Schlackenvolumina in den Tiegeln, während zugleich das Volumen der erzeugten Stahlbarren nur in wesentlich engeren Grenzen variierte. Insgesamt stellt sich der Prozeß, der wegen seiner geographischen Verbreitung als Fergana-Prozeß bezeichnet wird, als zweites Schmelzen nach einer traditionellen Eisenverhüttung im Rennofen dar. Er steht somit in deutlichem Unterschied sowohl zu dem Zusammenschmelzen von Schmiede- und Gußeisen ("co-fusion" nach Needham 1980: 526ff; "Persian Process" bei Feuerbach *et al.* 1998) als auch zum Aufkohlen von Schmiedeeisen, wie es vorwiegend im Indischen Subkontinent praktiziert wurde ("Indian" oder "Wootz Process"; Lowe *et al.* 1991; Guleff 1998; Wayman & Guleff 1999; Feuerbach *et al.* 1998).

Eine Betrachtung des weiteren wirtschaftsgeographischen Umfelds, in dem sich dieser Prozeß entwickelte, zeigt die enge Einbindung in und Optimierung auf ein komplexes überregionales Netzwerk von Rohstoffversorgung, Wertschöpfung und weitreichendem Handel. Trotz einer massiven Bindung an die wirtschaftlichen und politischen Bedingungen zur Zeit der islamischen Herrschaft über dieses Gebiet Zentralasiens wird vermutet, daß die Ursprünge dieser hochstehenden und sehr spezifischen Metallurgie weiter östlich zu suchen sind, eventuell in Ost-Turkestan, dem heutigen Xinjiang in nordwest China.

Offene Fragen betreffen vor allem die zeitliche und räumliche Entwicklung und Verbreitung des Prozesses sowie Details der Schlackenbildung im Tiegel, insbesondere unter Berücksichtigung der zahlreichen nicht durchreagierten mineralischen Einschlüsse in der Schlacke. Hierzu laufen archäologische und analytische Arbeiten, die in Zusammenarbeit der beiden Archäologischen Institute der Usbekischen Akademie der Wissenschaften in Samarkand und des University College London durchgeführt werden.

Authors' addresses

Dr. Olga Papakhristu, Institute of Archaeology, Academy of Sciences of Uzbekistan, Samarkand.

Prof. Dr. Thilo Rehren, Institute of Archaeology, University College London, 31-34 Gordon Square, London WC1H 0PY, Great Britain.

Bibliography

Abdurazakov, A. & Bezborodov, M. (1966): *Medieval glasses from Central Asia.* Tashkent.

Allan, J. (1979): *Persian Metal Technology 700 - 1300 AD.* Ithaca Press, London.

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

Coomaraswamy, A. (1908): *Medieval Sinhalese Art.* Pantheon Books, New York, 3rd ed. 1979.

Craddock, P. (1995): *Early Metal Mining and Production*. Edinburgh University Press, Edinburgh.

Crew, P. (2000): The influence of clay and charcoal ash on bloomery slags. In: C. Cucini Tizzoni & M. Tizzoni (Eds.), *Iron in the Alps. Deposits, mines and metallurgy from antiquity to the XVI century*, Breno, 38-48.

Feuerbach, A., Merkel, J. & Griffith, D. (1998): An examination of crucible steel in the manufacture of Damascus steel, including evidence from Merv, Turkmenistan. In: Th. Rehren *et al.* (Eds.), *Metallurgica Antiqua*, (=Der Anschnitt, Beiheft 8), Bochum, 37-44.

Freestone, I. & Tite, M. (1986): Refractories in the ancient and preindustrial world. In: W. Kingery (Ed.), *High Technology Ceramics - Past, Present and Future* (=Ceramics and Civilization 3), Columbus, Ohio, 35-63.

Juleff, G. (1998): *Early Iron and Steel in Sri Lanka - A Study of the Samanalawewa Area.* AVA Materialien 54, Verlag Zabern, Mainz.

Lowe, Th., Merk, N. & Thomas, G. (1991): An historical mullite fibre-reinforced ceramic composite: Characterization of the 'Wootz' crucible refractory. In: P. Vandiver *et al.* (Eds.), *Materials Issues in Art and Archaeology II* (=Materials Research Society Vol. 185), 627-632.

Mei, J. (1999): *Copper and Bronze Metallurgy in Late Prehistoric Xinjiang: Its Cultural Context and Relationship with Neighbouring Regions.* PhD dissertation, University of Cambridge.

Merkel, J., Feuerbach, A. & Griffith, D. (1995): Analytical investigation of crucible steel production at Merv. *IAMS* 19, 12-13.

Needham, J. (1980): The evolution of iron and steel technology in east and southeast Asia. In: Th. Wertime & J. Muhly (Eds.), *The Coming of the Age of Iron*, Yale University Press, New Haven and London, 507-541.

Nosek, E. (1994): The metallography of gromps. In: M. Mangin (Ed.), *La siderurgie ancienne de l'Est de la France dans son contexte europeen.* Annales litteraires de l'Universite de Besancon 536, Paris, 65-73.

Papakhristu, O. (1985): *Black metallurgy of Northern Fergana on materials of archaeological investigation at the fort of Akhsiket of the IX to early XIII centuries.* Abstracts of the Candidate of History Dissertation, Moscow.

Papakhristu, O. (1995): Experience of reconstruction of ferrous crucible metallurgy in Akhsiket (IX-XII cc). *Obshestvennye nauki v Uzbekistane* 9, 86-90.

Papakhristu, O. & Rehren, Th. (in press): Techniques and technology of the manufacture of ceramic vessels - crucibles for smelting wootz in Central Asia. *EMAC '99 Proceedings*, Athens.

Papachristou, O. & Swertschkow, L. (1993): Eisen aus Ustruschana und Tiegelstahl aus dem Fergana-Becken. *Der Anschnitt* 45, 122-131.

Rehren, Th. (1997): *Tiegelmetallurgie - Tiegelprozesse und ihre Stellung in der Archäometallurgie*. Habilitationsschrift, TU Bergakademie Freiberg.

Verhoeven, J. & Peterson, D. (1992): What is Damascus steel? *Materials Characterization* 29, 335-341.

Wayman, M. & Juleff, G. (1999): Crucible steel making in Sri Lanka. *Historical Metallurgy* 33, 26-42.